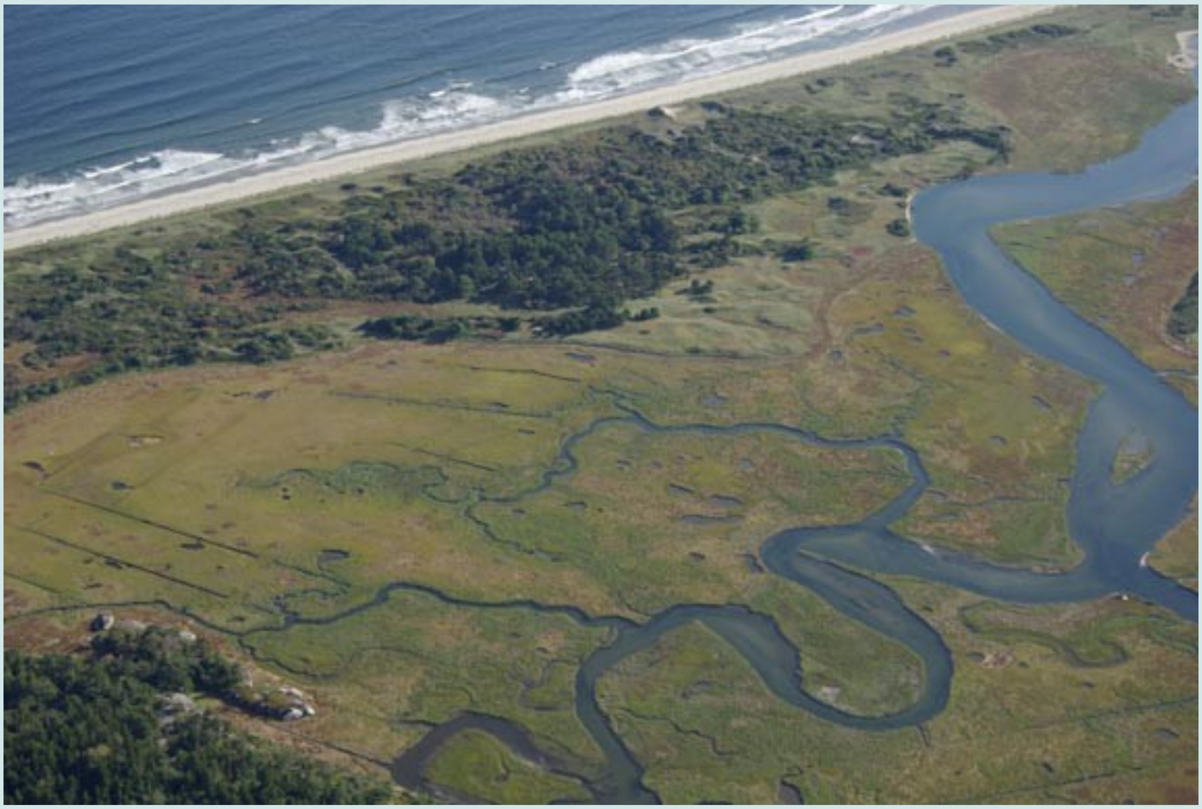
Chapter 6

Climate Change



The Sprague River beach and coastal marsh complex in Phippsburg supports several known elements of ecological management interest, including shorebird feeding and roosting areas and essential habitat for endangered terns and plovers. Marshes like this one are particularly vulnerable to climate change-induced permanent flooding, increased salinity, and storm-associated shifts in coastal morphology. Photo: Slade Moore and John Sowles.

Warming air and ocean temperatures over the next hundred years are projected to drive accelerated sea level rise, net loss of critical fish and wildlife habitats, distributional shifts in biological communities, and damage to coastal infrastructure. With a limited ability to predict the consequences of climate change, how can we marshal an effective response? What are the costs of inaction as they relate to the ecosystem functions and services that support public well-being?

Introduction

Like many disciplines that attempt to study complex natural systems, climate science moves forward while acknowledging the many uncertainties that hinder its progress. Efforts to interpret ongoing climate research and effectively release the results in a public forum have recently brought worldwide attention to global climate change. In February 2007 the Intergovernmental Panel on Climate Change (IPCC), a group of international scientists and policy makers convened by the United Nations, asserted that evidence of a global climate warming trend was "unequivocal" (IPCC 2007). In its assessment, the panel went on to state with a high degree of certainty that most of the increases in average temperatures since the mid-20th century were due to emissions of heat-trapping gasses, such as CO_2, that are associated with human activities (IPCC 2007). Their assessment concurred with the findings of previous studies conducted by 11 national science academies. In the northern hemisphere, atmospheric temperatures have increased more than 0.7 °C (1.3 °F) over the past 100 years and concentrations of carbon dioxide (CO_2) have reached their highest levels in more than 650,000 years—more than triple pre-industrial levels (IPCC 2007). It is not simply the issue of warming that warrants concern, for the earth has been previously subject to periods of warming. Instead it is the rate and magnitude of warming (which appears unprecedented in recorded human history), its potentially dramatic ecological consequences, and its commonly agreed-upon cause, the burning of fossil fuels.

Contextualizing climate change discussions in light of the longer-term continuum of shifting climate conditions is critical to understanding shorter-term trends. That Maine has long been subject to a shifting climate over the millennia is supported by overwhelming evidence easily observed throughout the landscape, which shows many effects of glacial advance (cooling) and retreat (warming). In contrast to the trend in global warming since the 1800s, Maine air temperatures over the same period have demonstrated a slight cooling, primarily due to trends in the northern climate division of the state (NERAG 2001). Over about the last 30 years, however, the trend in Maine is one of increased warming rates (Fernandez et al. 2009). In the northeastern United States, temperatures have increased at a rate of 0.3 °C (0.5 °F) per decade since 1970. Winter temperatures have experienced an even greater increase, rising 0.7 °C (1.3 °F) per decade between 1970 and 2000 (IPCC 2007). A variety of observations from northeastern ecosystems are apparently consistent with the onset of a warming trend, including (NECIAT 2006):

- increasing sea-surface temperatures
- more extremely warm (>32 °C / 90°F) days each summer
- longer plant growing seasons, with earlier leaf-out and bloom dates
- less snow and more rain
- proportionately more snow in a wet, dense condition
- earlier ice break-up in spring
- earlier snowmelt and peak spring stream flow
- earlier Atlantic salmon migration and frog mating

Modeling Climate Change Projections

Predicting future climate conditions requires scientists to address uncertainties regarding the magnitude of heat-trapping gases that industrial and land-use activities will emit over the coming century and how the climate is likely to respond to these emissions. Emissions scenarios developed by the IPCC are based on variables such as population growth, energy use, and other societal choices (Frumhoff et al. 2007). The IPCC's A1F1 higher-emissions scenario (940 ppm atmospheric CO_2) assumes that emissions-mitigating technologies are not introduced until the second half of the century. The B1 lower-emissions scenario (550 ppm atmospheric CO_2) represents a possible future where fossil fuel reliance ebbs more rapidly and resource-efficient technologies are implemented before mid-century. Many other scenarios are possible, including those where emissions are lower than B1 and higher than A1F1 (Frumhoff et al. 2007).

Predicting how climate will react to the various emissions scenarios requires the use of climate models. The Northeastern Climate Impact Assessment used three of the most recent models to generate projections. These included the U.S. National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory CM2.1 model, the U.K. Met Office's Hadley Centre Climate Model version 3, and the U.S. National Center for Atmospheric Research's Parallel Climate Model (Frumhoff et al. 2007). Responses of individual climate models to the same emissions scenario may differ; for instance, the first two models mentioned have medium and medium-high sensitivity to emissions, respectively, while the third has low sensitivity. To mediate these differences, the Northeastern Climate Impact Assessment used the average of results obtained from the three models. Based on their results, additional models have been developed to predict shifts associated with climate change in a number of areas including ocean temperatures, sea level rise, precipitation, storm frequency and intensity, and streamflow characteristics.

Warming Air and Ocean Temperatures

The heat-trapping gases already released into the atmosphere can remain there for decades or centuries; as a result, even if greenhouse gas emissions were cut considerably today, these reductions would probably not slow or halt the warming trend until years—possibly decades—later. Frumhoff and colleaguess (2007) predicted that regardless of the emissions scenario, over the next few decades, air temperatures in the northeastern United States will increase up to 2.2 °C (4 °F) in winter and 2.0 °C (3.5 °F) in summer (Table

	Summer			Winter		
	NR	Low	High	NR	Low	High
2010-2039	1.0-1.9			1.4-2.2		
2040-2069		1.1-2.8	2.2-4.5		2.2-2.8	2.2-3.9
2070-2099		1.7-3.9	3.4-7.8		2.8-4.5	4.5-6.7

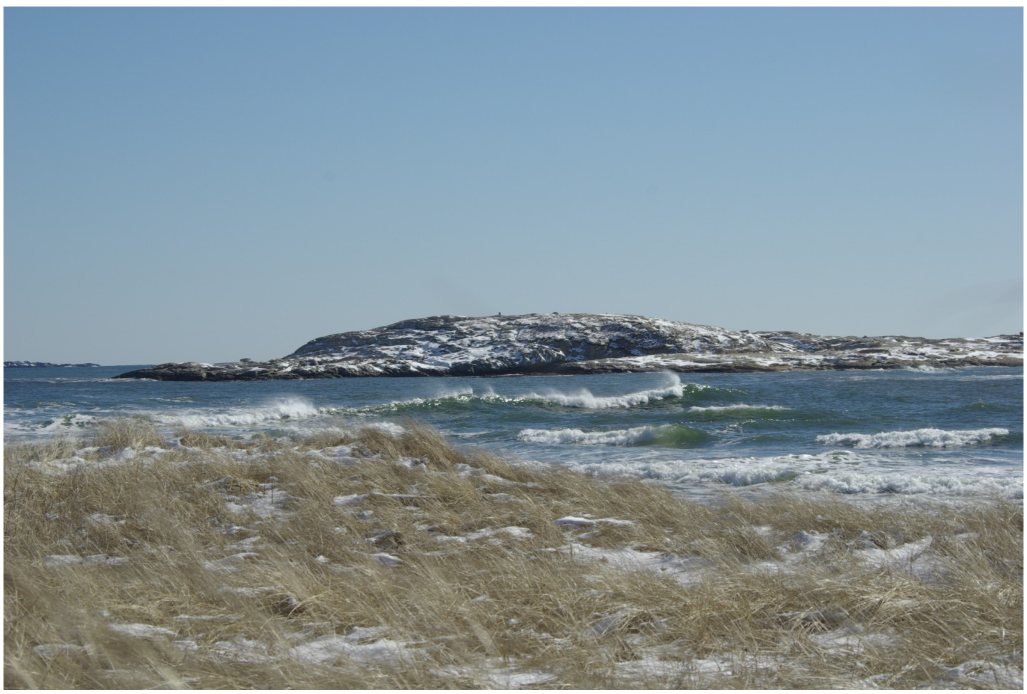
Table 6-1. Predicted air temperature (°C) increases as a result of climate change in summer and winter during the next few decades, by mid-century, and by late century. The NR (No Response) column represents projections of near-term temperature increases regardless of emissions scenarios used. The columns marked Low and High refer to low-emissions and high-emissions scenarios used in modeling.

6-1). However, if greenhouse gas emissions are not curbed, an even greater magnitude of warming is predicted (Frumhoff et al. 2007). Frumhoff and colleagues (2007) estimated that under the higher-emission scenario, by mid-century, winter temperatures in the northeastern United States could be as much as 3.9 °C (7 °F) warmer and summer temperatures could increase by 4.5 °C (8 °F) (Table 6-1). Under the lower-emissions scenario, winter and summer increases as high as 2.8 °C (5 °F) were projected. By this century's end, under the higher-emissions scenario, winter temperatures would warm by as much as 6.7 °C (12 °F) and summer temperatures by up to 7.8 °C (14 °F). Under the lower-emissions scenario, increases of as much as 4.5 °C (8 °F) in winter and 3.9 °C (7 °F) in summer (Frumhoff et al. 2007) have been projected.

Since 1900, northeastern U.S. sea-surface temperatures have increased by 0.6 °C (1 °F) and recent estimates project that they will continue increasing, albeit somewhat more slowly than air temperatures (Frumhoff et al. 2007). By the end of this century, sea-surface temperatures in the northeast are projected to increase by 3.4–4.5 °C (6–8 °F) under the higher-emissions scenario and 2.2–2.8 °C (4–5 °F) under the lower-emissions scenario (Frumhoff et al. 2007). At their seasonal highs, late-century western Gulf of Maine bottom temperatures are projected to increase 2.2 °C (4.0 °F) under the higher-emissions scenario and 1.3 °C (2.3 °F) under the lower-emissions scenario (Fogarty et al. 2007).

Accelerated Sea Level Rise

Sea level rise (SLR) due to melting glaciers on land and thermal expansion of the ocean represents a major agent of change to coastal ecosystems (IPCC 2001; Pugh 2004). Several researchers estimated an averaged global SLR rate of 1.6–1.8 mm (0.06–0.07 in.) per year from 1880 to 2000 (Church et al. 2004; Bindoff and



Winter waves batter Popham Beach at high tide, inducing a landward retreat of terrestrial plant communities. Combined with more frequent and intense storms, predicted accelerations in sea level rise threaten to re-shape vulnerable sections of Maine's coast. Photo: Slade Moore.

Willebrand 2007) but between 1993 and 2003, the rate of global SLR increased to 3.1 mm/yr (0.12 in./yr) (Holgate and Woodworth 2004; IPCC 2007).

With no further climate warming, by the end of the century global sea levels are projected to increase by 15 cm (6 in.) beyond current levels (IPCC 2007). By the end of this century, under the lower-emissions scenario, global sea levels are projected to increase 10–60 cm (4–24 in.) whereas the higher-emissions scenario estimates a global SLR increase of about 20–90 cm (8–35 in.) (Kirshen et al. 2008). In addition to citing these estimates, Kirshen and colleagues (2008) and Frumhoff and colleagues (2007) emphasized that analyses yielding SLR predictions of 0.6 to 1.4 m (2–4.6 ft) above 2005 levels under the higher-emissions scenario are within the range of possibility given the conservative nature of the models in widespread use (e.g., Rahmstorf 2007). Yet even these predictions may be conservative because they do not consider the influence of rapidly melting ice sheets and the potential for a dramatic increase in the rate at which these ice sheets melt.

At the regional and local scales, processes other than climate change can influence SLR, including processes with geologic origins (e.g., tectonic lift, land rebound, subsidence) and those with anthropogenic origins (e.g., compaction, fluid extraction) (Kirshen et al. 2008). SLR rates in Maine, like those elsewhere, have historically varied as a result of geologic and climatic conditions. Four thousand years ago the SLR rate was a tenth of the present rate (Kelley et al. 2005). One thousand years ago, the rate was a hundredth of the present rate. Gulf of Maine sea levels have increased a total of 30–40 cm (12–16 in) since 1800; this date marks the beginning of the latest period of regional climatic warming associated with thermal expansion of the Gulf of Maine and the North Atlantic sea surface (Gehrels et al. 2002). Kelley and colleagues (2005) found that despite annual and decadal variations, Maine's overall SLR from 1930 to 1992 was 2.2 mm/yr (0.09 in./yr). No recent predictions of SLR are available for the discrete section of Maine's coast that includes the Kennebec Estuary.

Shifting Precipitation Regimes

Precipitation varies between years considerably more than temperature, which makes it more difficult to distinguish long-term trends from short-term fluctuations (Hayhoe et al. 2007). Consequently, regional estimates of climate change induced shifts in precipitation patterns vary considerably (NAST 2001). Notwithstanding a severe drought in the early 1960s, annual average precipitationin the northeastern United States has increased 5–10% since 1900 (Frumhoff et al. 2007). Under either emissions scenario, the Northeast is projected to see a steady increase in annual precipitation, with a total increase of about 10 cm (4 in.) by the end of the century. The intensity of precipitation, characterized by the average amount of rain falling on any given rainy day, is predicted to increase 8–9% by mid-century and 10–15% by the end of the century (Frumhoff et al. 2007). Heavy-precipitation events (>5 cm or 2 in. of rain falling in 48 hours) are projected to increase 8% by mid-century and 12–13% by 2100 (Frumhoff et al. 2007).

At a finer scale within the annual cycle, winter precipitation is projected to increase 11% under the lower-emissions scenario and 14% under the higher-emissions scenario. Small decreases in summer precipitation are also forecast by the end of the century under the higher-emissions scenario (Hayhoe et al. 2007). Despite only small summer precipitation decreases, evapotranspiration increases due to warmer temperatures are likely to make summers dryer, with an increased incidence of droughts (Hayhoe et al. 2007).

Increased Storm Events and Flooding

Knutson and colleagues and (1998) and Knutson and Tuleya (1999) suggested that a 2.2 °C (4.0 °F) warmer sea surface could yield hurricane wind strength increases of 5–10%. As a result of greater wind strength, wave height and storm surge would probably also increase, resulting in as much as 25% more destructive power. Combined with increasing SLR, these changes would be expected to lead to a greater frequency and height of extreme storm surge events by 2050 throughout the northeastern United States (Frumhoff et al. 2007; Kirshen et al. 2008). For instance, under the higher-emissions scenario the current 100-year maximum flood in Boston would occur at least once every 8 years and at a height of about 4 m (13 ft), versus the current maximum height of 3 m (9 ft) (Kirshen et al. 2008). Under the lower-emissions scenario the current 100-year storm surge event in Boston would recur at least once every 30 years at all sites and the maximum height would be 3.5 m (11.5 ft) instead of the current maximum of 3 m (9 ft) (Kirshen et al. 2008).

Ecosystem Impact Projections

Assessments of potential climate change-related impacts to marine and estuarine systems must take into account a variety of possible interacting factors and cascading responses. Climate change-related physical changes to these systems—such as shifts in temperature, circulation patterns, and stratification—are anticipated, but not well understood. To varying extents, these changes will result in structural and functional shifts to biological systems that influence nutrient cycling, productivity, species distributions and abundance, and the delivery of ecosystem goods and services. Maine's steep climate gradient exists within just 3 degrees of latitude—a similar gradient in Western Europe spans 20 degrees. As a result, the likelihood for dramatic ecosystem change in Maine caused by even small climate shifts is high (Fernandez et al. 2009).

Nearshore Marine Systems

The complexity of direct and indirect interactions between physical, chemical, and biological factors greatly hinders confident predictions of ecosystem shifts associated with climate change. Further exacerbating the problem of predicting change are seasonal shifts and between-year variability in weather patterns that strongly influence ocean temperature, salinity, and other conditions on the continental shelf of the northeastern United States (Frumhoff et al. 2007). Along with other environmental factors, water temperature has a co-dominant role in shaping the nearshore and estuarine systems (Lalli and Parsons 1997) with which this report is concerned. In addition to the synergistic effect that warming ocean and air temperatures have on sea level rise, ocean temperature increases are projected to drive multiple ecosystem changes related to the physiological tolerances of vertebrate and invertebrate species, including invasive and pathogenic organisms. Under the climatic trends predicted over the next century, warming ocean temperatures are likely to facilitate range expansions into the Gulf of Maine of species more associated with regions south of Cape Cod. Increasing water temperatures may also prompt northward distributional shifts in species native to the northeastern United States, especially organisms for which cool Gulf of Maine waters currently represent a southernmost range limit. In some instances, these changes have already been observed in commercial species distributions, as have shifts in plankton abundance (Fogarty et al. 2007) that may signal the potential for effects that cascade across trophic levels (Frumhoff et al. 2007).

A major climate-associated concern of ecologists and planners is the fate of commercial fish stocks that have important cultural, economic, and ecological value. The productivity of some of these species, such as Atlantic cod and American lobster, is dependent on cool temperate environmental conditions. Fogarty and colleagues (2007) demonstrated that southern Gulf of Maine populations of cod and lobster have already experienced declines due to ocean warming and are projected to decline further as warming trends continue. However, they suggested that despite warming ocean temperatures, cod and lobster populations in western Maine waters are not likely to suffer negative population responses directly associated with thermal tolerances being exceeded. In the case of eastern Maine waters that are dominated by the cold Labrador Current, lobster productivity may be somewhat enhanced by warming waters (Fogarty et al. 2007). However, shifts in prey abundance, predator populations, and larval transport dynamics, among other factors that are difficult to predict, may nevertheless influence nearshore cod and lobster populations as a result of warming oceans. There are also concerns that warmer waters may facilitate a northward range expansion of lobster shell disease, which decimated the Rhode Island lobster fishery and caused dramatic declines south of Cape Cod (Glenn and Pugh 2006).

Lobster is among the few economically important species in Maine waters that has not experienced depletion. Representing the greatest annual landed value (nearly $300 million) of any fishery in the state, lobster is presently the mainstay of Maine's fishing industry, supplanting a historically more diversified portfolio of economically important species. A dramatic decline in the lobster fishery would represent an economic, cultural, and social upheaval in some ways mirroring the devastation caused by the Newfoundland cod fishery collapse. For stocks of other species that are presently depleted in the western Gulf of Maine, such as cod, climate change, by indirect or direct means, may represent an additional stress that inhibits recovery. If organisms representative of more southern faunal assemblages expand into the Gulf of Maine, their function as surrogates for displaced commercial species will depend on many factors including their market value, abundance, and whether the fishing industry has the adaptive capacity necessary to exploit shifting conditions as opportunities.

Coastal and Estuarine Ecosystems

Developed Areas

Estuaries and other coastal systems are constantly subject to the energy of waves, currents, and tides, which contribute to erosion, transport, and deposition of sediments. The rates and intensities at which these processes operate can influence ecological and economic conditions as well as public health and safety. Under the influence of rising sea levels and more frequent and intense coastal storms, changes in shoreline morphology are likely to increase (Scavia et al. 2002; Frumhoff et al. 2007; Kirshen et al. 2008). With each event that reshapes a coastal area, changes in the direction or intensity of currents and tides may also occur, further inhibiting accurate predictions of change.

One way researchers are applying climate change science to regional and local planning is by predicting linkages between sea level rise and economic impacts to developed coastal areas. One analysis in New England concluded that low-lying infrastructure would be at risk of considerable losses as a result of climate change (NERAG 2001). For the heavily developed Saugus River estuary north of Boston, flood losses associated with a 30.5 cm (12 in.) increase in sea level over the next 100 years were estimated at $1.4 million/year (USACE 1990).

The work of Kirshen and colleagues (2004, 2006) provided a comparison of potential economic impacts associated with climate change in the context of how adaptive actions and policies can mitigate those impacts. Depending on the magnitude of sea level rise and the adaptive actions taken, storm damage to infrastructure and associated emergency costs in the Boston area were predicted to range from $20–$94 billion between now and 2100. In the absence of increased SLR rates associated with climate change, costs could reach approximately $7 billion if flood management policies are not updated.

Cardinal flowers (*Lobelia cardinalis*) regally mark the upper intertidal zone on the rocky slope of a Merrymeeting Bay causeway. Where landward transgression is hindered by steep landforms, unsuitable soil conditions, or human infrastructure, the resilience of some intertidal communities to accelerated sea level rise will be compromised. Photo: Slade Moore.

Intertidal and Shallow Subtidal Communities

Coastal beach and dune complexes, saltmarshes and other tidal wetlands, along with the species that depend on them, may represent the ecological elements most vulnerable to fragmentation and loss due to sea-level rise. Accelerated sea-level rise will subject these communities to periodic flooding, inundation, erosion, and saltwater intrusion (Scavia et al. 2002). Although tidal marshes in the northeast have typically accumulated sufficient sediment and organic matter to increase their elevation in step with rising seal levels, some coastal wetlands in the region show signs of not being able to accommodate recent accelerations in SLR (Donnelly and Bertness 2001). Tidal wetlands lacking accretion rates necessary to keep in step with SLR acceleration are at risk to long-term inundation that could convert them to subtidal environments. Under the right landscape conditions, marshes with accretion rates insufficient to meet the demands of rising sea levels can nevertheless gain necessary elevation by moving upslope. However, landward transgression of marsh communities into formerly terrestrial environments depends in part on unimpeded upslope connectivity and favorable soil conditions. In some areas, upslope transgression of tidal marshes in Merrymeeting Bay and the lower Kennebec Estuary will be impeded by unfavorable geomorphic conditions including unsuitable parent material and high-angle slope. Human infrastructure, such as beach walls, rock-armored slopes, and berms, can also preclude colonization by marsh plants. As sea levels rise, some undeveloped adjacent areas may convert to tidal marsh under increasing SLR. These might include forested wetlands that fringe Merrymeeting Bay or low-elevation areas throughout the estuary that are immediately upslope of the current high tide mark. However, the overwhelming pattern in the northeastern United States is projected to be one of widespread and significant net tidal wetland loss (Frumhoff et al. 2007).

Another potential impact of rising sea levels is intrusion of the salt wedge further up into estuaries, which could impact natural communities that are less resilient to prolonged increases in water salinity. As a result the extensive, predominantly freshwater tidal marshes that confer upon Merrymeeting Bay its over-riding ecological and cultural value would potentially be at risk to losses related not only to SLR but also to salinity increases. Reductions in tidal wetland acreage of sufficient magnitude would be attended by losses of wetland services such those that attenuate the forces of erosion, wave action, and flooding, and that promote sequestering of nutrients and pollutants.

Also reduced would be the amount of habitat for marsh-obligate plant and animal communities that support organisms having ecologically important functional roles and commercial value. In addition to losses of ecosystem function and services, a reduction in wetland acreage facilitates the potential erosion of biodiversity through the loss of habitat for rare and uncommon species. Merrymeeting Bay's shallows, notable throughout the northeastern United States for harboring some of the most important habitat for assemblages of rare aquatic plant species (MNAP 2008*a*), may be particularly vulnerable to SLR-induced shifts in biodiversity. In addition, losses of saltmarsh and sand beaches in the lower Kennebec Estuary could hinder conservation efforts targeting imperiled species such as saltmarsh sparrows, piping plovers, and least terns.

Accelerated SLR is also likely to impact other ecological community types situated on an elevation gradient similar or adjacent to that of saltmarshes. Intertidal mudflats have economic value associated with clam and worm harvesting; among other ecological roles, they are critical to supporting the nutritional needs of long-distance migrant shorebirds and waterfowl. Shallow subtidal areas immediately downslope of flats and marshes would also be affected. Where compromised water clarity in these areas already limits the lower depths at which light-dependent submerged aquatic vegetation can persist, increased water depth associated with accelerated SLR can further limit distributions of these plant communities and the rich species assemblages that depend on them. Additional ecosystem functions and services of submerged plant communities that are subject to degradation through SLR include wave and current attenuation, stabilization of fine-grained substrates, sequestering of suspended fine sediments, and carbon export to benthic infaunal communities.

Over the coming century, climate change-associated shifts are predicted to increase annual precipitation, the length and intensity of precipitation events, the flashiness of streamflow, and the chances of severe storms and flooding. These projections, which call for more frequent and intense wet weather and flooding, are likely to flush greater amounts of soil, nutrients (due to scouring and erosion), and other pollutants into the estuary, all processes that are linked with degraded water transparency, increased phytoplankton productivity, and higher contaminant concentrations in water, benthic sediments, and organisms. Researchers suggest that recent massive blooms of red tide algae that had dramatic economic impacts were facilitated in part by elevated amounts of spring runoff (Carlowicz and Lippsett 2008). Commercial clams harvested in and around the Kennebec Estuary in 2007 had a landed value of close to $0.5 million (H. Bray, unpublished data), and an overall economic contribution of $1.5 million (D. Card, Maine DMR, personal communication). If the harmful algal blooms of 2005 are any indication, local economies dependent on fisheries affected by red tide closures may be particularly vulnerable to climate change-induced runoff increases. Predicted ocean acidification as a result of increasing greenhouse gas emissions may also impact fisheries dependent upon organisms that live within discrete pH tolerances necessary for the growth and maintenance of calcareous exoskeletons and shells (Anderson et al. 2009).

Tidal Freshwater and Tributary Streams

Climate change may influence habitat quality for freshwater and anadromous fish species that require cool waters and shallow spawning areas. No climate change vulnerability assessment for the broad spectrum of anadromous species has been conducted by state agencies, but of the species using the estuary, salmon (Dill et al. 2002), rainbow smelt, and sea-run trout might prove the least resilient to rising water temperatures (G. Wippelhauser, personal communication).

Research by Hayhoe and colleagues (2007) predicts a tendency toward increased winter-spring streamflow and less flow during summer and fall. The USFWS low flow threshold of 0.037 $m^3/s/km^2$ was developed to represent median August flows and is designated as the minimum streamflow necessary to support the habitat requirements of New England stream biota (USFWS 1981). Presently, mid- to late-summer streamflow in many drainages drops below this threshold for several weeks (Hayhoe et al. 2007). By the end of this century, under a higher-emissions scenario it is projected that streamflow will further drop below the USFWS low flow threshold for up to six additional weeks during the summer and early fall. Under the lower-emissions scenario, little change from present conditions is predicted (Hayhoe et al. 2007). Higher-emissions scenario changes have the potential to impact a broad range of aquatic organisms depending on their particular life-history strategies and responses to high and low flow conditions. Hayhoe and colleagues (2007) emphasized the need to examine life history traits of species in the context of vulnerability to climate-mediated streamflow changes. For instance, if peak migration of juvenile salmon from freshwater rivers in the spring is as much as two weeks out of phase with optimal environmental conditions in rivers, estuaries, or the ocean, survival of salmon can be impacted (McCormick et al. 1998). Other research determined that Atlantic salmon stock abundance was negatively correlated with warm ocean conditions in nursery areas and specifically asserted that June temperatures may be pivotal to smolt survival (Friedland et al. 2003). Given the magnitude of resources expended on re-establishing diadromous fish runs in Maine, the sensitivity of these species to climate change warrants attention if conservation priorities and investments are to successfully adapt to shifting conditions.

Constructed to guard the mouth of the Kennebec from Confederate warships, Fort Popham today is a reminder of Maine's historic past and cultural heritage. Equitable assessments of vulnerability to climate change will require systematic reviews of policies and programs relevant to social, ecological, economic, and cultural resources in coastal Maine. Photo: Slade Moore and John Sowles.

Marshaling a Response to Climate Change

The IPCC (2007) states that the ability to adapt to historical and projected SLR is uneven across North American coastal communities and that readiness is low. Managing risks associated with climate change is hindered by historical development and land-use choices, prevailing coastal policies, and the societal expectations these conditions have facilitated (Frumhoff et al. 2007). Even if immediate action is taken to dramatically reduce greenhouse gas emissions, climate change impacts to coastal areas over the next few decades are likely to exert stress on public health and safety, local and regional economies, ecosystem integrity, and a cherished coastal heritage. If emissions continue unabated until the middle of the century, the magnitude of change and its impact are likely to be much greater. Acting promptly to reduce emissions may afford society and ecosystems a higher probability of successfully adapting to changes that cannot be avoided (Frumhoff et al. 2007). However, successfully ameliorating the impacts and costs associated with climate change will require a major effort to comprehensively assess vulnerabilities and implement adaptation strategies. The costs associated with implementation will largely depend on how promptly actions are taken to reduce emissions and address vulnerabilities. Some or all of the following options, many of which have been previously suggested by other authors (Slovinsky and Dickson 2006; Frumhoff et al. 2007; Glick et al. 2007), may offer tools for mitigating these costs.

Assess Vulnerability and Resilience

Resilience, in the present context, can be said to represent an ecosystem's ability to accommodate shifting environmental conditions by continuing to function in ways we expect and value. A simplified approach toward supporting resilience is to prevent, limit, or mitigate negative impacts to ecosystems and natural communities and—where possible—increase positive influences. Conversion of relatively natural areas to anthropogenically altered community types, discharge of contaminants, nutrient enrichment, and influx of invasive species and pathogens are a few examples of stressors that can hinder resilience through either a slow erosion or a rapid disturbance of ecosystem structure, function, and overall integrity.

Assessments of coastal and estuarine ecosystems to determine vulnerability and expected resilience to climate change impacts will represent a critical step toward informing the planning and implementation of adaptation strategies. Specific indicators of resilience for coastal marshes and beaches may include acreage, rates of erosion or accretion, barriers to upslope transgression, landward retreat, and longshore current patterns. Similar approaches can be developed for other natural and anthropogenically altered community types that are likely to be affected by climate change. These assessments, in turn, can inform the work of identifying and ameliorating social, economic, and cultural impacts linked to ecosystem change.

Equitably Support Resilience and Adaptation

Promoting resilience and adaptation to climate change requires knowledge of factors that hinder and benefit ecosystem resilience under different conditions. Planning for climate change represents an immense challenge given the uncertainties inherent in modeling and our limited understanding of ecosystem interactions and responses under present conditions, let alone changing ones. There are, however, a number of actions that may reduce undesirable impacts with some certainty. A few of these include:

- Where public health, safety, and property are not put at risk by such actions, remove dams, causeways, dikes, armoring, and other impediments to transgression of natural communities in aquatic systems that are subject to SLR.
- Where public health, safety, and property are vulnerable, assess the future effectiveness of existing shoreside armoring, seawalls, jetties, breakwaters, and other structures intended to provide surge and wave protection. Also, determine the feasibility of protecting new areas that were not previously considered vulnerable.
- Encourage the protection of low elevation, undeveloped land adjacent to and upslope of intertidal areas to allow for landward transgression and connectivity between these communities.
- Update shoreland zoning, stormwater management, town open space ordinances, and flood zone designations to account for predicted increases in SLR, precipitation, and intense storm events.
- Prevent or mediate the impacts of other stressors on system function and biodiversity including habitat loss, nutrient enrichment, toxic discharges, and colonization of invasive species.

Develop Local Modeling and Track Environmental Shifts

Broad predictions of anticipated SLR for the northeast have been developed but few examples of SLR modeling are available for local areas or specific natural community types within the region. Modeling SLR impacts at a finer scale will be required to account for local impacts with greater certainty. For instance, preliminary work in this area by the Natural Resources Council of Maine (NRCM) recently projected acreage estimates for climate-change-induced flooding of coastal areas. Slovinsky and Dickson (2006) made an intensive investigation of predicted SLR in the Wells Estuary using high-resolution remote sensing techniques to determine land elevations with great accuracy. Moving forward, efforts that integrate NRCM's region-wide scope, Slovinsky and Dickson's high-resolution methods, and readily available digital ecological mapping data would facilitate an assessment of the types and acreages of natural communities and resource-use areas most vulnerable to change. An option for regional and subregional action in the northeastern United States might be the use of inundation modeling techniques that allow estimates of losses in ecosystem function and, by extension, ecosystem services. As modeling plans are developed, environmental monitoring requirements will be identified, including long-term efforts necessary for signaling when benchmarks or trigger points for adaptive management action are reached.

Tracking other environmental parameters, such as those developed to identify changes in water quality, are especially warranted given the potential for climate change to cause increases in runoff, nutrient enrichment, and contamination from toxic compounds and pathogens. These monitoring efforts are essential not only to aid planning and implementation of natural community conservation efforts but also to support the resilience of industries highly reliant on clean waters, such as fisheries for soft-shell clams and other fisheries in the extreme nearshore.

Heighten Awareness and Encourage Adaptation Policies

Informed societal choice requires of the general public and decision makers a better understanding of the factors contributing to climate change-induced environmental shifts and how these shifts are likely to influence ecological, economic, cultural, and social conditions. Along with discussions emphasizing the scientific basis for climate change predictions, the emerging public dialogue should focus on the merits of prompt emissions reductions and implementation of precautionary planning and actions. As part of any discussion of climate change, the predicted costs of inaction should also be unambiguously articulated.

Achieving a sufficient level of preparedness will require systematic reviews of potentially relevant government programming and policies to determine if priorities established prior to vulnerability assessments require revision. However, unless the development of adaptation strategies is mandated from the highest levels of state and federal government, marshalling adequate responses to climate change is likely to be hindered by a lack of resources, funding, and continuity. Without prompt development and implementation of a clear and proactive vision, opportunities to promote resilience and adaptation to climate change may be lost. Maine's technical expertise, persistent maritime tradition, and demonstrated public support for protecting ecological assets, would seem to predispose the development of a comprehensive and equitable response to climate change.