CLIMATE CHANGE
&
RHODE ISLAND'S COASTS

PAST, PRESENT, AND FUTURE

2012

Leanna Heffner, Rebecca Williams, Graduate School of Oceanography, URI
Virginia Lee, Pam Rubinoff, Carissa Lord, URI Coastal Resources Center

ISTOCK

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CLIMATE CHANGE is the preeminent environmental issue of our time. Ecologically, economically, and culturally, Rhode Island is inexorably linked to the ocean and hence faces challenges from climate change that are specific to the coastal landscape. The purpose of this document is to provide a synthesis of our current understanding of and impacts on Rhode Island's coastal communities.

SUMMARY

With more precipitation, storminess, and flooding, and more extreme heat days, climate change effects are already being felt throughout Rhode Island. Sea level rise and erosion are happening along the state's coastline. This document describes the changes that have occurred in Rhode Island's coastal areas and that are expected to occur in the future.

The Context of Global Climate Change Research

Climate change can be defined as systematic change in the long-term statistics of climate elements (such as air temperature, barometric pressure, or winds) sustained over several decades or longer (Glickman 2000). This change may be caused by any combination of (1) natural influences, such as changes in the energy being emitted from the sun, changes in the orbit of the earth around the sun, volcanic activity, and fluctuations in ocean and atmospheric circulation, and (2) human activities (called anthropogenic forcing) such as the burning of fossil fuels that change the composition of gases in the atmosphere of the Earth.

Human activities since the start of the Industrial Age have caused a significant increase in greenhouse gases in the atmosphere. The most prevalent greenhouse gas in the atmosphere in terms of anthropogenic emissions, carbon dioxide, has risen from a pre-industrial level of 280 parts per million (ppm) to 390 ppm in 2010 (Conway and Tans 2011), the highest it has been in 650,000 years (IPCC 2007; Allison et al. 2009). There is strong scientific consensus that this unprecedented increase in the level of carbon dioxide in the atmosphere is the leading cause of a rapid shift in global climate that has already begun to occur (IPCC 2007). As a result, the rate of sea level rise is accelerating; the ocean is becoming warmer and more acidic; regional weather patterns are shifting, leading to more extreme weather events (Anderegg et al. 2010); and average global temperatures are increasing, among other effects (IPCC 2007, Gleik et al. 2010). These changes that have already been observed globally are also occurring in Rhode Island are projected to intensify in years to come.

In recent years, greenhouse gas emissions worldwide have equalled or exceeded the high projections of the Intergovernmental Panel on Climate Change (IPCC) due to growing populations, increasing per capita gross domestic product, and use of fossil fuels (Raupach et al. 2007; Allison et al. 2009; UNEP 2009). To date there are no regions that are substantially decreasing greenhouse gas emissions (Raupach et al. 2007; UNEP 2009). In light of this, projections of climate change impacts under a low emissions scenario are becoming less likely as high rates of carbon emissions continue. It is important that decision-makers seriously consider and plan for a high emissions scenario.


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Glacial and polar ice melt is contributing to global sea level rise.

Longer summer seasons may increase coastal tourism, but will create more stress on those unable to escape the heat.

Some climate change impacts, such as precipitation, heat waves, and cloudiness, will occur quickly in response to increasing temperatures. Others, such as sea level rise and ocean acidification, will continue to respond on long time scales from centuries to millennia, even if emissions are reduced, due to a lag-effect from past carbon emissions (Solomon et al. 2009).

To prepare for future climate change, it is important to keep in mind the time-scales associated with future impacts. Natural climate variability, such as the El Niño-La Niña cycle, the North Atlantic Oscillation and Pacific Decadal Oscillation, plays a major role in the year-to-year variation of the global and regional climate regimes that can be greatly affected by anthropogenic forcing. Scientists are improving their ability to make climate projections on smaller scales of time and place.

Climate Change Impacts in Rhode Island: Major Findings

In Rhode Island, we can expect to see warmer temperatures, more extreme weather events (e.g. more droughts, more intense rainfall, more intense storms and flooding), accelerated rates of sea level rise, shorter winters and longer summers, less snowfall and more rainfall, and a more acidic ocean.

Rhode Island's coastal ecosystems have already been exhibiting signs of substantial change over the last half-century, some of which are very likely due to anthropogenic forcing, although natural variability also plays an important role. One striking change that has been observed, partly due to warming waters, is a shift in fish stocks from cold-water, bottom dwelling species to more warm-water, water-column habitat species. Other ecological changes observed include an increase in gelatinous zooplankton that consume other plankton and fish larvae and eggs, and a change in the dynamics of phytoplankton blooms in Narragansett Bay.

Likely future impacts include erosion, inundation, or migration of coastal habitats such as beaches and salt marshes, a northward shift in the geological range of many species, various impacts from ocean acidification, and changes in ecosystem dynamics such as the timing of important biological events, food web dynamics, community composition and structure, and species diversity. Ocean warming will impact Rhode Island fisheries, including a potential decline of lobster populations as they migrate northward, and shifts in types and abundance of fish targeted for commercial and recreational catch.

Coastal tourism and recreation and coastal infrastructure will also be impacted by change, such as warmer temperatures and longer summer seasons. Accelerated sea level rise and increased intensity of storms could lead to accelerated erosion of the south shore coastal barriers and headlands. Increased sea level rise, erosion, and flooding will affect both private as well as public property. Coastal infrastructure, especially bridges and roads, will be more susceptible to damage from more severe storms and heavy rainfall. Warmer air temperatures will create more stress on already vulnerable populations such as the elderly, children, and city dwellers who cannot escape the summertime heat.

Overall, average air and sea temperature locally, regionally, and globally have been increasing; regional weather is becoming more rainy and snowy; storms are becoming more severe; and there is evidence of ocean acidification worldwide (Table 1).

Table 1. A summary of observed and documented climate change trends described at the global, regional, and state levels.

Climate Change Variable	Geographic Scale	Observations of Recent Change
Air Temperature	Global	- Global mean temperature has increased 0.74°C (1.33°F) over the last 100 years.
	U.S. Northeast	- Since 1900, the annual mean temperature has risen 0.83°C (1.5°F).
	Rhode Island	- Average annual temperature rose 0.94°C (1.7°F) from 1905 to 2006.
Ocean Temperature	Global	- The ocean has been warming consistently over the past 50 years, with 2007 as the warmest on record.
	U.S. Northeast	- Annual average temperatures in the waters off the southern New England coast have increased by about 1.2°C (2.2°F) since the 1970s.
	Rhode Island	- In Narragansett Bay, winter sea-surface temperatures have risen 2.2°C (4°F) since the 1960s.
Sea Level Rise	Global	- Globally, sea level rose in the 20th century at an average rate of 1.8 mm (0.07 in) per year, a rate greater than that of the preceding eight centuries. - Between 1993 and 2003 this rate almost doubled to 3.4 mm (0.13 in) per year.
	Rhode Island	- In Newport, sea level has risen an average of 2.6 mm (0.1 in) per year since 1930.
Storminess	Global	- The severity of tropical cyclones has increased since the 1970s.
	U.S. Northeast	- The severity of tropical cyclones in the North Atlantic has increased.
Precipitation and Weather	Global	- Rainfall has decreased in the Northern Hemisphere subtropics and increased in mid-latitudes over the last 50 years.
	U.S. Northeast	- Studies have found a 5 to 17 percent increase in regional precipitation during roughly the last 100 years.
	Rhode Island	- Over the past 100 years, Rhode Island precipitation has increased by 3 mm (0.12 in) per year. - Annual mean wind speed at T.F. Green Airport has significantly declined since at least the 1960s.
Ocean Acidification	Global	- Current pH on the surface of the ocean is 0.1 units lower than pre-industrial levels.

CURRENT TRENDS

Air temperature is warming

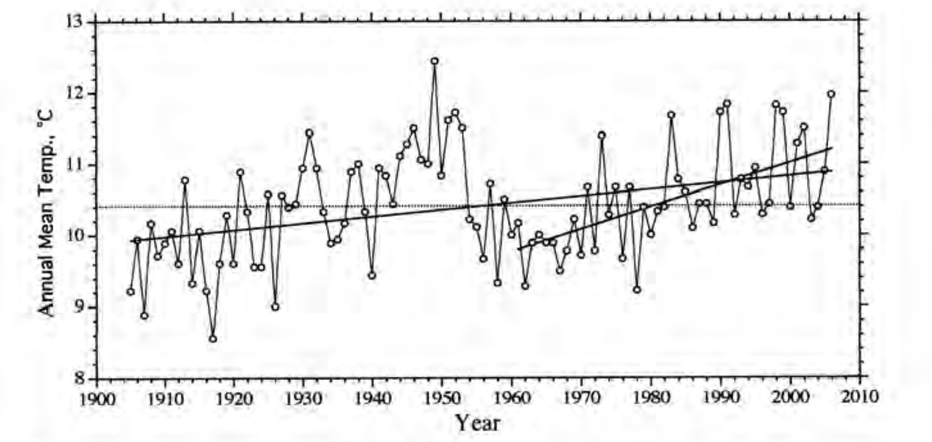
Global: The most recent report issued by the IPCC (IPCC 2007) states that the global average temperature has increased 0.74°C (1.33°F) over the last 100 years, with most of this increase during the last 50 years. This decade (2000-2009) has been the warmest since instrument records began in the mid 1800s (Allison et al. 2009), with 2010 tied with 2005 as the warmest year on record (Hansen et al. 2010, NCDC 2011), Global mean air temperature is projected to warm at least another 2°C and possibly 7°C (3.6°F to 12.6°F) by the end of the century (Allison et al. 2009; Richardson et al. 2009). This surpasses the estimated threshold range of 1°C to 3°C (1.8°F to 5.4°F), a dangerous climate tipping point, which will melt summer Arctic sea ice, Himalayan glaciers, and the Greenland continental ice sheet (Ramanathan and Feng 2008). An increase above 2°C (3.6°F) is cited as being a threshold beyond which the consequences from global warming will cause severe environmental and societal disruptions worldwide (Richardson et al. 2009).

U.S. Northeast: Since 1900, the annual mean temperature in the Northeastern U.S. has risen 0.83°C (1.5°F), with the majority of warming occurring in the past few decades. Since 1970 the regional temperature has increased by an average of 0.3°C (0.5°F) per decade (Frumhoff et al. 2007). Winter temperatures have risen even faster at about 0.74°C (1.3°F) per decade, with a total increase of 2.22°C (4°F) between 1970 and 2000 (Frumhoff et al. 2007).

Rhode Island: In Rhode Island, annual average temperature has risen 0.94°C (1.7°F) from 1905 to 2006, and 1.14°C (2.5°F) between 1961 and 2005 (Pilson 2008).

Ocean and coastal water temperatures are warming

Global: A long-term sustained warming trend in ocean surface temperatures is observed worldwide since 1959. Global ocean surface temperatures in 2010 were tied with 2005 as the third warmest on record, at 0.88°F (0.49°C) above the 20th century average, with 2007 as the warmest year (Domingues et al. 2008, Allison et al. 2009, NCDC 2011). Even slight increases in water temperature can produce large effects. Changes occurring in many marine ecosystems around the world



Annual mean temperature at the official Weather Bureau stations for Providence, R.I., beginning from 1905. Data are from NOAA (1983, 1971-2006a) and ESSA (1966-1970). Long-term mean temperature from 1905 until 2006 is 10.41°C. The increase over the record from 1905 to 2006 was 0.094°C per decade while the increase from 1961 to 2006 was 0.31°C per decade. *From Pilson in Desbonnet and Costa-Pierce (eds.) 2008. Used with permission.*

due to warming waters have already been documented (see section on ecological impacts).

U.S. Northeast: Annual average temperatures in the waters off the southern New England coast have increased about 1.2°C (2.2°F) since the 1970s (Oviatt 2004). Coastal water temperatures in Woods Hole, Mass., have increased at an average rate of 0.04°C (0.07°F) per year from 1960 to 2002, amounting to a total increase of 1.7°C (3°F) during that time (Nixon et al. 2004).

Rhode Island: Water temperatures in the salt ponds and in Narragansett Bay have been warming. In Narragansett Bay, winter surface temperatures have risen 2.2°C (4°F) since the 1960s.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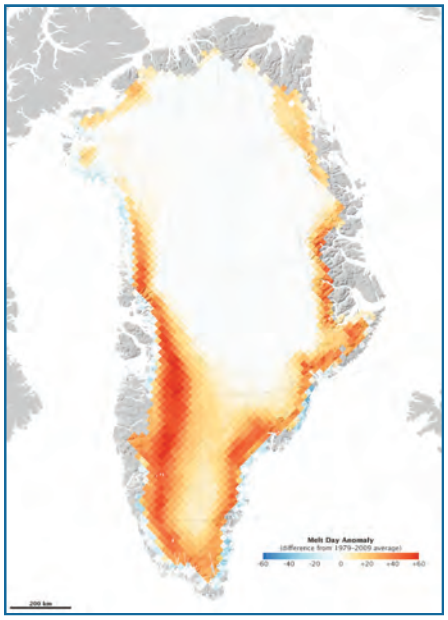
Sea level has risen 10 inches in Newport since the 1930s and is accelerating.

Sea level rise is accelerating

Global: Global mean sea level has been rising at an average rate of 1.7 mm/year (plus or minus 0.5mm) since 1950, which is significantly greater than the rate averaged over the last several thousand years. This increase is due mainly to thermal expansion of sea water and additional freshwater from land ice melt. From 1993 to 2009, the rate almost doubled to 3.3 mm (0.13 in) per year. The accelerated rate is likely due to loss of polar ice in Greenland and Antarctica and the addition of melt water to the sea (Nicholls and Cazenave, 2011). The current rate of sea level rise is 80 percent faster than what was projected for this time period by the IPCC Third Assessment Report (2001) (Allison et al. 2009).



This NASA image depicts record melting of Greenland's ice cap in 2010.

U.S. Northeast: In New England, sea level rose on average 1 mm (0.04 in) per year between 1300 and 1850, and much faster at 2.8 mm (0.11 in) per year from 1850 to 2003 (Donnelly et al. 2004).

Rhode Island: Local sea level is recorded at tide guages in Newport. The average rate of sea level rise from 1931 to 2011 was 2.68 mm per year, which is roughly equivalent to a rise of 10 inches over a century. This rate is expected to increase in the future (Boothroyd 2012). See graph on page 12.

Storm intensity is increasing

Global: Climate change may affect tropical cyclone intensity, frequency, track, size, and/or rainfall. Hurricanes require warm sea surface temperatures to develop and to be maintained. As the global climate warms, the sea surface temperature also increases in the tropical oceans where hurricanes form. In theory, hurricanes may then become more intense or better able to survive at a high intensity for longer periods of time.

The IPCC Fourth Assessment Report found a substantial increase in the severity of global tropical cyclones (hurricanes and typhoons) since the 1970s, with a strong link to the observed increase in ocean surface temperatures (IPCC 2007). There is evidence that storm intensity has increased in the North Atlantic in the last 30 years (Emanuel 2005; Webster et al. 2005; Emanuel et al. 2008; Holland 2009; Mann et al. 2009), and this is linked to rising ocean temperatures (Mann and Emanuel 2006; Holland and Webster 2007). Also, it has been found that major storm tracks have been moving northward and this has been attributed to the changing climate (Yin 2005).

It is important to note, however, that, owing to difficulties in measuring tropical cyclones, separating the effects of human-influenced climate change from natural variability on hurricane activity is very difficult. At present, it remains uncertain whether past changes in hurricane activity have exceeded the trends and variability due to natural causes (Ginis 2011). Determining the causes of changes in observed long-term hurricane activity is a daunting challenge. This issue is complicated by the fact that the existing record of Atlantic hurricane activity, while extending back to the mid-1800s in the Atlantic, is of uneven quality. Satellite-based monitoring, which allows for markedly improved detection and study of storms, only extends back to the 1960s, when satellites were launched that could monitor hurricanes (Ginis 2011).

Consensus statements on the potential link between tropical cyclones and climate change can be found in a recent assessment produced by a World Meteorological Organization expert team on climate change impacts on tropical cyclones (Knutson et al. 2010). Projections consistently indicate that oceanic warming will cause the globally-averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2 to 11 percent by the end of the century (Knutson et al. 2010). Existing modeling studies also consistently project decreases in the globally averaged frequency of hurricanes by 6 to 34 percent. Balanced against this, higher-resolution modeling studies typically project substantial increases in the frequency of the most intense cyclones, and increases of the order of 20 percent in the precipitation rate within 100 km of the storm center. Bender et al. (2010) estimate about a 30 percent increase in potential damage from the combined effect of fewer hurricanes overall and more very intense hurricanes.

Storm intensity is increasing. This photo shows flooding of the Blackstone River in 2010.

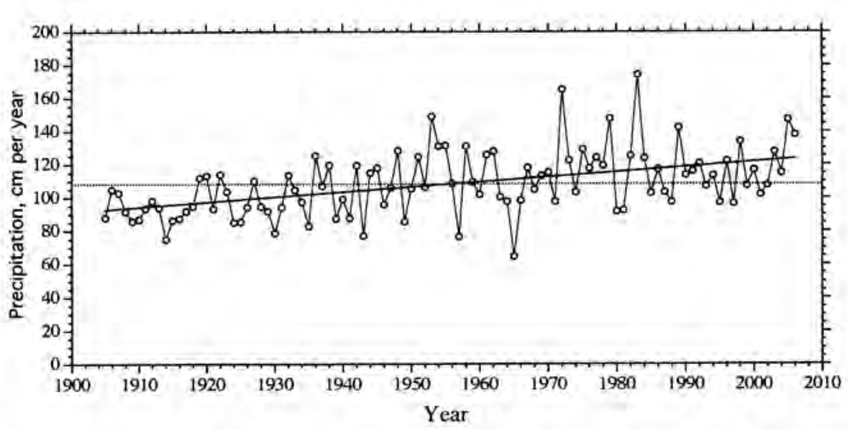
Flooding, such as in Matunuck during Tropical Storm Irene, is on the rise.

U.S. Northeast: Since 1850, 19 hurricanes have made landfall in the Northeast, six of them in a relatively active period between 1935 and 1960. By one estimate, hurricane damages along the East Coast over the past 80 years have averaged $5 billion per year, with most of the damage occurring during the largest storms. Approximately 12 to 15 nor'easters (extra-tropical storms) hit the U.S. Northeast from November to March every year (Frumhoff et al. 2007).

Rhode Island: Rhode Island has been impacted by a number of major storms, and they represent a major coastal and marine hazard. Disasters were declared for hurricanes in 1954, 1955, 1985, 1991, and 2005; Federal emergencies were declared for flooding from coastal storms and blizzards in 1993, 1996, 2003, 2005, and 2010.

Precipitation is increasing in the Northern Hemisphere

Global: In the Northern Hemisphere, rainfall has increased in mid-latitudes and decreased in the subtropics over the last 50 years (Zhang et al. 2007). The recent in-



Total annual precipitation (rain + snow) at the weather stations in Providence, R.I., from 1905 to 2006. Over the interval reported, the overall mean value was 108.2 cm yr^{-1}. *From Pilson in Desbonnet and Costa-Pierce (eds.) 2008. Used with permission.*

crease in heavy precipitation events in the Northern Hemisphere is due to warming of the atmosphere (Min et al. 2011). As air temperatures warm, the capacity for the atmosphere to hold water exponentially increases, and is responsible, in part, for the observed increase in extreme rainfall events.

U.S. Northeast: Rainfall and wind patterns have also been changing over time in the Northeast and coastal New England. Since 1985, precipitation has increased 16 percent in coastal New England (Pilson 2008). More of the precipitation is falling as rain, rather than snow.

Rhode Island: Precipitation in Rhode Island increased by 32 percent between 1905 and 2006 (Pilson 2008).

The watershed of Narragansett Bay receives 30 percent more precipitation now than it did 100 years ago (Pilson 2008). However, much of this precipitation evaporates due to warmer temperatures before entering the Bay, so annual average river flow into Narragansett Bay has only slightly increased during the last 30 years. The primary source for freshwater into Narragansett Bay is river flow rather than runoff or groundwater. Therefore, circulation, chemistry, and habitats within Narragansett Bay are greatly influenced by riverine freshwater inputs, and would very likely be impacted by changes in the magnitude and timing of river flow, and to a lesser extent, wind speed (Pilson 2008).

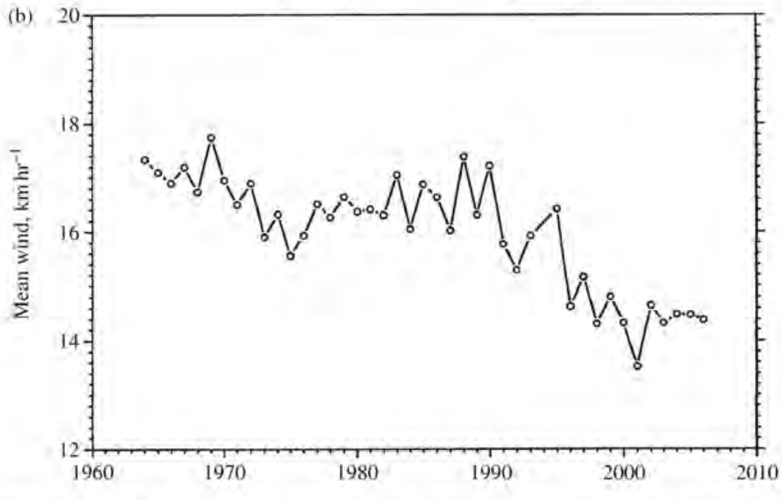
Wind speeds are declining in the Rhode Island

Wind speed recorded at T.F. Green Airport in Rhode Island has significantly declined from 1964 to 2004. This decrease can be seen during times of the year when wind speed is both strongest and weakest. The weakest winds are in the warmest months—July, August, and September (Pilson 2008). This has implications for the dynamics of coastal marine systems, which are strongly influenced by mixing and circulation due to winds.

The number of extremely hot days is increasing in the Northeast

Since 1962, the number of days with temperatures over 90°F in the Northeastern U.S. has roughly doubled (Frumhoff et al. 2007). Currently southern and inland regions of the Northeast experience up to 20 days of temperatures above 90°F each year, and about 2 days above 100°F in cities such as Boston and New York. Many northeastern cities, such as Providence, can expect dramatic increases in the number of days with extreme heat.

The length of the summer season is projected to increase by a number

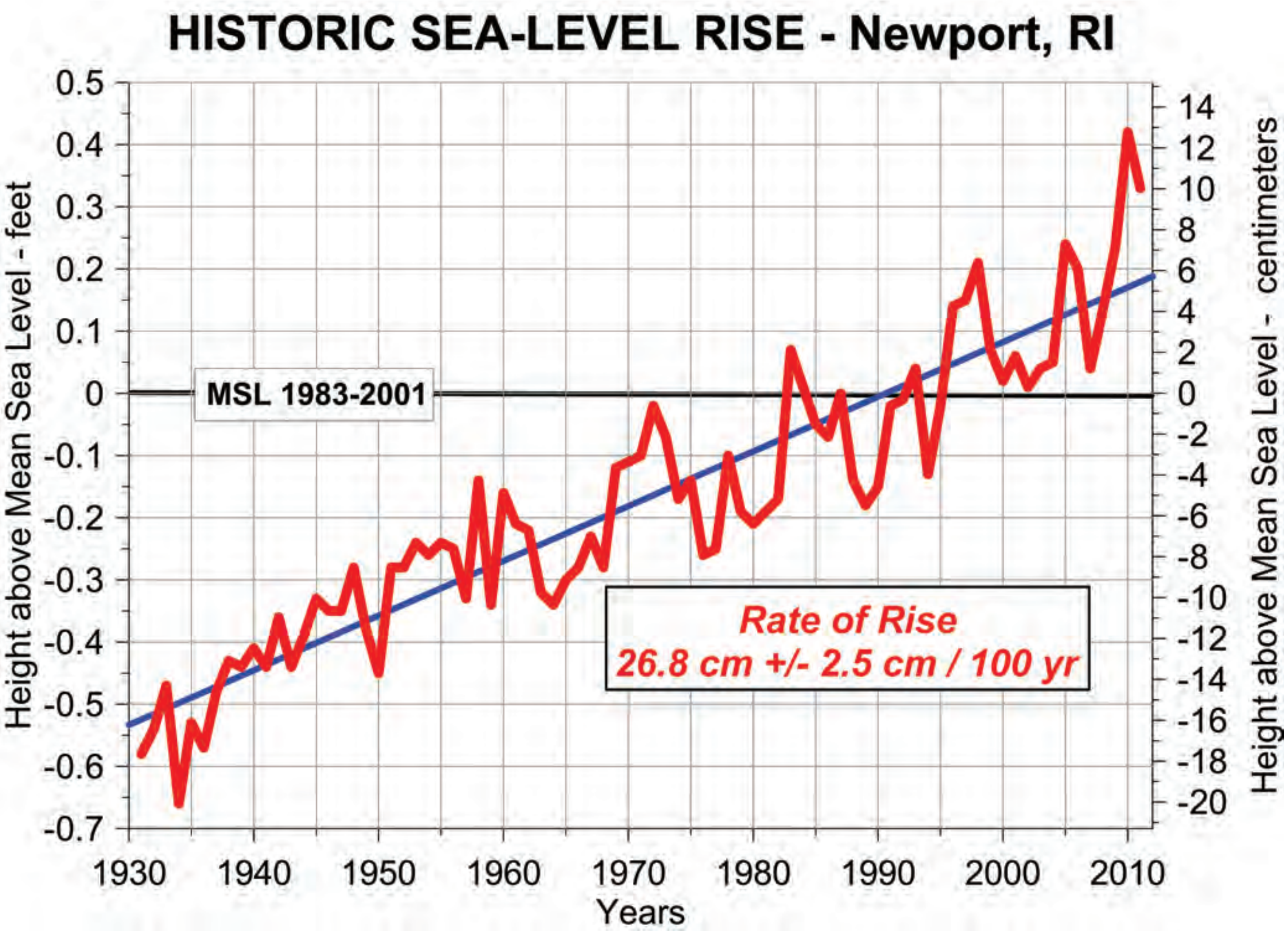


Annual mean wind speed at T.F. Green Airport during the years 1954-2006. *From Pilson in Desbonnet and Costa-Pierce (eds.) 2008. Used with permission.*

of weeks and the winter season is projected to be shorter (Frumhoff et al. 2007).

Coastal and ocean waters are becoming more acidic

Global: Roughly half of the carbon emitted from human activities between 1800 and 1994 has been absorbed by the ocean (Sabine et al. 2004), and one-third of recent emissions is currently being absorbed (Feely et al. 2004; Canadell et al. 2007 in UNEP 2009; Cooley and Doney 2009; U.S.GCRP 2009). This has resulted in a reduction of surface ocean seawater pH levels by 0.1 pH units (U.S.GCRP 2009), a change by a factor of 10. The most recent IPCC report projects that by late-century, globally, pH will drop 0.3 to 0.4 units from current levels (IPCC 2007). With the exception of rare events, a change of this magnitude has not occurred in the last 300 million years (Caldeira and Wickett 2003). Such ocean acidification is essentially irreversible over a time scale of centuries with many resulting physical and biological impacts (U.S.GCRP 2009).



This graph shows the difference between average sea level at Newport, R.I., from 1983 to 2001 and mean annual sea level plotted for each year between 1930 and 2011. The blue trend line shows a 26.8cm increase in sea level per century. *Graph courtesy of Jon Boothroyd, 2012. Data from: http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8452660%20Newport,%20RI.*

CONSEQUENCES OF CLIMATE CHANGE ON HUMAN USES OF RHODE ISLAND COASTS

Coastal flooding increases

Rhode Island has 47.1 square miles of land lying within 4.9 vertical feet of sea level with an additional 24 square miles between 4.9 and 11.5 feet (Titus and Richmond 2001). This 4.9-foot contour roughly represents the area that would be inundated during spring high water with a 2.3-foot rise in sea level, the current end-of-century projection.

With higher sea levels and storms projected to become more intense, the probability will increase for major flooding events to occur. Higher sea levels mean that waves ride on a higher base level, and thus storm surge impacts, such as coastal erosion, increase, possibly dramatically. With accelerated sea level rise, low-lying coastal ecosystems are greatly threatened and will be more vulnerable to extreme weather events and storms. For example, each year there is a 1 percent chance that a 100-year flood will occur, based on historical trends. This chance increases as storms intensify and sea level rises.

The flooding of 2010 caused $43 million in R.I. national flood insurance claims (RIEMA 2012).

A rise in relative sea level will increase the extent of flood damage over time, with areas of lower elevation more susceptible to flooding. Storm surge will be increased because the relative sea level is higher than in the past. According to the National Flood Insurance Program, "the increase in the expected annual flood damage by the year 2100 for a representative National Flood Insurance Program (NFIP) insured property subject to sea level rises is estimated to increase by 36 to 58 percent for a one-foot rise" (FEMA 1991).

Sea level rise will also reduce the effectiveness of existing coastal structures such as seawalls and revetments, roads, bridges, and residential and commercial buildings. Low-lying areas adjacent to these structures will be subject to increased flooding during storms. Coastal erosion of beaches and bluffs will increase with increased frequency and intensity of storms. Other risks associated with sea level rise include salt intrusion into aquifers and higher water tables.


FFRED FULLERTON

Coastal flooding, like this in Pawtuxet Cove, will become more common.

Impacts to marine transportation, navigation, and related infrastructure

Marine transportation, navigation, and related infrastructure support transport by sea of various types of goods and services as well as people. Climate change may influence numerous aspects of the way marine transportation and navigation occurs in Rhode Island waters as well as the infrastructure that supports it.


DERELL LICHT

The shipping season may lengthen, and icing threats may decrease.

Warmer temperatures may extend the shipping season, which has positive implications for the shipping industry. Warmer air and water temperatures will reduce concern of icing in waterways and on vessels and infrastructure.

Increased vulnerability of infrastructure will also be of significant concern to shipping and navigation. Coastal and offshore infrastructure may be subject to greater damage from more intense storms and increased decay from increasingly acidic seas (PIANC 2009). In addition, coastal infrastructure is more likely to be flooded by higher sea levels, and more coastal infrastructure will be exposed to higher wave loads and tidal fluxes, with consequent fatigue and corrosion.

Sea level rise will reduce the effectiveness and decrease the life of existing coastal structures such as seawalls and revetments, docks, roads, and bridges (PIANC 2009). The amount of sea level rise that is projected for the coming decades could compromise wastewater treatment systems, municipal sewage treatment plants, and storm water infrastructure.

Flooding will impact roads and bridges

When natural disasters occur, public safety depends on usable roads and bridges that are part of a network of evacuation routes. The projected increase in storm intensity may lead to more debris on the roads, hindering response and recovery efforts of emergency personnel. Similarly, sea level rise and storm intensity will increase flooding of roads.

Increases in precipitation will affect the moisture levels of soils, consequentially compromising the stability of retaining walls and road pavement subgrades (NRC 2008) leading to road failure. During heavy rain events, not only will some roads be impassable due to flooding, but after the waters recede, more roads and culverts may need repair. Additionally, the increase in precipitation levels will change stream flow and sediment delivery, scouring bridge foundations (NRC 2008).

Warmer temperatures during the winter months will reduce the costs spent on snow and ice removal. A typical snow season may become increasingly rare in much of the Northeast toward the end of the century.

The construction season could also be extended with more favorable temperatures. Conversely, higher temperatures may limit construction periods due to the health risks and safety concerns of the workers (NRC 2008). Longer periods of high temperatures may compromise the integrity of the asphalt on roads, making them softer and more prone to rutting from traffic loads (Rossetti 2002). More extreme heat can also cause thermal expansion of certain bridge joints, affecting bridge operations and safety (NRC 2008). Greater extremes between temperatures can cause road and runway buckling, potholes, and frost heaves (NRC 2008).

In order to reduce vulnerability to climate change, adjustments will have to be made for long-term capital improvement projects, facility designs, maintenance practices, operations, and emergency response and recovery plans (NRC 2008) throughout Rhode Island. This applies to local and state governments, as well as to private construction firms.

NATIONAL WEATHER SERVICE

Flooding in West Warwick in 2010 demonstrates how low-lying areas are already vulnerable to flooding.

Coastal historical and cultural assets are at risk from flooding and erosion

Climate change could impact the preservation and maintenance of historical and cultural assets in a


PAM RUBINOFF

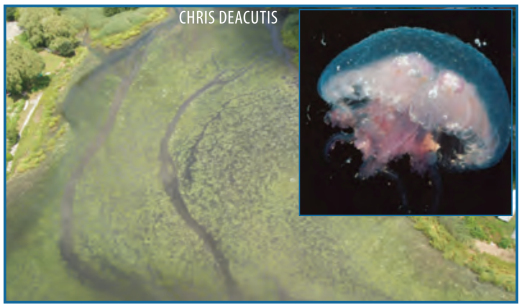
Coastal erosion may lower coastal property value.

variety of ways. Potential impacts include sea level rise and storm surge, which could increase erosion of coastal infrastructure, such as historic lighthouses, while more severe storms and ocean acidification could increase damage to submerged items, such as shipwrecks.

Rhode Island's lighthouses are important historic assets, which are highly vulnerable to the effects of sea level rise, storms, and sea surge. Several lighthouses have been moved in the past due to erosion and have been fortified for protection from storms. Some will likely need to be moved as sea level rises and storm intensity increases with climate change (Reynolds 1997, Lighthouse Friends 2010).

Coastal recreation and tourism will change

Climate change may impact people's decisions about recreation and tourism destinations due to the implications of climate change on the coastal and marine landscape, ecosystem, and infrastructure (Agnew and Viner 2001). While the research in this area is sparse with respect to the impacts of climate change per se, the following is based on research on the effects of these potential impacts to the types of recreation and tourism in coastal Rhode Island.


CHRIS DEACUTIS

Increased water temperatures may lead to more algal blooms and an increase in the abundance of jellyfish.

Increasing air and sea temperatures may enhance recreation and tourism activities by extending the summer season. However, warmer water may stimulate harmful algal blooms and an increase in jellyfish, reducing water quality and the attractiveness of beach and other marine recreational activities (Hoagland et al. 2002).

Increased rainfall and runoff may increase nutrients and other land-based sources of pollution flowing into the sea, and may increase the overflow from combined storm and wastewater sewer systems (Dorfman and Rosselot 2009). This can compromise water quality and lead to more beach and shellfish area closures.

With increases in sea level and storminess, Rhode Island's shorelines are expected to change significantly. Coastal barriers in particular will be especially vulnerable to increased erosion and landward migration as sea level rises. This can result in damage or loss to coastal parks, coastal public access points, and open space. The network of coastal lagoons, locally referred to as salt ponds, that lie along Rhode Island's south shore are important shallow marine ecosystems that may migrate or be lost due to higher sea levels (Anthony et al. 2009, Frumhoff et al. 2007). These ecosystems are used for wildlife-viewing and other activities such as quahogging, kayaking, and recreational fishing.

The retreat of beaches and the shoreline due to accelerated erosion loss and inundation may increase private property litigation. In addition, it is suggested that the combined impacts of warming, sea level rise, and coastal hazards will coincide with falling property values in coastal areas and loss of tourism revenue (Phillips and Jones 2006).

Marine fisheries will shift

Climate variability has always had a large impact on fisheries. The main climate change drivers impacting fish populations include changes in temperature, circulation, salinity, disease, invasive species, ocean acidification and food availability, all of which could affect the spawning and distribution of fish and shellfish causing changes in fishing.

With warming ocean temperatures, local species that are at or near the southern extent of their range are likely to move north, decreasing in abundance and/or the extent of time in which they can be caught by commercial fishers (Perry et al. 2005, Nye et al. 2009, Hare et al. 2010). Commercially valuable species most likely to be impacted in this way include American lobster, Atlantic cod, silver hake and winter flounder (Frumhoff et al. 2007). Conversely, species such as Atlantic croaker, black sea bass, blue crab, butterfish, scup and summer flounder that are at or near the northern extent of their range are likely to increase in abundance and/or extent of time in which they can be caught locally (Hare et al. 2010, Nye et al. 2009).

Warming sea temperatures are likely to bring more southern fish species such as Atlantic bonito, bluefish, false albacore, striped bass and yellowfin tuna that are primarily, but not solely, targeted by recreational fishers. With increasing populations of these species, some of them may become targeted by commercial fisheries more often. It is important to keep in mind the role of short-term climate trends that could affect fisheries. It has been shown that fluctuations in some fish populations has corresponded with decadal climate oscillations, such as the North Atlantic Oscillation and Atlantic Multidecadal Oscillation, and that changes in these climate oscillations will likely have a significant impact on New England fisheries (Nye et al. 2009; Oviatt 2011).


ALAN DESBONNET

Local lobster populations may decline as water temperatures increase.

As species move and targeted fish stocks change, there could be significant impacts on Rhode Island commercial fisheries. Potential impacts include (1) increased time and cost to travel to fishing grounds, (2) reduced catch per unit effort, (3) reduced market value of more abundant southern species compared with less abundant northern species, and (4) costs of altering gear.

Fishers who target Rhode Island waters often use a variety of gear types and are accustomed to modifying gear to target different stocks as they change seasonally. Therefore, if fish communities change, fishers may be able to adapt their fishing practices accordingly. An exception is the lobster fishery, in which lobstermen typically fish almost exclusively for lobster. With the prediction of northern movement of the species with increased water temperatures, and increased incidence of shell disease associated with increased water temperature, lobster fishing is likely to decline (Frumhoff et al. 2007).

Human health will suffer from several factors

The change in weather patterns and temperature extremes will affect Rhode Islanders' health. Particularly at risk to climate change impacts are vulnerable populations such as the elderly, disabled, children, non-English speaking residents, and low-income groups (Maine 2009). There are several factors that will be detrimental to human health.

More extreme heat days

An increase in average annual temperature due to climate change will mean more and higher extreme heat days in the summer. Hotter air temperatures in the summer can cause more heat-related stress and heart attacks (Frumoff 2007). Rhode Islanders may suffer from at least 45 more heat-related deaths from now until 2090 if climate change tracks on the higher emission scenario and adaptation measures are not taken (Roberts 2010). The predicted hotter conditions are most dangerous in the urban areas because of already present potentially vulnerable people and the heat-island effect (buildings and pavements absorb and radiate the sun's energy) (Frumoff 2007). This phenomenon worsens the ground level ozone that can lead to respiratory trouble. Rhode Island's metropolitan centers such as Providence, Cranston, and Warwick need to expect and prepare for hot conditions by mitigating impacts to vulnerable populations. This can be done by providing heat warning systems and

ISTOCK

Vulnerable populations will be particularly affected by exteme heat days.

opening cooling centers in these urban areas (Union of Concerned Scientists 2009).

Extended respiratory, allergy, and asthma risks

Climate-related changes in plant growing seasons can adversely affect human health. Warmer weather and increasing levels of carbon dioxide in the air stimulate plant growth, accelerating seasonal pollen production over several decades (Union of Concerned Scientists 2009). This could extend the allergy season and increase asthma risk in Rhode Island, affecting the 10 percent of Rhode Islanders that have asthma (Pearlman 2009). This same boom in plant growth may result in increased abundance of poison ivy (Schlesinger et al. 2006).

Higher air temperatures are directly linked with poor air quality, leading to potential increases in respiratory-related hospitalizations and deaths. Surface level ozone is of particular concern because it is a byproduct of the reaction of sunlight with certain air pollutants (such as hydrocarbons or nitrogen oxides), and ozone production increases at higher temperatures (Climate-TRAP, 2009). While ozone in the stratosphere plays an important role in protecting the Earth from harmful UV rays, surface-level ozone is a pollutant that damages lung tissue and can aggravate respiratory ailments, such as asthma or chronic obstructive pulmonary disease (WHO, 2009). Deaths attributed to air pollution can only be expected to rise as ozone concentrations increase.

Increased vector-borne diseases

According to the IPCC, "vector-borne diseases are among the most well-studied of the diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors. There is some evidence of climate-change related shifts in the distribution of tick vectors of disease, of some (non-malarial) mosquito vectors in Europe and North America" (IPCC 2007).

Studies specific to the U.S. Northeast have shown that increased air temperatures and earlier arrival of spring have prompted changes in the genetic responses of a certain mosquito species (Bradshaw and Holzapfel 2001). Although the species studied does not transmit vector-borne disease, it is closely related to vector species that may be undergoing similar evolutionary changes (Bradshaw and Holzapfel 2001).

Degraded water quality

Increased precipitation and flooding as a result of climate change may threaten water quality. Flooding and heavy runoff on nonporous surfaces can pick up dangerous chemicals, heavy metals, and other hazardous substances (e.g., pesticides) on the land (IPCC 2007). More intense flooding will impact the operation and maintenance of the infrastructure meant to maintain clean water. The coastal location of the Narragansett Bay wastewater treatment plant, pumping stations, and the various chemical storage facilities in flood zones poses a health risk to nearby residential areas during a natural disaster (Pogue 2008). Residents may have to deal with accidental sewage spills from over-taxed systems, displaced propane tanks, and household septic system failure. In March 2010, the Warwick wastewater treatment facility, located on the Pawtuxet River, was overcome by floodwaters and had to shut down for three days. During this time, wastewater was backing up and going directly into the river (Burke 2010).

RIDOT

Flooding in 2010 closed this wastewater treatment facility, and sewage discharged into the Pawtuxet River.

Polluted runoff and water treatment facility failure can also release pathogens and other pollutants into the nearshore areas where people swim. The Rhode Island Department of Health currently monitors 131 beaches for water quality and safety. Accelerated climate change may increase the occurrence of beach closures, thereby limiting the places that people can go to seek relief from the heat.

Additionally, as sea level rises and storm surges move further inland, saltwater intrusion can contaminate freshwater drinking water wells, particularly shallow ones (Pogue 2008). About 38 percent of Rhode Islanders depend on wells for drinking water (ECRI ND). Wells that are deep enough to withstand drought conditions will start to draw in brackish water as sea level rises (Titus 1990).

Social well-being will be stressed

Social vulnerability to climate change is difficult to measure, because the effects clearly attributable to climate change are limited (IPCC 2007). Variables such as income or age do not determine who will be hit by a natural disaster, but rather the population's ability to respond and recover from disaster (Oxfam 2009). The vulnerability of any population is determined by the availability of resources and the ability of individuals and groups to call upon these resources (Adger and Kelly 1999). An estimated 12 percent of the Rhode Island population is below the poverty level (U.S. Census 2000). Further, 20 percent of Rhode Islanders speak a language other than English at home (U.S. Census 2000). The ability of populations to cope with changing conditions, especially during a disaster, depends on financial well-being, literacy, political representation, access to transportation, and communication (Frumhoff 2007). Occupants of rental properties are also vulnerable to climate change. They are dependent on landlords for protecting the property from storms and floods, and may lack access to information about financial aid during recovery (Heinz Center 2002). As Rhode Island invests in climate change adaptation projects, municipalities should identify populations within their community that may be most at risk.

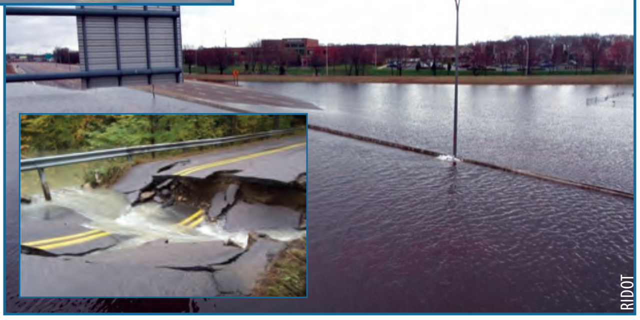
Individual homeowners may already be feeling climate change impacts. Some major insurance companies have withdrawn coverage from thousands of homeowners in the Northeast (Frumhoff 2007). Coastal properties may also be at risk of accelerated erosion due to increased storm surge and sea level rise. Over time, the landward migration of the sea will decrease the value of affected property and ultimately reduce their acreage.

Climate change will impact homes, health, and livelihoods, as well as infrastructure, recreation, and historic landmarks.


PAM RUBINOFF


CLARA RUBIN

LAURA SKROBE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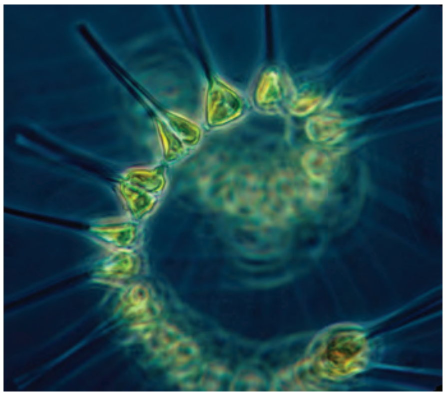
CONSEQUENCES OF CLIMATE CHANGE ON MARINE RESOURCES

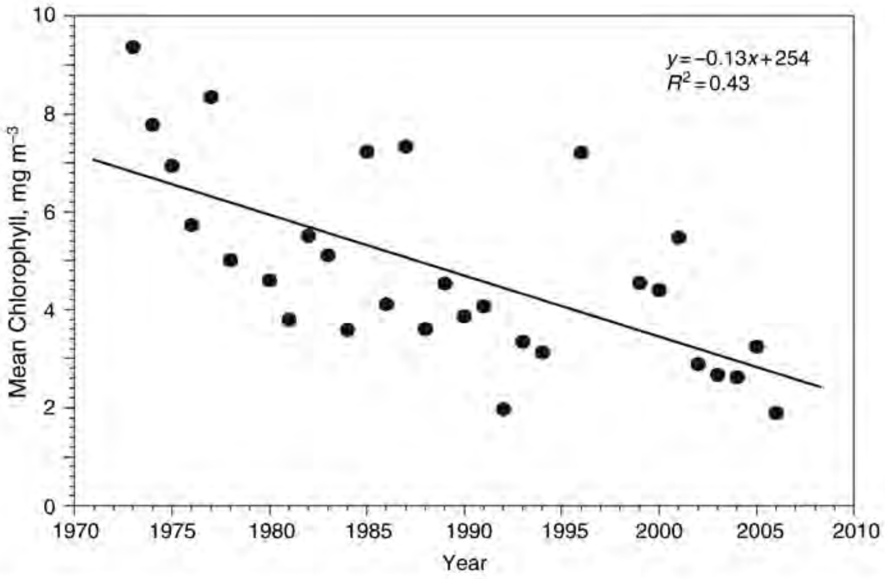
Plankton, the base of the marine food web, will change

Phytoplankton are microscopic plants that form the foundation of marine food webs. Therefore, changes in phytoplankton dynamics can have significant impacts on animals higher up the food chain. . Tiny crustaceans and other animals called zooplankton and bottom-dwelling filter feeders typically consume phytoplankton. Depositions of organic material from phytoplankton and zooplankton on the bottom of many marine habitats are an important source of food for deposit and filter-feeding bottom-dwelling species. Zooplankton are directly fed on by a number of different species, including some species of whales and schooling fish such as herring and mackerel. Fish species like cod, silver hake, bluefish, and dogfish prey on the schooling fish.

Narragansett Bay has experienced a change in the winter-spring bloom of phytoplankton. The timing of the annual-cycle of phytoplankton has shifted from a prolonged, bay-wide, large winter-spring bloom to a less consistent, less intense, shorter winter bloom with short intense blooms in the spring, summer, or fall (Oviatt 2004, Nixon et al. 2009). Data show that at least since the 1970s, the biomass of phytoplankton has decreased significantly in Narragansett Bay (Li and Smayda 1998, Smayda 1998, Nixon et al. 2009). It has been hypothesized that these changes have been induced by climate change, specifically warming waters (Keller et al. 1999; Oviatt et al. 2003) and an increase in cloudy days (Nixon et al. 2009). Warmer waters allow for higher rates of grazing of phytoplankton by zooplankton (Keller et al. 1999). The above factors are projected to decrease food availability to juvenile bottom-dwelling fish due to declines in the bottom filter- and deposit-feeders that readily consume dead phytoplankton and zooplankton (Nixon et al. 2009).

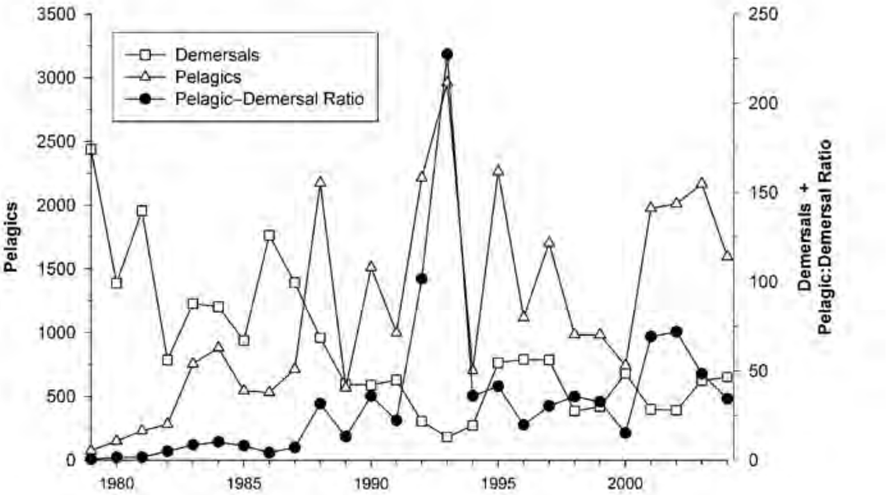


Warming waters in Narragansett Bay have decreased phytoplankton, the base of the marine food web.



Mean concentrations of phytoplankton chlorophyll during June, July, and August in the near-surface and near-bottom waters off Fox Island, in the middle of the West Passage of Narragansett Bay. Data from the early 1970s through 2996 are from T.J. Smayda, Graduate School of Oceanography (GSO), University of Rhode Island, personal communication. Data from 1999 through 2006 are from the plankton monitoring program maintained by the GSO (*http://www.gso.uri.edu/phytoplankton*). *From Desbonnet and Costa-Pierce (eds.) 2008. Used with permission.*

It has been additionally observed that in recent years, populations of the ctenophore *Mnemiopsis leidyi*, known as comb jellies, have grown in size and the timing of their annual arrival in local waters has shifted from late summer to early summer due to warming waters. This has caused the significant decline of *Acartia tonsa*, a once abundant copepod (a common type of zooplankton) in Narragansett Bay (Sullivan et al. 2001, Costello et al. 2006, Sullivan et al. 2007). Cancer crabs, lobster, and some fish populations could also be affected by their larvae being consumed in larger quantities by ctenophores (Sullivan et al. 2001, Oviatt 2004).



Changes in pelagic and demersal fish populations in Narragansett Bay, and in the Pelagic:Demersal ratio for 1979–2004. Based on RIDEM 20-min fish trawls (RIDEM Fish and Wildlife unpublished fisheries trawl data 1979–2004). *From Deacutis in Desbonnet and Costa-Pierce (eds.) 2008. Used with permission.*

Fish and shellfish species and abundance will shift

There has been mounting evidence that over extended periods of time, even small increases in water temperature can significantly affect species composition, distribution, and abundances of fish communities (e.g. Murawski 1993, Genner et al. 2004, Perry et al. 2005, Grebmeier et al. 2006, Frumhoff et al. 2007, Kirby et al. 2007). For example, a recent study found that 24 of 36 fish stocks assessed in the northwest Atlantic had a significant response to warming water temperatures (Nye et al. 2009). It has been projected that with warming, the geographical distribution of cold-water species will shift toward the poles and to deeper waters where temperatures are cold, causing a general reduction of cold-water species while expanding the ranges of warm-water species (Nye et al. 2009).

Warming waters are already having an impact on marine species, such as Atlantic cod.

In Narragansett Bay, dramatic shifts have been observed during the last half century in local fish populations associated with warming winter sea surface temperatures and fishing pressure (Oviatt 2004, Collie et al. 2008). The role of climate is likely significant, as overfishing alone cannot explain changes in fish populations in Narragansett Bay (Collie 2011). The increase in winter sea surface temperature is correlated with the decline of various species that reside in Rhode Island waters during the cold winter months (Jeffries and Terceiro 1985). These cold-water species may be in the process of being replaced by seasonal southern migrants that are increasingly abundant during summer months (Jeffries 2001, Collie et al. 2008).

Regionally it has been predicted that with increased warming, the distribution of American shad, alewife, Atlantic mackerel, American plaice, lobster, and winter flounder among other species will shift north (Rose 2005, Frumhoff et al. 2007). Lobster fisheries, for example, are expected to grow in the northern Gulf of Maine while declining in Rhode Island waters (Frumhoff et al. 2007). Commercially important species such as blue crab may thrive and increase in Rhode Island waters with warming. Other commercially valuable species may migrate from the south, though the influx of southern species will undoubtedly include nuisance and invasive species, such as jellyfish.


WENDY ANDREWS-BOLSTER

Lobster fishing is likely to decline due to multiple impacts from climate change.

In addition, data analyzed through 2005 demonstrated a major shift in the Rhode Island Sound coastal fish community from benthic (bottom-dwelling) fish species to smaller pelagic (water-column) southern fish species and large invertebrates (e.g., squid) (Oviatt 2004, Collie, in prep.). The shift from benthic to pelagic species began abruptly around 1980 and is consistent with similar benthic-to-pelagic shifts in other estuaries, such as Chesapeake Bay (Jackson et al. 2001, Attrill and Power 2002, Genner et al. 2004). This shift has been attributed primarily to increasing sea surface temperatures and secondarily to fishing (Oviatt et al. 2003, Collie et al. 2008).

Other factors that will likely affect fish populations include changes in food availability due to changing plankton dynamics (see section on plankton) as well as changes in predation on fish larvae as a result of warmer waters (e.g., Jeffries 2001, Taylor 2003). Changes in habitat, invasive species, hypoxia, ocean acidification, and disease will also likely affect fish and shellfish communities.

Marine mammals will shift northward

Sea surface temperature and distribution of preferred prey are important determinants in the range of marine mammals (Learmonth et al. 2006, Kaschner et al. 2006). The geographical range of cold-water marine mammals is expected to shrink and migrate northward with increasing water temperatures. This will likely affect the cold-water species that typically inhabit Rhode Island during winter months. On the other hand, some warm-water species (such as the West Indian manatee) will be more likely to enter Rhode Island waters as their range is extended northward (Learmonth et al. 2006).

Among the 36 marine mammals identified in Rhode Isalnd waters, ringed seal, gray seal, harp seal, and hooded seal are dependent on sea ice (Learmonth et al. 2006). Species that rely on sea ice or the environment close to the ice edge as part of their habitat will be more vulnerable to climate change (e.g., ice-breeding seals). In general, species that are more adaptable to changing prey conditions will be less vulnerable to climate change. Changes in prey distribution, abundance, and composition resulting from climate change are recognized by the IPCC (2001) as primary impacts of a changing climate on the marine mammals that feed from the top of the food chain. Changing water temperature and prey availability can also impact the reproductive success of marine mammals (IPCC 2007; Whitehead 1997). Finally, warmer sea temperature has been linked to increased susceptibility to disease, contaminants, and other potential causes of marine mammal death (Learmonth et al. 2006). Climate change has the potential to increase pathogen development and affect survival rates, disease transmission, and host susceptibility (Harvell et al. 2002).


COURTESY BOB KENNEY

Marine mammals will shift north with increasing water temperatures.

Sea turtles will lose nesting areas

Six species of sea turtles are known to inhabit the North Atlantic, with four—green, loggerhead, Kemp's ridley, and leatherback sea turtles—occurring rarely or occasionally in Rhode Island waters (Kenney and Vigness-Raposa 2009). All four are on the U.S. endangered species list. The major impact of global climate change on local sea turtles is that sea level rise will affect nesting areas and feeding grounds on low-level sand beaches that they typically use in areas south of Rhode Island (Fuentes et al. 2009a). In addition, rising temperatures will affect incubating sea turtle eggs, including hatchling success and sex ratios (Fuentes et al. 2009a, b).

Seabirds will lose nesting and breeding habitat


USFWS

Species such as piping plover could lose nesting habitat due to sea level rise.

It is known that changes in climate affect seabird behavior and populations in terms of food availability, nesting and feeding habitat, the ability to carry out courtship behavior, breeding, survival of young, and migration patterns (IPCC 2001; U.S.FWS 2010; Wanless et al. 2007; Durant et al. 2004; Jenouvrier et al. 2009). Each type of seabird (e.g., wading birds, sea ducks, gulls and relatives, and shorebirds) has a slightly different seasonal use of the area and, therefore, the impacts of climate change may affect them differently.

Those species that are found in Rhode Island that nest in coastal habitats are also vulnerable to sea level rise from climate change (U.S.FWS 2010). For example, piping plovers (federally threatened) and least terns (state threatened) could lose critical beach nesting habitat (pers. comm., P. Paton, URI). Vulnerable species that nest in salt marsh habitats in the Northeast include salt marsh sharp-tailed sparrows (this species is only found nesting in Northeastern salt marshes), seaside sparrows, and willets (pers. comm., P. Paton, URI). Species that nest on the ground on low offshore islands (e.g., roseate terns, federally listed as endangered and the common tern) would be extremely vulnerable to sea level rise and loss of critical nesting habitat. Rhode Island provides valuable stopover habitat for a wide array of migratory species, particularly in the fall for species that breed throughout the tundra of Canada/Alaska and stop in R.I. and coastal New England to refuel before heading farther south to the southern U.S., Caribbean, and South America (pers. comm., P. Paton, URI).

Intertidal habitats will shrink

Climate change may impact intertidal communities through large-scale shifts in oceanographic processes (e.g., see reviews by Harley et al. 2006, Helmuth et al. 2006). For example, changes in ocean circulation patterns may impact larval transport within and among intertidal regions (Gaylord & Gaines 2000), and affect factors such as colonization rates and the speed of invasions of exotic species (Connolly & Roughgarden 1999, Stachowicz et al. 2002a). Because intertidal communities are characterized by a strong spatial pattern of vertical zonation, with each species occupying an area according to levels of tidal inundation (Connell 1961), changes in water temperature may disproportionately affect low intertidal species (Harley 2003). These species are often less tolerant of environmental variation, and the impact of rapid warming on important species, such as top predators, can produce large-scale changes in intertidal communities.

Although such changes will almost certainly interact with human variables such as fishing and eutrophication, the complexity of these interactions makes them difficult to predict. These changes will also be affected by rising sea levels that will force intertidal communities to migrate landward (if undeveloped land is available for colonization), and also changes in ocean chemistry, such as acidification, may impact species unequally (Fabry et al. 2008). Ultimately, warming water and air temperatures may increase the rates of biological invasions by exotic species, causing local extinctions of cold-adapted species (Helmuth et al. 2006), which could lead these communities to become more homogenous with southern intertidal areas.

Diseases common to fish, shellfish and marine plants in southern waters will move northward

Diseases that are regional to southern waters could extend northward and negatively impact local communities of marine plants and animals. For example, the American oyster, which had repopulated Narragansett Bay and the south shore salt ponds


BARBARA SOMERS

Lobster with advanced shell disease

in the 1990s after being absent from commercial fisheries for nearly four decades, was severely afflicted by a southern oyster parasite causing the Dermo disease (Ford 1996, Cook et al. 1998). A 1998 disease survey found this parasite, which was rarely seen north of the Chesapeake Bay until the 1990s, in over half of the dead oysters (Cook et al. 1998). The spread of Dermo is attributed to warming waters by having extended the northern limit of the parasite's geographical range (Ford 1996, Cook et al. 1998, Oviatt 2004, Frumhoff et al. 2007).

A disease caused by bacteria in lobsters, often referred to as "shell disease" or "shell rot," has become highly prevalent in Rhode Island's lobster populations. Lobster catch in Rhode Island has declined sharply in the last decade beginning with a 1997 die-off in Rhode Island and Buzzards Bay, Mass., likely associated with the onset of the temperature-sensitive bacterial shell disease (Castro and Angell 2000, Castro et al. 2005, Frumhoff 2007). Though the cause of the spread of this disease is unknown, it has been speculated that anthropogenic forces are responsible, including warmer water temperatures (Cobb 2006, Castro et al. 2006). Currently, the southern extent of the commercial lobster harvest appears to be limited by this temperature-sensitive disease, and these effects are expected to increase as near-shore water temperatures rise (Frumhoff et al. 2007).

Nuisance species will invade from more southern waters

Phragmites is one invasive species already common in Rhode Island.

As local and regional waters warm, additional exotic species that once found the colder temperature inhospitable will be able to reproduce and spread (Frumhoff et al. 2007). Similarly, cold-water invasives that inhabit Rhode Island's coastal waters may migrate northward. Invasive species that can breed in warmer winter waters may have an advantage over late-recruiting native species (Stachowicz et al. 2002a). Natural processes such as changes in ocean currents and the expansion of the northern limits of warm water species could introduce new species into Rhode Island's coastal waters and warmer temperatures could prolong the stay of current seasonal migrants (Oviatt et al. 2004, U.S. EPA 2008). Additionally, as environmental changes affect native species composition and abundance, and potentially diversity, resistance to the establishment and spread of invasive species could decline (Stachowicz et al. 2002b). Resistance to invasives may also be impeded by compound stressors such as anthropogenic disturbance (McCarty 2001) or the spread of new diseases (Harvell et al. 2002), in addition to the stress of temperature increases (Stachowicz et al. 2002b).

Invasive species currently present in Rhode Island coastal waters include tunicates (multiple species), Asian shore crab (*Hemigrapsus sanguineus*), smallmouth flounder (*Etropus microstomus*), the common reed (*Phragmities australis*), and Japanese beach sedge (*Carex kobomugi*) (Source: http://nas.er.usgs.gov/).

Ocean acidification will deplete shell formation

Marine animals that have shells or skeletons made of calcium carbonate (such as corals, shellfish, foraminifera, snails, and sea stars) may be impacted by ocean acidification (Cooley and Doney 2009). As ocean and coastal waters become more acidic with increased concentrations of $CO_{2,}$ the dissolution rate of calcium carbonate increases and less dissolved carbonate ions are available for animals to take up and use to form shells and skeletons (USGCRP 2009). Young larval forms of these species are even more sensitive to acidification than adult forms.

Shellfish such as oysters are vulnerable to ocean acidification.

Acidification could also depress the metabolism of marine organisms with high metabolic rates, such as pelagic fishes and squid, which could lead to a decreased capacity to take up oxygen in the gills and cause asphyxiation in some fish, squid, and shrimp (TRS 2005, Fabry et al. 2008). Impacts to reproduction and larval development of marine fish have been shown in a lab setting, but additional possible impacts could include effects on immunity and on development at other life stages (Holman et al. 2004; Burgents et al. 2005; Fabry et al. 2008).

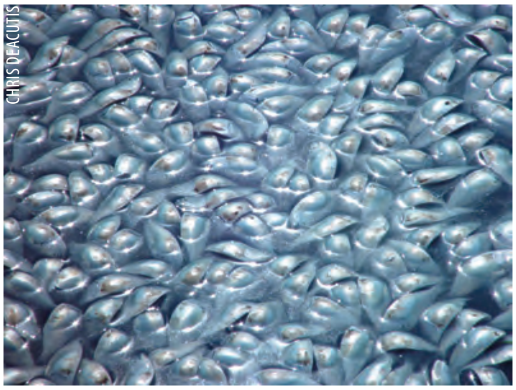
The effects of ocean acidification may be highly varied among species. A recent study at the Woods Hole Oceanographic Institution has shown that in some shellfish, net calcification actually increased in environments with elevated CO_2. (Ries et al. 2009). However, those tolerant species may still be negatively impacted by a decline of less tolerant species in their environment.

Hypoxia will become more common and widespread

When dissolved oxygen in the water is depleted to a level that is injurious to coastal and marine organisms it is referred to as hypoxia. Hypoxia is more likely to occur when the water is warmer because warmer water increases metabolic rates of aquatic organisms and their need for more dissolved oxygen. In addition to increasing oxygen consumption by organisms, higher water temperatures decrease the solubility of oxygen in water (the amount of oxygen that the water can hold) (NBEP 2009, Pilson 1998). Moreover, when fresh water from land runoff and river flow sits on the surface of saltwater, setting up density stratification, it shuts off mixing of deeper water with the surface and the relatively oxygen-rich atmosphere. In addition to delivering more nutrients (which can exacerbate hypoxia), higher river runoff during wet years leads to stronger density stratification in Narragansett Bay (Codiga et al. 2009). The long-term trend of increasing precipitation and river runoff will likely enhance stratification and lead to more severe hypoxia.

Wind speed, wind direction, and storminess play a large role in the interplay of the development of density stratification and the mixing processes that break down stratification. While the long-term trend of weakening annual-mean wind speed (Pilson 2008) may promote hypoxia, the formation of density stratification is also very sensitive to wind direction and storminess. For example, in nearby estuaries similar to Narragansett Bay (Long Island Sound, Wilson et al. 2008; Chesapeake Bay, Scully 2010), trends in wind direction (as opposed to solely wind speed) have been shown to play a large role in hypoxia severity. Thus long-term trends in wind direction, though not known well, may shape long-term trends of hypoxia severity in Narragansett Bay at least as strongly as long-term trends in wind speed.

The long-term increase in coastal water temperature could be due to various factors, including an increase in air temperature and long-term changes in circulation and mixing patterns, which control the flushing rate of the bay and thus the exchange between bay waters and coastal waters. Circulation and mixing are responsive to river runoff associated with precipitation, wind speed, wind direction and storminess. The variation in circulation and mixing that result from long-term trends in these driving factors are not well understood, but is an area of active research (Codiga 2011).


CHRIS DEACUTIS

Severe hypoxia in Greenwich Bay in August 2003 caused this menhaden fish kill.

Coastal habitats will change

About one-third of commercial fish and shellfish catches depend on estuaries and wetlands for food or protection during their juvenile or adult stages (NERAG 2001). Because the communities in these ecosystems often are adapted to specific temperature, salinity, nutrient and sea level conditions, they are extremely vulnerable to changed environmental conditions resulting in loss of habitats such as eelgrass beds and salt marshes.

Beaches will shrink

With increases in sea-level and storminess, Rhode Island's shorelines will change significantly. The beaches serve as important habitat

Beaches will be more vulnerable to erosion; previous efforts to stabilize them with seawalls and revetments have often led to even greater erosion.

for shorebirds such as the piping plover and numerous coastal species. Rhode Island's beaches on the south shore will be especially vulnerable to increased erosion and migration as sea-level rises. Increased storminess will result in increased storm overwash, breaching, and damage to real estate (Frumhoff et al. 2007). Previous efforts to stabilize shorelines from erosion have inadvertently led to exacerbated beach and wetland loss. Changes to the coastal barriers will also have implications for the ecologically important coastal lagoons, locally referred to as salt ponds, behind them.

Submerged aquatic vegetation will die off

Beds of submerged aquatic vegetation (SAV), and eelgrass (*Zostera marina*) in particular, serve as vital habitat for many commercially important marine species, especially functioning as nursery grounds where juvenile fish can hide from predators. It is predicted that eelgrass populations will decline in coastal waters of southern New England as a result of warmer water temperatures, decreased light levels from sea-level rise, and possibly increased storminess (Short and Neckles 1999).

Distribution of eelgrass in Narragansett Bay and the south shore salt ponds has declined significantly from historical levels, most likely due to impacts associated with excess anthropogenic nutrient inputs (i.e. nutrient pollution) (NBEP 2009). Impacts associated with climate change will further stress remaining eelgrass populations in Rhode Island's coastal waters. A study conducted at the URI Graduate School of Oceanography found that eelgrass died when exposed to temperatures 4°C (7.2°F) higher than average water temperatures and that this was exacerbated by nutrient additions (Bintz et al. 2003). In areas where eelgrass typically grows, such as the salt ponds, temperature increases will be higher than those predicted for general coastal and off-shore waters, due to the shallow depths of these areas (Harley et al. 2006, Anthony et al. 2009). Increased flushing could benefit eelgrass and other SAV populations by cooling water temperatures and helping to alleviate eutrophication.

Also, in areas such as the Rhode Island salt ponds, breaching events could negatively impact local eelgrass populations by increasing sand sediment in over-wash events in the ponds. As sea level rises, however, the inundation of shorelines could create new SAV habitat.

Coastal lagoons (salt ponds) will warm

The network of coastal lagoons, or salt ponds, that lie along Rhode Island's south shore are important shallow marine ecosystems with historically high productivity of commercially important fish and shellfish. They also provide habitat for resident and migrating shorebirds and water birds. These lagoons are particularly vulnerable to changes associated with accelerated sea level rise. The coastal barrier beaches, which separate the lagoons from the ocean, are dynamic systems that naturally migrate landwards along undeveloped shorelines with moderate rates of sea level rise (Hayes 2005). Natural migration of the coastal barrier and lagoon shorelines will be impeded in areas that are hardened, which could result in loss of lagoon habitat and may increase vulnerability of man-made coastal structures to storm damage (Titus 1998). With increased storminess and sea level rise, the potential increase of breaching events and inundation would result in changes in salinity, flushing, and depth, which have the potential to significantly alter the ecosystem


MONICA ALLARD COX

Coastal lagoons such as Winnapaug Pond are especially vulnerable to warming and sea level rise.

(Zimmerman 1981, Bird 1994, Mackenzie et al. 2007, Lloret et al. 2008, Anthony et al. 2009).

Temperature increases will likely be exacerbated in the lagoons, which could result in numerous impacts, such as loss of eelgrass beds, decreases in oxygen concentrations (Bopp et al. 2002, Joos et al. 2003), changes in species composition, physiology, and migration patterns (Woodward 1987, Turner 2003), increasing susceptibility to invasive species (Stachowicz et al. 2002a), and stressed benthic communities (Anthony et al. 2009). Increased flushing rates, however, could help to cool lagoon waters. Additionally, the seasonality and timing of natural lagoon dynamics, such as the timing and route of migrating birds, and the development and reproductive timing of marine species could be altered by temperature increases (Anthony et al. 2009).

Salt marshes will be inundated

Salt marshes are ecologically important habitats that provide a variety of ecosystem services, such as serving as nurseries and feeding grounds for marine species, filtering pollutants, and protecting adjacent land and infrastructure from storms, erosion and flooding. Loss of salt marsh habitat will likely occur due to accelerated sea-level rise. Historically, salt marshes in Rhode Island have been able to keep up with gradual sea-level rise (Bricker-Urso et al. 1989). With rapid rates of sea level rise resulting from climate change, salt marsh accretion will not be able to keep up past a certain threshold rate (Scavia et al. 2002, Frumhoff et al. 2007). The inland migration of salt marshes as sea level rises could also be disrupted by armored structures, such as seawalls, which would contribute to the loss of the marshes (Scavia et al. 2002). The loss of salt marshes will negatively impact many shorebirds and commercially important species of fish and shellfish, allow more pollutants to reach coastal waters, and leave the coastline more vulnerable to storms and erosion (Frumhoff et al. 2007). However, lost marshes could be converted to other important habitats, such as open water or mudflats.

Other factors, such as increased carbon dioxide, increased air and water temperatures, and changes in precipitation could have numerous and unpredictable effects on marsh primary production, species composition, hydrology, and associated salt marsh structure and function (e.g. Donnelly and Bertness 2001, Bertness and Ewanchuk 2002). Some effects could be beneficial, such as a possible increase in plant productivity due to increased carbon dioxide levels. Though many uncertainties are associated with these possible impacts to salt marshes, accelerated sea-level rise has been established as the likely biggest threat to marshes.


ROB HANCOCK

Salt marshes provide habitat for many animals, as well as protect coastal waters from pollution and limit erosion.

CONCLUSION

Rhode Island is rich in natural resources and cultural heritage and many scientists at URI and elsewhere are working to better understand the impact of climate change on the state and its inhabitants. Climate change is already affecting our weather, rates of erosion, extent of coastal flooding, the ranges of indigenous plants and animals, and the health of our citizens.

Please visit our website at seagrant.gso.uri.edu/climate to learn more about how climate change is affecting you and your region.

RIDOT

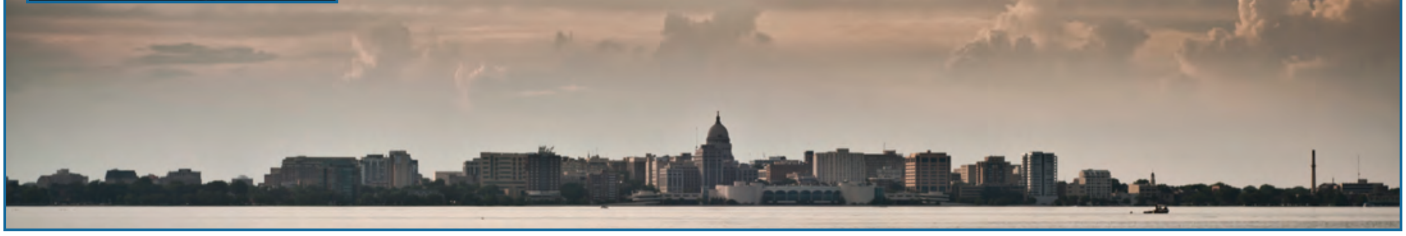
RIDOT


PAM RUBINOFF


RIDOT

Climate change is increasing temperatures, precipitation, storminess, nuisance species, and erosion. Its effects are already being felt in Rhode Island and beyond.


JIM BOYD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