Some Anticipated Consequences of Global Warming:

Implications for the Nature of Massachusetts

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Introduction

Climate change[1] is an abstract concept to many people, not as immediate as other threats to our ecosystems such as invasive species, fragmentation of habitats, and pollution. The goal of this document is to make climate change more tangible by describing some of the changes we have already experienced in Massachusetts and the risk accelerated climate change presents to the future nature of Massachusetts. We focus on the predicted impacts of climate change on the natural communities across Massachusetts, often using examples from Mass Audubon sanctuaries and other protected lands. We also describe how valued characteristics of our natural history and culture in New England are likely to change.

Our information is synthesized from peer reviewed sources, the standard for acceptance of scientific studies. Two major sources of information are the IPCC's Fourth Assessment Report (IPCC 2007) and the Northeast Climate Impact Assessment's 2007 report (Frumhoff et al. 2007). IPCC is a scientific panel of hundreds of scientists from many nations set up by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). IPCC was established in 1990 with a mandate to be an objective voice on the causes and consequences of climate change. It periodically evaluates information on climate studies and produces reports that summarize the state of knowledge on climate change. The first IPCC report was completed in 1990 and the most recent in 2007 (IPCC 2007). The reports are consensus documents, meaning that the scientists from each member country must sign off on the conclusions in the report. Thus the information is considered by most scientists to be conservative.

NECIA was a collaboration between the Union of Concerned Scientists (UCS) and more than fifty independent scientists primarily from universities around the northeast. Its goal was to develop a new assessment of climate change, impacts on climate-sensitive sectors, and solutions in the northeastern United States and to communicate this assessment to policymakers and the public. Teams of scientists produced technical reports on specific topics that were published in peer reviewed literature. Frumhoff et al. (2007) is a synthesis report derived from the technical reports. In addition to IPCC and NECIA, we also include information from other peer reviewed journals.

Climate change resulting from the release of greenhouse gases associated with human activities now has widespread acceptance among scientists across the earth. The notion that this is a serious issue with potentially dire consequences has been made

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[1] We use the term "climate change" throughout this document to refer to the current period of rapid overall warming of the earth in response to anthropogenic (human-caused) release of greenhouse gases. What we term climate change is sometimes referred to as, anthropogenic climate change, global warming, anthropogenic global warming, rapid global warming, and disruptive climate change.

repeatedly and in increasingly definitive language by the Intergovernmental Panel on Climate Change (IPCC) on the global level (IPCC 2007), by the Northeast Climate Impacts Assessment team in the New England region (NECIA, Frumhoff et al. 2007), and by many scientists studying a wide variety of habitats in many parts of the world. Future projections by these climatologists and ecologists are consistent with the accelerated warming of the climate that began in the Industrial Revolution when humans first began expanded use of fossil fuels for energy. The level of carbon dioxide CO_2, the major greenhouse gas associated with this warming, is currently at its highest levels in at least the past 650,000 years and may eventually double or triple what it was before the Industrial Revolution (IPCC 2007).

It is not the purpose of this document to make the case that there currently is accelerated climate change related to human activities and to address alternative perspectives. That task has been accomplished in a large number of scientific reports, and proceedings, such as those mentioned in the preceding paragraph. At Mass Audubon we accept the conclusion based on overwhelming scientific consensus that climate change related to an unprecedented increase in the amount of CO_2 emitted to the atmosphere from the burning of fossil fuels has been occurring on earth and is a serious threat to our earth's ecosystems. We also accept the models that show that the actions we take now will make a big difference in how much the earth will warm overall in the future climate and therefore the severity of the impacts.

The current warming trend over the past century has led to northward range shifts of birds, fish, and other groups of organisms, earlier flowering of plants and breeding of birds and amphibians, shrinkage of glaciers, thinning of the arctic ice pack, and later freezing and earlier thawing of lakes. The IPCC and NECIA predict that these changes are currently accelerating and will result in drastic consequences for the humans and the biosphere unless humans take rapid and strong action to reduce the amount of CO_2 we are currently emitting into the atmosphere.

Temperature and CO_2 have fluctuated naturally during the history of the earth. Over the past two million years, there have been about 40 cycles of glaciation followed by interglacial periods of warming. Some of these changes have occurred over a relatively short period. One of the most dramatic documented changes occurred around 12,000 years ago, a period known as the Younger Dryas, when the mean temperature of the North Atlantic dropped about 5^oC over a decade and remained cooler for about 1000 years (NRC 2002). These were natural events; all evidence clearly indicates that the current steep rise in temperature is related to human activities - the burning of fossil fuels combined with the loss of forests.

The Massachusetts ecosystems under our management will undoubtedly change in response to climate change over the next century, and we are beginning to consider the implications of these changes for our management priorities. There is still much uncertainty about how climate change will affect the earth's ecosystems. There will undoubtedly be some surprises because we do not know the rates at which various components of ecosystems will change. Analysis of the changes on our sanctuary system and other protected lands could serve as a barometer for climate change in New England ecosystems.

This remainder of this document is organized into a series of modules focusing on specific predicted impacts of climate change on different elements of the nature of Massachusetts. Each of these modules can be read independently of the others, but together they are intended to form a reasonably complete picture of the predicted impacts of climate change on the Nature of Massachusetts.

The sections include:

Changes in the Massachusetts climate
Terrestrial ecosystems
Freshwater ecosystems
Coastal and near-shore marine ecosystems
Birds and their habitats
Pathogens and Pests
References

We begin with a brief description of the predicted response of Massachusetts climate and sea-level.

How will the climate and sea level in Massachusetts change over the next century?

Several models are used to project future climates and are incorporated into synthesis reports (IPCC 2007; Frumhoff et al. 2007). The models differ to some extent in the inputs they use that affect climate, such as future population growth, and how the emissions of greenhouse gases will change in the future. Models may also differ on how they incorporate clouds and precipitation into climate projections. As an example, two widely accepted climatic models related to global climate change are the Hadley and Canadian models, produced by the Hadley Center in the United Kingdom and the Canadian Center for Climate Modeling and Analysis respectively (National Assessment Synthesis Team 2000). Both models predict that the earth's climate will get warmer, that the warming will be most pronounced at middle and higher latitudes, and that there will be an increase in extreme weather events. They disagree on the extent of the temperature rise and how precipitation will change. The Canadian Center model predicts a greater increase in temperature over the United States than the Hadley, but the Hadley predicts greater precipitation.

The facts of climate change

1) There has been a 0.5^{o}C rise in air temperature in Massachusetts between 1895 and 1999 (New England Regional Assessment Group 2001). Even if we were to suddenly reduce our CO_2 emissions to zero, the earth's temperature would continue to rise throughout this century because it is not yet in equilibrium with the amount of additional CO_2 we have already placed in the atmosphere.

2) Current CO_2 levels are higher than they have been in at any time in the past 650,000 years (IPCC 2007).
3) Analyses of past climates and atmospheric gases shows that CO_2 levels are strongly correlated with mean temperatures.
4) IPCC (2007) states that the increase in CO_2 is primarily the result of burning of fossil fuels (coal, oil, and natural gas) with land use changes, such as the cutting of forests, a smaller contributor.
5) Ocean surface temperatures have increased by about 0.5^{o}C in the northeast in the past 100 years.
6) Satellite data indicate that the aerial extent of Arctic sea ice has declined 2.7% per decade since 1978 with higher amounts (7.4%) in summer (IPCC 2007). Global climate change related to human activities is likely responsible for thinning of the arctic ice pack by about 15% per decade (Scavia et al. 2002).

Projections of future climate

1) By 2100, CO_2 levels are expected to rise to levels not seen on earth for millions of years. Model projections indicate that atmospheric CO_2 concentrations will rise to twice that of pre Industrial Revolution levels by the end of this century even under a low emissions scenario[2] (Frumhoff et al. 2007). Under a higher emission scenario, concentrations will be triple that of pre industrial times.
2) Frumhoff et al. (2007) predicts that by 2100, winters in the northeast U.S. will be 4-7^{o}C warmer, and summers will be 3-8^{o}C warmer than they are now. If accurate, Boston's climate would be similar to the current climates of either Baltimore, MD or Charleston, SC. The difference depends on actions we take now to control greenhouse gases.
3) The lower future emission scenario projects an increase of 2-3^{o}C by 2100, and a 4-6 ^{o}C increase in the higher emission scenario. This warmer ocean will likely change the ranges of some of New England's signature marine life, such as cod and lobsters.
4) Most models predict that annual precipitation is likely to increase by about 10% in the Northeast by 2100, although other parts of the country may experience more frequent droughts (Frumhoff 2007). There already has been a gradual increase in annual precipitation of 5-10% since 1900. The biggest predicted change in precipitation will be in the winter months where a greater amount will fall as rain, rather than snow.
5) The extent of winter snow cover will be considerably reduced compared to its present extent, affecting the annual hydrologic cycle. Those ecosystems and species that are connected with the cycle of winter snow pack followed by spring thawing are likely to be most affected.
6) Although current models do not give a clear indication that there will be an increase in the frequency of hurricanes and other severe storms, they do suggest that the intensity of storms is likely to increase. Current 25-year floods may occur as often as every four years.
7) There will likely be increases in smog and acid precipitation.

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[2] Low and high emission scenarios are the results of cumulative actions humans take (or do not take) to curb future greenhouse gas emissions.

Projected changes in sea levels

1) On average, relative sea level has risen about 2 mm/yr in New England over the last 100 years. .
2) Under different climatic scenarios, models estimate that sea level will rise about 10-50 cm under the lower emission scenario and 20 to 80 cm under the higher emission scenario. These models are based on the thermal expansion of water when it is heated, but do not take in to account the melting of ice caps and glaciers. Thus these models are possibly underestimating the actual rate of sea level rise.
3) A recent study suggests that meltwater from Greenland Ice Sheet could cause an additional rise along the northeast United States coast of 30-50 cm.

Projected increase in ocean acidification

1) The pH of the ocean has dropped about 0.1 unit from its value before the Industrial Revolution, an indication that the ocean is becoming more acidic.
2) In the absence of any efforts to control greenhouse gas emission, the pH of the ocean is projected to drop another 0.3-0.4 units by 2100. Such a drop in pH is likely to cause severe stress to marine organisms that produce shells and for corals.

How will climate change affect terrestrial ecosystems of Massachusetts?

Range shifts that have already occurred over the past century

As indicated earlier in this document, the climate of New England has been warming for at least the past 100 years with much of the warming occurring in the past 30 years. Examining the changes that have already occurred provides some hints as to what might happen in the future with additional warming.

Changes in the ranges of many different types of organisms from birds to salamanders to insects have been occurring in the past 100 years and have been attributed to warming climate. Parmesan and Yohe (2003) examined 1700 species of organisms and found that 279 showed long-term trends. There was an average range shift of 6.1 km per decade toward the poles consistent with what might be predicted from temperature increases. According to the Union of Concerned Scientists,

> Range shifts in areas with regional warming trends have been reported in alpine plants (Grabherr et al., 1994), butterflies (Parmesan, 1996; Parmesan et al., 1999), birds (Thomas and Lennon, 1999), and mosquitoes (Epstein et al, 1998). In a study of 35 European non-migratory butterfly species, 63% had ranges that shifted to the north by 35-240 km during the past century, and only 3% shifted to the south (Parmesan et al., 1999). The range shift parallels a 0.8°C warming over Europe during the last century,

which has shifted climatic isotherms northwards by an average of 120 km (Beniston et al., 1998).

Predicted effects on forest types

The composition of our forests will likely change as our climate warms. The United States Environmental Protection Agency (EPA) estimates that, 30-60% of Massachusetts's forests are vulnerable to climate change (USEPA 1997). Overall, the northeast may actually gain in terms of the number of tree species, but we will lose some of our most valued trees (Iverson et al. 2009). As our climate warms, there will likely be an increase in the extent of oak-hickory forests (*Quercus* and *Carya* spp.) at the expense of northern hardwoods – sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and American beech (*Fagus grandifolia*) (Iverson et al. 1999, Iverson et al. 2009). There is evidence that paper birch *(Betula papyrifera*) already has receded northward in the past 50 years (LaRoe 1996) and this is one of the trees that is likely to become increasingly rare in Massachusetts as the climate warms. Other predicted losses include red maple (*Acer rubrum*), black cherry (*Prunus serotina*), balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), quaking aspen (*Populus tremuloides*), white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), and white ash (*Fraxinus americana*). One would expect the understory to change as well. Oak-hickory forest currently dominates the regions of Virginia or Georgia that our climate is projected to resemble in 2100. Thus, the future forest in Massachusetts under global climatic change will have different trees and more than likely a different suite of understory species. The New England woodland wildflower and fall colors for which New England forests are famed may become a thing of the past.

Parts of Massachusetts that are currently forested with northern hardwoods are likely to experience a great change in vegetation. This includes Mass Audubon sanctuaries such as Wachusett Meadow, Pleasant Valley, and a number of unstaffed sanctuaries in the central and western part of the state. Isolated communities with northern affinities, such as the spruce-fir forest that occurs on Mt. Greylock, are particularly vulnerable to climate change since there is no place for this community type to migrate. They may only survive in isolated pockets with suitable microclimates, such as northward facing slopes at relatively high elevations.

Although an overall pattern of forest change is certain, one should treat projections of responses of individual species to climate change with a certain amount of caution. Predicting such changes is fraught with more uncertainty than predicting the actual temperature change. Most projections rely on relating the current distribution of a species to the climatic range and then determining where that species should occur under a changed climate. Species, whether they are plants, animals, fungi, or bacteria, respond individually to changes in their environment and disperse to new habitats at different rates. They are also influenced by their interactions with other species; therefore one cannot assume that all species from the south are simply going to move up north in tandem. There will likely be surprises as new ecological interactions are forged.

One of the consequences of a change from northern hardwoods to oak hickory forests is a decline in maple sugar production in New England (New England Regional Assessment Group 2001, Frumhoff et al. 2007). Production of maple syrup in Vermont, currently the nation's largest producer, is now only one third of what it was in 1900. Some of this change is related to socio-economic factors however there is also a climate change component. Syrup production in New England is inversely correlated with winter temperatures, and this relationship is evident even on a year-to-year basis. In Vermont, the sap used to flow between mid-March and mid-April, but now it starts as early as the beginning of February because winter temperatures are warmer. In contrast, production of maple syrup has tripled in Canada since the 1970s. Canada now dominates the world market in maple syrup, much of it from the Gaspe Peninsula. Although some of this is related to technological improvements that made it possible to harvest sap more easily over a wider area of forest, a factor in Canada's recent success may be the increase in the number of days in which the Gaspe winter temperatures climb above freezing, thereby promoting the flow of sap (New England Regional Assessment Group 2007).

Effects on New England mountain communities

The high-elevation ecological communities of New England are likely to show profound changes in response to climate change and are likely to be one of our most sensitive indicators of climate change. Ascending in elevation on a mountain is equivalent to traveling north in latitude[3], thus warming climates will likely push the boundaries between lower and upper elevation communities upslope. The upper slopes and summits of New England's mountains currently harbor rare boreal and alpine communities and many rare species, thus the changes will have profound implications for regional biodiversity. New England's mountains contain only about 21 square kilometers of alpine tundra, primarily in the Presidential Range of the White Mountains. These may be the ecological communities most threatened by climate change in New England.

Changes in forest communities along an elevation gradient were documented in a study of three mountains in Vermont (Camel's Hump, Mt. Abraham, and Bolton Mountain), all over 1000 m in elevation. Beckage et al. (2008) compared the ecotone (ecological boundary) between the northern hardwoods (sugar maple, American beech, yellow birch) forest which occupies the lower slopes and the upper elevation boreal (red spruce, *Picea rubens*-balsam fir, *Abies balsamia*) forest. They compared data sets from 1964 and 2004 and found that this boundary had shifted about 91-119 m upslope in elevation in the 40-year period. They attributed the change to a decline of the boreal forest species at the 1964 ecotone and an increase in the same elevation by northern hardwoods. They noted that this change occurred during a period when the annual average temperature increased about 1.1°C. The authors also stated that the change in canopy tree species occurred more rapidly than many would have predicted for trees, which are slow growing, relatively stable organisms. Their results suggest that the high elevation forests are particularly vulnerable to the increased level of climate change anticipated for the rest of this century.

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[3] There is roughly a 1°C decrease in average temperature for every 200 m increase in elevation. An increase in elevation of 100 m is roughly equivalent to an increase in latitude of 130 km. Calculations derived from Slack and Bell (1995).

In Massachusetts, Mount Greylock is an isolated outpost for boreal species of plants and animals. Bicknell's Thrush, a boreal nesting species, no longer nests there and it is likely that other birds, such as Blackpoll Warbler, will abandon Mt Greylock as a nesting area once northern hardwoods move upslope. Similarly, the future climate on Mt. Greylock is likely to be no longer suitable for rare boreal plants, such as mountain cranberry (*Vaccinium vitis-idaea*) which occurs nowhere else in the Commonwealth.

Changes in phenology – the seasonal timing of events

Root et al. (2003) and Parmesan and Yohe (2003) have recently published meta-analyses demonstrating changes in phenology consistent with climate change over the past 100 years. Root et al. examined 143 taxa from widely different phyla (e.g., mollusks, amphibians, birds, trees, and non-woody plants). Over 80% showed phenological shifts with an average shift of approximately five days. Parmesan and Yohe (2003) estimated that the timing of spring events has shifted 2.3 days earlier per decade in the 20th Century.

Flowering phenology

Miller-Rushing and Primack (2008) made use of the well-known journals of Henry David Thoreau to compare flowering times of plants in Concord, MA in the mid 19th century to the present. Thoreau had meticulously recorded the first flowering dates of about 500 species of plants from 1852-1858. Miller-Rushing and Primack made their own observations from 2004-2006 of a similar set of species. The average Concord temperature has increased about 2.4°C during this period due to a combination of climate change and urban development. A third source of information was the observations of Alfred Hosmer, another Concord botanist who recorded first flowering dates from 1872-1902. Using 43 common spring-flowering species, Miller-Rushing and Primack determined that plants were flowering on average about seven days earlier now than in Thoreau's time. They calculated that plants flower about three days earlier for each 1°C increase in temperature. Not surprisingly, responses varied by species. Two of the species showing the greatest change were highbush blueberry (*Vaccinium corymbosum*) and yellow wood-sorrel (*Oxalis europaea*). These now flower 21 and 32 days earlier, respectively, than they did in Thoreau's time.

Using a larger data set of 296 species, Miller-Rushing and Primack were able to look at how monthly variations in temperatures affected first flowering dates. They determined that average temperatures during the months with the largest association with the earlier flowering times were January, April, and May. 94% of the taxa flowered earlier in years with warmer January temperatures. No species exhibited a later flowering time in response to warmer monthly temperature. Closely related species do not always show similar responses to warming temperatures. Black birch (*Betula lenta*) flowered 2.8 days for each 1°C increase in January, April, and May temperatures whereas first flowering date in gray birch (*Betula populifolia*) showed no relationship to temperature. Rough-stemmed goldenrod (*Solidago rugosa*) flowered about 11 days earlier for each

1^{o}C increase in temperature whereas most other goldenrod species showed no relationship between flowering time and temperature.

Willis et al. (2008) used the same Concord data sets to explore how climate change may be affecting patterns of species loss in plants. They note that many of the species that have declined substantially since Thoreau and Hosmer's times are those that do not show a phenological response in flowering times to warmer temperatures. These include asters, bladderworts, buttercups, dogwoods, lilies louseworts, mints, orchids, saxifrages, and violets. Other factors potentially contributing to the decline of plants in these families include an increase in the extent of forest cover and the substantial increase in deer since Thoreau's time. Climate change does not operate in isolation from these other stressor.

Observations of changes in flowering times attributed to climate change have been noted in other parts of the world. David Wolf of Cornell has documented earlier flowering times of lilacs in Ithaca, New York. Oglesby and Smith (1996) examined time of first flowering for 15 species of spring wildflowers of the Hudson Highlands and found that six exhibited a statistically significant trend of earlier flowering times over the past 50 years. The remaining species showed no change. The species that flowered earlier tend to occur in open areas that may warm up quicker. One fall bloomer, witch hazel (*Hammemelis virginianus*), also has been flowering earlier.

Amphibians

Many species of frogs and other amphibians throughout the world are already undergoing drastic population declines attributed to pollution, a widespread chytrid fungus, and possible other factors (Alford and Richards 1999, Stuart et al. 2004). This decline has been a source of alarm to ecologists, since amphibians are considered sensitive environmental indicators and are often key components of ecosystems. It is hard to predict how increasing global temperatures will directly affect amphibians, but warming could serve as an additional stressor to populations already in decline. The response to climate change of vernal pool-breeding inhabitants of the Northeast, such as the mole salamanders (*Ambystoma* spp.) is also uncertain (see Freshwater Ecosystems section below). Several authors have noted that the phenology of amphibians, like that of birds and flowers, has changed in response to climate change over the past several decades (Root et al. 2003). On average, amphibians in the northeast are breeding several weeks earlier than in the past.

Effects on Ecological Processes

Rising global temperatures will likely produce a cascade of effects that influence many processes of terrestrial ecosystems. As an example, Melillo et al. (2004) found that the release of CO_2 from the soil to the atmosphere occurs at a more rapid rate in warmer forest plots. Similarly, microbial mineralization of nitrogen occurs more rapidly at warmer temperatures and the warmer temperatures allow greater degradation of more recalcitrant forms of nitrogen. In sum, there are likely to be changes in our forests at the microbial level that have as yet undetermined consequences on forest dynamics.

Elevated CO_2 levels influence plant growth and chemistry. These changes could affect consumption of plants by herbivores. Coviello and Trimble (1999) suggest that plants will become less palatable and nutritious to insects, which could result in shifts in insect populations with implications for agricultural and forest pests as well as insects of conservation concern. Mattson et al. (2004) found that elevated CO_2 stimulates the production of tannins and other phenolic secondary metabolites that act as defensive compounds in silver birch (*Betula pendula*) and paper birch (*B. papyrifera*). High CO_2 led to reduced feeding by rabbits (*Sylvilagus floridanus*) and hares *(Lepus timidus*) on the birches, a response that could be reversed by adding high amounts of nitrogen. These studies illustrate how wide reaching and complex some of the responses to the rapidly warming climate are likely to be.

Massachusetts Forests as Carbon Sinks

Forests on Mass Audubon sanctuaries and other conservation land in the Commonwealth provide obvious ecological benefits. From the perspective of climate change, our forests serve as carbon sinks, because growing trees take up carbon dioxide and sequester it as organic carbon in wood. The soil also acts as a carbon reservoir from the accumulation of litter and belowground parts of plants. Thus the preservation of our forests contributes to the removal of carbon dioxide from the atmosphere and provides some mitigation to greenhouse warming.

Freshwater Ecosystems

Freshwater ecosystems in Massachusetts will likely be subjected to several changes as a result of global climate warming. The exact nature of these changes is unclear. Although we are certain that the climate will continue to become warmer in the future, we do not know whether precipitation will increase or decrease.

The effect of climate change on vernal pools is not clear. One speculation is that climate change could reduce the amount of time vernal pools are flooded affecting vernal pool inhabitants with relatively long developmental periods, such as spotted salamanders (*Ambystoma maculata*)[4]. Increasing temperatures without any change in precipitation would lead to more rapid drying out of the pools, and, therefore, less time for tadpoles to reach adulthood. A further complication is that vernal pools will likely be ice free earlier in the season, thus leading to earlier migrations to breeding pools. The actual extent of impact depends on whether there will be more or less precipitation in the future. Current climate models do not agree on this point.

Streamflow patterns are likely to change as warmer temperatures reduce the extent and duration of the winter snowpack in New England. With less winter snow, particularly in the “fringe months” of December and March, scientists predict that the typical New England hydrographic pattern in rivers of intense spring flooding followed

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[4] Brooks, R. 2002. Effects of climatic change on vernal pools. From a lecture presented at the 2002 Annual Meeting of the Association of Massachusetts Wetland Scientists, March 23, 2002, Boxborough, MA.

by lower summer flow will be altered. The 1980s and 1990s contained an unusually number of low snow years at the Hubbard Brook Experimental Forest in New Hampshire (New England Regional Assessment Group 2001), and this trend is likely to continue under increased climate change. With warmer winters there will likely be more frequent freezing and thawing in winter and a less well-defined spring peak flow. This pattern could change migration of anadromous and other fish that are cued to spring peak flows.

Warmer temperatures will likely increase demand for water for human consumption during the summer. Increased human consumption may result in reduced flow in rivers and streams and lower surface and groundwater levels in wetlands. Many rivers, streams, and wetlands in Massachusetts are already affected by low summer water levels due to water withdrawals for human use. Increased consumption and altered patterns of precipitation associated with climate change could exacerbate these problems. Another problem for future water supplies under the climate change scenario is the likelihood of salt water intrusion resulting from rising sea levels. These intrusions would likely increased demand on more limited freshwater sources.

Several climate models predict more intense storms could lead to more frequent episodic flooding throughout the year. It is not clear how riverine forests such as those that occur at Arcadia and Ipswich River wildlife sanctuaries, will respond to such a change in hydrography.

Cold water fish, such as trout, that inhabit Massachusetts rivers and lakes are expected to decline as a result of climate change. An EPA modeling study cited in New England Regional Assessment Group (2001) predicted a 50-100% loss of habitat for brook, brown, and rainbow trout in New England. The latter two are non-native species introduced specifically for angling; brook trout, however, are native. As with forest trees and animals, species at the southern limits of their distribution may experience a range shift northward that would result in their departure from Massachusetts.

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How will global climate change affect Massachusetts coastal ecosystems?

The two major climate drivers that will affect our coastal and marine habitats are rising sea levels and increased sea temperatures. Both of these have already been increasing in New England waters for at least 30 years and the models suggest that such changes will accelerate over the next 100 years. Sea surface temperatures have fluctuated around a mean for much of the past century, as measured by continuous 100+ year records at Woods Hole, and Boothbay Harbor and shorter records from Boston Harbor and other bays. Periods of higher than average temperatures (in the 1950s) and cooler periods (1960s) have been associated with changes in the North Atlantic Oscillation (NAO), which affects current patterns. Over the past 30 years however, the temperature change has become pronounced in the upward direction. Boothbay Harbor's temperature has increased by about 1^{o}Csince 1970. The model projections are for an increase of somewhere between 3-4^{o}C by 2100 (Frumhoff et al. 2007).

Relative sea level rise incorporates a number of factors: thermal expansion of water as it gets warmer, the melting of polar and glacial ice which releases vast volumes of water into the oceans, and the extent to which the adjacent coastal land is uplifting or subsiding in response to geologic and sometimes anthropogenic processes. Some sections of the New England coast may still be rebounding from the last period of glaciation (Koteff, C., et al/ 1993), thus our rates of relative sea level rise are less than those coastal areas where the land is subsiding substantially, such as the Mississippi delta. The rise in sea level over the past century has been roughly at 2 mm per year along the Massachusetts coast (Frumhoff et al. 2007). Because projections into the future are based on several factors that are difficult to model accurately, the models encompass a fairly broad range of values, an increase of 10 to 90 cm by 2100. The model projections have tended to underestimate the amount of melting from the Arctic and Greenland ice caps, and when combined with the unknown effect continued warming will have on the stability of the huge Greenland and Antarctic ice caps many scientists believe that the projection of sea level rise used by IPCC is likely to be an underestimate (Stroeve et al. 2007).

Loss of land

The rise in sea level combined with the anticipated increase in intense storms likely will lead to increased coastal erosion and loss of uplands along many parts of the Massachusetts coast. One attempt to quantify the loss of upland on a broad scale for Massachusetts was carried out by Giese et al. (1987), who estimated the passive retreat of coastal upland due to relative sea level rise on a town-by-town basis. When their report was written, predictions of how high the sea level rise would rise varied more widely than they do today. Giese et al. incorporated four different projections of relative sea rise into their analysis, projecting increases of 1.8, 4.7, 7.1, and 11.3 feet by 2100. The lowest of these increases is closest to the one most widely accepted now. They based their projections of upland losses on hypsometric curves (cumulative frequency diagrams). These graphs show the percent of upland at different elevation levels above sea level for each Massachusetts coastal town. Under this scenario, towns that contain Mass Audubon sanctuaries would lose land as indicated in Table 1. The climate change scenario used for the projections in Table 1 are based on an approximate 0.5 m rise in sea level due to climate change from 1980-2025, which is somewhat higher than the rates projected in the Hadley and Canadian climate models.

In a more detailed analysis of four coastal Massachusetts communities, Giese et al. (1987) projected extensive changes in wetlands areas and a sand spit with the projected sea level rise that is most similar to current predictions. Upland loss was not extensive, although they do note, "…the increased potential for storm wave and flooding damage should be of concern."

A preliminary examination of coastal areas vulnerable to future seashore changes classifies much of southeastern Massachusetts, the southern shore of Cape Cod and the Islands as either moderately or highly vulnerable to the effects of sea level rise (Thieler and Hammar-Klose 1999). This was based on the development of a coastal vulnerability index (CVI), which includes geomorphology ("erodibility" of the landform), regional coastal slope, rate of relative sea-level rise, shoreline change rates, mean tidal range and mean wave height. USGS did a more detailed analysis of Cape Cod National Seashore and adjacent areas concluding that the most vulnerable areas were those with the least slopes, most susceptible to inundation, and the highest rates of shoreline change (Hammar Klose et al. 2002). The area of highest vulnerability was from Nauset Spit south to Monomoy Island. The Great Island area on Cape Cod Bay in Wellfleet was classified as of high vulnerability. Another analysis lists outer Cape Cod, the Islands, and the Plum Island/Salisbury region as "severely eroding" with the remainder of Massachusetts as "moderately eroding (National Assessment Synthesis Team 2000)." Naturally eroding geological formations, such as coastal bluffs are likely to experience increased rates of loss. The rocky shorelines of the North Shore, being a relatively stable land form, are less susceptible to sea level rise.

As communities and individual landowners confront the issue of increased coastal erosion, there are likely to be increased proposals for armoring of the coast (i.e., revetments, sea walls, groins, etc.) and for pumping sand onto beaches to raise elevations. Mass Audubon has been active in commenting on such proposals as they have come under permit review under Massachusetts Environmental Policy Act (MEPA) and by the United States Army Corps of Engineers. Environmental organizations and government resource agencies may need to allocate an increased amount of staff time to reviewing these projects and developing policy guidelines. One notion that has been discussed by the United States Environmental Protection Agency (USEPA) is a policy of rolling easements as a more ecologically sound response to increasing sea levels rather than armoring (Titus 1998). Easements would be granted upland of current shorelines to allow the natural migration of the coast.

Shifts in plankton and fish in coastal waters

Researchers in New England have already documented changes in the planktonic community and shifts of ranges of marine fish and macroinvertebrates in response to climate change (Frank, et al. 1990; Murawski 1993, Keller et al. 1999, Sullivan et al. 2008, Fogarty et al. 2009) and these are projected to become even more pronounced in the future (Frumhoff et al. 2007). Elevated CO_2 concentrations in water may act as a stimulant to phytoplankton growth, favoring some species over others, even without any temperature change (Hein and Sand-Jensen 1997). Any changes in the planktonic community from the effects of CO_2 directly or through warming seawater temperatures would cascade throughout the marine food web. The effects of warming seawater temperatures on the marine community are superimposed on other human-induced stressors, most notably eutrophication of estuaries (excess nutrient loading which can lead to low or no oxygen) and overfishing (Buchsbaum and Powell 2008, Collie et al. 2008).

Keller, et al. (1999) documented a correlation between warmer seawater temperatures and the decline in the intensity of the spring phytoplankton bloom in the northeastern United States. They attribute this decline to increased grazing by zooplankton, which in turn stimulates the pelagic food web. Changes in water temperature were related to changes in the phase of the NAO. Keller, et al. noted declines in benthic macrofauna and increases in pelagic fauna during warmer periods with a positive NAO phase.

Similar patterns have been observed in Narragansett Bay where scientists have documented changes in phytoplankton, zooplankton, ctenophores (comb jellies), and fish in response to climate change (Collie et al. 2008, Sullivan et al 2008). The Bay has warmed about 2^{o}C overall (3^{o}C in winter) since 1960. The traditional winter-spring phytoplankton bloom, an annual event characteristic of New England estuaries is now much diminished or sometimes does not occur at all. Zooplankton, which formerly lagged behind phytoplankton in their annual phenology are now going through their life cycle earlier in the season due to warmer seawater temperatures in early spring. Thus their populations are large enough in late winter and early spring to graze down the phytoplankton before it has a chance to build up to the traditional bloom. Without the annual bloom fewer diatom and other phytoplankton cells sink to the bottom to nourish the benthic (bottom) community. The overall effect has been a shift in the fish community to a more pelagic (open water) dominated system (Collie et al. 2008). Eutrophication also favors a shift to pelagic species in Narragansett Bay, however this shift from a benthic to pelagic dominated fish community associated with warmer seawater temperatures has also been observed in the Bering Sea where eutrophication is not an issue (Grebmeier et al. 2006). Another factor stressing the fish community is that ctenophores, voracious feeders on fish eggs and larvae, can now survive all winter in the bay.

Winter flounder, a popular recreational and commercial fish, is susceptible to impacts of climate change, as indicated by studies in Narragansett Bay (Keller and Klein-McPhee 2000, Walker 2001, Collie et al. 2008). This species, which spawns in many shallow estuaries in New England, has been declining for about 30 years, due primarily to overfishing. A mesocosm study by Keller and Klein-McPhee 2000 showed that survival and growth of larval winter flounder declined at elevated temperatures. Walker speculated that warmer seawater temperatures have also contributed to the decline in winter flounder by other mechanisms including 1) reduced availability of benthic food due to greater consumption of phytoplankton by zooplankton, as described above and 2) decreased survival of flounder larvae due to increased predation by sand shrimp. The shrimp formerly departed the bay in colder seasons but now are able to winter in the bay as it has warmed. Flounder used to spawn in winter and their larvae were too large for the shrimp by the time the shrimp entered the bay in spring. Now the shrimp are present to feed on the newly spawned winter flounder larvae.

Atlantic Cod, one of New England’s most signature marine fish, will likely shift its range to the north in response to warming seas (Scavia 2002, Fogarty et al. 2009). Cod is a cold water species whose abundance in New England has typically declined during cycles of warmer temperatures. An annual average of 12^{o}C is considered the upper limit for cod range distribution, but egg and juvenile stages are more sensitive to higher temperatures than adults. Based on laboratory studies, the optimum temperature for egg survival is 6^{o}C and annual mean bottom temperatures above 8.5^{o}C result in declining recruitment. Higher temperatures reduce rates of egg and larval development and increase egg mortality. Fogarty et al. predict that southern New England and Georges Bank will no longer provide spawning and juvenile habitat to cod in the future under the higher emission future scenario. Those regions are already near the upper limit of the temperature tolerance for the early life stages of this species. George Bank, currently one of the major areas for cod spawning in the northeast, has averaged 9.0^{o}C bottom temperature from 1978-2002. Even at the lower emission scenario, the increased temperature on Georges Bank will result in lower rates of cod recruitment.

Warming of sea temperatures may affect predator-prey relationships with population consequences for cod. Larval cod depend heavily on copepods for food, particularly *Calanus finmarchicus*. The timing of cod spawning tends to be consistent from year to year regardless of annual differences in temperatures, but the copepod will spawn earlier in the season if temperatures are warmer than normal. Fogarty et al. (2009) suggest that the climate change may create a mismatch in the timing of cod spawning and their copepod prey abundance.

Juvenile cod are themselves prey to larger fish and there is some indication that warmer sea temperatures are affecting that predator-prey relationship. Atlantic mackerel has expanded its range north and is now feeding on juvenile cod. They previously did not prey on cod because their ranges did not overlap.

Fogarty et al. predict a range shift northward for lobster, New England’s most valuable commercial species. The optimum temperature for larval development of lobsters and recruitment to the benthos is from 12-20^{o}C, which is why shallow coastal waters (<30m depth) are critical for lobsters. Long Island Sound at their southern limits will no longer being suitable for lobsters under climate change scenarios, since it even now exceeds 20^{o}C, the temperature above which lobsters are stressed. On the other hand, some deeper and northern waters that are currently too cold to support lobsters will likely be in the correct temperature range in the future.

Barrier Beaches

Barrier beaches in Massachusetts provide habitat for endangered species and other species of management concern. Narrow, undeveloped barrier islands and sand spits such as Sampson’s Island, Tern Island, Smith Point, and Sunken Meadow Spit are likely to be moved shoreward as rising sea levels erode sand from the seaward side of these islands and deposit it in the relatively calm waters behind (Scavia et al. 2002). Whether these islands will be reduced in aerial extent or actually grow is a matter of conjecture. Sandy Neck grew more during periods of more rapid sea level rise than in more stable periods due to increased erosion of coastal bluffs that act as a sand source[5].

New areas of “blowouts” on barrier beaches are often attractive as nesting habitats to Piping Plover. With rising sea levels and increased severity of winter storms, blowouts and washovers may form with greater frequency, thus providing favorable nesting sites

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[5] D. Fitzgerald, 5/30/2002, personal communication

for the plovers, at least in the short term. We can expect greater long-term instability in these naturally unstable habitats.

According to Scavia et al. (2002) barrier beaches that are developed or covered with dune grass are less likely to migrate inland due to trapping of sand by structures. These might eventually erode and the sand deposited in sandbars offshore, much like the pattern of winter beaches. Revetments, groins, and similar structures intended to prevent erosion along barrier beaches actually interfere with the natural migration of sand along the coast and often resulting in erosion problems down current, as has occurred at Sunken Meadow Spit in Eastham and Wellfleet.

Salt Marshes and Tidal Flats

Salt marshes are ecosystems that flourish during periods of slowly rising sea levels. As long as the marsh can keep up with sea level rise through the steady accumulation of peat from the growth of the plants and by trapping sediment brought in by rivers and the ocean, a marsh will expand both seaward and toward the upland and remain healthy. Unfortunately, there is concern that marshes may not be able to keep up with the rapid rates of relative sea level rise that are anticipated as a result of climate change.

EPA estimated that a two-foot (0.6 m) rise in sea level could result in a national loss of 17-43% of our wetlands. About half of that loss would occur in Louisiana, which contains about one fourth of the United States' coastal wetlands; about 1 million acres of wetlands have been converted to open water since 1940 (Burkett et al. 2001). This loss is due to both sea level rise and land subsidence, a consequence of the channeling of rivers behind levees and the building of canals. These have severely reduced the natural sediment deposition from the rivers. The projected loss of wetlands in coastal Louisiana with an additional 20 inch sea level rise is at least another 1.28 million acres (National Assessment Synthesis Team 2000). Changes in New England will not be as dramatic, but some losses of coastal marshes are likely.

Many salt marshes in Massachusetts may no longer be able to migrate toward the upland as sea level rises due to development around their borders. Joppa Flats, for example, is bordered by a short coastal bank and the Plum Island Turnpike. There is likely to be some transformation of the salt marsh to tidal flats and tidal flats to subtidal flats as sea level rises in this location. Mass Audubon salt marshes at sanctuaries like Felix Neck, Wellfleet Bay, North River, Allens Pond, and Rough Meadows will become more significant because they still are surrounded by protected conservation uplands and therefore could migrate upwards.

Rising sea levels will likely change the balance between different habitats within the salt marsh. Bertness et al. (2002) project a loss of irregularly-flooded high marsh, *Spartina patens*-dominated habitats as the more flood tolerant *S. alterniflora* migrates landward in response to sea level rise and the invasive form of *Phragmites australis* spreads seaward from the upland in response to anthropogenically-derived nutrient loading. Such high marsh habitats are nesting areas for the obligate salt marsh bird, the Salt Marsh Sharp-tailed Sparrow. Marshes are also likely to be characterized by a greater percentage of open water, such as salt pannes.

Several preliminary studies have suggested that loss of high marsh habitats has likely already occurred in some parts of New England. The Plum Island Sound Long Term Ecological Research Project has noted an increase in marsh pools and pannes over the past 50 years based on a comparison of old nautical charts with current aerial orthophotos. This increase is likely from a combination of sea level rise and the abandonment of many of the mosquito ditches that formerly drained open water habitats on the marsh surface.

The recent and apparently rapid loss of vegetation on marshes on Cape Cod was initially termed “sudden marsh dieback” and related to similar rapid declines of marsh vegetation elsewhere along the east and Gulf coasts (Alber et al. 2008). The initial observations indicated a rapid loss of tall cordgrass, *Spartina alterniflora*, creating large, bare patches of up to an acre or more in extent. This decline has happened at a several locations on Wellfleet Bay Wildlife Sanctuary as well as other locations in Wellfleet and Truro.

Smith (2009) examined some of these sites and historic photos of marshes from around the Cape and concluded that there has been a loss of both high marsh, *Spartina patens* and low marsh, *S. alterniflora* habitats. The high marsh losses are associated with more frequent inundation consistent with sea level rise and possibly wrack accumulation and other disturbances.

Coincidentally, Holdredge et al. (2009) documented herbivory by *Sesarma reticulatum*, the square-back marsh crab, as a cause of loss of *S. alterniflora*. It is possible that a decline of *S. patens* due to sea level rise may be masked by its replacement by *S. alterniflora* in marshes throughout much of New England, because *S. alterniflora* is more tolerant of frequent flooding. This replacement of species is not occurring on Cape Cod marshes because the herbivorous crab is grazing on *S. alterniflora*; the result is a bare area. A second connection with climate change is that the herbivorous crab is a relative newcomer to the Cape Cod Bay marshes, previously only being known from southern New England and the mid Atlantic states. It apparently has no predators, at least yet, on the Cape Cod Bay marshes.

Coastal Ponds

Increased sea levels and coastal storm intensities could affect coastal pond ecosystems. For examples, Sesachacha Pond on Nantucket, Sengecontacket Pond on Martha’s Vineyard, and Allens Pond in Dartmouth are coastal ponds, bordered in part by Mass Audubon sanctuaries. Natural coastal ponds typically go through periods of connection and isolation from the ocean in response to the movements of sediments and storms. Under natural conditions, the movement of sediments keeps Sesachacha Pond isolated from the ocean except during occasional breaches caused by intense storms. This breaching occurs naturally with a period of several years. Between these episodes, the pond freshens and water levels increase. The frequency of breaching of this pond is likely to increase with sea level rise and more intense coastal storms.

In contrast, Sengekontacket Pond and Allens Pond are kept artificially connected to the sea by the local community, because regular flushing creates a more stable environment for shellfish and prevents the water quality from degrading due to stagnation. Sengekontacket Pond has two permanent openings protected by groins. In recent years, it has suffered from loss of eelgrass and scallops, possibly due to enhanced nutrient loading from increased development on Martha's Vineyard. Allens Pond has an inlet that migrates along the beach with longshore currents, which occasionally is closed off by sediments. The town keeps it open by periodic dredging. Increased sea levels may increase the frequency of flushing in these two ponds.

Anadromous fish

Anadromous fish are affected by temperature and freshwater discharges in their migrations upstream to spawn. With reduced winter snow accumulation and warmer winters, the springtime freshet that may stimulate upstream migration is likely to be diminished in strength. Increasing ocean and river temperatures may make it all but impossible to restore Atlantic salmon to the more southerly rivers in its historic range (e.g., the Connecticut and Merrimack). Smelt is another "northern" anadromous species, and its range is shrinking in southern New England.

Other Marine Organisms

Like fish, marine invertebrates and seaweeds respond to changes in water temperature. Sagarin et al. (2000) resampled study plots that had been first sampled in 1931-1933 in a rocky intertidal community at Hopkins Marine Station, Pacific Grove, California. They found changes in the abundance of macroinvertebrates consistent with predicted effects of recent warming. Most southern species increased in abundance during the 60 year time period whereas northern species decreased. Shoreline temperatures had increased by 0.79^{o} C on an annual basis with a 1.94^{o} C increase in summer temperatures. The changes they observed were far greater than those resulting from short-term climatic shifts, such as an El Nino Southern Oscillation Event. Changes in marine invertebrate populations attributed to warming temperatures along the Pacific coast were also reported in Barry et al., (1995). No similar analysis has been done on the east coast.

The incidence and persistence of harmful algal blooms in marine waters may increase in response to warmer water temperatures (New England Regional Assessment Group 2001). Increased algal blooms are both a human health and an ecosystem issue.

There has been increased concern regarding invasions by exotic marine species (Pederson, 2000, Carlton 2001), and climate change is often discussed as a potential contributor to these invasions. A 25-year trend of warming winter temperatures along the eastern coast of the United States has been implicated in the northward expansion of oyster diseases (MSX and dermo disease (Harvell et al., 1999). It has been less clear with other groups of organisms. There is no clear pattern that climate change has been responsible for increased invasions of more northerly marine habitats, at least yet.

Ocean Acidification

Ocean acidification has been termed the “other CO_2 problem” because it is another consequence of increasing concentrations of CO_2 in the atmosphere (Doney et al 2009). A rise in atmospheric CO_2 causes a subsequent rise of CO_2 in the oceans, since concentrations in the atmosphere are in equilibrium with that in the ocean. The oceans serve as a major sink for CO_2 absorbing about 1/3 of the CO_2 emitted by human activity. Without the oceans absorbing this much CO_2, the atmospheric concentration of CO_2 would be about 450 ppm now instead of its present 380.

The oceans have had a high capacity to remain at a fairly constant, slightly basic pH (around 8.2 in preindustrial times), due to their ability to buffer strong acids and bases. As atmospheric CO_2 has increased, however, the pH of the ocean has dropped about 0.1 unit from its value before the Industrial Revolution. While it is not hard to imagine human activity causing acidification of an isolated water body like a lake, the notion that our release of CO_2 into the atmosphere has already affected something so vast and presumably well-buffered as the oceans may come as a surprise to many people. In the absence of any efforts to control greenhouse gas emission, the pH of the ocean is projected to drop another 0.3-0.4 units by 2100 (Doney et al. 2009).

This drop in pH and increased alkalinity would have many, negative consequences for ocean life, particularly for corals, bivalves, snails, and planktonic organisms that make structures out of calcium carbonate, such as shells and reefs. CO_2 reacts with water to form carbonic acid, a weak acid, which dissociates into hydrogen ions + bicarbonate and carbonate ions. Higher oceanic CO_2 concentrations favor increased concentrations of hydrogen ions, thereby lowering the pH while at the same time causing a decline in carbonate. This results in a reduced ability to calcify (form calcium carbonate, the major constituent of shells) from calcium and carbonate ions in seawater under acidic conditions.

Although different forms of calcium carbonate (calcite, aragonite) may remain saturated in seawater even with a more acid ocean, the lowered degree of saturation reduces the ability of organisms to calcify (Doney et al 2009). The increased acidity also enhances dissolution of existing structures made of calcium carbonate. Studies of corals on the Great Barrier Reef indicate a decline of 21 percent in calcification rates from 1988- 2003, a decline associated with increased oceanic CO_2 combined with effects of temperatures and nutrients (Doney et al. 2009).

Many studies of the effects of ocean acidification have been done in laboratories under controlled conditions. In a summary of lab studies, Doney et al. (2009) reported that of 25 marine species, including 11 corals, 22 showed a decline in response to increased acidification. In one dramatic experiment, two species of corals kept in highly acidified seawater for 12 months completely lost their skeletons, although the polyps remained alive. The skeleton reformed after the corals were transferred back into seawater at a normal pH.

One potential positive benefit of increased oceanic CO_2 concentrations is increased photosynthetic rates and productivity of producer organisms. Almost all laboratory studies of seagrasses have indicated higher rates of biomass accumulation and reproduction under higher CO_2 conditions. Studies of cyanobacteria indicate higher rates of photosynthesis and nitrogen fixation when exposed to increased concentrations of CO2. Studies on phytoplankton have been mixed, however, and it is likely that the increased stratification anticipated with warmer oceans will lower the nutrients available to plankton, thus negating any potential positive effects of CO_2 on photosynthesis. Higher temperatures would also cause thermal stress on seagrasses growing at the southern limits of their ranges.

One interesting natural experiment on an entire marine ecosystem subjected to higher CO_2 is in the vicinity of an underwater volcanic vent near Sicily. The Mediterranean Sea near the vents is characterized by increased oceanic CO_2 and acidity. Its fauna is marked by an absence of corals and limited numbers of coralline algae, sea urchins, and snails compared to more distant reference areas. The affected area was characterized by more seagrasses but also a higher percentage of non native, invasive species (Doney et al. 2009).

There are past periods in the earth's history where oceans have been subjected to increased temperatures and acidity related to CO_2. One of the most dramatic occurred during the massive extinction at the end of the Permian period, approximately 251 million years ago (Erwin 2006). An estimated 90-95% of all marine species went extinct at this time, as did about 70% of all land species. The extinctions occurred very rapidly in geologic time, perhaps as briefly as only over 8,000 years[6]. Scientists have looked toward a natural catastrophe, either rampant volcanism or a asteroid as potential causes.

Evidence is mounting that an enormous amount of volcanic activity may have triggered the warmer temperatures and ocean acidification. The volcanoes, centered in Siberia, were huge by any standard. One estimate is that the amount of lava released at the time was about 15 million times that of the Mt. St. Helens eruption in 1980[7]. Warming occurred through the rapid release of CO_2 and other greenhouse gases by the volcano itself and by rampant fires they spawned. This was followed by further release of CO_2 due to peat decomposition and subsequent further warming. Ocean acidification and wide areas of hypoxia (low oxygen) put incredible stresses on marine life. Many of the species that disappeared were non motile species dependent upon calcium metabolism to build shells for protection (Erwin 2006). Erwin noted that the few brachiopod species that survived this extinction, as evidenced from the fossil record, were those that could metabolize calcium phosphate instead of calcium carbonate. The loss of many primitive reef forming organisms at the end of the Permian opened up a niche for the spread of

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[6] NASA 2001. The great dying. http://science.nasa.gov/headlines/y2002/28jan_extinction.htm

[7] ibid

scleractinian (“modern”) corals, the form that creates the reefs in modern times. But that only occurred after a lag period of 10-15 million years, during which the seas may still have been too acidic to support reef building via calcium carbonate. Marine organisms with hard shells are notably few in the fossil record throughout the lower Triassic (Payne et al. 2006). Like the laboratory study described above, it could be that the corals survived without their stony envelope in the species depauperate ocean until conditions gradually improved to the point where they could mineralize calcium again.

Erwin (2006) suggests that there are parallels between the conditions that caused the Permian extinction in the oceans and the condition of modern oceans. Perhaps most critical is that the acidification is taking place relatively rapidly, in the past 150 years, but recovery could take much longer, over a period of a thousand or more years.

Effects of Climate Change on the Birds of Massachusetts

Mass Audubon has a long history of working to protect birds, and one of our major concerns is how the disruptive effects of rapid climate change may change our avifauna. In the following section we outline changes that have already been documented in the distribution, migration patterns, and phenology of the Commonwealth’s avifauna. We then examine predictions of future based on climate change scenarios.

Northern movement of certain bird species

One of the more obvious trends in the natural history of New England over the past century has been the number of “southern” birds that have expanded their ranges northward. These include such species as Glossy Ibis (*Plegadis falcinellus*), Red-bellied Woodpecker (*Melanerpes carolinus*), Tufted Titmouse (*Baeolophus bicolor*), Carolina Wren (*Thryothorus ludovicianus*), Mockingbird (*Mimus polygottos*), and.Northern Cardinal (*Cardinalis cardinalis*).[8] Some of these expansions also could be related to the proliferation in the use of bird feeders in winter, habitat changes, and wildlife management efforts. There has not been a major increase in northern species moving south so the observed changes are consistent with rising global temperatures rather than random events.

Changes in bird distributions in response to warming over the past century have been well documented in the scientific literature. Root (1988) showed that the winter ranges of 50 species of songbirds were related to the average minimum January temperatures and that their ranges could vary annually based on this temperature. Her studies on Northern Cardinal have led to the speculation that survival in a cold winter is related to the amount of fat a bird can store. As the average minimum temperature rises, the birds should expand their range northward. In a study of British birds, Thomas and

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[8] One of the best sources of information documenting these range shifts in Massachusetts is the Breeding Bird Atlas (BBA) project currently being carried by Mass Audubon in collaboration with the United States Geological Survey (USGS). See http://www.massaudubon.org/birdatlas/bbaportal/index.php

Lennon (1997) estimated that the northern margins of the ranges of many species have moved about 18.9 km north in a 20-year period.

Valiela and Bowen (2003) examined annual Audubon Christmas Count data from Cape Cod to determine if there were changes in the winter distribution of birds since the 1930s. The authors related shifts in populations to both temperature and habitat changes as a way of distinguishing global from local factors. They found that the ratio of southern to northern birds wintering in Cape Cod has increased over the past 70 years as the temperature warmed. Southern species increased across all habitat types, suggesting that they were responding to warmer winters, but not to changes in habitat types. Northern birds associated with forest habitats declined since the 1970s. They attribute the increase in southern species to climate change, and the more recent decline in northern forest birds to the rapid loss of forested habitat on Cape Cod to development.

Effects of food resource changes on seabirds

Changes in food resources have been implicated as affecting bird populations in other regions. Seabirds are affected by large scale, cyclic oceanic events that effect seawater temperatures, such as the El Nino Southern Oscillation (ENSO). Periods of warmer ocean temperatures reduce food resources and are associated with declines in populations of a number of seabird species (Gjerdrum et al. 2003; Hedd et al. 2006). ENSO is complicated because it affects upwelling of nutrient rich waters in some areas of the ocean as well as seawater temperature. The climate change-induced warming of the oceans is superimposed on ENSO and other cyclic events as it is on other stressors, most notably overfishing and pollution.

Nonetheless the responses of birds to these temporary periods of higher temperatures provide some clues as to what the impacts of future warmer oceans will be. A number of authors have suggested that because of their sensitivity to ocean temperatures, seabirds are a useful barometer of the impacts of global climate change (Gjerdrum et al. 2003, Hedd et al. 2006, Shaffer et al. 2006). In warmer years, sea birds will almost completely abandon their nests, leading to complete nest failure. This has been observed for Cassin’s Auklets (*Ptychoramphus aleuticus*) nesting on islands off the Pacific Coast (Lee et al. 2007). Declines in Sooty Shearwaters (*Puffinus griseus*) off the Pacific Coast have been attributed to overall effect of climate change on their food resources (Veit et al. 1996, Lyver et al. 1999).

Bird migration and nesting

Birds are showing the effects of climate change in their migrations and nesting phenology. Oglesby and Smith (1996) used the records of the Cayuga Bird Club dating back to 1903 in examining first arrival of spring migrants around Ithaca, NY. Fifty-one percent of 76 species arrive earlier than they did around 1900 with an average of 5.5 days earlier. Forty six percent showed no change and two species (Louisiana Waterthrush, *Seiurus motacilla*, and Mourning Warbler, *Oporornis philadelphia*) actually are arriving later. Eighty five percent of those species showing an earlier spring arrival time are neotropical migrants. The American Bird Conservancy website states that many bird species are arriving an average of 21 days earlier in the Upper Peninsula of Michigan[9]. An analysis of 30 years of arrival and departure dates of migrants in Great Britain documented both earlier spring arrival and earlier fall departures of approximately 8 days (Cotton 2003).

The timing of bird nesting has also responded to warming climate. Crick et al. (1997) report earlier laying of eggs by British birds, and this corresponds with an increase in the growing season of about 8 days in northern latitudes. Geese in the arctic nest about 30 days earlier than they did around 1960 (Laroe and Rusch 1996).

Future projections of bird distributions

Future projections of species distributions under climate change scenarios typically use bioclimatic "envelopes." This technique involves relating the current distribution of the birds to a particular climate range and then using models to project where that climate range will be in the future with the assumption that the birds will move as well.

A state by state analysis of the impact of the anticipated climate change on the summer distribution of passerines was funded by EPA and carried out by the American Bird Conservancy, the University of Michigan, Goddard Institute for Space Studies, Boston University, and Stratus Consulting. For Massachusetts, Price (2000) predicted that 33 species that currently nest here would be extirpated as summer residents (Table 1). These include species of northern affinities, including many wood warblers, finches, flycatchers, and swallows. Nine species would undergo summer range contraction. Fifteen species would expand their summer range, and seven species that do not breed here, may breed here in the future.

Mathews et al. (2004) used bioclimatic models to predict changes in the abundance and distribution of birds in the eastern United States. The total abundance and species richness were predicted to remain the same but there would be significant shifts in the abundance of individual species. Out of 150 species, they predicted that 40% will decline in abundance and 45% will increase. Migrants would be more likely to decline than residents, possibly because they rely on a greater number of cover types that are changing in response to climate change.

Rodenhouse et al. (2008) extended the research of Mathews et al. by looking at current distributions and abundances of 150 common New England species in relation to climate, elevation and association with certain combinations of tree species. They derived anticipated future ranges under higher and lower future emissions scenarios. Like Mathews et al., they conclude that there will be little change in overall abundance of birds averaged across the region, assuming southern species expand into New England to

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[9] http://www.abcbirds.org/conservationissues/globalwarming/global_warming_factsheet.pdf

make up for existing species that move north. Generalist, year-round resident species, including Blue Jays (*Cyanocitta cristata*), American Crow (*Corvus brachyrhynchos*), European Starling (*Sturnus vulgaris*), House Sparrow (*Passer domesticus*), and American Robin (*Turdus migratorius*), will show little change under either emissions scenario. Two resident species projected to decline are Black-capped Chickadee (*Poecile atricapillus* - our state bird), and Ruffed Grouse (*Bonasa umbellus*). The latter is already seriously in decline in Massachusetts for reasons that are not well understood. For American Goldfinch (*Carduelis tristis*), Cedar Waxwing (*Bombycilla cedrorum*), and Song Sparrow (*Melospiza melodia*) the anticipated losses are minor under the low emission scenario, but more pronounced under high emissions (Matthews et al. 2004). A number of migratory species, including some that currently nest in Massachusetts, are also likely to decline. These include many iconic New England species, such as wood warblers, thrushes, and loons. Baltimore Orioles (*Icterus galbula*) are projected to experience a serious decline in Massachusetts only under only the higher emission scenario, however Purple Finch (*Carpodacus purpureus*), and Hermit Thrush (*Catharus guttatus*)are projected to decline under either emissions scenario.

Rodenhouse et al. noted that Bicknell’s Thrush (*Catharus bicknelli*) and other high elevation, boreal species that occur in New England are highly vulnerable to climate change. Under the low emission scenario, Bicknell’s Thrushes will disappear from all southern New England mountain outposts and occur only in the White Mountains and Maine. Under higher emissions, this endemic species could be completely gone from the northeast.

A number of climate scenarios indicate future problems for certain groups of birds. The prairie pothole region of North America is an important breeding area for many of the waterfowl species that winter in the northeast; the predicted drying in this region could have continent-wide impacts. Sorenson et al. (1998) have predicted that drying in the pothole region could lead to a 50 % decline in waterfowl nesting success. According to the World Wildlife Fund, the Great Basin, which has geographically isolated wetlands, will also become drier and breeding areas located there may no longer be productive for birds. Birds that inhabit salt marshes and tidal flats are likely to be stressed by changes in those habitat (Galbraith et al. 2002-see section on marine habitats).

On a continental scale, the decline in the tundra due to both the melting of permafrost and the expansion of the boreal forest northward has implications for the Massachusetts aviafauna. Many of our wintering waterfowl and migratory shorebirds nest in tundra habitat, thus a loss or alteration of this habitat could have profound consequences. Birds may also face changes in their migration routes, particular those that migrate through the central United States and the Great Basin, areas that are likely to become more prone to drought. Species that use coastal wetlands may also be affected, as described earlier.

The web of relationships between birds and their habitats

Although birds in general are highly mobile animals and may be able to respond quickly to warmer climates by moving north, all components of the ecosystem are likely to move at their own pace. Changes in tree species, for example, will depend to a large extent on random events, such as fire, intense storms, or outbreaks of insect pests that remove current species and facilitate colonization by new plant species. Species respond individually to changing climate, yet they depend on a web of ecological relationships, such as those between predator and prey. A major unknown is whether birds and their insect prey will change in phenology and distribution at the same pace. If not survival of individual species will depend on new ecological relationships being forged.

One of the concerns about climate change is that it will decouple certain ecological processes that support key species. A prime example is the spawning of horseshoe crabs along the mid Atlantic Coast, particularly in Delaware Bay. Delaware Bay is the largest staging area for a number of species of shorebirds in the Atlantic Flyway during their spring migration (Clarke et al. 1993, Burger et al. 1996). These long distant migrants arrive at Delaware Bay at the same time that horseshoe crabs are spawning. Horseshoe crab eggs are a vital food source for these migratory birds (Myers 1986, Castro and Myers 1993). There is concern that if the horseshoe crabs respond to warming seawater temperatures more rapidly than the migrating birds or vice versa, the synchrony will be disrupted, leading to severe problems for the shorebirds. The Red Knot (*Calidris canutus*) is closely associated with horseshoe crab spawning in Delaware Bay, and this species has already undergone a drastic population crash as the populations of horseshoe crabs have declined due to overharvesting and erosion of their spawning beaches.

Another example of the how complex the responses of different ecosystem components can be when faced with a changing climate is illustrated by a simulation model of nesting success of Black-throated Blue Warblers, *Dendroica caerulescens* (Rodenhouse 1992). Based on studies at the Hubbard Brook Long Term Ecological Research site in the White Mountain National Forest, the author concludes that the effects of warming on these birds depends on the amount and intensity of precipitation. Greater precipitation leads to increased nestling mortality due to chilling, but it also extends the breeding season and enhances food resources for the birds. In more recent studies, Rodenhouse found that insects consumed by Black-throated Blue Warblers are more abundant in the higher elevation forests, leading to higher fecundity at these higher elevation forests.[10] . Climate change may allow the poorer quality low elevation forests to move upslope.

Coastal Waterbirds and their habitats

Several scientists have examined the potential impacts of global climate change on coastal waterbirds. Erwin et al (2001) suggested that populations of marsh specialists, such as Laughing Gull (*Leucophaeus atricilla*) , Foster's Tern (*Sterna fosteri*), Clapper Rail (*Rallus longirostris*), Seaside Sparrow (*Ammodramus maritimus*), and Salt Marsh Sharp-tailed Sparrow *Ammodramus caudacutis*) will be vulnerable to the loss of

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[10] from Feb. 9, 2009, lecture at Nuttall Ornithological Club

important salt marsh nesting areas due to sea level rise. Nauset Marsh on Cape Cod lost about 180 acres, or 25.4% of its area, between 1947 and 1994 due to sea level rise. On the other hand, Erwin et al. (2001) also speculated that wintering waterfowl and migratory shorebirds may benefit from increased intertidal and subtidal flats (associated with rising sea level?). Galbraith et al. (2001), however, projected that mud flat habitat would decline much more than salt marshes (57% versus 12 %) in Delaware Bay under a 2°C rise in temperature over the next century. This decline would seriously jeopardize shorebird habitat. Erosion of barrier beaches could affect nesting habitat of beach nesting birds. Projected impacts on salt marshes, barrier beaches, and other marine habitats are described later in this document.

Pathogens and other “Pest” Species

Climate change will likely expand the range of some undesirable southern species. Changes already attributed to warming include increases in hemlock wooly adelegid, bark beetles, and pathogens of oysters, and bark beetles (Frumhoff et al. 2007). This trend likely will accelerate with warmer temperatures in the future.

Milder winters and warmer night temperatures may allow destructive insects and pathogens to move into forests at higher latitudes and elevations (Kirschbaum and Fischlin, 1996, Frumhoff et al. 2007). For example, infestations of the spruce bark beetle (*Ips typographus*) have increased in the boreal forests of Alaska. The hemlock wooly adelgid (*Adelges tsugae*), which is devastating hemlocks in the southern New England, may be benefit from milder winters. This species is projected to invade nearly all of New England, although northern Maine, New Hampshire, the Northeast Kingdom of Vermont and the higher elevations in the Adirondacks would be spared under a lower emission scenario (Frumhoff et al. 2007). Additional pests and pathogens of trees that may benefit from warmer climates include emerald ash borer, pine bark beetle, balsam wooly adelgid, Dutch elm disease, white pine blister rust, and beech bark disease.

Human health may be affected by the influence of warming climate on pathogens. Warmer, wetter winters could increase the survival of the tick that spreads Lyme disease and the mosquitoes that are responsible for Eastern Equine Encephalitis (New England Regional Assessment Group 2000). The spread of West Nile Virus into southern New England could also be related to a warming climate. The United States Environmental Protection Agency (1997) noted that mosquitoes that can carry malaria do occur in Massachusetts. Such changes in insect-borne diseases are speculative now, since the survival of these pests will be affected by patterns of precipitation as well as temperature

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Tables

Table 1. Losses in acreage of upland in towns containing Massachusetts Audubon sanctuaries by 2025 based on Giese et al. (1987). These losses and percentages are for the entire town, but do not include salt marshes. Further analysis is required to determine projections for individual sanctuaries. (Place all tables and figures at the end of the document.)

Town	MAS Sanctuary	Projected acreage lost by 2025 at historical rate of sea level rise (3mm/yr)	Percent of upland lost by 2025 at historical rate of sea level rise (3mm/yr)	Projected acreage lost by 2025 under a global warming scenario	Percent of upland lost by 2025 under a global warming scenario
Dartmouth	Allen's Pond	92.4	0.27	234	0.67
Wellfleet	Wellfleet Bay	45.6	0.50	115	1.27
Barnstable	Long Pasture	167.2	0.54	423.6	1.38
Edgartown	Felix Neck	109.9	1.10	278.3	2.79
Marshfield	South Shore	27.1	0.19	68.6	0.48
Gloucester	Eastern Point	21.6	0.14	54.8	0.36
Newburyport	Joppa Flats	9.7	0.21	24.7	0.52

Table 2. Modeled changes in summer ranges of Massachusetts passerines (from Price 2000)

Species that may be extirpated as summer residents:
Flycatchers: Olive-sided, Yellow-bellied , Alder, Willow, Least
Swallows: Tree, Bank, Cliff
Red-breasted Nuthatch
Winter Wren
Blue-headed Vireo
Warblers: Nashville, Chestnut-sided, Magnolia, Black-throated Blue, Yellow-rumped, Black-throated Green, Blackburnian, Northern Waterthrush, Mourning, Hooded, Canada
Sparrows: Vesper, Savannah, Swamp, White-throated
Dark-eyed Junco
Icterids: Bobolink, Rusty Blackbird
Finches: Purple, Pine Siskin, Evening Grosbeak

Species whose summer range may contract
Black-capped Chickadee
House Wren
Warbling Vireo
Warblers: Blue-winged, Yellow, American Redstart
Finches: Rose-breasted Grosbeak, House
Sparrows: Song

Species whose summer range may expand
Acadian Flycatcher
Horned Lark
Purple Martin
Carolina Wren
Northern Mockingbird
Vireos: White-eyed, Yellow-throated
Warblers: Pine, Prairie, Cerulean, Prothonotary, Louisiana Waterthrush, Yellow-breasted Chat
Grasshopper Sparrow
Orchard Oriole

Species whose future range may include Massachusetts
Carolina Chickadee
Loggerhead Shrike
Warblers: Yellow-throated, Kentucky
Summer Tanager
Blue Grosbeak
Dicksissel