Synthesis of Climate Change Drivers and Responses in Long Island Sound

ICF International and EPA are working with the Long Island Sound Study (LISS), a partner in EPA's Climate Ready Estuaries (CRE) Program, to: (1) review and synthesize information on climate change drivers and responses in Long Island Sound; (2) develop a prioritized list of indicators for monitoring climate-driven change; and (3) prepare recommendations on elements of a final monitoring plan. This short report summarizes the findings of the first step. It describes first the projected changes in climate that will be of most relevance to the Sound. It then describes current stressors and risks from climate change, as well as the impacts of climate change on the Sound's ecological systems.

1 Purpose and Scope of Synthesis Report

This draft report qualitatively characterizes the type, relative magnitude, and degree of uncertainty of key predicted changes in climate to Long Island Sound (LIS) and summarizes how those changes may interact with non-climate stressors. Many of the projected impacts described here apply to similar estuarine habitats along the Northeast (NECIA, 2006). This report focuses on local impacts, however, as described in both published and unpublished documents and online sources concerning the LIS estuary (Figure 1). Findings will inform the development of the prioritized list of indicators for monitoring climate-driven change and the recommendations for a long-term climate change monitoring program.

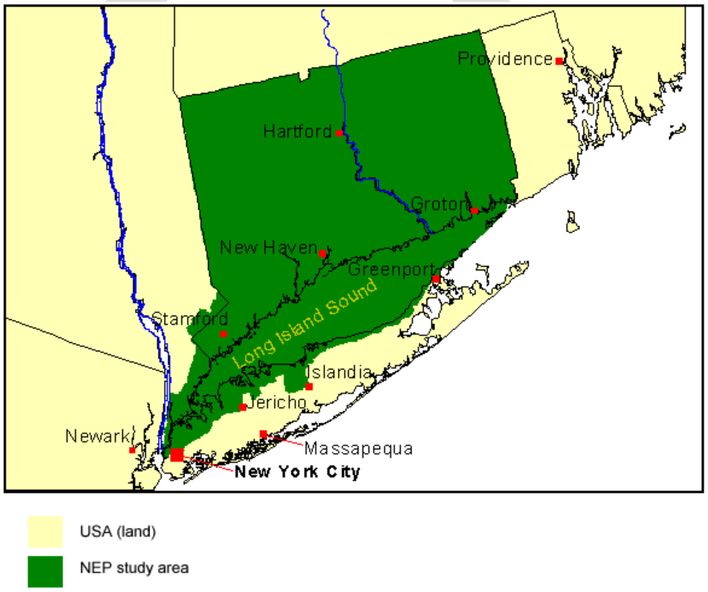


Figure 1 Study Location
Graphic courtesy of EPA: http://www.epa.gov/owow/estuaries/programs/studies/lis.gif

A number of significant climate changes have been observed over recent decades, and are projected to continue for the foreseeable future. While climate change is global in scale, as detailed in the Intergovernmental Panel on Climate Change (IPCC) 2007 Synthesis Report (the Fourth Assessment Report, known as AR4) (IPCC, 2007), the magnitude and type of expected changes vary regionally (GCRP, 2009; NECIA, 2006). Sea level rise, for example, could be more rapid and pronounced along regional coastlines in the Northeast (defined here and after as the states of New Jersey and Pennsylvania, northward) (Yin et al., 2009; GCRP, 2009).

The following sections summarize information on:

- Uncertainties associated with climate change predictions;

- Projected local and regional changes in climate, including projected changes in air temperatures; changes in wind; changes in precipitation and storm climatology; and changes in the ocean;
- Implications for existing stressors; and
- Risks to the Sound's ecosystems.

2 Assessing Magnitudes of Change and Degrees of Uncertainty

There will always be some level of uncertainty with regard to the magnitude of predicted changes in climate. The degree of uncertainty varies for different climate variables (e.g., temperature, precipitation, sea level rise), and the degree of change will vary by region or locale. For example, while IPCC expresses a high level of confidence in observed and predicted changes in global average temperature (for all emissions scenarios), sea level rise projections are more uncertain. While scientific observations indicate that global sea level rise is occurring and will continue to occur, the magnitude of future sea level rise will depend heavily on rates of Greenland and Antarctica ice sheet melt, changes in ocean circulation due to additional freshwater inflow (from melting ice), and naturally-cyclic hemispheric climate patterns. According to IPCC (2007), "[b]ecause understanding of some important effects driving sea level rise is too limited, [the AR4] report does not assess the likelihood, nor provide a best estimate or an upper bound for sea level rise." There is also a great deal of uncertainty regarding "the extent to which society resolves to reduce further emissions of heat trapping gases" (NECIA, 2006). It *is* certain that CO_2 emissions will continue to rise for at least the next several decades regardless of future actions to reduce emissions (IPCC, 2007). Uncertainty is not formally addressed in this report, as most of the cited papers do not discuss uncertainty in a manner that could be consistently presented across the study topics. However, where possible, a range of scenarios is presented to describe the potential extent of impacts.

3 Projected Changes in Climate in LIS

Changes in Air Temperature

Globally, air temperature has increased an average of 1.5°F (0.8°C) since 1970. In the Northeastern U.S., the average annual temperature has increased considerably more, by as much as 4°F (2.2°C) in winter averaged over the period 1970 to 2000. The average increase in annual temperature has been 0.14°F (0.08°C) per decade over the full period of record; however, the rate of temperature increase has been accelerating, averaging 0.5°F (0.3°C) per decade between 1970 and 2002. Under a high-emissions scenario (continued heavy reliance on fossil fuels), average temperatures in the Northeast by 2100 could increase 8-12°F (4.4-6.7°C) above historical levels in winter and 6-14°F (3.3-7.8°C) in summer. Under a low-emissions scenario (a shift away from fossil fuels), increases would be about half as much (NECIA, 2006).

The frequency of summer days with a high *heat index* (temperature, with humidity as a factor) is also projected to increase. There will be more days with high temperatures reaching 90+°F (32+°C) in many Northeastern cities. Projections indicate that Hartford could see more than 30 days reaching 100+°F (38+°C) (NECIA, 2006). According to the Northeast Climate Impact Assessment (NECIA), "the typical northeastern summer day is projected to feel 12 to 16°F [6.7-8.9°C] warmer than it did on average between [the reference period] 1961 and 1990" (NECIA, 2006). NECIA's analysis indicates that by the end of the century under a high emissions scenario, summers in the NYC Tri-State Region are likely to feel similar to South Carolina summers of today (see Figure 2.

Changes in Wind

Wind speed and direction are important components of the circulation of an estuarine system, as they contribute to patterns of upwelling, downwelling, and mixing near coastal areas. At least one study has attempted to quantify projected changes in wind speed under future climate conditions. Kunkel et al. (2008) investigated changes to wind speeds under both high and low emissions scenarios, applying several different methodologies. Compared to the reference period (end of 20th century), New York could see a decrease of 0.44 miles per hour (mph) (-0.2 ms^{-1}) in average summer wind speed under a high emissions scenario or as much as a 2.01 mph (+0.9 ms^{-1}) increase under the low emissions scenario (Kunkel et al., 2008).

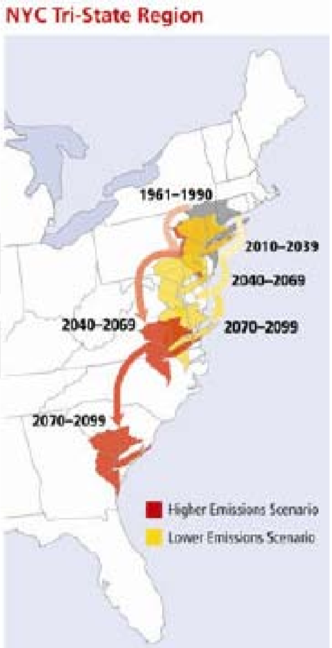


Figure 2 Tri-State Summers over the 21st Century (*NECIA, 2006)*

Changes in Precipitation and Storm Climatology

Changes in Seasonal Precipitation

Over the last several decades, the Northeast has experienced measurable changes to precipitation patterns; changes in these patterns are expected to continue and are likely to accelerate during this century. The primary observed change in precipitation over the region is a marked increase in annual precipitation of 5 to 10 percent since the turn of the twentieth century. By 2100, the region could see an additional four inches of precipitation annually, compared to the 1961-1990 reference period (NECIA, 2006). The greatest increases are expected with winter precipitation, with projected changes of 11 to 16 percent by 2050 and 20 to 30 percent by 2100. Additionally, as air temperatures rise, the Northeast can expect a continuation of recent trends in the type of precipitation experienced during winter--less snow and more rain (NECIA, 2006).

Changes in the Climatology of Heavy Precipitation Events

In addition to changes in seasonal and annual average precipitation, heavy precipitation events are expected to continue late-twentieth century trends, increasing in frequency and intensity. By 2050, the amount of precipitation for a "rainy day" event is expected to increase eight to nine percent, with an increase of 10 to 15 percent by 2100. The frequency of such events is also likely to increase by as much as 13 percent by the end of the century. Kirshen et al. (2008) suggest that the 100-year Northeastern coastal storm event (by the 2005 definition) will increase in frequency to every 70 years by 2050 and to every 50 years by 2100. Heavy winter storms are also projected to reach the Northeast (becoming "Nor'easters") with increasing frequency (NECIA, 2006).

Changes in the Ocean

Sea Level Rise

Among the impacts of climate change are those that are projected to affect the world's oceans. Global sea level has been increasing due to thermal expansion of surface waters and increasing freshwater flow from melting glaciers and ice sheets at high latitudes. In the last century, the planet has witnessed a sea level rise of 8 inches (20.3 centimeters), compared to almost no rise for the previous 2,000 years (GCRP, 2009). The amount of sea level rise varies depending on local conditions, such as subsidence and uplift. An assessment of NOAA tidal gauge data for New London, CT, for 1938-2005, indicates that the average rate of sea level rise over that period was 0.08 inches per year (2.13 mm/yr) (Kirshen et al., 2008).

The IPCC projects a sea level rise of up to 2 feet (0.6 meters) by 2100, even without accounting for the current break-up of Greenland ice sheets (IPCC, 2007). Another recent study, also not accounting for recent ice sheet break-ups, indicates that global sea level could rise 2-4.5 feet (0.6-1.4 meters) by 2100 (compared to the 2005 global average sea level) (Frumhoff et al., 2007).

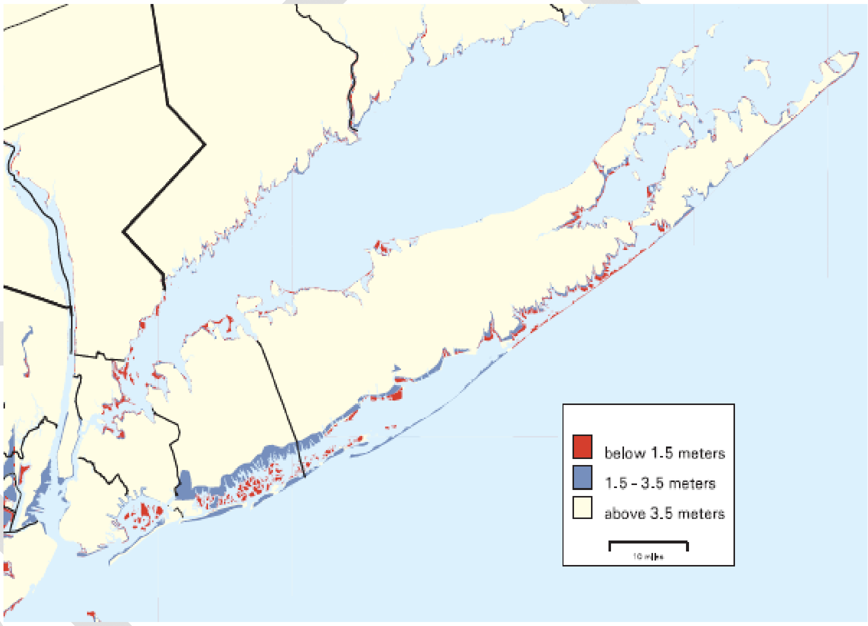


Figure 3 Lands susceptible to climate change.
Titus and Richman (2001)

A 2009 study projects that, when ice sheet melting and the associated changes in ocean currents are considered, coastlines of the Northeast could see an even greater rise in sea level compared to the global estimate. Boston and New York City, for example, could see an even greater rise by the end of the century, with New York City experiencing an increase in sea level of 5.9-8.3 inches (14.99-21.08 centimeters) (in addition to changes to eustatic sea level); the projection for Boston is similar (Yin et al., 2009). A map of the shoreline in New York and Connecticut that is susceptible to sea level rise from a 2001 analysis is presented as Figure 3.

It should be noted that strong storm events exacerbate the threat of sea level rise. Kirshen et al.'s (2008) analysis indicates that in 100 years, during 100-year storm events, the maximum sea level at New London, CT could be about 10.2 feet (3.1 meters) above base sea level. For comparison, the current maximum sea level height expected at New London during 100-year storm events is about 7.2 feet (2.2 meters) above average sea level (Kirshen et al., 2008).

Changes in Ocean Temperatures

Projected increases in sea surface temperatures (SSTs), and temperature changes deeper in the water column, are of concern for storm climatology (greater ocean heat content feeds coastal storms), sea level rise (via thermal expansion of water), and ecosystem health. In the Northeast, SSTs are an important determinant of regional climate, as they are responsible for "the steepness of the north-to-south air temperature gradient in the region" and, in one example, variations in SST patterns have been linked to the Northeast drought of the 1960s [Hayhoe et al., 2007; Bradbury et al., 2002 (in Hayhoe et al., 2007)]. SSTs along the Northeast coastline have been increasing over the last century. Since 1900, regional SSTs have risen by approximately 1°F (0.6°C) (Frumhoff et al., 2007). The Gulf of Maine has experienced a rise of 0.9°F (0.5°C) per decade over the same time period (Hayhoe et al., 2007). Under IPCC's higher-emissions scenario, by 2100, Northeast SSTs could rise as much as 6-8°F (3.3-4.4°C) and by as much as 4-5° F (2.2 to 2.8°C) under the lower-emissions scenario (Frumhoff et al., 2007).

The projected changes to bottom water temperatures vary significantly with different emissions scenarios. Under the higher-emissions scenarios, the increase in the bottom water temperature in the Northern Mid-Atlantic Bight during spring months is projected to be about 7°F (3.9°C) by the 2080s. For the same time frame, under the lower-emissions scenario, this increase could be 2°F (1.1°C) (Frumhoff et al., 2007).

Ocean Acidification

Although the impact of increased atmospheric carbon dioxide (CO_2) is most often linked to the warming of the atmosphere, it is also responsible for acidification of ocean waters. Ocean acidification occurs when CO_2 dissolves in seawater, initiating a series of chemical reactions that increases the concentration of hydrogen ions and makes seawater more acidic, measured as a decline in pH. An important consequence of this change in ocean chemistry is that the excess hydrogen ions bind with carbonate ions, making the carbonate ions unavailable to marine organisms for forming the calcium carbonate minerals (mostly aragonite or calcite) that make up their shells, skeletons, and other hard parts (Doney et al., 2009; Pew Center, 2009).

Under pre-industrial conditions, the atmospheric concentration of CO_2 did not change over many millennia (Caldeira and Wickett 2003). However, as emissions have increased, there has been an accumulation of CO_2 in the atmosphere and a net flux of CO_2 from the atmosphere to the oceans. As a result, the pH of today's ocean has declined in relation to the pre-industrial period by 0.1 pH unit (on a log scale), representing a 30-percent increase in ocean acidity (Caldeira and Wickett 2003). The pH and carbonate ion concentrations of the world's oceans are now lower than at any time in at least the past 420,000 years (Hoegh-Guldberg et al. 2007). By 2100, depending on the emissions scenario modeled, the average ocean pH could decline by 0.3 to 0.5 pH units in relation to pre-industrial levels (Caldeira and Wickett 2005).

The primary concern with decreasing pH is the effects on marine calcifiers. In laboratory experiments, sea urchins showed reduced early development (Kurihara and Shirayama 2004) and shell growth (Shirayama and Thornton 2005) in seawater with elevated CO_2 concentrations. Gazeau et al. (2007) found that calcification in a mussel species and Pacific oyster declined by 25 percent and 10 percent, respectively, when grown in seawater at the concentration expected by 2100 under a "business as usual" emissions scenario. Shifts in community composition were observed in a mussel-dominated rocky intertidal community experiencing rapid declines in pH; years of low pH were accompanied by declines in calcerous species (e.g., mussels, stalked barnacles) and increases in non-calcerous species (e.g., acorn barnacles, algae) (Wootton et al. 2008). Moy et al. (2009) provided direct evidence that ocean acidification is affecting shell formation, finding that the shells of modern foraminifera in the Southern Ocean are 30-35 percent lighter than foraminifera shells in core samples from ocean sediments that predate the industrial revolution.

Although the most information to date indicates adverse effects on marine calcifiers, recent research indicates that responses to increasing acidification may vary in a species-specific manner, even among closely-related species. In experiments by Miller et al. (2009), the larvae of the Eastern oyster (*Crassostrea virginica*) showed a 16 percent decrease in shell area and a 42 percent reduction in calcium content when preindustrial and end of 21st century pCO2 treatments were compared, whereas the Suminoe oyster (*C. ariakensis*) showed no change in either growth or calcification.

4 Climate Change and Current Stressors

Land Use

Many changes to the health of water bodies and watersheds are related to land use. A U.S. Geological Survey report, based on an evaluation of 400 environmental variables in New Jersey and on Long Island, indicated that the health of aquatic invertebrate populations correlates positively to the area of wetlands and forests within the watershed and negatively to the impervious land area (USGS, 2000). Compounded by the negative impacts to LIS that are linked to loss of vegetative cover (such as wetlands), the presence of impervious surfaces associated with urban land use creates additional pathways for direct runoff of pollutants into the Sound. While the entire state of Connecticut is only 19 percent developed, it saw an increase in its developed land cover of 2.9 percent between 1985 and 2006. Slightly greater than four percent of the state's land is wetlands (tidal, forested, and non-forested) (CLEAR, 2009).

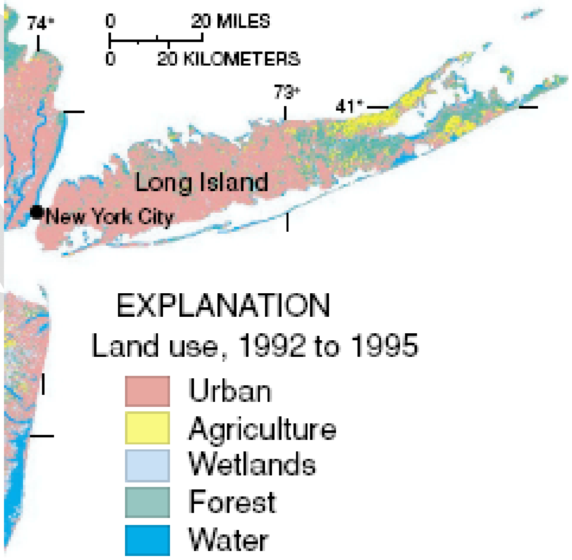


Figure 4 Land use on Long Island, 1992-1995 (USGS, 2000).

As of 2000, the human population of the 15 coastal counties of the LISS study area was 14.6 million for a density of 2,170 people per square mile (837 people per square kilometer), which is more than double the average population density for all National Estuary Partner (NEP) counties in the Northeast.

Efforts are underway to restore tidal wetlands (465 acres in CT since 1993 and 65 acres in NY since 1996), but most urban lands will remain unchanged in the short- to mid-term. Threats posed by climate changes will exacerbate the known stressors associated with impervious surfaces. Qualitatively, increases in the severity of heavy precipitation events will further contribute to problems posed to LIS by runoff, perhaps with a greater-than-linear relationship if storm drain infrastructure is overwhelmed.

Freshwater Inflow

Freshwater inflow from the Sound's tributaries, including the Connecticut, Housatonic, Thames, and Quinnipiac Rivers, helps determine surface water conditions in the estuary. In the Northeast, more extreme precipitation events are expected, with more rain and flooding in winter and intense droughts in the summer (NECIA, 2006). Heavy precipitation events will reduce the salinity of the waters of the Sound and increase nitrogen and sediment loadings. Low salinity can lead to die-offs of shellfish and finfish and reduce the spatial extent of benthic habitats such as seagrass beds. Drought that chokes off freshwater flow, increasing the salinity of the Sound, can increase mortality rates of salt-sensitive plants and animals; allow invasive marine species that tolerate higher salinities to thrive in the Sound; and decrease flushing, potentially leading to increased eutrophication.

Predicted decreases in the volume of the spring freshet as a result of reduced snowmelt will inhibit ponding and the formation of natural impoundments, which are important for migrating waterfowl.

Coastal Flooding and Erosion

Sea level rise is expected to increase the severity of storm surges and coastal flooding. Storm surge results from a combination of sea level rise, increased tidal range, and heavy precipitation, all of which are expected to increase as a result of global warming. A recent study of the effects of projected sea level rise in the Metropolitan East Coast Region (New Jersey, New York, and Connecticut) predicted that regional 100-year flood levels could increase by 9.8-11.5 feet (3.0-3.5 meters) in the next decade, by 10.2-12.5 feet (3.1-3.8 meters) by 2050, and by as much as 13.8 feet (4.2 meters) by the 2080's. In the Sound, surge waters pile up at the western end, putting this area at high risk of flooding. Low risk areas include the shorelines fronting bluffs and steep cliffs along the north shore of Long Island and rocky headlands in Connecticut (Gornitz, 2000).

Where coastal flooding occurs, additional threats include erosion, saltwater damage to coastal properties and sensitive habitats, and the introduction of additional pollutants to nearshore waters upon retreat of flood waters. Increases in the magnitude or frequency of storm surges could also have devastating effects on roads, electrical transmission lines, and other coastal infrastructure. As seas rise, the salt wedge moves upstream, where saline waters can impair aquifers and water infrastructure that supplies freshwater for a range of human uses. Storm surges can also reduce water quality by contaminating groundwater supplies with pathogens and pollutants carried in flood waters.

Nutrient Runoff

Excess nutrients (nitrogen and phosphorous) create adverse conditions in estuarine waters. Excess nitrogen is carried to the Sound from tributaries that have high concentrations of nitrogen from both point and nonpoint sources. Levels of dissolved inorganic nitrogen (DIN) in excess of 0.5 milligrams per liter (mg/l) in seawater can lead to algal blooms over large areas and of long duration (USEPA, 2008). Because of concerns about nutrient enrichment, New York and Connecticut reduced nitrogen loadings by 28% between 1994 and 2003 (LISS, 2003), and there is evidence that conditions continue to improve. Annual nitrogen loadings to the Sound (measured as tons of total nitrogen per year) showed a decreasing trend from 1991 to 2001 (USEPA, 2007). However, anticipated increases in extreme precipitation events will result in greater runoff and nutrient loadings to the Sound. Increased winter precipitation, for example, may transport more nutrients to the Sound, increasing the potential for spring blooms.

Harmful Algal Blooms

Increases in heavy precipitation and associated increases in runoff will carry more nutrients to estuaries, increasing the likelihood of harmful algal blooms (HABs). HABs can have a number of adverse effects. Dying algae sink to the bottom, reducing dissolved oxygen (DO) levels as they decompose, which can alter in the composition of benthic biota and, in extreme cases, produce fish kills. Decomposing algae also increase turbidity, inhibiting the growth and survival of SAV. Some algal species (toxic dinoflagelettes) produce neurotoxins that accumulate in filter-feeding shellfish and result in paralytic shellfish poisoning when consumed by humans.

Hypoxia

Hypoxia occurs when DO levels in seawater are below that needed to support marine life, defined as < 1.4 milliliters of oxygen per liter (ml/l) of seawater (USEPA, 2008). Although on average, hypoxia in the Sound has improved since the late 1980s (see Figure 5), it remains a concern, particularly in western Long Island (USEPA, 2007). Hypoxic conditions will become more extensive if a greater frequency or intensity of storms under climate change results in elevated nutrient loadings to the Sound.

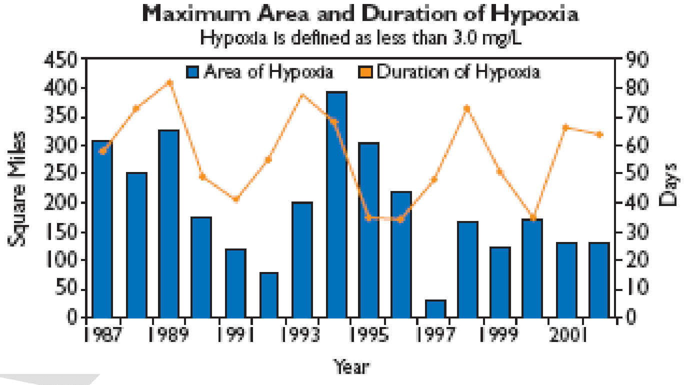


Figure 5 Hypoxia Trends in LIS (USEPA, 2007).

Pathogens

In nearshore embayments of the Northeast, bacterial contamination continues to be a major issue, causing closures of shellfish beds and beaches. Some beach closures are preemptive as a result of sanitary sewer overflows or high levels of stormwater runoff during high rainfall events (USEPA, 2007). Such episodes will increase with projected increases in the frequency and severity of extreme precipitation events.

5 Impacts of Climate Change on Ecosystems of LIS

The Sound's shoreline habitats can be divided into beaches, tidal wetlands, tidal flats, subtidal habitats, open waters, and freshwater habitats of tributaries. The following sections discuss the ecological values of these habitats and their vulnerabilities to anticipated climate change.

Coastal Barriers, Beaches, and Dunes

Headland erosion is the main process of beach development along the Sound's Long Island shoreline, creating narrow strips of beach below bluffs and steep cliffs. The Connecticut shoreline overlies bedrock, making erosion much less likely (LISS, 2003).

Where beaches occur, beach retreat in response to sea level rise depends on the average slope of the beach profile. It is estimated that in the region from Maine to Maryland, a one-meter rise in sea level would result in beach retreat of 164-328 feet (50-100 meters) (Gornitz, 2001).

Sandy beaches not only serve as popular recreational areas, they also provide protection of nearby property against erosion from wind and coastal storm surges. Without beaches, it would be necessary to install man-made barriers to protect adjacent property, at an estimated cost of $100-$600 per linear foot (LISS, 2003).

Beaches also provide habitat for a wide variety of species. The invertebrate infauna of the foreshore, between the highest and lowest tide zones, provides forage for migrating shorebirds. The maritime beach community between mean high tide and the primary dunes provides nesting sites for horseshoe crabs and several rare bird species, including piping plover, American oystercatcher, black skimmer, least tern, common tern, and roseate tern. This area also provides habitat for horseshoe crabs and the northeastern beach tiger beetle, which is federally listed as threatened. Dunes and the upper back barrier beach provide nesting habitat for diamondback terrapins (Strange, 2008 and references therein).

Tidal wetlands

The extraordinarily high primary production of tidal wetlands supports an extensive estuarine food web. Among the many species supported by the Sound's abundant food supply are over 170 species of finfish, including 50 species that spawn in the Sound (LISS, 2003). Wetlands also filter sediments and contaminants; protect against erosion and flooding; and provide habitat for both aquatic and terrestrial wildlife (Teal, 1986; Mitsch and Gosselink, 2003).

There are about 20,820 acres (8,426 hectares) of tidal wetlands in the Sound, including all tidal wetland types. About 85 percent of the total occurs along the Connecticut shoreline. The remaining 15 percent are along the shorelines of Westchester and Bronx counties in New York State (Holst et al., 2003).

Tidal wetlands occur infrequently along the north shore of Long Island because of the area's steep uplands and sea cliffs. Along this shoreline, salt marshes are found in embayments, such as Mount Sinai, and the three large bays of western LIS (Little Neck Bay, Manhasset Bay, and Hempstead Harbor) (NYDCR, 2004). The largest marsh areas along the Connecticut shoreline include the Barn Island Marshes near the Rhode Island border in Stonington and the marshes of Bluff Point State Park, Hammonasset State Park, East River, and the Wheeler Wildlife Management Area (Tiner et al., 2006).

Tidal wetlands can respond to sea level rise in a number of ways depending on local elevation, geomorphology and land use. As seas rise, tidal wetlands can expand inland if not impeded by geological features or human-made barriers such as seawalls and roads and if the rate of migration exceeds the rate of erosion at the seaward edge. Wetlands that are unable to accrete sufficient sediment to keep pace with sea level rise will become increasingly flooded and will eventually convert to open water or tidal flat. High marsh may convert to low marsh, and in situations where the coastal plain is not obstructed, upland habitat may convert to salt marsh. There may also be changes in the relative abundance of marsh vegetation, with increases in the invasive *Phragmites australis*, which tolerates lower salinity.

Over the past few decades, local scientists have noted marsh submergence in some areas, and emergent marsh (particularly low marsh) is converting to tidal flats along many of the tidal rivers draining to the Sound). A survey of six sites along the Sound’s Connecticut shoreline (Cos Cob Harbor, Grays Creek, Scott Cove, Five Mile River, Greenwich Cove, and Canfield Island Cove) found evidence that higher water levels are inundating lower portions of these marshes and converting them to tidal flats, while portions of the high marsh are being converted to low marsh (Tiner et al., 2006). A sea level rise of several feet, projected for the Northeast by Yin et al. (2009) and IPCC (2007), would make it less likely marshes in this region will be able to fully compensate for the rise in sea level.

Salt marsh islands provide nesting sites for a number of bird species, particularly colonial nesting waterbirds. Gull-billed terns, common terns, American oystercatchers, and black skimmer commonly nest on marsh islands. Studies show that the submergence and erosion of marsh islands as a result of sea level rise are already affecting bird species that depend on these areas for protection from predators (Erwin et al., 2006).

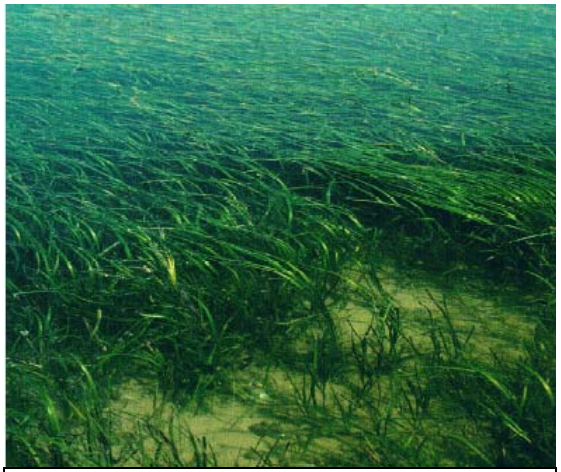
Tidal flats

Sediments eroded from bluffs along the north shore of Long Island are carried by longshore drift, primarily east to west, and later deposited to form tidal flats and shoals. Tidal flats provide invertebrate forage for waterbirds and habitat for shellfish such as clams. One of the largest areas of tidal flat in the Sound occurs near Conscience Bay, Little Bay, and Setauket Harbor, where there are large beds of hard clams, soft clams, American oysters, and ribbed mussels (NYSDCR, 2004).

The largest threat to the tidal flats of LIS is sea level rise. Initially, rising seas may convert low marsh to tidal flat, but eventually tidal flats will become entirely submerged, making the invertebrate infauna of the flats inaccessible to foraging waterfowl and shorebirds. Accessibility of invertebrate forage is directly tied to the ability of shorebirds to thrive (Nicholls et al., 2007).

Subtidal Zone

Subtidal habitats include nearshore benthic habitats of unconsolidated sediments (ranging in size from clays to gravel) and areas of SAV, mostly eelgrass. Eelgrass provides food, shelter, and nursery habitats for many economically-valuable species, including shellfish such as lobsters, scallops, clams, and mussels, and finfish such as Atlantic cod, Atlantic herring, and several varieties of flounder. Some bird species feed on eelgrass.



Eelgrass bed. Photo courtesy of F. Short, University of New Hampshire, via Johnson et al., 2007

Eelgrass was once distributed along Connecticut's entire coastline, but is now found only along parts of eastern Long Island Sound and Fishers Island Sound between the towns of Westbrook and Stonington (Johnson et al., 2007).

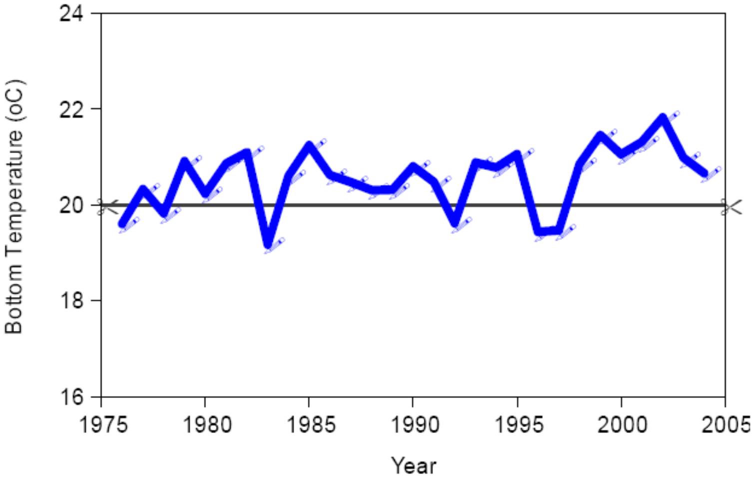
There is concern that as sea levels rise, seagrass beds may fail to thrive because of reduced light penetration and an inability to move into shallower water where shorelines are hardened. Short and Neckles (1999) predicted that a 19.7 inches (50 centimeters) increase in water depth as a result of sea level rise, which could occur by 2100, would reduce the light available for seagrass photosynthesis by 50 percent, resulting in a 30-40 percent decline in seagrass growth. The movement of eelgrass beds shoreward as sea levels rise could be impeded in areas with steep shores or where there is erosion and water turbidity in front of shoreline protection structures such as seawalls and bulkheads. Rising water temperatures could also pose a problem for eelgrass (Lee et al. 2007). On the other hand, experimental results indicate that seagrass beds that are photosynthetically-limited by CO2 could show increased productivity in more saturated waters (Palacios and Zimmerman, 2007).

Benthic animals such as mollusks (e.g., clams) and crustaceans (e.g., lobster) may also fail to thrive as waters warm.

A decline in the Sound's lobster population in the past decade has been linked to increased water temperatures (see Figure 6). A critical temperature threshold for lobster survival is approximately 68°F (20°C). Above this threshold plankton abundance declines, reducing food availability for lobster, and there is concomitantly an increase in a parasite that is harmful to lobster. Over the past decade, this temperature threshold has been frequently exceeded during summer months, and scientists believe there is a high probability that it will be consistently exceeded by 2050 (Fogarty et al., 2007).

Soft clams (*Mya arenaria*), however, require temperatures near 90°F (32°C) (Kennedy and Mihursky, 1971 cited in Pyke et al., 2008). On the other hand, there is evidence that warmer waters may enhance production of blue crab (Fogarty et al., 2007).

Figure 6 August Bottom Water Temperatures (°C) at Millstone Power Station in Eastern LIS. The 68°F (20°C) Threshold is indicated by the horizontal line (Fogarty et al., 2007).



Open Waters

The plankton and finfish of the Sound's open waters are vulnerable to a number of changes in physiochemical conditions that are expected to result from climate change. Open water species may experience adverse effects with increases in water temperatures, lower DO as waters warm, and increased nutrient loadings from increased runoff and freshwater inflow resulting from an increase in the frequency and/or intensity of heavy precipitation events.

Plankton are an important food source for finfish. Larval fishes feed on zooplankton and their growth and survival can be reduced if the peak in zooplankton abundance does not coincide with the presence of fish larvae.

Excessive phytoplankton blooms or changes in the timing of blooms, initiated by the timing of the spring freshet, can result in adverse effects on finfish and other open water species. If phytoplankton blooms do not occur when fish move inshore to spawn, larvae may lack sufficient zooplankton resources. Zooplankton depend on the spring phytoplankton bloom. At the same time, excessive blooms, promoted by higher nutrient levels resulting from increased runoff, can deplete DO, harming both zooplankton and fishery species.

Ocean warming is already having a discernable effect on a number of species in the region. Scientists have observed a shift from coldwater finfish species such as winter flounder to species found in warmer waters to the south (Wood et al., 2009). In Narragansett Bay warmer waters have led to an overlap in the presence of early life stages of winter flounder and comb jellies (*Mnemiopsis leidyi*), which feed on winter flounder eggs and larvae, contributing to reductions in winter flounder populations (Sullivan et al., 2001). According to a new study, about half of 36 fish stocks in the Northwest Atlantic Ocean have shifted northward over the last four decades, with some stocks nearly disappearing from U.S. waters as they move farther offshore (Nye et al., 2009).

Freshwater Tributaries

The Sound's tributaries provide a number of ecological values that support resident and migrant species of the Sound. Important freshwater wetlands are found along the lower Connecticut River. The river was designated a Wetland of International Importance under the Ramsar Convention because it supports the best examples of fresh and brackish marshes and SAV beds in the Northeastern U.S. Depending on the amount and timing of precipitation and freshwater flow in spring, these areas provide impoundments that are important for migrating birds (LISS, 2003). Freshwater wetlands may support greater bird diversity than any other wetland type (Mitsch and Gosselink, 2003).

As sea level rise raises salinity in tributaries, freshwater wetlands will convert to brackish marshes. Eventually only vegetation favored by high salinity will remain. While spring precipitation is necessary for the development of impoundments for migrating birds, increases in storm intensity may accentuate marsh fragmentation.

Increased runoff carries heavier loads of nutrients (such as nitrogen), pathogens, and harmful chemicals. Additional runoff could not only overwhelm the ability of tributary wetlands to filter these elements before entering LIS, but could also directly damage the health of animal and plant species in these habitats (Nicholls, et al., 2007).

6 References Consulted

Bradbury J., S. Dingman, and B. Keim. 2002. New England drought and relations with large scale atmospheric circulation patterns. Journal of the American Water Resources Association, 8:1287-1299.

Caldeira, K., and M.E. Wickett. 2003. Anthropogenic Carbon and Ocean pH. Nature 425:365.

Caldeira, K., and M.E. Wickett. 2005. Ocean Model Predictions of Chemistry Changes from Carbon Dioxide Emissions to the Atmosphere and Ocean. 2005. Journal of Geophysical Research 110:1-12.

CLEAR (Center for Land Use Education and Research). 2009. 2006 Statewide Land Cover (Connecticut). University of Connecticut website. Available at: http://clear.uconn.edu/projects/landscape/statewide.htm. Accessed 11/06/2009.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas. 2009. Ocean Acidification: The Other CO2 Problem. Annual Review of Marine Science 1:169–192.

Erwin, R.M., G.M. Sanders, D.J. Prosser, and D.R. Cahoon. 2006. High tides and rising seas: potential effects on estuarine waterbirds. In: Terrestrial Vertebrates in Tidal Marshes: Evolution, Ecology, and Conservation. [Greenberg, R. (ed.)]. Studies in avian biology number 32. Cooper Ornithological Society, Camarillo, CA, pp. 214-228.

Fogarty, M., L. Incze, R. Wahle, D. Mountain, A. Robinson, A. Pershing, K. Hayhoe, A. Richards, and J. Manning. 2007. Potential Climate Change Impacts on Marine Resources of the Northeastern United States.

Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, and D.J. Wuebbles. 2007. *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. Synthesis report of the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS).

Gazeau, F., C. Quiblier, J.M. Jansen, J-P. Guttuso, J. J. Middleburg, and C.H.R. Heip. 2007. Impact of Elevated CO2 on Shellfish Calcification. Geophysical Research Letters 34:1-5.

GCRP (United States Global Changes Research Program). 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press. Available at: http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/full-report

Gornitz, V. 2001. Sea-Level Rise and Coasts. Pages 21-46 in Rosenzweig, C. and W.D. Solecki (Eds.). Climate Change and a Global City: The Potential Consequences of Climate Variability and Change—Metro East Coast. Report for the U.S. Global Change Research Program, National Assessment of the Potential Consequences of Climate Variability and Change for the United States, Columbia Earth Institute, New York. 224 pp.

Hartig, E.K. A. Kolker, D. Fallon, and F. Mushacke. 2001. Wetlands. Pages 67-86 in Rosenzweig, C. and W.D. Solecki (Eds.). Climate Change and a Global City: The Potential Consequences of Climate Variability and Change—Metro East Coast. Report for the U.S. Global Change Research Program, National Assessment of the Potential Consequences of Climate Variability and Change for the United States, Columbia Earth Institute, New York. 224 pp.

Hayhoe, K., C. Wake, T. Huntington, L. Luo, M. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics 28: 381-407.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. Science 318:1737-1744.

Holst, L., R. Rozsa, L. Benoit, S. Jacobsen, and C. Rilling. 2003. Long Island Sound Habitat Restoration Initiative,Technical Support for Habitat Restoration, Section 1: Tidal Wetlands. EPA Long Island Sound Office, Stamford, CT, p. 1-7, Available at: http://www.longislandsoundstudy.net/habitat/index.htm.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Johnson, M., E. J. Beckwith, D. Carey, E. Parker, E. Smith, J. Volk, P. Aarrestad, M. Huang, E. Mariani, R. Rozsa, D. Simpson, and H. Yamalis. 2007. An assessment of the impacts of commercial and recreational fishing and other activities to eelgrass in Connecticut's waters and recommendations for management. report. Connecticut Department of Environmental Protection and Connecticut Department of Agriculture. 119 pp.

Kennedy, V. S. and J. A. Mihursky. 1971. Upper temperature tolerances of some estuarine bivalves, Ches. Sci., 12: 193–204. Referenced in: Pyke, C. R., R. G. Najjar, M. B. Adams, D. Breitburg, M. Kemp, C. Hershner, R. Howarth, M. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, and R. Wood. 2008. Climate Change and the Chesapeake Bay: State-of-the-Science Review and Recommendations. A Report from the Chesapeake Bay Program Science and Technical Advisory Committee (STAC), Annapolis, MD. 59 pp.

Kirshen, P., C. Watson, E. Douglas, A. Gontz, J. Lee, and Y. Tian. 2008. Coastal Flooding in the Northeastern United States due to Climate Change. Mitigation and Adaptation Strategies for Global Change V13: 5-6. June 2008.

Koch, E.W. and S. Beer. 1996. Tides, light and the distribution of *Zostera marina* in Long Island Sound, USA. *Aquatic Botany* 53(1-2), 97-107. Referenced in: Short, F.A. and H.A. Neckles. 1999. The effects of global climate change on seagrasses. *Aquatic Botany* 63(3-4):169-196.

Kunkel, K. E., H.-C. Huang, X.-Z. Liang, J.-T. Lin, D. Wuebbles, Z. Tao, A. Williams, M. Caughey, J. Zhu, and K. Hayhoe. 2008. Sensitivity of future ozone concentrations in the Northeast U.S. to regional climate change. *Mitigation and Adaptation Strategies for Global Change* 13: 597-606.

Kurihara, H., and Y. Shirayama. 2004. Effects of Increased Atmospheric CO2 on Sea Urchin Early Development. Marine Ecology Progress Series 274:161–169.

Lee, K. S., S. R. Park, and Y. K. Kim. 2007. Effects of irradiance, temperature, and nutrients on growth dynamics of seagrasses: A review. Journal of Experimental Marine Biology and Ecology 350: 144-175.

LISS (Long Island Sound Study). 2003. Long Island Sound Habitat Restoration Initiative: Technical Support for Coastal Habitat Restoration. February 2003. http://www.longislandsoundstudy.net/habitat/LIS.Manual.pdf

LISS (Long Island Sound Study). 2009. Sound Health 2008: {Climate Change} Overview. Interview with Cynthia Rosenszeig. Available at: http://www.longislandsoundstudy.net/soundhealth/overview.htm. Accessed November 10, 2009.

Miller, A.W., A.C. Reynolds, C. Sobrino, G.F. Riedel. 2009. Shellfish face uncertain future in high CO2 world: Influence of acidification on oyster larvae calcification and growth in estuaries. PLoS ONE 4(5): e5661. doi:10.1371/journal.pone.0005661

Mitsch, W.J. and J.G. Gosselink. 2003. Wetlands. Van Nostrand Reinhold, New York.

Moy, A.D., W.R. Howard, S.G. Brayl, and T.W. Trull. 2009. Reduced Calcification in Modern Southern Ocean Planktonic Foraminifera. Nature Geoscience 2:276–280.

NECIA (Northeast Climate Impacts Assessment). 2006. *Climate Change in the U.S. Northeast*. Published October 2006. Available at: http://www.climatechoices.org/assets/documents/climatechoices/NECIA_climate_report_final.pdf

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden and C.D. Woodroffe, 2007: Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315-356.Orth, R. J.,and K. A. Moore. 1983. Chesapeake Bay: An unprecedented decline in submerged aquatic vegetation. Science, 222: 51–53.

NOAA (National Oceanic and Atmospheric Administration). 2009. Northeast Fisheries Science Center: Science Spotlight. North Atlantic Fish Populations Shifting as Ocean Temperatures Warm. November 2, 2009. Available at: http://www.nefsc.noaa.gov/press_release/2009/SciSpot/SS0916/Shifting%20stocks.pdf

Nye, J.S. Link, J.A. Hare, and W.J. Overholtz. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Mar. Ecol. Prog. Ser. 393:111-129.

NYSDCR (New York State Division of Coastal Resources). 2004. Significant Coastal Fish and Wildlife Habitats: Long Island Sound and Long Island. Available at: http://nyswaterfronts.com/waterfront_natural_narratives.asp.

Palacios, S., and R.C. Zimmerman. 2007. Response of eelgrass *Zostera marina* to CO2 enrichment: possible impacts of climate change and potential for remediation of coastal habitats. Marine Ecology Progress Series 344:1–13.

Pew Center for Global Climate Change. 2009. The Science and Consequences of Ocean Acidification. Science Brief 3, August 2009. Available at: http://www.pewclimate.org/docUploads/ocean-acidification-Aug2009.pdf

Shirayama, Y. and H. Thornton. 2005. Effect of Increased Atmospheric CO2 on Shallow Water Marine Benthos. Journal of Geophysical Research 110:1-7.

Short, F.A. and H.A. Neckles. 1999. The effects of global climate change on seagrasses. *Aquatic Botany* 63(3-4):169-196.

Strange, E.M. 2008. North Shore, Long Island Sound and Peconic Estuary. Section 3.2 in: Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1, J.G. Titus and E.M. Strange (eds.). EPA 430R07004. U.S. EPA, Washington, DC.

Sullivan, B. K., D. Van Keuren, and M. Clancy. 2001. Timing and size of blooms of the ctenophore *Mnemiopsis leidyi* in relation to temperature in Narragansett Bay, R.I., Hydrobiologia, 451: 113–120.

Teal, J.M. 1986. The Ecology of Regularly Flooded Salt Marshes of New England: A Community Profile. Biological report 85(7.4). U.S. Fish and Wildlife Service, Washington, DC, 69 pp.

Tiner, R.W., I.J. Huber, T. Nuerminger, and E. Marshall. 2006. Salt Marsh Trends in Selected Estuaries of Southwestern Connecticut. U.S. Fish and Wildlife Service, National Wetlands Inventory Program, Northeast Region, Hadley, MA. Prepared for the Long Island Studies Program, Connecticut Department of Environmental Protection, Hartford, CT. NWI Cooperative Report. 20 pp.

Titus, J., and C. Richman. 2001. Maps of Lands Vulnerable to Sea Level Rise: Modeled Elevations Along the U.S. Atlantic and Gulf Coasts. Long Island modeled elevation map available at http://www.epa.gov/climatechange/effects/downloads/linyc.pdf. Accessed October 13, 2009.

USAID (U.S. Agency for International Development). 2006. Managing freshwater inflows to estuaries : a methods guide. PN-ADH-650. Available at: http://pdf.usaid.gov/pdf_docs/PNADH650.pdf.

USEPA (U.S. Environmental Protection Agency). 2009a. Ecosystem Services Research Program: Wetlands Research. Available at: http://epa.gov/ord/esrp/quick-finder/wetlands-research.htm. Accessed October 7, 2009.

USEPA (U.S. Environmental Protection Agency). 2009b. Marshes. Available at: http://www.epa.gov/owow/wetlands/types/marsh.html. Accessed October 8, 2009.

USEPA (United States Environmental Protection Agency). 2008. National Coastal Condition Report III: Chapter 3: Northeast Coastal Region. Office of Research and Development/Office of Water, EPA/842-R-08-002, December 2008, Washington, DC 20460. Available at: http://www.epa.gov/nccr.

USEPA (U.S. Environmental Protection Agency). 2007. National Estuary Program Coastal Condition Report. Chapter 3: Northeast National Estuary Program Coastal Condition, Long Island Sound Study. Published June 2007.

USGS (United States Geological Survey). 2000. Water Quality in the Long Island–New Jersey Coastal Drainages New Jersey and New York, 1996–98: U.S. Geological Survey Circular 1201. Available at http://pubs.water.usgs.gov/circ1201/

Wood, A.J.M., J.S. Collie, and J.A. Hare. 2009. A comparison between warm-water fish assemblages of Narragansett Bay and those of Long Island Sound waters. Fish. Bull. 107:89–100.

Wootton, T.J., C.A. Pfister, and J.D. Forester. 2008. Dynamic Patterns and Ecological Impacts of Declining Ocean pH in a High-Resolution Multi-Year Dataset. Proceedings of the National Academy of Sciences 105:18848–18853.

Yin, J., Schlesinger, M., and R. Stouffer. 2009. *Model projections of rapid sea-level rise on the northeast coast of the United States*. Nature GeoScience 2:262-266. March 15, 2009.