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ORIGINAL ARTICLE

A discussion of the potential impacts of climate change on the shorelines of the Northeastern USA

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Abstract An increase in the rate of sea-level rise and potential changes in storminess represent important components of global climate change that will likely affect the extensive coasts of the Northeastern USA. Raising sea level not only increases the likelihood of coastal flooding, but changes the template for waves and tides to sculpt the coast, which can lead to land loss orders of magnitude greater than that from direct inundation alone. There is little question that sea-level rise, and in particular an increased rate of rise, will result in permanent losses of coastal land. However, quantitative predictions of these future coastal change remains difficult due in part to the complexity of coastal systems and the influence of infrequent storm events, and is further confounded by coastal science's insufficient understanding of the behavior of coastal systems over decadal timescales. Recently, dramatic improvements in technology have greatly improved our capabilities to investigate and characterize processes and sedimentary deposits in the coastal zone, allowing us, for the first time, to address some of the over-arching problems involved in shoreline change. Despite advances in many areas of coastal geology, our fundamental understanding of shoreline change has been limited by a lack of a broad and integrated scientific focus, a lack of resources, and a lack of willingness on the part of policymakers who make crucial decisions about human activity along the coast to support basic research in this area. Although quantitative predictions remain constrained, there remains little doubt that the predicted climates changes will have profound effects upon the Northeastern coast.

Keywords Climate change · Sea-level rise · Northeastern US · Coastal vulnerability · Coastal hazards · Hurricane impacts · Bruun rule · Coastal monitoring

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1 Introduction

The Northeast United States has an extensive and varied coast (Fig. 1), including wave-dominated sandy barrier beaches, mixed-energy coasts where waves are relatively small, extensive tidal marshes, and even rocky coasts that prevail further

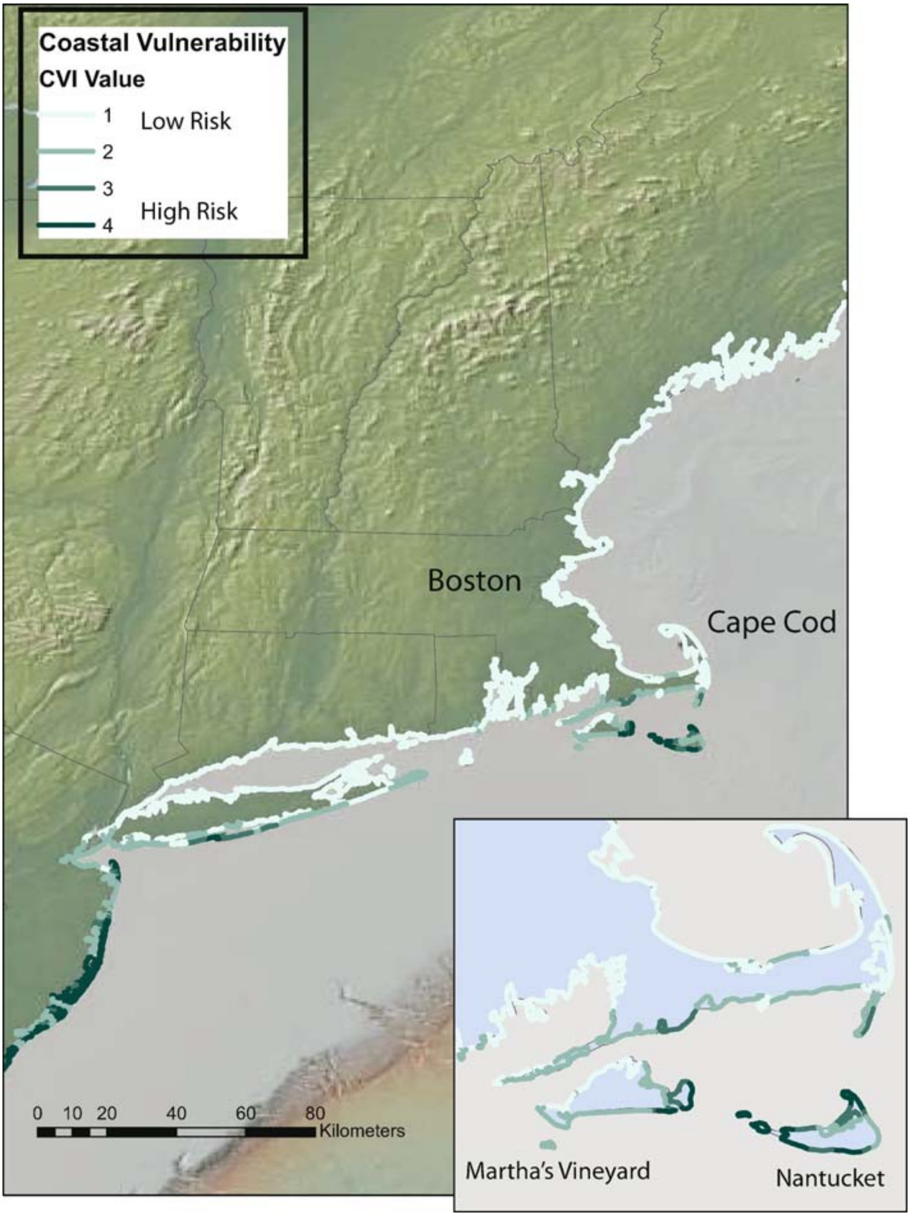

Fig. 1 Map of the Northeastern U.S. coast. Shoreline color coded with a Coastal Vulnerability Index (CVI), which relates the general susceptibility of a coast to sea-level rise, with 1 representing little risk and 4 representing high risk (CVI classification from Hammar-Klose and Thieler 2001)

north. Like many coastal regions of the world, the Northeast has experienced unprecedented development over the past century—development that is incompatible with the dynamic nature of the coast. This coast will be impacted throughout by future human-influenced climate change, mostly through increased rates of sea-level rise and changes to storm tracks, frequency, and intensity. There is little doubt that projected changes in climate and the resulting increased rates of sea-level rise would result in definite and dramatic changes to the shoreline throughout the Northeast. Unfortunately, the complex nature of the coast and the current relatively inexact knowledge of the processes that sculpt it limit quantitative and emissions-scenario-based predictions of coastal change over the next century.

1.1 Dynamic coasts of the Northeast

The coast is continuously being reshaped by processes occurring across many temporal and spatial scales. Even in the absence of climate change, the coastline is constantly shifting. Climate change, and specifically an increase in the rate of sea-level rise, will likely exacerbate changes along the coast. The influence of the driving forces of waves, currents, and tides, and the importance of sea level fluctuations, depends on the local geological framework – for example, sea-level rise might be hardly noticeable along a rocky, cliffed coast in Maine. However, a barrier beach on Long Island, NY, that is already low-lying will be more vulnerable to erosion during storms if sea level is raised (Fig. 1). The resulting landward shoreline retreat might be many orders of magnitude larger than the retreat expected from a passive response to sea-level rise itself.

The coast is a complex system consisting of more than just the beach; while shoreline erosion threatens property near the coast, it can also profoundly influence marshes behind the beach; these changes can in turn regulate the exchanges of water, nutrients, and pollutants with the open ocean. Furthermore, changes in the shoreline are inextricably linked across the entire coastal zone, from the onshore subaerial and lagoonal components, through the surf zone, and seawards onto the continental shelf itself.

Evidence suggests that the rate of sea-level rise in New England has increased over the last 150 years (Donnelly et al. 2004), and this rate is likely to increase in the future (Fig. 2) (Church et al. 2001; Cayan et al. 2006). Although sea-level rise will exacerbate flooding (Gutowski et al. 1994; Kirshen et al. 2007), the coast does not typically respond passively to sea-level changes as would be expected from flooding alone. Modest sea-level rise over the last several thousand years is in part responsible for the extensive barrier beach system across the southern reaches of the Northeast. Left alone, these barrier systems can remain intact as they migrate landward given sea-level rise rates typical of those of the last few centuries and millennia. Although property and homes would be lost, beaches and the barrier systems would remain. However, whether the barrier systems can continue to evolve under an accelerated sea-level rise is less clear, particularly as human interference generally does not permit the barriers to continue to freely move landward. For all anticipated rates of future fossil fuel emissions, sea level is predicted to continue accelerating throughout the Northeast, causing loss of oceanfront housing through erosion, increased coastal flooding, increased vulnerability to the impact of storms and the potential loss of salt marsh. All of these effects will be multiplied dramatically if fossil fuel emissions continue to increase. Although quantitative differentiation of the effects of higher

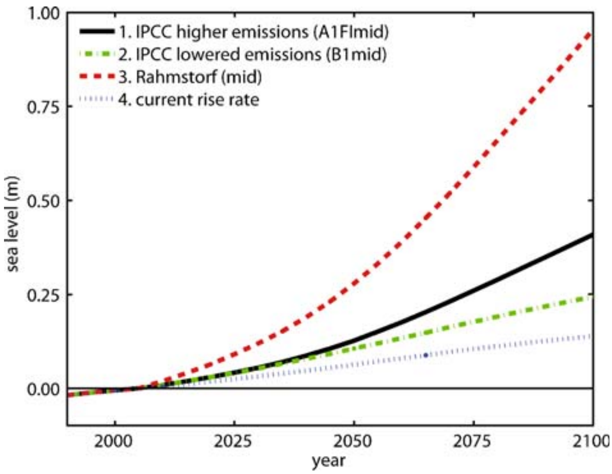

Fig. 2 Projected sea-level elevations for *1* the mid-range of the IPCC AR4 projections under a higher-emissions scenario and *2* the mid-range of the IPCC AR4 projections under a lower-emissions scenario (IPCC 2007; NECIA 2006), *3* the mid-range of projections by Rahmstorf (2007) under a higher-emissions scenario, *4* a linear extension of historical global SLR rate of 0.18 mm/year (1961 to 2003, IPCC 2007)

versus lower rates of future fossil fuel emissions are beyond the realm of current coastal science, it is clear that, especially for a scenario of high emissions, the impacts of climate change will likely be profound.

1.2 Economic risk

The large and rapidly growing human populations in coastal settings are likely to exacerbate the economic consequences of shoreline change. More than 155 million people (53%) of the US population now reside in coastal counties, and this number is expected to grow to 168 million over the next decade (National Academy of Sciences 1999). Another 180 million people visit the US coast every year (Houston 1996), including substantial numbers of foreign visitors. Between 300 and 350 thousand homes and buildings are located within 500 ft of the ocean, and 85 thousand homes are located within 60-year erosion hazard areas. The Heinz Center (THC 2000) estimates that across the US, as many as 1,500 homes and adjacent land are lost to erosion each year. In the Northeast about 52.6 million people lived in coastal counties in 2003 and that number is projected to increase by 1.7 million by 2008 (Crossett et al. 2004). The census bureau estimated that in 1990, 78,000 people in northeast states lived within 500 ft of the ocean (THC 2000). Much of the projected gain in population is around the metropolitan cities of Boston, New York, and Washington, DC.

Pielke and Landsea (1998), in a review of hurricane damages, estimate "normalized" damages for US East Coast hurricane events over the last 80 years averaged $5 billion annually, with most of the property damage occurring during the largest storm events. Hurricane Andrew in 1992 alone caused over $30 billion of damage (in 1992 dollars). The cost of Hurricane Katrina in 2005 is still unknown, but estimates from the House Budget Committee are around $150 billion. The September 21, 1938 hurricane, the most intense hurricane to strike New England over the last century, caused extensive damage along the south coast of New England and

Long Island, NY. If this storm were to hit today it would likely result in over $20 billion in damage (from Pielke and Landsea 1998, adjusted to 2005 dollars). North Atlantic hurricane activity exhibits significant multidecadal (Goldenberg et al. 2001) to centennial (Donnelly and Woodruff 2007) variability, and increased sea-surface temperatures due to global warming may increase the frequency and intensity of hurricanes (Emanuel 1987, 2005; Webster et al. 2005). Nineteen hurricanes have made landfall in the Northeast since 1850. Six occurred in the relatively active period between 1935 and 1960. If the region were to experience a similar period of activity today it would result in about $55 billion in damage (as above, using Pielke and Landsea 1998 adjusted to 2005 dollars). Hurricane damage estimates typically do not include damages to natural landforms or ecosystems or the costs of lost coastal recreation and tourism opportunities. Further, the nature of risks can change over time as demographic patterns shift.

Earlier intense hurricane strikes illustrate the vulnerability of the heavily populated northeast US to landfalling hurricanes. For example, the coast-parallel track of the 1821 hurricane resulted in the center of the storm passing over several Atlantic seaboard states (MD, DE, NJ, NY, and CT), whose coasts have all been extensively developed in the last century. Coastal populations in these states total over 31 million and insured coastal property exceeds 1 trillion dollars (IIPLR/IRC 1995). The financial loss associated with a hurricane similar to the 1821 storm striking this region today would likely far exceed that of the nation's most costly natural disaster, Hurricane Katrina in 2005. Many lives may also be lost because of difficulties evacuating this densely populated region in advance of a fast-moving intense hurricane. Warming-induced sea-level rise will only exacerbate this threat; sea level has already risen about 15 cm in southern New England since 1938 (Donnelly et al. 2004).

Other parts of New England are more susceptible to winter storms, in particular strong "Nor'easters" which intensify over the relatively warm ocean waters along the east coast of the United States, south of New England. These storms, named for their northeast winds, can cause storm surges of similar magnitude to those resulting from minor or near-miss hurricanes. Because these storms are more frequent and generally last longer than hurricanes, they can have a significant impact on north- and east-facing coasts (Snow 1943; Dickson 1978; Fitzgerald et al. 1994). Many severe winter storms have battered southern New England since European settlement, with some of the most infamous occurring in 1723, 1888, 1944, 1953, 1962 (Ash Wednesday Storm), 1978 (Blizzard of 1978), 1991 (Perfect Storm) and 1993 (Storm of the Century).

The Heinz Center (THC 2000) conducted a study of the costs of coastal erosion. Their study finds that the costs of coastal erosion are at least as large as the costs from flooding, with national losses amounting to between $3.5 to $5.5 billion per year. Recent estimates of the cost of sea-level rise incorporate assumptions of economically rational adaptation, such as the possibility of allowing structures to depreciate in anticipation of sea-level rise and the option of investing in either permanent or temporary shoreline protection. These new estimates are an order of magnitude lower than the earlier vulnerability estimates, amounting to about $500 million a year by the year 2065 (Yohe et al. 1999). These figures include estimates of neither the costs of storm damages nor the impacts on natural areas.

Faced with expectations of a potentially rapidly changing global climate system, decision makers, scientists and the general public have become increasingly concerned about potential risks to coastal communities and ecosystems related to possible increased storm activity. The potential losses were made abundantly clear in 2005 through the devastating impact of Hurricane Katrina. Gaining an understanding of how storm activity, both hurricanes and less intense but more frequent events such as Nor'easters, may be linked to changes in climate is imperative in order to project future changes and possibly mitigate socioeconomic impacts.

2 Effects of rising seas

In some areas of the Northeast, land subsidence has been compounding global sea-level rise, with both tide gauges and geological reconstructions indicating that current subsidence rates across the region range between ~0.5 and ~1 mm/year (Donnelly 1998; Peltier 1996; Peltier and Jiang 1997; Davis and Mitrovica 1996). Over the last several thousand years, the overall rate of sea-level rise in the Northeast slowed to between ~0.5 and ~1 mm/year, although this rate appears to have increased (to 2.5–3.0 mm/year) over the last 150 years (Donnelly et al. 2004; Donnelly 2006).

2.1 Future rise in sea level

Although projections of future sea-level elevations suffer from many uncertainties, a small subset of potential scenarios serves as a useful guide (Fig. 2). Two scenarios computed using the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC, http://www.cgd.ucar.edu/cas/wigley/magicc/) using different rates of ice melt and values for climate sensitivity demonstrate the potential reduction in sea-level rise by the end of the century if emissions are curbed. A recent projection by Rahmstorf (2007), using a simpler model, suggests larger potential heights for sea level. For perspective, an extrapolation of the measured 1961–2003 global eustatic rise rate of 0.18 mm/year is also plotted (Fig. 2; IPCC 2007); this information serves as a comparison, and should not be interpreted as a thoughtful projection of future sea level.

Comparing the MAGICC simulations of different emissions scenarios, (Fig. 2a,b) indicates little inter-scenario difference by mid-century with a rate of sea-level rise of 3 mm/year (low emissions) and 4 mm/year (high emissions). By the end of the century, rates for a low emissions scenario off at ~3 mm/year with a total rise of 0.23 m by 2100; however, for high emissions, rates accelerate to 6 mm/year by the end of the century, with a total rise of 0.38 m. This high-emissions rate easily surpasses local subsidence rates throughout the Northeast, and eustatic sea-level rise rates as large as these have not been experienced for many thousands of years. On the other hand, the more modest, low-emissions rate 3 mm/year over the second half of the century is closer in magnitude to current rates (Fig. 2). The Rahmstorf (2007) projections suggest much higher rates of sea-level rise, up to 15 mm/year by end-of-century. Even these higher projections are potentially conservative, overlooking potential threshold climatic behaviors, such as run-away melting of the Greenland ice sheets and calving of ice, suggested by some to have already started (Alley et al. 2005; Overpeck et al. 2006; Ekstrom et al. 2006), that could result in dramatically faster sea-level rise.

2.2 Shoreline response

Increased rates of sea-level rise will be felt throughout the Northeast, universally contributing to landward shoreline retreat. The magnitude of this coastline erosion, however, depends on local factors such as the wave climate and geologic framework. Researchers have applied empirical concepts (such as the 'Bruun Rule') in an attempt to quantitatively predict shoreline response to sea-level changes (Bruun 1962; Leatherman et al. 2000; Zhang et al. 2004). Geometric models such as these suggest that wave action superimposed on sea-level rise will lead to coastal erosion with horizontal coastal retreat rates orders of magnitude larger than the vertical increase in local sea level. Backbarrier and estuarine tidal marshes also represent a critical component of the coastal ecosystem and are particularly vulnerable to accelerated sea-level rise – we discuss the impacts on these systems below. Recent research suggests that there are threshold rates of sea-level rise, beyond which these marshes will likely experience unprecedented changes, including the potential that some marsh ecosystems will disappear altogether.

Beaches erode and accrete naturally over seasonal cycles, driven by fluctuations of wave energy. It may take many years or longer for a beach to recover from a large storm event. Measurements suggest that, over long time-scales, the shoreface, or off-shore portion of the beach profile, tends towards an equilibrium shape (Dean 1991). Based upon an assumed 'equilibrium' shoreface shape and geometric considerations, Bruun (1962; 1988) presented a formulation for land loss due to sea-level rise:

$$X = R/S \tag{1}$$

where X is the landward shoreline retreat due to a rise in sea level R, and S is a slope defined from the local geometry (Fig. 3a). In this formulation, S is the shoreface slope, defined by the location of the 'depth of closure' or 'wave base' where cross-shore sediment exchange is assumed to become insignificant (due to the depth dependence of wave action), typically taken as between 10 and 20 m for open ocean coasts. This relationship does not depend on the shoreline shape, but it assumes that the shoreface maintains the same shape over time. Shorefaces generally slope gently, with typical slopes on the order of 1/100; per the Bruun rule, shore erosion due to

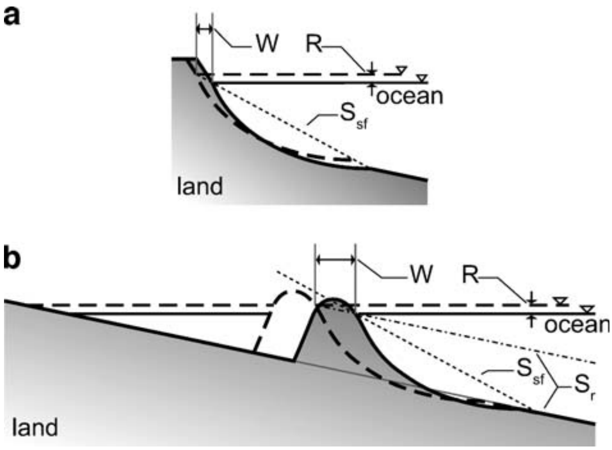

Fig. 3 Profile views of schematics (not to scale, with extreme vertical exaggeration) of **a** the typical 'Bruun rule' relationship, where the response of the shore is expected to depend upon the shoreface slope (S_{sf}) and **b** a 'modified' Bruun-type relationship based upon the conservation of mass showing that the true long-term trajectory of a barrier sandbody must follow the regional slope (S_r) if cross-sectional sediment is conserved. Note that in this case, the long-term shoreline trajectory is independent of the shoreface slope

waves with a raised sea level should be typically several orders of magnitude larger than the inundation caused by the rise in sea level itself.

This response to sea-level rise, however, should not be instantaneous, and pronounced shore losses will accumulate over time, mostly during infrequent, high-energy events (both seasonal events and rare extreme storms). The depth of closure itself depends on the time scale of interest (Hallermeier 1981), and deeper portions of the shoreface and inner shelf will take longer to respond to changes in sea level, possibly never coming into 'equilibrium' (Stive and de Vriend 1995). The predicted Bruun response depends upon the timescale of interest.

Several studies claim to demonstrate the applicability of the Bruun rule (Leatherman et al. 2000; Zhang et al. 2004), and, perhaps because of its elegant simplicity, it has become commonplace for the Bruun rule to be used by coastal planners and managers (Pilkey and Cooper (2004) claim it has been applied in over 26 countries). However, criticisms of the Bruun rule have been many and varied (Pilkey et al. 1993; Cooper and Pilkey 2004), and Leatherman et al.'s (2000) results have been questioned (Sallenger et al. 2000; Pilkey et al. 2000). Beyond the lack of a demonstrated Bruun rule response in nature, other researchers question several of the oversimplifications used to derive the relationship, which, for example, ignores natural heterogeneity such as mixed-grained sediments and the effect of the underlying geological framework (Riggs et al. 1995; Hammar-Klose and Thieler 2001). In one sample application, List et al. (1997) demonstrate that the Bruun rule is incapable of predicting historic shoreline changes for the Louisiana barrier islands.

Dean and Maurmeyer (1983) revised the Bruun relationship to account for overwashing sediment, suggesting an even smaller effective slope (and correspondingly predicting more erosion for a given sea-level rise). Further, Cowell et al. (1995), using models of coastal retreat based upon equilibrium geometries, demonstrate that long-term coastal response to sea-level changes depends on regional slopes, independent of the shoreface slope (Fig. 3b). Although not discussed explicitly, these studies help reveal that the simple Bruun rule, as commonly understood and applied, does not sufficiently account for mass conservation on the landward beach side.

These geometric models demonstrate that if the shoreface maintains a constant shape over long timescales, a concept that underlies the Bruun rule, not only is the shoreface shape irrelevant (as long as it does not change), but so is the shoreface slope. Studies that claim to show a correlation between coastal retreat rates and shoreface slopes therefore must be demonstrating another, non-equilibrium shoreline response that remains poorly understood. For most of the Northeast, regional slopes along barrier coasts tend to be an order of magnitude gentler than shoreface slopes (1/1,000 or flatter), more exact Bruun-type rules based upon mass conservation principles therefore would suggest that over centennial or longer scales, erosion rates due to sea-level rise could be an order of magnitude greater than those predicted by the standard Bruun rule.

However, over the last century, most coasts have not demonstrated these predicted kilometer/century erosion rates, suggesting that the coast is not in an 'equilibrium' required by these geometric relationships. If anything, these geometric models don't ask the question 'why is the beach eroding', but ask 'why aren't the beaches eroding more?' The ability for these geometric models to predict, even qualitatively, shoreline changes over the next century should be seriously questioned until they can be shown to predict historical changes.

Although scientists agree that the predicted sea-level rise will result in severe beach erosion and shoreline retreat through the next century, quantitative predictions of these changes are currently questionable, hampered not only by our limited understanding of coastal responses, but also by the innate complexity of the coastal zone. There are reasons to believe that coastal response to climate change may not be as alongshore-homogeneous as is assumed by these simple models (Slott et al. 2006; Valvo et al. 2006). One key to future success will be a better understanding of the role of underlying geologic framework. Also, even long-term coastal response depends on the magnitudes and timing of the stochastically unpredictable future storm events. Despite the insight gained from simple geometric models of sea-level response, successful application to natural systems over the next decades and century remains limited, due to both oversimplification and inaccuracies of existing models.

2.3 Coastal wetland response

Salt marshes are the principal estuarine habitat in the Northeast. These coastal wetlands provide important ecosystem functions in coastal environments, for example, filtering and absorbing terrestrial nutrients and pollutants, buffering coastlines from wave stress and erosion, and providing nursery grounds for fish, birds, and invertebrates. Increasing temperatures and sea-level rise resulting from climate change, as well as coastal eutrophication, are among the most intense and extensive threats to community structure and function of estuarine ecosystems.

In addition to the direct impacts of increased temperature, climate change will indirectly affect coastal ecosystems through accelerated sea-level rise. Salt marshes in the Northeast have developed over the last several thousand years under a regime of relatively slow rates of sea-level rise (Redfield 1972) of between 0.5 to 1.0 mm/year over the last several thousand years (Donnelly 1998). Marshes over that interval have accreted vertically, maintaining an elevation in equilibrium with sea level. In response to those relatively modest increases in sea level, marshes grew into expansive systems.

Apparently already responding to the recent increase in the rate of sea-level rise over the last century (Donnelly et al. 2004), low marsh flora is overtaking high marsh in some locations in New England (Donnelly and Bertness 2001). Low marsh can sustain faster rates of accumulation than high marsh; however, there exists a maximum accumulation rate even for low marsh, sea-level rise faster than this threshold would likely result the wholesale turnover of estuaries from a vegetated to a non-vegetated state. For marsh systems in the southeastern US, Morris et al. (2002) suggest that vegetation can sustain a maximum rate of relative sea-level rise of 12 mm/year. This threshold would be exceeded soon after mid-century under the Rahmstorf (2007) scenario. Marshes in the Northeast are different than those in the south; for example, maximum accumulation rates may be less in Northeastern marshes given a shorter growing season, lower suspended sediment concentrations, and different substrates and ecomorphology.

The recent expansion of water-logged pannes in salt marshes in the northeast US have been attributed to increased tidal flooding associated with accelerated rates of sea-level rise (Orson et al. 1985; Warren and Nehring 1993; Hartig et al. 2002). In fact, significant expansion and coalescing of pannes have been invoked as a mechanism leading toward extensive salt marsh loss in some areas (Orson et al.

1985; Day et al. 2000; Baumann et al. 1984; Hartig et al. 2002). Even if we presume that vertical accretion is solely a function of inorganic and organic matter influx and ignore the effects of regional subsidence along our coastlines, it is clear that many marshes will not be able to keep up with the projected acceleration in the rate of sea-level rise, which could result in the wholesale conversion of marshlands to subtidal and unvegetated intertidal areas.

2.4 Potential changes to barrier systems

Accelerated sea-level rise might do more than just persistently eat away at the shoreline. Because of the linkages between the elements, sufficiently high rates of sea-level rise could result in threshold behaviors that could result in wholesale reorganizations of entire barrier systems, as suggested by FitzGerald et al. (2006) and Riggs (2004). The Fitzgerald et al. model (Fig. 4) addresses the fate of mixed-energy barrier coasts found throughout the Northeast, characterized by short, fragmented stubby barrier islands, numerous tidal inlets, well-developed ebb-tidal deltas, and a backbarrier consisting of salt marshes and tidal flats incised by tidal creeks. As mentioned above, an accelerated rate of sea-level rise could result in wholesale changes in marsh vegetation. Removal of high marsh vegetation changes the hypsometry of the backbarrier transforming these areas to open water environments. The loss of marshlands would then increase tidal exchange between the ocean and backbarrier and ultimately change the hydraulic regime of the tidal inlets (FitzGerald 1988). If this occurs, the growth of both ebb and flood-tidal deltas would further sequester sediment from the littoral system and barriers, which would lead to a fragmentation of the barrier chain.

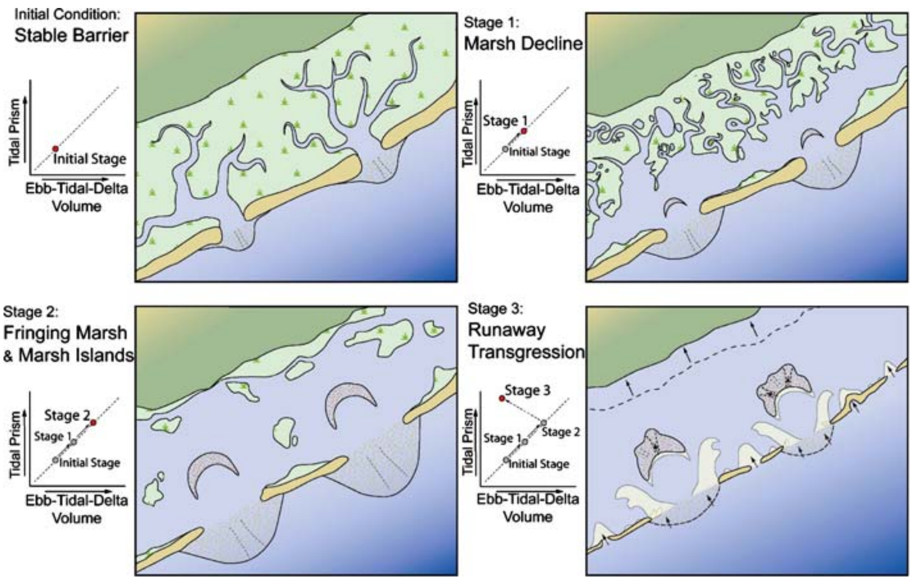

Fig. 4 Conceptual model of mixed energy barrier coast evolution in a regime of accelerated sea-level rise (from FitzGerald et al. 2006). Tidal prism, the volume of water entering the backbarrier during a tidal cycle, increases with rising sea level

The general progression from stage to stage in this model is robust; however, the rate and the thresholds at which the coast evolves given a certain rate of sea-level rise is unknown (Van Goor et al. 2003). For example, it has not been determined at what stage an inlet will be transformed from a channel system that naturally flushes sand by dominant ebb tidal currents to one in which dominant flood tidal currents import sand to the backbarrier. Many investigators have shown that the relative strength of the ebb versus flood tidal flow, which controls the net movement of bedload through an inlet, is a function of inlet geometry, bay tidal prism, and backbarrier hypsometry (Mota Oliveira 1970; Boon and Byrne 1981; van de Kreeke 1998). The conceptual model (Fig. 4) suggests that as intertidal areas and supratidal areas are converted to open water (subtidal areas), inlet hydraulics transition from ebb dominance (present condition of most mixed energy barrier coasts) to flood dominance (predicted future conditions).

3 Extreme events

Significant coastal change typically occurs during extreme events. Processes such as barrier overwash and breaching, which can radically reshape a shore, typically occur only during large storms. However, storms also deliver the majority of the wave energy felt at a coast, and even long-term changes, including responses to sea-level rise discussed above, require punctuated, extreme events to occur. Even if storm frequency remains constant, rising sea-level will make low-lying barriers more susceptible to storm damage and breaching during single events. Changes in storm frequency, intensity, and tracks due to climate change could also change patterns of alongshore sediment transport, which could reconfigure sandy coasts throughout the Northeast, further exacerbating erosional patterns at some locations. For much of the Northeast, predictions of the response to climate change would require not just an understanding of changes in the frequency and tracks of extra-tropical storms, but also predictions of changes in tropical hurricane frequency and intensity.

3.1 Historical storm events

Hurricanes make landfall relatively frequently in the Northeast. Hurricane Bob, which caused eight deaths and over $1.5 billion in damage, was the last hurricane to come ashore. This category 2 storm passed over eastern Rhode Island and southeastern Massachusetts on August 19, 1991. The most recent intense (category 3 or greater) hurricane to strike the region made landfall September 21, 1938 in central Long Island and tracked north into Connecticut, Massachusetts and Vermont (Minsinger 1988; Brooks 1939; Neumann et al. 1993). The 1938 hurricane was moving north at between 22 and 28 m s^{-1} (50–60 mph). Wind speeds to the east of the storm's track exceeded 53 m s^{-1} and a maximum wind gust of 83 m s^{-1} was recorded at the Blue Hills Observatory in Milton, Massachusetts (Donnelly and Webb 2004). The lowest recorded barometric pressure was 946 mb at the Coast Guard Station, Bellport, New York. Storm surge and an astronomical high tide combined to cause the water level to rise over 3 meters above normal spring tide levels along the open coast, and focusing in Narragansett and Buzzards Bays resulted in over 4 meters of storm surge in some areas (Paulsen 1940; Redfield and Miller 1957). Over 600 lives were lost and property damage was estimated at approximately 400 million dollars (Brooks 1939). As mentioned earlier a storm of similar intensity striking the region today would likely result in over 20 billion dollars (2005 dollars) of property damage (Pielke and Landsea 1998).

Significant coastal modification and erosion occurred from Long Island, NY to southeastern Massachusetts in 1938 as a result of the combined effect of storm surge and wave action (Wilby et al. 1939; Nichols and Marston 1939). Extensive sheet-overwash fans were deposited in the backbarrier environment from central Long Island, NY to western Cape Cod, MA as storm surge washed over nearly every barrier beach in the region. Many inlets were cut through barriers resulting in the establishment of flood-tidal deltas. In many cases the breaches filled in rapidly closing the newly formed inlets. In other cases the tidal prism was sufficient to maintain inlets following the breach. In still other cases, the 1938 hurricane set in motion a major reorganization of the coastline. For example, in Little Narragansett Bay (at the CT/RI border), the 1938 hurricane breached the barrier spit near Napatree Point. Following the initial breach the inlet has enlarged and an approximately 2 km stretch of the barrier to the north of Napatree Point has migrated landward between 0.6 to 1 km. Warren and Nehring (1993) suggested that this change in geomorphology has exacerbated the sea-level rise induced degradation of marshes behind the barrier by reducing the sediment flux to the marsh.

Although hurricanes are important, the coast also responds to more frequent, lower-energy events. The breaching of Nauset Beach off Chatham, Massachusetts during an intense Nor’easter on January 2, 1987 illustrates the consequences of the collision of coastal processes and recent coastal development. Following the opening and widening of this new inlet, upland areas newly exposed to increased wave attack began to erode and many homes were eventually destroyed (Giesse 1990). Barrier inlet formation has significant ecological consequences when it alters the tidal regime in backbarrier environments. For example, recent studies have documented changes in the composition of salt-marsh vegetation resulting from inlet formation and alteration of tidal range associated with the landfall of the 1938 Hurricane in southern New England (Orson and Howes 1992; Warren and Nehring 1993) and other storms (Roman et al. 1997). Storms can also have positive impacts. For example, overwash deposition in a southern Rhode Island marsh has increased sedimentation rates that has promoted relatively stable marsh communities in the face of increased rates of sea-level rise (Donnelly et al. 1999).

3.2 Climate change impact on storminess

Some studies have suggested that the intensity (Emanuel 1987; Henderson-Sellers et al. 1998) and frequency (Haarsma et al. 1993; Broccoli and Manabe 1990) of hurricanes may increase in a warmer climate. In a case study from the western Pacific, model results suggest a 5–12% increase in hurricane intensity with a 2.2°C increase in SSTs (Knutson et al. 1998). Levitus et al. (2000) have shown that, globally, SSTs increased by 0.31°C in the last half of the 20th century, possibly as a result of anthropogenic greenhouse gas emissions (Levitus et al. 2001). In fact, Emanuel (2005) and Webster et al. (2005) attribute recent increases in tropical cyclone activity to human-induced warming. Goldenberg et al. (2001) attribute the recent increase in North Atlantic hurricane activity to increasing SSTs and lower amounts of vertical wind shear that are part of the Atlantic Multidecadal Oscillation (AMO) resulting primarily from natural climatic variability.

Numerous studies have postulated links between changing modes of interannual climate variability, like El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), to patterns of tropical cyclone activity. Studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during strong La Niña years and suppressed during strong El Niño years (Gray 1984; Bove et al. 1998). In strong El Niño years, increased vertical wind shear associated with a strengthening of the subtropical jet over the tropical North Atlantic that hinders tropical cyclone development is thought to be responsible for this relationship. Donnelly and Woodruff (2007) demonstrated that intense hurricane activity has been modulated by ENSO variability over the last 5,000 years.

Based on a positive statistical relationship between a weak NAO and increased global tropical cyclone activity from 1966–1997, Elsner and Kocher (2000) have proposed that global tropical cyclone activity may, in part, be modulated by the NAO. In addition, Elsner et al. (2000a) propose a possible link between a weak NAO and increased intense hurricanes in the North Atlantic, possibly related to the strength of the trade winds. Landsea (2001) questioned the conclusions drawn by Elsner et al., suggesting that the database used may have biased the results. Using sandy overwash deposits preserved in a coastal lake from the Florida Panhandle, Liu and Fearn (2000) inferred two relatively quiescent intervals of intense hurricane activity in the Gulf of Mexico from present day to 1,000 and 3,400–5,000 years ago. They suggest that this millennial-scale variability may be associated with changes in the position of the Bermuda High that may alternately focus hurricanes into the Gulf Coast and East Coast of the US. Elsner et al. (2000b) document this kind of see-saw pattern in Atlantic hurricane tracks associated with the position of the Bermuda High and NAO intensity over the last 200 years, where the Gulf Coast experiences more hurricane activity during a weak NAO and the US East Coast experiences more activity during a strong NAO. However, recent reconstructions from the New York City area reveal similar patterns of intense hurricane landfalls to the Gulf coast over the last several millennia, suggesting that observed variability is the result of basin-wide changes in activity and not simply a change in prevailing tracks (Scileppi and Donnelly 2007).

In New England, Nor'easters play an important role in coastal dynamics. However, links between Nor'easters and climate change remain even less understood and researched. For example, Heyhoe et al. (submitted), analyzing climate models, suggest little future change in northeast storm distributions for either emissions scenario. More research of both hurricanes and Nor'easters will be needed in order to understand how Northeast coasts will respond to climate change. Future climate projections predicting local and regional wave climates would be particularly useful, as recent research (Slott et al. 2006) suggests that, for at least some types of sedimentary coasts, even slight changes in wave climates could result in coastline reorientation with local erosion and accretion patterns of the same magnitude as those expected for an equilibrium shoreface response to sea-level rise.

4 Predicting coastal change

Coasts are affected by processes that occur across many temporal scales, from the oscillation period of single waves, to diurnal tidal cycles, up to the millennial and longer scales of tectonic changes. Increasingly detailed measurements demonstrate that the coast changes in seemingly surprising ways over all of these time scales. The extreme nonlinearity of coastal sedimentary systems and the stochastic nature of the driving forces further hinders our ability to make predictions of coastal change at the larger scales of human development, particularly as ‘upscaling’ of processes from smaller scale to those relevant to coastal management is a difficult (and sometimes ill-advised) practice, further limiting our ability to predict future shoreline change. Additionally, our understanding of historic shoreline change at decadal and longer scales is often based on extrapolation of a limited set of measurements of past changes into the future, further constraining our understanding of how coastal systems responded to past changes in sea level and storm regimes. Our incomplete understanding of the past limits our ability to make accurate future predictions.

4.1 Observations and measurements

The underlying controls on shoreline change depend upon the time scales of interest. Short-term changes are caused by fluctuations in waves and tides, modulated by seasonal climatic factors. Long-term changes also depend on waves and tides, but, even more than short-term changes, are directly constrained by sediment availability, geologic framework and sea-level trends.

Recent, increasingly high-resolution measurements of the shoreline position reveal that shoreline change is much more complicated than previously thought. For example, high-resolution measurements along the Outer Banks shoreline show unexpected alongshore-heterogeneous response of the shore to storms (List and Farris 1999). Erosion and accretion patterns can vary along the coast during a single storm, patterns not replicated after future storms that do not directly correspond to longer-term, accumulated shoreline change (List et al. 2006). Tebbens et al. (2001), using LIDAR data, demonstrate that the signals of alongshore change varies across all alongshore scales; this self-affine, or ‘fractal’ signal suggests that shoreline changes exhibit an element of randomness or stochasticity that will limit the types of exact predictions desired by engineers and planners.

In many cases, projections of future shoreline changes merely extrapolate previous changes into the future. Historical shoreline records are typically scant, sporadic, and of varying quality. Forecasting usually consists of defining a trend from a limited set of measurements. As recent measurements reveal that the shoreline shows great variability across all time scales, estimated trends are aliased, subject to considerable error (imagine using 3 randomly spaced climatological measurements to project future conditions). Even if such projections were reliable, extrapolation does not account for future changes in forcing conditions (e.g., storminess, precipitation, wave conditions).

The modern coastal system has developed over the last few millennia with relatively stable sea levels, with most places experiencing relatively modest amounts of sea-level rise; however, the remarkable diversity displayed by coastal landforms, even in this stable sea-level context, stresses the importance of other parameters in forcing the dynamics of the shoreline. Coasts are complex transitional environments that respond to the variability of both continental and marine processes. Many coastal and shelf settings have high sedimentation rates recording this complex variability, but these archives have yet to be systematically studied. By matching paleo-environmental information from coastal settings to established land and marine proxies, a common chronological and spatial framework can be established and used to understand how the interaction of terrestrial and marine processes controls the dynamics of the coast. Geological and geophysical datasets are needed from a variety of coastal depositional settings that would allow a detailed reconstruction of their stratigraphic architecture, coupled with biological, geochemical, and sedimentary proxy records of local/regional paleoenvironmental variability that can be correlated/compared to global indices.

Much of the recent coastal research has been dedicated to the measurement of waves, sediment transport and morphodynamics of straight and homogenous coastlines, which can be more easily conceptualized for modeling purposes. However, most coastal regions, particularly those of the Northeast, are complex and not tenable to such simplification. Estuaries and inlets, anthropogenic structures from groynes to harbors, headlands and bays, all depart significantly from two-dimensionality.

4.2 Anthropogenic influence

At many locations, particularly along the heavily developed coasts of the Northeast, anthropogenic activities, such as the construction of sea walls, revetments, groynes, and jetties, and active sand replacement ('renourishing') overwhelm or mask the natural responses. Anthropogenic impacts on coastlines also feed back into the effects of storms. Because many barriers are armored against erosion, they cannot evolve as they would naturally. For example, overwash events from storms are an important mechanism for moving sediment into the backbarrier, maintaining the integrity of the barrier system. In many cases, the process of overwash has been prevented along developed coastlines. Unraveling these complications raises the level of complexity in understanding beach erosion during storms, yet the long-term impacts of such armoring are of vital interest to coastal residents and coastal managers.

4.3 Coastal modeling

Analytical and numerical models are increasingly being used to help to understand, and often to attempt to predict, the behavior of coastal systems. Models allow scientists to test ideas about coastal morphodynamics over a range of spatial and temporal scales, and can be a useful tool for understanding possible future behaviors that have no present-day analog. In general, oversimplification, limited observations, and unknowable future conditions strongly limit models' ability to make quantitative future predictions. For example, accurate and coeval historical directional wave measurements are scant along much of the coast, making it difficult to even understand previous shoreline changes.

Many of the models of coastal processes that have been traditionally used have, by necessity, made critical simplifying assumptions that limit their applicability. One example is simple analytical relationship of the Bruun rule discussed above. Dramatically different are newer 3D circulation models, coupled with sediment transport processes, that are demonstrating success modeling shorter-timescale changes (Lesser et al. 2004; Roelvink 2006). A suite of numerical models have been developed to quantify the response of the seafloor to wave-orbital forcing to better understand sediment transport processes (e.g., Hsu et al. 2004; Drake and

Calantoni 2001). For example, these new models have helped improve the predictions of surf-zone bar migration not only offshore during storms, but also onshore during calmer periods (e.g., Trowbridge and Young 1989; Thornton et al. 1996; Elgar et al. 2001; Hoefel and Elgar 2003). Whether these models exactly capture the morphodynamic feedbacks essential of the coastal zone over much larger spatial and temporal scales remains undetermined. Furthermore, applying such detailed models over the scales of decades and larger would require impractically intense site characterization and knowledge of forcing conditions – increased model complexity does not guarantee better predictive ability. The myriad variables and behaviors that can arise from model complexity can even obfuscate which processes drive model behavior, reducing the model's ability to provide insight and enlighten future conceptual model development. Recently, a series of less complex models has been developed, and show promise that such simplified approaches can adequately simulate important aspects of coastal change (Ashton et al. 2001; Dearing et al. 2006), particularly over longer time periods.

In general, most studies of nearshore processes have been conducted on long, straight shorelines, and the mechanisms driving shoreline change along more typical coasts with complicated nearshore and surf zone bathymetry, inlets, and headlands are less understood. In particular, to improve decadal and longer-term models for shoreline change, much more needs to be known about how the interplay between alongshore and cross-shore sediment transport affects beach erosion and accretion, including the role of inlets and underlying geological framework. Future studies focused on wave propagation on complex coastlines, and the corresponding wave-driven nearshore circulation, sediment transport, and morphological change, are needed to develop and test models that coastal planners can use to predict shoreline evolution in response to changing climate, sea level, and storminess. Models of previous and future coastal changes must account for the influence of human intervention at the coast; at many locations across the heavily developed Northeast, anthropogenic alterations equal or overwhelm the signals of natural shoreline evolution.

4.4 Advances in field data collection

There have been dramatic improvements in technology that have greatly increased our capabilities to observe the coastal zone and which allow us, for the first time, to address some of the over-arching problems involved in shoreline change. Such understanding requires a broad suite of geophysical and oceanographic tools, sampling, and dating methods given the active role of geological framework in controlling large-scale coastal behavior and sediment availability, the wide range of critical spatial and temporal scales, as well as the inherent heterogeneity of coastal sedimentary systems.

Recently, spectacular images of seafloor morphology have been collected, with fine, centimeter-scale resolution previously unattainable. The high resolution can, with frequent repeat surveys, permit us to understand the large scale behavior of features such as ripple fields (e.g., Mayer et al. 2002; Goff et al. 2005). When these repeat surveys are combined with small-scale process-based studies (e.g. Traykovski et al. 1999), we can start to understand the key sediment transport processes on much larger spatial scales. Increasing use of LIDAR, both aerial- and ground-based, is allowing rapid, detailed measurements of the coast, particularly after storms. It is also now becoming possible to combine the high LIDAR with offshore data, providing a seamless data set from one regime to the other. This is especially important in the context of rising sea level as, in the past, the critical inter-tidal region was poorly defined.

The onshore portion of the coastal zone, including beaches, dunes, lakes, wetlands, and deltas, constitutes an integral part of the coastal zone and contains an archive of oceanographic, climatic, and sea-level changes. Sediment sampling and ground-truthing of geophysical data requires a variety of coring techniques, suited for a range of sediment compositions and saturation regimes. Standard vibracores allow preservation of physical sedimentary structures, with penetration depths of 5–6 m in coarse-grained sediments and deeper in muddy sequences. Other systems, such as hand-operated boring apparatus, although disruptive to sedimentary structures, are highly portable and enable penetration of more than 10 m in sandy coastal lithosomes. In areas where deeper sampling is needed, commercially available drilling platforms, such as Geoprobe, are being used.

In many mixed-sediment regions, coring can be difficult, making geophysical tools indispensable in stratigraphic research. Ground-penetrating radar (GPR) is a high-resolution geophysical tool that has revolutionized coastal stratigraphic research, and has been used for imaging the facies boundaries within barrier and deltaic systems, mapping paleo-shorelines and stratigraphy of lake-basin fills, resolving the erosional features in coastal lithosomes (buried storm scarps, unconformities, and breach channels), and for hydrogeological studies in the coastal zone (e.g., Buynevich and FitzGerald 2003; Buynevich et al. 2003). Other methods that are being used in terrestrial and lacustrine settings, as well as offshore, include electromagnetic surveying and electrical resistivity imaging (e.g., Evans et al. 1999, 2000; Evans and Lizarralde 2003; Ruppel et al. 2000), which provide data on the physical properties of sediments in the shallow subsurface.

These improvements in technology are a potentially important tool in mitigating the impacts of sea-level rise by increasing our understanding of the shoreline behavior and ultimately in making better-informed management decisions. Such understanding will require investment in basic research infrastructure and programs at large scales, perhaps through the redistribution of funding that is currently being spent on mitigation and unfocused research programs.

5 Future outlook

5.1 Projected impacts of climate change in the Northeast

The USGS have carried out a study highlighting the areas of coastline most vulnerable to the impacts of sea-level rise (Hammar-Klose and Thieler 2001) (Fig. 1). The various factors considered in calculating a coastal vulnerability index (CVI) for a particular stretch of beach include past changes in shoreline position, typical wave climates, tidal range, coastal geomorphology and sea-level history. Each region is assigned a CVI from 1 (low-risk) to 5 (high-risk). These assessments do not allow us to predict where shorelines might be in the future, nor do they account for the impacts of large events such as hurricanes, but they do highlight some of the most at-risk locations.

Within the New England area, areas of high CVI include most of Nantucket Island, the eastern portions of Martha's Vineyard and parts of the South Cape Cod.

Further south, areas of Long Island and the New Jersey coast are marked as vulnerable; not surprisingly, most of the vulnerable areas are low-lying barriers. The simple CVI does not provide site-specific insight, however. For example, the south shore of Martha's Vineyard, a relatively sparsely inhabited region, is known to be exhibiting increased and rapid (1–2 m/year) rates of shoreline retreat. The area is also exposed to the Atlantic and thus is vulnerable to the impacts of storms that pass to the west. However, more damage could be caused if a northerly tracking hurricane were to pass up Buzzard's Bay, as storm surge trapped within the bay would cause devastating flooding along low-lying areas. Many regions within the bay are only a few feet about sea-level and will become increasingly vulnerable as sea-level rises; these areas are listed as having a low CVI.

Generally, low-lying and low-sloping coastal areas will be at the greatest risk. First, these areas will be exposed to increased flooding due increased baseline water levels and the possible increase in storm frequency (Wood 2001; Kirshen et al. 2007). Barriers will not only be subjected to erosion that may be up to three orders of magnitude greater than the rise in sea level itself, but will be more susceptible to barrier overwash. This overwash not only transports beach sediment landward, it can cause barrier breaching, with the formation of either temporary on permanent inlets. In developed regions, the tendency to not allow barrier overwash to perform its natural function of widening islands will further increase the possibility of barrier breaches.

Even along the steeper cliff and bluff coasts found from Massachusetts to Maine, increased sea levels will increase wave attacks at the scarp foot, increasing the pace of cliff retreat. Also, increased inundation will tend to increase the risks of failure through mass wasting. In areas where anthropogenic works and interference prevail, erosion and land loss may be counteracted, but as sea levels rise, the costs of these interventions will continue to increase over the next century and beyond.

The approximately threefold increase in the rate of sea-level rise starting in the late 19th century may have already caused profound changes to salt marsh form and function. As a result of this relatively recent increase in the rate of sea-level rise, marshes need to accrete vertically at a faster rate in order to prevent drowning. Continuing land subsidence in the region (Donnelly 1998) and the relatively low quantities of sediment available to salt marshes in the Northeast (Morris et al. 2002) may make these systems highly susceptible to changes in morphology, community structure, and drowning-related increased rates of sea-level rise. The documentation of cordgrass invasion of the New England high marsh (Orson and Howes 1992; Warren and Nehring 1993; Donnelly et al. 1999; Donnelly and Bertness 2001) and marsh drowning in other areas (Day et al. 2000; Hartig et al. 2002) may already indicate that marshes are failing to keep up with the increased rate of inundation. Extensive marsh loss since 1938 at the Blackwater Wildlife Refuge in Maryland has been attributed to local rates of sea-level rise outpacing marsh accretion (Pendleton and Stevenson 1983; Orson et al. 1985). About 2,300 ha of salt marsh were lost there, between 1938 and 1979 primarily through the growth and coalescing of pannes. Similar losses have been documented in Jamaica Bay, NY (Hartig et al. 2002). Several marsh islands within the bay have decreased in size by about 12% since 1959.

If current rates of sea-level rise persist or increase only slightly over the next century in southern New England, marshes will likely continue to be transformed into cordgrass-dominated wetlands. Moreover, if sea-level rise rates accelerate to 6 mm/year or more over the second half of the century, cordgrass communities may drown as well, leading to significant loss of coastal wetlands throughout the Northeast. In the face of these changes and the potential for significant wetland loss, many questions need to be addressed. How will the productivity of coastal wetlands change? Coastal wetlands are intimately linked to the productivity and health of other estuarine ecosystems. More frequent flooding of the cordgrass-dominated high marsh surface may result in greater export of organic matter to the surrounding estuarine environment and may result in more fine-grained inorganic material being sequestered within marsh sediments. How might these potential changes impact the estuarine productivity? What are the potential impacts to migratory bird populations as the diversity of marsh flora decreases? What mitigation strategies should be implemented in order to prevent future marsh loss? How will the loss of salt marshes impact coastal ecosystems?

In addition to the potential loss of housing comes the potential impact on the regional tourism industry through loss of beach and increased frequency of storm damage. These impacts are hard to quantify. Loss of beach in one location may result in establishment of new beach in close proximity and over long time frames the industry may be able to act in an adaptive fashion to the changes imposed by shoreline change. Similarly, the loss of oceanfront property can result in appreciation in property values for neighboring units (Yohe et al. 1999), making the impact on the property market similarly difficult to estimate. In fact, Yohe et al. suggest that because of this transfer of value to neighboring properties, significant costs are only incurred after decisions are made to protect against erosion.

Strategies for protection range from what has been termed the “World Markets” to the “local stewardship” responses. Hall et al. (2006) describe these scenarios in full detail, but here we summarize their conclusions. In the World Markets scenario, the value of property along the coastline is of such significant value to the international economy that any level of protection response is more than offset by the return to the economy by maintaining the property. Large low-lying urban areas such as Boston, or areas with large industrial complexes such as the Gulf coast refineries, would be examples of this kind of infrastructure. Local Stewardship refers to community level or property owner levels of protection where decisions are made on the basis of individual beaches or properties. Because of the smaller available funds at this level, these efforts tend to be more environmentally friendly with retreat from the shoreline and abandonment of land an option. Of course, at this level, regulatory issues become involved. In Massachusetts, for example, there are strict regulations about what can and cannot be done to armor a shoreline. Most of the economic models of the impacts of sea-level rise on coastal housing markets assume that hard protection measures can be constructed (e.g. Titus et al. 1992; Yohe et al. 1996, 1999). Groynes are still permissible, but few have been built recently and they are generally discouraged. Hard structures are not permitted at all (J. O’Connell, personal communication, 2006), although other states have different rules. Despite the warnings of increased risk and the increasing difficulty of obtaining insurance for housing close to the shoreline, our desire to live by the ocean shows no signs of abating.

5.2 Research on coastal change

We need to eventually develop the capability to predict at least a regionally averaged shoreline response to a given change in the rate of sea-level rise. However, historical records are too short for a meaningful projection of coastal response to sea-level change even for the next few decades. Most measures of shoreline change are based on repeat aerial photographs taken typically a decade or more apart. While such approaches are instructive, the measurements are too limited to contain all the complexities of shoreline change. For example, if a large storm event occurs within the time period of the photograph, the impact of the storm may dominate over the local shoreline retreat rates leading to erroneous conclusions as to the long term behavior of the shoreline. A long-term record of coastal changes is preserved in the geological record, and scientists need to turn to detailed geological reconstructions to understand the background against which to examine human-influenced sea-level changes. Such geologically preserved analogs record the response of the coast in situations similar to those predicted in the future. There is ample evidence that there is no simple way to perform these reconstructions without knowing much about the geologic framework and sediment budget of a region (i.e., sources or sinks related to tidal inlets or coastal bluffs).

Although there has been progress in many areas of coastal geology, our fundamental understanding of shoreline change has been limited by a lack of a broad and integrated scientific focus, a lack of resources, and a lack of willingness on the part of policymakers who make crucial decisions about human activity along the coast to support basic research in this area. The National Research Council has highlighted "an inadequate understanding of the physical and biological mechanisms of beach and littoral systems." The report issued by the US Commission on Ocean Policy (2004) notes that "An enormous stumbling block to improved sediment management is a poor understanding of sediment processes in the marine environment." The report further highlights that funding in this area is fragmented, uncoordinated and insufficient.

There are clear, process-based basic science problems that need to be addressed before we can achieve the goals of accurate shoreline change prediction and better assessments of the potential risks to coastal systems. For example, at present our modeling capabilities do not allow us to answer the rudimentary question of how the shoreline will respond to rising sea level. Because factors such as sediment supply, offshore geology, engineering structures, and wave forcing all affect the coast, the shoreline response to rising sea level will be more complicated than simple drowning alone. Further, we need to better understand the links between barrier beach systems and back-barrier marshes and estuaries. We also need to understand the impact on and recovery of the shoreline to major events such as storms (and even potential tsunami). Recent advances in technology make this an ideal time to launch such an effort. Our capability to map, monitor, model, and understand the fundamental processes shaping the shoreline has never been better, but these capabilities need to be applied in a coordinated and integrated program. The ultimate benefits to society are significant – scientifically based management of the coastal zone, including practical knowledge of where and where not to build roads and structures, the impacts of coastal armoring and beach management, and realistic plans for ecosystem management and restoration.

In recommendation 12-4 of the Commission on Ocean Policy report, the Army Corps of Engineers, NOAA, the US EPA and the USGS are encouraged to develop a strategy for improved assessment, monitoring research and technology development to enhance sediment management. It is unfortunate that the recommendation does not go further and suggest that NSF and other agencies support basic science research in this area to increase understanding of the fundamental processes of sediment transport deemed so important, but which are so poorly understood. The specific missions of the different federal agencies can be better addressed by working cooperatively, amongst themselves and in their interactions with academia and the private sector. One means to do this would be the creation of a multi-agency initiative that addresses the mission criteria of the participating agencies, such as has been done for the highly successful ECOHAB and GEOHAB programs studying the impacts of harmful algal blooms (Anderson 1995; GEOHAB 2001, 2003).

6 Summary

If sea-level rise accelerates due to climatic change, coastal retreat will increase and coastal wetlands will be lost. However, the complexities of coastal sedimentary systems constrain scientists' ability to make quantitative predictions of future behaviors, not only because many processes remain poorly understood, but also due to the random variability of the meteorological forces that drive coastal change. Over the long run, wave-dominated shores can expect to respond to sea-level rise by retreating at rates many orders of magnitude greater than the rise in sea level itself. Increased storminess and/or changes in storm patterns will also affect coastal evolution. Although salt marsh environments can adjust their levels in response to sea-level rise, they will not be able to keep up beyond a (poorly known) threshold rate. If this threshold rate is surpassed, intertidal marshes may convert to open-water marshes, a process that could in turn dramatically affect the rest of the coastal system. As coastal dynamics remain poorly understood, quantitative understanding of the effects of climate change on the Northeast will require renewed national commitment to broad and integrated studies of coastal processes.

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