
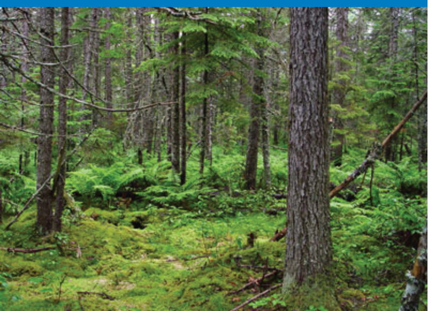


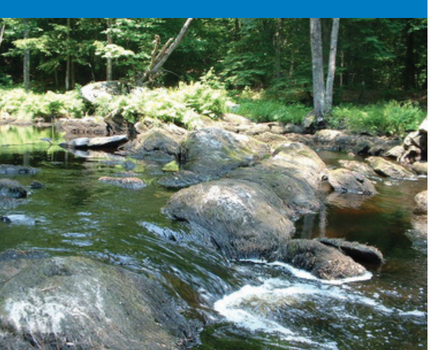

CLIMATE CHANGE AND MASSACHUSETTS FISH AND WILDLIFE:

Volume 1
INTRODUCTION AND BACKGROUND

Manomet Center for Conservation Sciences
&
Massachusetts Division of Fisheries and Wildlife
An Agency of the Massachusetts Department of Fish and Game

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A Report to the Commonwealth of Massachusetts

TABLE OF CONTENTS

1. INTRODUCTION

Although it is a small state and highly developed, Massachusetts retains an impressive level of biodiversity, with over 1,500 plant species, 221 breeding bird species, 46 reptiles and amphibians, 85 mammals, and 5,000-7,000 invertebrates (Biomap, 2001). Much of the credit for the successful conservation of these resources goes to the state's Division of Fisheries and Wildlife (DFW) within the Department of Fish and Game, as well as to federal (particularly the U.S. Fish and Wildlife Service) and non-governmental agencies, including The Nature Conservancy (TNC), the Massachusetts Land Trust Coalition, the Massachusetts Audubon Society, the New England Wildflower Society, The Trustees of Reservations, and others. Approximately 17% of the total state area is now protected by these and other agencies.

The statistics cited above testify to the success that Massachusetts conservation agencies have had in preserving biodiversity from traditional stressors such as habitat destruction, contaminants, invasive species, etc. However, in the last three decades, an important new stressor, climate change, has been recognized. Given the key role of climate in determining the distribution and abundance of organisms, climate change has the potential to inflict major impacts on Massachusetts' biological communities and species. Indeed, we are already seeing clear climate change impacts on ecosystems and species in North America and elsewhere (Parmesan and Galbraith, 2004; Root *et al.*, 2003; Parmesan and Yohe, 2003). If we are to continue to protect valued ecological resources in Massachusetts under climate change, four urgent conservation questions need to be addressed:

1. How vulnerable are Massachusetts' ecological resources (i.e., habitats and species) to climate change?
2. How will the distribution, composition, and condition of these resources be affected?
3. What are our options for managing change and preserving valued resources?
4. How should we plan future land acquisition strategies under climate change?

When these questions have been answered, we then need to integrate climate-change-specific management tools and policies into the overall suite of strategies and tools with which we have successfully conserved important resources in the past.

Funded by a grant from the Wildlife Conservation Society, Manomet Center for Conservation Sciences began working in early 2008 with the DFW and other partners, including TNC, to begin to address the conservation questions raised above. Our specific objective was to make "climate-smart" the state's existing State Wildlife Action Plan (SWAP) – DFW's "blueprint" for future conservation in the state. We are presenting the results of this project in a series of reports. This first report provides background to the project by describing how biodiversity conservation is currently carried out by DFW; the history, objectives, and methods of the SWAP; and how the climate in Massachusetts has been changing and is expected to change over the remainder of this century. In subsequent reports, we address habitat and species vulnerabilities, likely ecological shifts under climate change, and potential management/conservation options.

2. CONSERVATION OF MASSACHUSETTS' BIODIVERSITY

The Massachusetts Division of Fisheries and Wildlife, founded in 1866, is the designated steward of "all wild amphibians, reptiles, birds, mammals, and freshwater and diadromous fishes in the state, including endangered, threatened, and special concern species, and all native wild plants and invertebrates" (DFW, 2008). As the steward, the DFW engages in multiple activities for the protection and conservation of the Commonwealth's biodiversity: research, management, land protection, monitoring and restoration, public recreation and education, and regulation of possession or use of wildlife (DFW, 2008). The DFW operates via three research arms: Fisheries, Wildlife, and the Natural Heritage and Endangered Species Program (NHESP). The Fisheries and Wildlife divisions are game/sport-oriented, yet their activities benefit many non-game species. NHESP is the primary vehicle for management of endangered, threatened and special concern species in the Commonwealth. The DFW is the author or coauthor of several fundamental reports on biodiversity and land protection in the Commonwealth:

Natural Heritage Atlas. The Natural Heritage Atlas is the statewide delineation of the boundaries of Priority Habitats and Estimated Habitats. It reflects the latest state-listed species data, understanding of species biology and habitat requirements, and GIS technology and data. Per the Massachusetts Endangered Species Act (MESA; M.G.L. ch. 131A) and its regulations (321 CMR 10.00), the Director of the DFW determines whether or not a plant or animal merits state listing (Threatened, Endangered, Species of Special Concern) and, at least every 5 years, reviews the status of each listed species. Priority Habitat is the “mapped geographical extent of known habitat for all state-listed rare species” (DFW, 2008). Habitat alteration within Priority Habitat is subject to review by the NHESP under the regulations. All of this information is readily available to the public in the form of maps and other publications.

Our Irreplaceable Heritage. Although now a decade old, this report was a thorough survey of the Commonwealth’s rare species and natural communities (Barbour *et al*., 1998). The authors report 16% of native species to be state-listed Endangered, Threatened, or Special Concern. These listed species are disproportionately distributed across the state, the majority being found in the Taconic Mountains, Western New England Marble Valleys, Connecticut River Valley, and Cape Cod and Islands ecoregions. The authors, arguing for a community or ecosystem approach to conservation, identify eight natural communities – coastal, maritime sandplain, coastal plain pond, barrens, riverine, acidic peatland, vernal pools, calcareous wetlands – as “conservation targets for protecting rare plants and animals” in the Commonwealth (Table 1). Collectively, these communities host 70% (296/424) of the state-listed species and, in addition, provide habitat for many common species.

BioMap and *Living Waters.* The goal of the *Biomap* was “to produce a statewide map designed to guide the protection of Massachusetts biodiversity” (Biomap, 2001). To achieve this, the NHESP reviewed their database to determine which rare plant and animal populations and natural communities are most viable (i.e., have long-term persistence). NHESP then created a map of these populations and communities, referred to as “Core Habitat.” In addition, *Biomap* identified “Supporting Natural Landscape,” defined as “the most intact lands adjacent to and near Core Habitat.” The results indicate that 23% of Massachusetts (1,160,000 acres) is Core Habitat, and 19% (970,000 acres) Supporting Natural Landscape; this represents 246 and 129 species of rare plants and animals, respectively, and 643 occurrences of natural communities. As of the publication of *Biomap*, 14% of Core Habitat and 15% of Supporting Natural Landscape remained unprotected.

To augment the *BioMap*, in 2003 the NHESP completed *Living Waters*, a guide for the “management and stewardship of [freshwater] natural resources and a tool [to inform] land protection” (NHESP, 2003). To identify these areas, NHESP organized existing information, conducted surveys to document species occurrences, and evaluated sites for their ability “to support intact freshwater communities.” The program then identified Core Habitat and Critical Supporting Watersheds. A notable difference between Supporting Natural Landscape and Critical Supporting Watershed is that the latter incorporates threats to biodiversity (e.g., agricultural development, percentage of impervious surface, sediment pollution). From the union of the *BioMap* and *Living Waters*, 35% of lakes and ponds and 34% of river and stream miles are considered “important for the protection of biodiversity.”

The State Wildlife Action Plan. The most recent addition to conservation planning in Massachusetts is the Comprehensive Wildlife Conservation Strategy, also known as the State Wildlife Action Plan (SWAP;

DFW, 2005). Title IX of the Commerce, Justice, State Appropriations Act (Wildlife Conservation and Restoration Account) and Title VIII of the Interior Appropriations Act (Land Conservation, Preservation, and Infrastructure Improvement), via the Wildlife Conservation and Restoration Program and the State Wildlife Grants Program, respectively, provide funding opportunities to states "to enhance fish and wildlife conservation and restoration" (U.S. Fish and Wildlife Service, 2001). The intent is to "identify the wildlife species that need proactive attention in order to avoid additional formal protections [i.e., Threatened or Endangered status]" (Association of Fish and Wildlife Agencies, 2008). To be eligible for funds, states submit "comprehensive wildlife conservation strategies" to the U.S. Fish and Wildlife Service, the grant administrator. The Service requires states to incorporate eight elements in their plans: 1) the "diversity and health of wildlife"; 2) the "extent and condition of wildlife habitats"; 3) threats to species and natural communities; 4) a plan of action; 5) a monitoring program; 6) a mechanism for plan review; 7) provisions for collaboration; and 8) provisions for public participation (U.S. Fish and Wildlife Service, 2001).

With a strong "commitment to conserving biodiversity" and a preexisting non-game program, the DFW approached the Massachusetts SWAP as a mechanism to unite individual components of the non-game program and the Division as a whole (John O'Leary, DFW, pers. comm.). The plan serves as an umbrella, and, as such, incorporates *Our Irreplaceable Heritage*, *BioMap*, and *Living Waters* as the "basis for identifying a broader list of species in greatest need of conservation, highlighting the habitats they require, identifying threats to the species and their habitats, listing additional information needs to be addressed through survey and research, and, finally, developing conservation strategies and monitoring efforts to ensure their continued existence" (DFW, 2005). The SWAP, written by DFW staff, is a wide-reaching, habitat-based framework for biodiversity conservation in Massachusetts. It serves as both an appraisal, internal and external, of DFW activities and as a vision for future action (John O'Leary, DFW, *pers. comm.*). Further, it informs local and regional planning. In addition to the State Wildlife Grant money (<$1 million annually), the plan is a platform to attract other organizations to collaborate with the Division of Fisheries and Wildlife. The plan is the reference point for wildlife management in the state and knowledge of its framework is an essential first step in conservation initiatives.

The state's SWAP identifies the following as species in greatest need of conservation (DFW, 2005): 1) all federally Threatened and Endangered species; 2) state-listed Threatened, Endangered, and Special Concern species; 3) globally rare species (Nature Serve, G1-G3, September 2004); 4) a draft list of vertebrates and mussels of regional conservation concern; 5) Partners in Flight Tier I conservation priority list species; 6) populations in decline from the North American Breeding Bird Survey; 7) U.S. Shorebird Conservation Plan Species of High Concern; 8) North American Waterbird Conservation Plan Species of High Concern; 9) At Risk Breeding Species (birds); 10) declining game bird species; 11) mammals with large home ranges (Black Bear, Bobcat, Moose); and 12) Black Racer and Sea Lamprey (resulting from the public comment period). Although it lists the aforementioned species, the state's SWAP assumes a habitat approach to wildlife conservation. Hence, the authors identify six large-scale, nine medium-scale, and seven small-scale habitats as important for species in greatest need of conservation (Table 1).

Table 1. The 22 habitats identified in the Massachusetts State Wildlife Action Plan as important for the species in greatest conservation need.

Large-Scale Habitats	Medium-Scale Habitats	Small-Scale Habitats
Connecticut River and Merrimack River Mainstems	Small Streams	Vernal Pools
Large and Mid-sized Rivers	Shrub Swamps	Coastal Plain Ponds
Marine and Estuarine Habitats	Forested Swamps	Springs, Caves and Mines
Upland Forest	Lakes and Ponds	Peatlands and Associated Habitats
Large, Unfragmented Landscape Mosaics	Salt Marsh	Marshes and Wet Meadows
Pitch Pine/Scrub Oak	Coastal Dunes, Beaches, and Small Islands	Rocky Coastlines
	Grasslands	Rock Cliffs, Ridgetops, Talus Slopes, and Similar Habitats
	Young Forest and Shrublands	
	Riparian Forest	

The SWAP identifies the major stressors that currently threaten wildlife habitats in Massachusetts, including habitat destruction and fragmentation, invasive species, and contaminants. However, it does not deal with the potential implications of climate change for conservation in the state in any detail, except to say that it is an important issue and needs further evaluation. The objective of our Wildlife Conservation Society-funded project is to provide that further evaluation and thereby increase the future relevance of the Commonwealth's SWAP.

3. CLIMATE CHANGE IN MASSACHUSETTS

The evidence that the planet is in an era of rapid climatic change is unequivocal. Since 1900, global mean temperatures have risen by about 1.3^{o}F and are now higher than they have been for at least the last 600 years, with 12 of the 13 years between 1995 and 2007 being the warmest recorded since instrumental record-keeping began (IPCC, 2007). The Intergovernmental Panel on Climate Change (IPCC, 2007) has concluded that anthropogenic emissions of greenhouse gases are playing a major role in driving planetary warming, and that temperatures will continue to rise so long as emission rates are not reduced from their present high levels. Nevertheless, greenhouse gas global emission rates continue to increase – by 70% between 1970 and 2004. Best projections for future change are that under a conservative scenario of a doubling (above pre-industrial levels) of atmospheric CO_2, global mean temperatures are likely to increase by a further 2º-5ºF by 2100. The pre-industrial atmospheric CO_2 level was approximately 275 ppm and the current level is approaching 390 ppm, so we are well on the way to a doubling. A tripling of CO_2 would result in a global mean annual temperature increase of about 4º-11ºF by 2100 (IPCC, 2007). IPCC (2007) predicts "major changes in ecosystem structure and function…" if global mean temperatures increase by 2.7º-4.5º.

3.1 The Paleoecological Context

Since the end of the last glacial period, the climate of New England has been in a state of flux, resulting in marked changes in the status and distribution of vegetation. In the Younger Dryas (14,500 to 11,500 yr bp), as continental ice sheets retreated and arctic air masses prevailed, a forest-tundra landscape was characteristic of the region (Foster *et al.*, 2004), dominated by spruce (*Picea*) and pine (*Pinus*) (Oswald *et al.*, 2007). Around 11,500 yr bp, there was an abrupt shift in climate as rapid temperature increase and declining moisture availability initiated a shift in regional vegetation: *Picea* abundance declined, while pine and oak (*Quercus*) increased. Likely in response to a moderate increase in water availability, ~10,500-9,500 yr bp, white pine (*Pinus strobus)* decreased in regional abundance and hemlock (*Tsuga canadensis*) became more prevalent (Oswald *et al.*, 2007).

Another major climatic event, a post-glacial cooling 8,200 years ago, further influenced regional vegetation. In this period, moisture availability increased in the region and, in response, birch (*Betula*), beech (*Fagus*), and hemlock (*Tsuga*) replaced *Pinus* populations (Shuman *et al.*, 2001; Shuman *et al.*, 2002). Subtle climatic changes may also influence vegetation patterns: between 5,500 and 3,000 years ago, dry conditions and insect activity/disease contributed to a decline in *Tsuga* populations (Shuman *et al.*, 2001). A period of cool, moist conditions (3,100 years ago to present), resulted in the recovery of *Tsuga* and the expansion of chestnut (*Castenea*) and *Picea*, eastward and southward, respectively. More recently, anthropogenic activities have largely influenced landscape composition (i.e., a cultural landscape) and “mask the environmental gradient that has controlled regional vegetation patterns during much of the Holocene” (Oswald *et al.*, 2007).

The paleological changes described above show that the distribution and composition of major vegetation communities in New England are largely a function of climate (with anthropogenic influences increasing in importance since the European colonization). Although the origin and projected rate of current climate change are unlike any other period in Earth’s history, the reconstruction of the past vegetation record indicates that additional large-scale changes and disruptions are likely under global climate change.

3.2 The Current New England Climate

Latitude, coastal orientation, and topography are the most influential factors on New England climate (Zielinski and Keim, 2003). Solar radiation and hours of daylight, both influential to a temperature regime, vary by latitude; for this reason, southern Massachusetts experiences warmer temperatures than northern Maine. Secondly, the Atlantic Ocean moderates temperature, and the region does not experience extreme temperatures like the Midwest. Additionally, the Labrador Current and the Gulf Stream converge near the southeastern tip of Cape Cod and influence the spatial variability in the New England climate; for example, the southern shore of New England is considerably warmer than the northern shore. Finally, there is great variation in elevation in the region, from sea level to thousands of feet above sea level; mountains exert a strong influence on temperature, precipitation, and wind patterns locally and in the surrounding region. The result of this interplay of latitude, coastal orientation, and topography is a “very complex” climatic pattern in New England (Zielinski and Keim, 2003).

3.3 Climate Change in the Northeastern United States

The Northeast Climate Impacts Assessment

In 2005, the Northeast Climate Impacts Assessment (NECIA), a collaboration between climate experts and the Union of Concerned Scientists, began an evaluation of climate change and associated impacts in the northeastern United States. It is arguably the most comprehensive assessment of climate change for a region in the U.S. Technical papers and synthesis reports are available at (http://www.northeastclimateimpacts.org). NECIA (2006) notes that “changes consistent with global warming are already underway across the Northeast” . In Appendix A, we present the most recent findings of the NECIA in the context of global patterns. The NECIA findings are the foundation of our review of projected climate change in the state and, in that section, we review the resource in more detail.

The Commonwealth of Massachusetts: 1957-2006

To evaluate recent patterns in the Massachusetts climate, we employed The Nature Conservancy's *Climate Wizard*, a web-based tool to support "free and open sharing of climate information and knowledge" (http://www.climatewizard.org/). Our resource for historical climate data is the Oregon State PRISM Group (Daly *et al.*, 1999). PRISM (Parameter-elevation Regressions on Independent Slopes Model) is a statistical-geographical interpolation method to generate gridded estimates of temperature and precipitation (Daly *et al*., 2008). The method, regression-based and expert-guided, integrates point data (National Weather Service cooperative network, Natural Resources Conservation Service SNOTEL network, and local networks), digital elevation models, and additional datasets to produce GIS-compatible estimates; in addition to location and elevation, the method accounts for coastal proximity, topographic orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain (Daly *et al.*, 2008). The PRISM process is flexible, open-ended, and subject to extensive peer review (Daly and Johnson 1999; Daly *et al.*, 2008).

As the foundation for PRISM data, the spatial and temporal distribution of Cooperative Weather Station Network is an important consideration for analysis. From a survey of station history, few stations were active in Massachusetts pre-1948; however, by 1960, most stations were online. For this reason, we analyzed climate data (temperature: mean, maximum, minimum and total precipitation) for the most recent fifty years (1957-2006). This time period is important for two additional reasons: 1) it serves as a reference time period for the IPCC; and 2) it includes the period of notable warming (IPCC, 2007).

Observed Patterns in Temperature and Precipitation

The linear trend in temperature in Massachusetts during the last century was +0.011°C per year (Figure 1). The rate of increase was not constant but accelerated during the post 1960s period, when the 50-year linear trend in annual mean surface temperature in Massachusetts was +0.018°C per year (Figure 1) or a total increase of 0.9°C (~1.6°F). These values are in keeping with published estimates for the northeastern U.S. (Hayhoe *et al.*, 2008: 1900-1999, +0.008 °C per year and 1970-1999, +0.025°C per year).

Due to the physiological thresholds of organisms, minimum and maximum temperatures are of particular interest to biologists and natural resources managers. During the period of the 1960s until the present the increases in annual mean maximum and minimum temperatures were 0.8°C (~1.4°F) and 1.1°C per year (~2.0°F), respectively (Figure 2). Temperature increases varied by season, being greatest in winter. This seasonal pattern is likely attributable to decreasing snow cover and the resultant increase in the retention of solar energy.

Average annual precipitation in Massachusetts is 1,185 mm (47 inches), but periods of severe drought are not uncommon. The 50-year linear trend indicates an increase in total annual precipitation, +3.92mm per year (Figure 3). Hayhoe *et al.* (2008) document a pattern of increasing precipitation in the northeastern U.S. for the twentieth century (+1.0 mm per year), but a non-significant, decreasing pattern for the period 1970-2000 (-0.08 mm per year). Due to high inter-annual variability in precipitation, seasonal patterns are more difficult to discern.

***Figure 1. Annual mean temperature in Massachusetts for two historical periods: 1907-2006 (left) and 1957-2006 (right). The blue line is the 5-year moving average and the red line is the least squares regression. The slope of the regression line is reported as the change rate. Data source: PRISM Group, Oregon State University, http://www.prismclimate.org, created December 2008; The Nature Conservancy* Climate Wizard.**

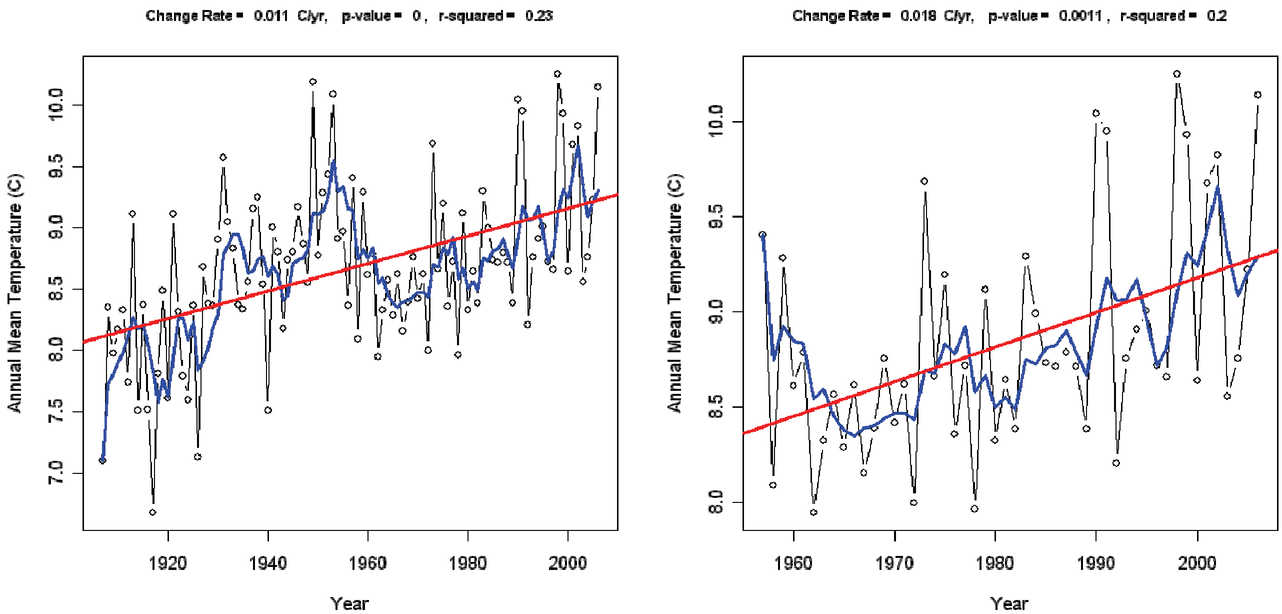


Figure 2. Annual maximum temperature (top) and annual minimum temperture (bottom) in Massachusetts for two historical periods: 1907-2006 (left) and 1957-2006 (right). The blue line is the five-year moving average and the red line is the least squares regression. The slope of the regression line is reported as the change rate. Data source: PRISM Group, Oregon State University, http://www.prismclimate.org, created December, 200; The Nature Conservancy **Climate Wizard.**

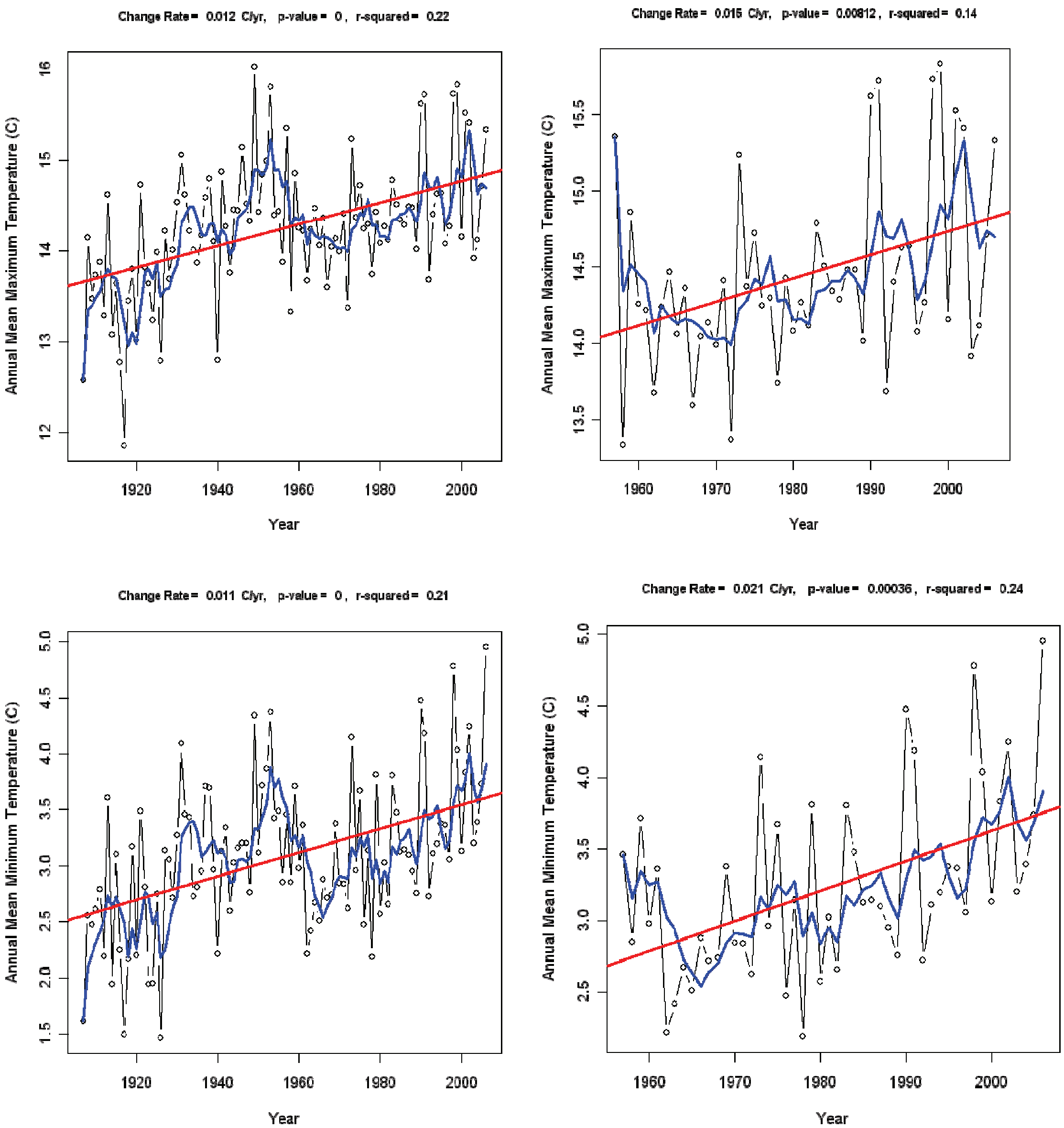
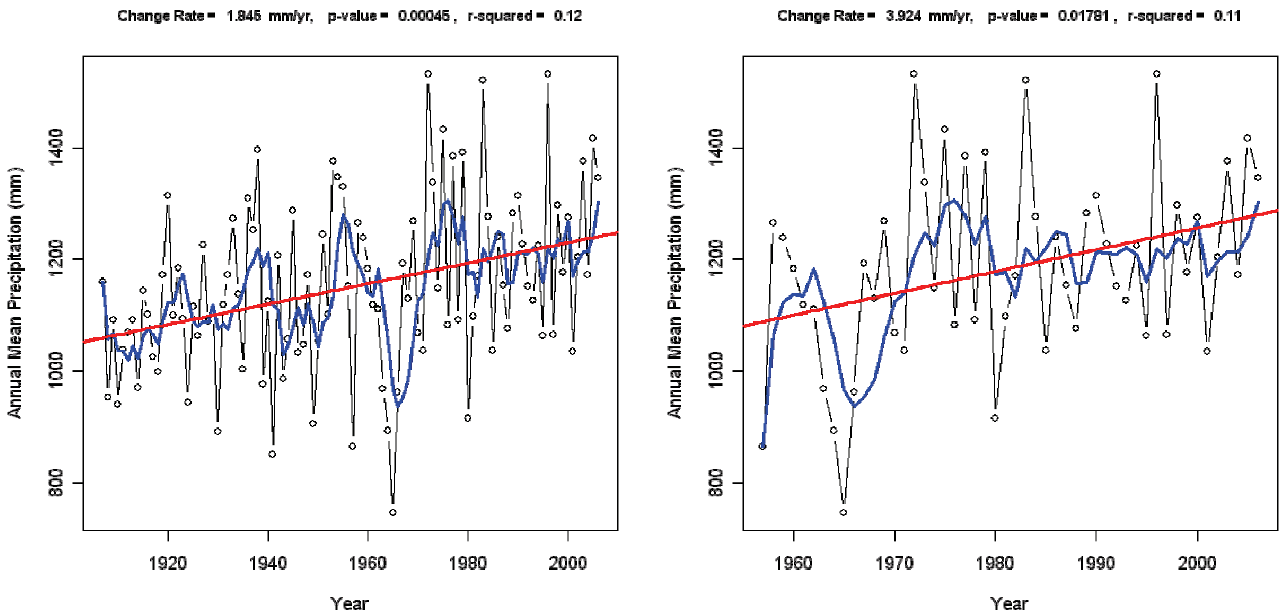


***Figure 3. Annual precipitation in the state of Massachusetts for two historical periods: 1907-2006 (left) and 1957-2006 (right). The blue line is the five-year moving average and the red line is the least squares regression. The slope of the regression line is reported as the change rate. Data source: PRISM Group, Oregon State University, http://www.prismclimate.org, created December, 2008; The Nature Conservancy* Climate Wizard.**



To evaluate spatial variation in temperature and precipitation trends, we employed Spatial Analyst in ArcView 9.2 to calculate the mean pixel value for the three U.S. National Oceanic and Atmospheric Administration (NOAA) climate divisions in Massachusetts: Coastal, Central, and West. The rate of increase in minimum and maximum temperature was heterogeneous across the state. Although not statistically significant, we detected the greatest increases in annual minimum temperature in the Coastal Division, with a westward pattern of less substantial increase; in contrast, the greatest increase in annual maximum temperature was in the West Division, with an eastward pattern of less substantial increase. The former likely represents the large influence of urbanization (i.e., urban heat island) on minimum temperatures and the latter the strong correlation between elevation and maximum temperatures (Jarvis and Stuart, 2001). From the evaluation of spatial variation in total annual precipitation, we found the Western and Central divisions to have the most substantial increases in total annual precipitation; however, the pattern is not statistically significant.

The Commonwealth of Massachusetts: Twenty-first-century projections

Data Source and Analysis

In 2006, the NECIA published climate projections for the Northeastern United States (NECIA, 2006; Hayhoe *et al.*, 2008). The study incorporates two IPCC emission scenarios, A1FI (fossil fuel intensive) and B1 (low emission scenario) as input for three atmosphere-ocean general circulation models (AOGCMs): NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1; the United Kingdom Meteorological Office's Hadley Centre Climate Model, version 3 (HadCM3); and the National Center for Atmospheric Research's Parallel Climate Model (PCM; NECIA, 2006). These models were selected because they bracket the range of emissions scenarios and model sensitivities. The authors documented the ability of the selected models to reproduce observed climate patterns in the Northeast; the models generally underestimated observed patterns and "regional processes may be acting to enhance warming trends in the Northeast relative to the global average in a way not captured by global-scale models"

(Hayhoe *et al.*, 2006). To improve the resolution of the general circulation models, and, hence, increase their relevance for the region, the authors employed statistical downscaling to generate monthly and daily temperature and precipitation projections on a 1/8° grid. The historical reference period for the analysis was 1971-2000. The results are available to the public (Hayhoe *et al.*, 2008; http://northeastclimatedata.org). This data set is the source of the following results for the state of Massachusetts (as defined by Hayhoe *et al*., 2008: this includes portions of Vermont, New Hampshire, Rhode Island, Connecticut, and New York).

Projected Changes in Climate and Associated Factors

By mid-century, mean annual temperature is projected to increase 3.7°-5.8°F under the B1 and A1FI scenarios, respectively; by the end of the twenty-first century, the increase is greater, 5.0°-9.5°F. End-of-century projections suggest a greater mean annual temperature increase in the western part of the state. Mean winter temperatures are projected to increase 4.3°-6.1°F (mid-century) and 5.8°-9.8°F (end-of-century); under the higher emissions scenarios, the northern-northeastern part of the state may experience greater increases in mean winter temperature. Mean summer temperatures are projected to increase 3.8°-6.4°F (mid-century) and 5.1°-10.6°F (end-of-century); under the higher emissions scenarios, the western part of the state may experience the greatest increase.

Temperature extremes are of particular importance for wildlife. Annual minimum temperatures are projected to rise 3.4°F and 5.4°F, mid-century, under the B1 and A1FI scenarios, respectively; increases of 4.7°-9.2°F are possible for the end of the century. Again, end-of-century projections indicate a slightly greater increase in the western part of the state. By mid-century, annual maximum temperature is projected to rise 3.4°-5.6°F; the projections for the end of the century are comparable to those for minimum temperature (4.7°-9.2°F). By mid-century, the number of days reaching a temperature over 90°F are projected to increase by an average of 10 to 24 days under the B1 and A1FI scenarios; while some locations may experience little increase, other regions may experience an additional 35 days of temperatures at or exceeding 90°F. By the end of the century, the estimates increase to an average of 16-49 days at or exceeding 90°F; some areas may experience more than the equivalent of 2 months of such conditions. Mid-century, there is little projected increase in the number of days with temperatures reaching or exceeding 100°F; however, by the end of the century, some regions may experience more than 15 additional days of temperatures at or exceeding 100°F under the A1FI scenario.

By mid-century, projections indicate an increase of approximately 100 mm in total annual precipitation for the state; the estimate is nearly identical for both emission scenarios. The increase in total precipitation is greater for the end-of-century projections, +150-170 mm annually. For both time periods, the increase is greater under the A1FI emissions scenario. There is slight spatial variation in precipitation patterns; eastern regions of the state may receive 25-50 mm more in total annual precipitation than western regions of the state. Similar increases are projected for the Rhode Island Connecticut, and portions of Maine. Projections indicate even greater changes in winter precipitation. By mid-century, mean snow depth in the state will be 13-20 cm less than the reference period (1971-2000); the projections indicate slightly greater decreases by the end of the century: 14-22 cm.

Two metrics of the relationship between climate and biological systems, growing season length and plant hardiness zone, are also important. The growing season, the number of days between last and first frost, is projected to lengthen. By mid-century, projections indicate an increase of 25 to 34 more days in the growing season under the B1 and A1FI emissions scenarios, respectively; by the end of the century, this increases to 29 to 51 days. Hardiness zones represent the range of average annual minimum temperature. The reference (1971-2000) hardiness zones for the state are 5a to-6b (-20°-0˚F); this pattern is projected to shift to 5b-7a (-15°-5˚F), mid-century, and by the end of the century, hardiness zones 6 and 7 represent the vast majority of the state. Currently, cities like Branson, Missouri; Oklahoma City, Oklahoma; and Little Rock, Arkansas, are characteristic of such zones.

Rising planetary temperatures are also triggering sea level rise through the steric expansion of sea water and the melting of glaciers, ice sheets, and ice caps. Sea levels are rising globally and the rate has accelerated over the last few decades (UCS, 2007). Conservative future projections (IPCC, 2007) suggest that global mean sea level could rise by between 0.3 and 1.0 m by 2100, depending on the emissions scenario. More recent analyses (e.g., Rahmstorf, 2007; Pfeffer *et al.*, 2008) have projected mean sea level rises of between about 1-2 m by 2100 under plausible emissions scenarios. Even greater increases could occur over the course of this century if the melting of Greenland and Antarctic ice caps accelerates greatly. In southern New England (including Cape Cod and the Massachusetts shoreline), the current rate of sea level rise approximates 1.8-2.9 mm per year and has increased three-fold over the past 150 years (Clough and Larsen, 2009).

4. CONCLUSIONS

The paleoecological record shows that the past distributions and representations of major vegetation communities and wildlife habitats in Massachusetts have been greatly affected by climatic shifts. We know from the climatic record that the climate is currently changing, with a shift toward increased temperatures and precipitation. Climate models tell us that unless greenhouse gas emissions are greatly reduced this shift will accelerate over the next century. If the state's temperature and precipitation change to the degree projected under even relatively modest emissions scenarios, then there is a high risk that we will experience major shifts in habitats and species. While the Commonwealth has shown remarkable success in preserving species, habitats, and biodiversity in the face of many serious stressors, many of these gains could be jeopardized by the climatic changes predicted by the climate models. It is important that we understand just how future climate change might affect our valued habitats and species, which habitats and species are likely to be most vulnerable, and how we can continue to hedge against expected challenges to these resources by ensuring that our conservation and management policies and tools are climate-smart. These issues are the focus of the two subsequent reports from this project.

5. REFERENCES

Barbour, H., T. Simmons, P. Swain, and H. Woolsey. 1998. *Our Irreplaceable Heritage: Protecting Biodiversity in Massachusetts*. Natural Heritage and Endangered Species Program, Massachusetts Division of Fisheries and Wildlife and Massachusetts Chapter of The Nature Conservancy. Boston, Mass.

Biomap, 2001. *Guiding Land Conservation for Biodiversity in Massachusetts*. Natural Heritage and Endangered Species Program, Division of Fisheries and Wildlife. Boston, Mass.

Clough and Larsen, 2009. Application of the Sea-Level Affecting Marshes Model (SLAMM 5.0) to Parker River, Monomoy, and Mashpee NWRs. Obtainable from: Dr. Brian Czech, Conservation Biologist U. S. Fish and Wildlife Service National Wildlife Refuge System Division of Natural Resources and Conservation Planning Conservation Biology Program 4401 N. Fairfax Drive - MS 670 Arlington, VA 22203.

Daly, C., M. Halbleib, J. Smith, W. Gibson, M. Doggett, G. Taylor, J. Curtis, and P. Pasteris, 2008, Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. *International Journal of Climatology* DOI: 10.1002/joc.1688.

Daly, C. and G. Johnson. 1999. Climate mapping with PRISM. http://www.prism.oregonstate.edu/pub/prism/docs/prisguid.pdf

DFW (Massachusetts Division of Fisheries and Wildlife), 2008. http://www.mass.gov/dfwele/dfw/

DFW (Massachusetts Division of Fisheries and Wildlife, Department of Fish and Game, Executive Office of Environmental Affairs), 2005. *Massachusetts Comprehensive Wildlife Conservation Strategy*. Revised September 2006. Boston, Mass.

Foster, D., G. Motzkin, J. O'Keefe, E. Boose, D. Orwig, J. Fuller, and B. Hall, 2004. "The Environmental and Human History of New England," in Foster, D.R. and J.D. Aber. *Forests in Time: the environmental consequence of 1,000 years of change in New England*. Yale University Press, New Haven, Conn.

Hayhoe, K., C. Wake, B. Anderson, X.-L. Liang, E. Maurer, J. Zhu, J. Bradbury, A. DeGaetano, A. Stoner and D. Wuebbles, 2008. Regional climate change projections for the Northeast USA. *Mitigation and Adaptation Strategies for Global Change* DOI 10.1007/s11027-007-9133-2.

Hayhoe, K., C. Wake, T. Huntington, L. Luo, M. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe, 2006. Past and future changes in climate and hydrological indicators in the U.S. Northeast. *Climate Dynamics* **28**:381–407.

IPCC, 2007: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds). Cambridge University Press, Cambridge, UK.

Jarvis, C.H. and N. Stuart, 2001. A comparison among strategies for interpolating maximum and minimum daily air temperatures. Part I: The selection of guiding topographic and land cover variables. *Journal of Applied Meteorology* **40**: 1060-1074.

NHESP, 2003. *Living Waters. Guiding the Protection of Freshwater Biodiversity in Massachusetts*. Natural Heritage and Endangered Species Program, Division of Fisheries and Wildlife. Boston, Mass.

NECIA. 2006. *Climate Change in the U.S. Northeast. A report of the Northeast Climate Impacts Assessment.* Union of Concerned Scientists, Cambridge, Mass.

Oswald, W., E. Faison, D. Foster, E. Doughty, B. Hall, and B. Hansen, 2007. Post-glacial changes in spatial patterns of vegetation across southern New England. *Journal of Biogeography* **34**: 900-913.

Parmesan, C. & G. Yohe 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**:37-42.

Parmesan, C. and H. Galbraith. 2004. *Observed Impacts of Global Climate Change in the U.S*. Report published by Pew Center on Global Climate Change, November, 2004.

Pfeffer,W.T., Harper, J.T., O'Neel, S.O. 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science* **321**:1340-1343.

Rahmstorf, S. 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. *Science* **315**: 368-370.

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig & J. A. Pounds (2003) Fingerprints of global warming on wild animals and plants. *Nature* **421**:57-60.

Shuman, B., P. Bartlein, N. Logar, P. Newby, and T. Webb III, 2002. Parallel climate and vegetation responses to the early Holocene collapse of the Laurentide Ice Sheet. *Quaternary Science Reviews* **21**:1793-1805.

Shuman, B., J. Bravo, J. Kaye, J. Lynch, P. Newby, T. Webb III, 2001. Late Quaternary water-level variations and vegetation history at Crooked Pond, Southeastern Massachusetts. *Quaternary Research* **56**:401-410.

UCS, 2007, Confronting Climate Change in the U.S. Northeast: Science, Impacts and Solutions. Union of Concerned Scientists Report. July, 2007. Cambridge, Mass.

U.S. Fish and Wildlife Service, 2001. W*ildlife Conservation and Restoration and State Wildlife Programs*. Department of the Interior. Federal Register **66**: 7657-7660.

Zielinski, G.A., and B.D. Keim, 2003. *New England Weather, New England Climate*. University Press of New England, Hanover, New Hampshire.

APPENDIX A

OBSERVED AND PROJECTED PATTERNS IN CLIMATE CHANGE AT BOTH THE GLOBAL AND REGIONAL SPATIAL SCALES

	Observed	***Projected***
Emissions	Between 1970-2004, global anthropogenic greenhouse gas emissions increased 70% and "atmospheric concentrations of carbon dioxide and methane exceed by far the natural range over the last 650,000 years" (IPCC, 2007a). Global atmospheric concentrations of carbon dioxide measure 370ppm, with the greatest increase documented in the last 10 years (IPCC, 2007a). As a whole, the northeastern U.S. ranks seventh in global emissions – more than Canada, the United Kingdom, and Australia (Frumoff et al., 2007).	In the next 30 years, SRES emissions scenarios project a 40-110% increase in carbon dioxide emissions and "fossil fuels are projected to maintain their dominant position in the global energy mix" (IPCC, 2007a). Regionally, a coalition of the New England governors and Eastern Canadian Premiers seeks to reduce greenhouse gas emissions to the 1990 level by 2010 and, by 2020, at least 10% below the 1990 level (New England Governors and Eastern Canadian Premiers, 2001).
Surface Temperature	The 100-year (1906-2005) linear trend in global surface temperature is +0.74°C and the linear trend for the most recent fifty years is +0.13°C per decade (IPCC, 2007a). Hayhoe et al. (2007) document a parallel increase in surface temperature in the Northeastern United States of 0.08°C per decade in the twentieth century; for the time period 1970-1999, the rate of increase is 0.25°C per decade. Temperature increases are substantially greater in winter than summer (Hayhoe et al. 2007). Warm extreme temperature occurrences are more common in recent decades (IPCC, 2007a), particularly for the eastern continental U.S (DeGaetano and Allen, 2002).	Near-term projections indicate a global surface temperature increase of 0.2°C per decade; increases from 1.8 to 4°C (baseline, 1980-1999) under B1 and A1FI emissions scenarios, respectively (IPCC, 2007), are predicted for the end of the twenty-first century. Hayhoe et al. (2007) predict surface temperature increases in the northeastern U.S. of 2.9 to 5.3°C (baseline, 1961-1990) under B1 and A1FI emissions scenarios, respectively; temperature increases are greater in summer than winter for all emissions scenarios. Globally, more frequent extreme temperature events (heat waves, hot extremes) are very likely (>90%) in the twenty-first century (IPCC, 2007a).
Sea Surface Temperature	From 1950-2000, the temperature in the global ocean increased less than 1°C (IPCC, 2007a). Although land surfaces experience the greatest increase in temperature, the global ocean absorbs the vast majority of additional heat in the climate system (IPCC, 2007a). In the Northeastern U.S., Hayhoe et al. (2007) estimate a rate of change in SST of +0.5°C per decade and +0.3°C per decade in the Gulf of Maine and Gulf Stream, respectively (1900-2000).	There is regional variation in projected sea surface temperature; for example, the Southern Ocean and northern North Atlantic may experience relatively less temperature increase than other global oceans (IPCC, 2007a). Hayhoe et al (2007) predict increases in future (2070-2099) SST in the Gulf of Maine of 1.9°C (B1 SRES) to 3.3°C (A2 SRES) above the 1961-1990 baseline; projected temperature increases for the Gulf Stream under the same scenarios are 1.2 to 2.3°C.
Sea-level Rise	The rate of global sea-level rise is accelerating— +3.1mm per year (1993-2003) in comparison to +1.8mm per year (1961-2003); thermal expansion accounts for more than 50 percent (IPCC, 2007a). From measurements taken over the last century, the Northern Atlantic experienced little to no change in mean sea level trend	Although there is more uncertainty in sea-level projections, a late twenty-first century rise in global sea-level of 0.18-0.59 meters is projected (baseline, 1980-1990); thermal expansion will contribute to further increases (0.3-0.8m by 2300) (IPPC, 2007a). Equivalent sea level rise in the Northeastern U.S. equates to increased flooding, storm damage, wetland loss, and erosion (Frumoff et al., 2007).

	(+1.76 to +4.06mm/year) (NOAA, 2008).	
Precipitation	There are notable changes in global precipitation patterns for the twentieth century; for instance, precipitation increased significantly in eastern North America and globally, heavy rainfall events are more prevalent (IPCC, 2007). For the northeastern U.S., Hayhoe et al. (2007) document an increase in annual precipitation, but decrease in winter precipitation [conversely, the 30-year trend suggests decreasing annual precipitation but an increase in the winter component of annual precipitation]. Less winter precipitation is in the form of snowfall (Hayhoe et al. 2006) and heavy rainfall events may be more common.	Projections indicate increasing precipitation in high latitudes and decreasing precipitation in subtropical regions; more frequent heavy precipitation events are very likely (>90%) (IPCC, 2007a). For the northeastern U.S., Hayhoe et al. (2007) predict (2070-2099) increases in annual and winter precipitation, 7-14% for the former and 12-30% for the latter, respectively; increases are greatest under the A1FI emissions scenario. Little to no change is projected in summer precipitation (Hayhoe et al. 2007). Large reductions in number of snow days and length of the snow season are projected for the northeast (Hayhoe et al. 2007). The number of heavy precipitation events is projected to increase 12-13% by the end of the twenty-first century (Frumoff et al., 2007).
Hydrology	The IPCC notes several changes in hydrological systems: increased runoff, earlier spring peak discharge, and an increase in the extent of drought-affected areas (2007a). On a regional scale, trends are more difficult to detect. For the northeast, Hayhoe et al. (2007) report no significant trends in historical models of evaporation, soil moisture, and runoff; however, the authors report an advance of spring peak flow of 0.44 days/decade (1950-1999). This is similar to the finding of Hodgkins et al. (2003) in the advance of the stream flow metric, winter/spring center of volume date (WSCV), in New England; the results are strongly correlated with early spring air temperature.	Globally, runoff is projected to increase in high latitudes and some wet tropical areas and decrease in dry tropics and mid-latitude regions (IPCC, 2007a). A further increase in the extent of drought-affected areas is projected. For the northeast, Hayhoe et al. (2007) project significant increases in runoff and evaporation. Additionally, for the end of the twenty-first century, model results indicate an advance of spring peak flow of 11-13 days and an increase in drought frequency, particularly those of short and medium duration. Changes are most substantial under the A1FI emissions scenario.