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The potential impacts of sea level rise on the coastal region of New Jersey, USA

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Abstract This study presents an assessment of the potential impacts of sea level rise on the New Jersey, USA coastal region. We produce two projections of sea level rise for the New Jersey coast over the next century and apply them to a digital elevation model to illustrate the extent to which coastal areas are susceptible to permanent inundation and episodic flooding due to storm events. We estimate future coastline displacement and its consequences based on direct inundation only, which provides a lower bound on total coastline displacement. The objective of this study is to illustrate methodologies that may prove useful to policy makers despite the large uncertainties inherent in analysis of local impacts of climate and sea level change. Our findings suggest that approximately 1% to 3% of the land area of New Jersey would be permanently inundated over the next century and coastal storms would temporarily flood low-lying areas up to 20 times more frequently. Thus, absent human adaptation, by 2100 New Jersey would experience substantial land loss and alteration of the coastal zone, causing widespread impacts on coastal development and ecosystems. Given the results, we identify future research needs and suggest that an important next step would be for policy makers to explore potential adaptation strategies.

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1 Introduction

Anthropogenic global warming is expected to continue to contribute to an increase in global-mean sea level during this century and beyond (Church et al. 2001; IPCC 2007). Sea level rise will increase the vulnerability of coastal populations and ecosystems via permanent inundation of low-lying regions, inland extension of episodic flooding, increased beach erosion and saline intrusion of aquifers (Mclean et al. 2001).

This study presents an assessment of the potential impacts of sea level rise on the New Jersey, USA coastal region (see also Psuty 1996; Titus 1990; Wu et al. 2002). Recent geologic data (typical of data from the mid-Atlantic coast of the USA) shows a relatively uniform rate of sea level rise of 2 mm/year over the last 7,000 years (Stanley et al. 2004; see also Psuty 1986) increasing to about 3.5 mm/year during the twentieth century.

A host of descriptive and empirical studies has considered national or regional impacts of sea level rise in the USA (Titus and Barth 1984; Titus et al. 1985, 1991; Titus 1989; Gornitz 1990; Nicholls and Leatherman 1996; Najjar et al. 2000; Field et al. 2000; Rosenzweig and Solecki 2001; Gornitz et al. 2002). Nevertheless, the availability of locally relevant information, required by policy makers, coastal managers and residents of the coastal zone in order to formulate effective and efficient policies, remains limited.

We produce two projections for local sea level rise over the next century. These projections are applied to a digital elevation model to illustrate the extent to which coastal areas are susceptible to permanent inundation and episodic flooding due to storm events. We find that absent human adaptation, by 2100 New Jersey would experience substantial land loss and alteration of the coastal zone due to a combination of enhanced inundation as well as more frequent episodic flooding of low-lying areas during storms. We also characterize the potential impacts of these changes for New Jersey's coastal development and ecosystems. Our objective is to illustrate methodologies that may provide useful information for policy makers despite the large uncertainties inherent in analysis of local impacts of climate and sea level change. This study focuses on what might be termed zero-order vulnerability: we do not consider in any detail either the economic costs of these consequences; nor the potential for and costs of adaptations that may ameliorate the projected vulnerabilities.

2 Study area

New Jersey's coastal area extends 204 km along the USA Mid-Atlantic coast with an additional 134 km of shoreline along the Raritan and Delaware Bays (Fig. 1). New Jersey is the most densely populated US state with over 8.6 million people inhabiting 19,210 km^2. Development along the coast varies from heavily urbanized centers, such as Atlantic City, to sparsely populated communities on the Cape May peninsula. The population of New Jersey's coastal counties grew from 3,345,010 in 1950 to 5,281,247 in 2000 (Ocean County Department of Planning 2002; N.J. Department of Labor and Workforce Development 2004) accounting for approximately 60% of the current state total.

The New Jersey coastal region supports an estimated \$16 billion tourism industry with the Atlantic City area alone drawing more than 37 million visitors annually (NJ Coastal Management Program 2002a; Atlantic City Regional Chamber of Commerce 2004). The multi-state region including New Jersey sustains a \$50 billion maritime industry centered at the Port of New York and New Jersey, and a \$100 million commercial fishing industry (NJ Coastal Management Program 2002a, b).

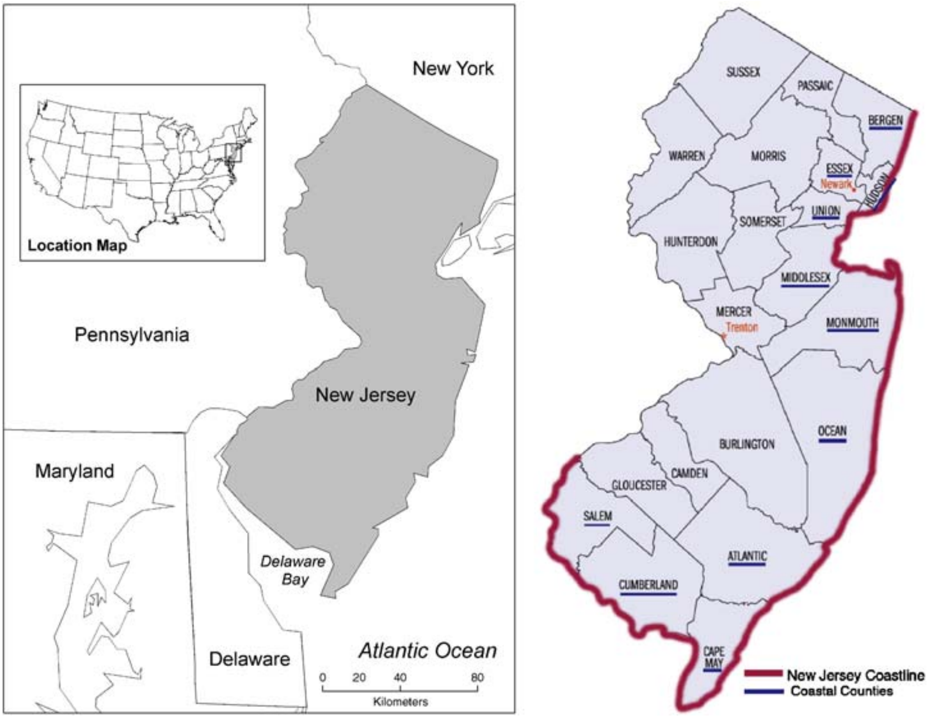

Fig. 1 State of New Jersey and coastline (adapted from: US Census Bureau 2004)

The coast encompasses a diverse range of features including barrier islands, low cliffs, sandy beaches, dunes, mud flats, estuaries, wetlands, and forests (Psuty and Ofiara 2002) harboring a wide range of ecosystems and habitat for flora and fauna, including at least 24 endangered and threatened species (NJ DEP 2003; US FWS 2004). The beaches and coastal wetlands serves as a globally significant stopover point for an estimated 1.5 million migratory shorebirds and are home to the world's largest population of horseshoe crabs (NJ Coastal Management Program 2002a).

3 Coastal processes

The extant New Jersey coast is the product of a dynamic system that has evolved over thousands of years (Psuty and Ofiara 2002) and whose evolution is ongoing. The coastline, including barrier islands, coastal dunes, wetlands and estuarine habitats, has been shaped by a combination of wind, waves, tides, currents and human interventions. The configuration of New Jersey's contemporary coastal features developed as global sea level rose more or less continuously from the end of the Pleistocene and throughout the Holocene. A variety of factors contributed locally (see section 4), including accumulation, erosion, and rearrangement of sediments.

At specific coastal localities and at varying intervals, pulses of sediment accumulation are interspersed with periods of erosion depending on sediment supply, storm intensity and frequency, and rates of long term sea level rise. The largest source of accumulation to the mainland shore is sediment transported down rivers to the shore–ocean interface. A second major source derives from coastal features such as barrier islands, bluffs or cliffs that are eroded over time due to wave action. The remainder originates offshore as material from the near-shore continental shelf is moved onshore. Coastal storms are central to the latter process as powerful waves disturb offshore sediments and distribute them to beach areas.

Where sediments are lacking and sea level rise is ongoing, the result is the gradual inundation of coastal areas. For beaches characterized by barrier islands and gently sloping terrain, the horizontal extent of inundation is about 100 times the vertical sea level rise (see discussion below, Bruun 1962; Psuty and Ofiara 2002). Near bluffs or river deltas, the extent of inundation is much smaller due to the availability of sediment. Such natural processes are modified or interrupted altogether by structural impediments such as sea walls or the artificial sediment accumulation associated with beach nourishment or dune construction.

In the short term (~days to years), the effects of storms and human-made barriers that channel and transport sediments are much more important than sea level rise in determining the local coastal configuration. But in the long term (~decades to centuries), rapid sea level rise outpaces sediment delivery and gradually displaces the shoreline, submerging coastal land.

Sea level rise leads directly to inundation (submergence) and enhances ongoing erosion (net loss of sediment), and both combine to hasten shoreline displacement (Zhang et al. 2004). Inundation is a condition that results as rising sea levels drown low-lying lands. Unlike direct inundation, erosion is a distinct process, which redistributes sediment from onshore to offshore areas. Sea level rise does not directly erode coastal zones. Rather, rising sea levels allow waves to act higher up on the shoreline and permits larger waves to reach the coast (Zhang et al. 2004).

A range of studies has assessed the susceptibility of the New Jersey coast to shoreline displacement and erosion (United States Army Corps of Engineers 1971; Nordstrom et al. 1977; NJ DEP 1981; Kyper and Sorenson 1985; Phillips 1986; Gornitz 1990; Psuty and Ofiara 2002; Zhang et al. 2004) and additional ones are ongoing (Farrell et al. 2003). Despite disparate approaches, there is a broad consensus that much of the New Jersey shoreline is experiencing net erosion. Acceleration of this trend should be anticipated as rates of sea level rise increase.

Past erosion along the New Jersey coast has been attributed to several factors including changes in the availability of sediment, sea level rise, changes in storm frequency and severity, and coastal development. Although the coastal area is densely populated, development does not appear extensive enough to produce the amount of erosion taking place recently (Zhang et al. 2004). It is also unlikely that marginal changes in storm frequency and severity account for century-scale erosion rates (although a trend in major storms along the New Jersey coast since 1980 has been suggested by Psuty and Ofiara 2002). For example, global storm frequency data demonstrates large inter-annual and inter-decadal variability with no significant secular increase during the twentieth century (Zhang et al. 1997, 2002; Landsea et al. 1999). Moreover, evidence from sites worldwide suggests that shorelines generally recover positions determined by long term trends regardless of storm severity (Zhang et al. 2002). New Jersey's lack of significant river deltas, gentle coastal plain and deficient offshore sources limits the effective "build up" of sediment in shoreline areas, making it susceptible to the effects of sea level rise, which appears to be an important cause of long term erosion (see Leatherman 1991; Leatherman et al. 2000; Zhang et al. 2004). These factors also make the coastline susceptible to inundation resulting directly from sea level rise.

Zhang et al. (2004) found that shorelines along the east coast of the USA have retreated approximately 23.8 m on average for each 0.3 m of sea level rise over the last century. New

Jersey shoreline change was estimated by Zhang et al. (2004) at about 36.6 m per 0.3 m of sea level rise. This rate is the highest estimated from New York to South Carolina. The study only considered beach segments not influenced by inlets, spits, and protective structures and included only about 18% of the state's coastline. The values presented by Zhang et al. appear in agreement with the Bruun rule that predicts coastlines will retreat at a rate roughly 50 to 100 times greater than the rate of sea level rise (Bruun 1962). However, the Bruun model is limited to considering only the movement of sediments perpendicular to the shoreline (cross-shore) and not parallel to the shore (long-shore). Moreover, recent research suggests that under the current (and future) rate of sea level rise the cross-shore effects expressed in the Bruun rule may be subordinate to a variety of other processes including sediment supply and exchange (Zhang et al. 2004; Cooper and Pilkey 2004; Stive 2004). Therefore, it is difficult to build a general relationship between sea level rise and coastal displacement without information specific to many particular locations.

In the following section, we take a different approach, estimating future coastline displacement and it consequences based on direct inundation only, calculated from local shoreline elevations and projected sea level rise. Given the ongoing net erosion of the coast, this approach may provide a lower bound on total coastline displacement (see Bruun 1988).

4 Sea level rise projections

Sea level change reflects a complex and dynamic interaction between local, regional and global contributions from both land and ocean processes. Relative sea level rise, the rate of sea level change at a specific location relative to a local land benchmark, is composed of the eustatic and steric contributions to global-mean change adjusted to account for regional and local processes, including vertical local land displacement, local sediment transport, isostatic adjustment, and sea level responses to local and regional meteorological and oceanographic variations (Emery and Aubery 1991; Gregory et al. 2001; Church et al. 2001). The latter two terms cause large geographic variations in absolute sea level yielding regional sea level rise trends as much as 10 times the global-mean (Cazenave and Nerem 2004; Lombard et al. 2005) over decadal timescales. Models have not shown much skill at reproducing these regional historical changes.

Analysis of tide-gauge data indicates a rate of global-mean sea level rise during the twentieth century from 1.0 to 2.0 mm/year or a total of 10–20 cm (Gornitz and Lebedeff 1987; Douglas 1991, 1997; Peltier and Jiang 1997; Church et al. 2001) recently updated to 17 cm (±5 cm) by the IPCC (2007). The rate of sea level rise for the Mid-Atlantic coast of the USA appears significantly higher than the global-mean, averaging 3–4 mm/year (Titus and Narayanan 1995) based on tide gauges.

Sea level rise for New Jersey has been calculated from tide-gauge data collected by the National Oceanic and Atmospheric Administration at five locations off the greater New Jersey coast: Sandy Hook (3.88 mm/year), Atlantic City (3.98 mm/year), Cape May (3.98 mm/year), Battery Park (2.77 mm/year), and Lewes (3.16 mm/year) (NOAA 2004). Averaging the mean values from each tide-gauge provides an approximate twentieth century relative sea level rise trend of 3.53 mm/year. The New Jersey sea level rise trend mirrors estimates for the Mid-Atlantic coast and is almost double the global-mean (Stanley et al. 2004). This implies a local sea level rise component of approximately 2 mm/year.

We estimate future rates of rise in relative sea level for New Jersey by adding a local component of 2 mm/year to estimates of the future global-mean change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has developed scenarios indicating that global-mean sea level may rise between 0.18 and 0.59 m by 2090–2099 compared to 1980–1999 (IPCC 2007). The range reflects uncertainty in three components that contribute to these scenarios: future emissions of greenhouse gases, future climate change, and ocean and ice sensitivity to climate. If the local adjustment above is taken into account, relative sea level rise for the New Jersey coast of between 0.38 and 0.79 m over the twenty-first century would result.

Such an approach for determining rise in relative sea level has limitations. With regard to global sea level change, uncertainties in emissions scenarios and climate and ocean models, suggest that larger (or smaller) global-mean change cannot be ruled out. Furthermore, the IPCC specifically notes that its global range excludes “future rapid dynamical changes in ice flow” (IPCC 2007: 13). A new empirical analysis published after conclusion of the Fourth Assessment proposes an extended range of 0.5 to 1.4 m for 2100 compared to 1990 (Rahmstorf 2007).

The potential magnitude of anomalies due to local meteorological and oceanic variations at any location on a century timescale cannot be satisfactorily estimated so we disregard them. Adding a spatially and temporally constant local term based on historical evidence to obtain relative sea level rise from the global-mean change is obviously a simplification (Psuty and Ofiara 2002). Nevertheless, virtually all current models and scenarios project that global-mean sea level will continue to rise, and that the overall rate of this rise likely will be greater over the next century than in the last (Church et al. 2001; IPCC 2007). Consequently, the local estimates we use must be regarded as plausible outcomes, within a larger range of possible futures.

5 Modeling the effects of sea level rise on the New Jersey coast

We applied the above sea level rise projections to a digital elevation model to illustrate the extent to which coastal areas are vulnerable to direct, permanent inundation and episodic flooding due to storm surges. We originally developed two benchmark values for relative sea level rise based on the middle and high values of the range proposed in IPCC’s Third Assessment, 0.09 to 0.88 m (Church et al. 2001). Since the digital elevation model provides elevation in integral feet (USGS 2000; NJ DEP BGIS 2004), we used the 2 ft (0.61 m) and 4 ft (1.22 m) contours relative to the North American Vertical Datum of 1988 as benchmarks for our analysis. Given the uncertainties, extrapolation and interpolation seemed unwarranted. The lower benchmark value corresponds approximately to the middle of the new IPCC (2007) global range while the higher value corresponds to considerably greater sea level rise than the upper end of the new IPCC range. However, the high benchmark value still corresponds to a lower global mean change than the high value proposed by Rahmstorf (2007).

Several studies have used digital elevation data to model the vulnerability of coastal regions to inundation and flooding as a result of sea level rise (Titus and Richman 2000; Gornitz et al. 2002; Weiss and Overpeck 2003). These studies relied principally on digital elevation models of relatively coarse horizontal and vertical resolution such as the US Geologic Survey (USGS) 1-degree digital elevation series (Titus and Richman 2000), the 1999 Digital Elevation Dataset and the Global 30 Arc-second Elevation Dataset (Weiss and Overpeck 2003), and have limited accuracy (Titus and Richman 2000).

The results here were computed using digital elevation grids for New Jersey’s nine coastal watersheds acquired from the New Jersey Department of Environmental Protection (NJ DEP BGIS 2004). The grids were created from 7.5 min digital elevation models with

10 m horizontal resolution (for information on this dataset see USGS 2000). The USGS 7.5 min digital elevation models were created from digital line graph hypsographic and hydrographic data projected on the Universal Transverse Mercator projection. Shoreline boundaries are an inherent feature of this dataset. The grids are referenced horizontally to the North American Datum of 1983 and vertically to the North American Vertical Datum of 1988. These datums represent the current geodetic control datums published by the National Geodetic Society (for further information on geodetic datums see National Geodetic Survey 2004). The digital elevation grids used in this study have undefined horizontal and vertical accuracy.

Combining sea level rise projections and digital elevation models must be interpreted with caution. Models characterize a fixed representation based on land elevation and are not able to represent the effects on future shorelines arising from sediment accumulation, land subsidence, erosion, or other dynamic processes, except insofar as they are captured in the average by the local adjustment we apply. Nor are the models able to incorporate future development or adaptations such as seawalls or beach nourishment projects. Furthermore, due to the "concave up" profile of the coastal zone, inadequate benchmarks, and insufficient vertical resolution, elevation grids may also overestimate land elevations and therefore underestimate the susceptibility of coastal areas (Titus and Richman 2000).

5.1 Land loss by direct inundation

The vulnerability of New Jersey coastal areas to permanent inundation can be illustrated by applying future sea level rise projections to a digital elevation model. We assume that all coastal areas below the selected elevations (see Fig. 2) will be permanently inundated if relative sea level rises by 0.61 or 1.22 m. We estimate that between 170 and 442 km^2 or 1% to 3% of the land area of New Jersey would be inundated over the next century, for the two projections, respectively.

The model gives a gross estimate of coastal land loss that is understood to be superimposed on the natural variation of shoreline processes. The interaction of accelerated sea level rise with other coastal processes and human responses will ultimately determine the future shoreline.

5.2 Episodic flooding

Northeasters and offshore hurricanes are key storm events that shape and erode the New Jersey coast (Zhang et al. 2001). Storm events off the coast of New Jersey have increased in frequency and intensity since 1980, a period that included 12 major northeasters (Psuty and Ofiara 2002). These storms can produce significant wave heights and storm surges (see below) due to their long wind fetch and several-day duration. The high water levels and waves associated with northeasters and offshore hurricanes, along with intense precipitation and high winds, interact to inflict considerable erosion, flooding, and other damage. For instance, the "Ash Wednesday" northeaster that struck New Jersey in March of 1962 had storm surges that overtopped barrier islands and penetrated coastal wetlands (Donnelly et al. 2001). However, offshore hurricanes also have a beneficial aspect. As hurricanes pass by, swells are produced that transport and mobilize sediment from offshore to onshore areas. For example, the large swell preceding Hurricane Fabian in 2003 broadened New Jersey's beach areas to the widest of that year (NJ Marine Sciences Consortium et al. 2004).

A storm surge is an increase in water level above normal sea level and is a function of storm intensity and duration. Storm surges combine with astronomical tides to create a

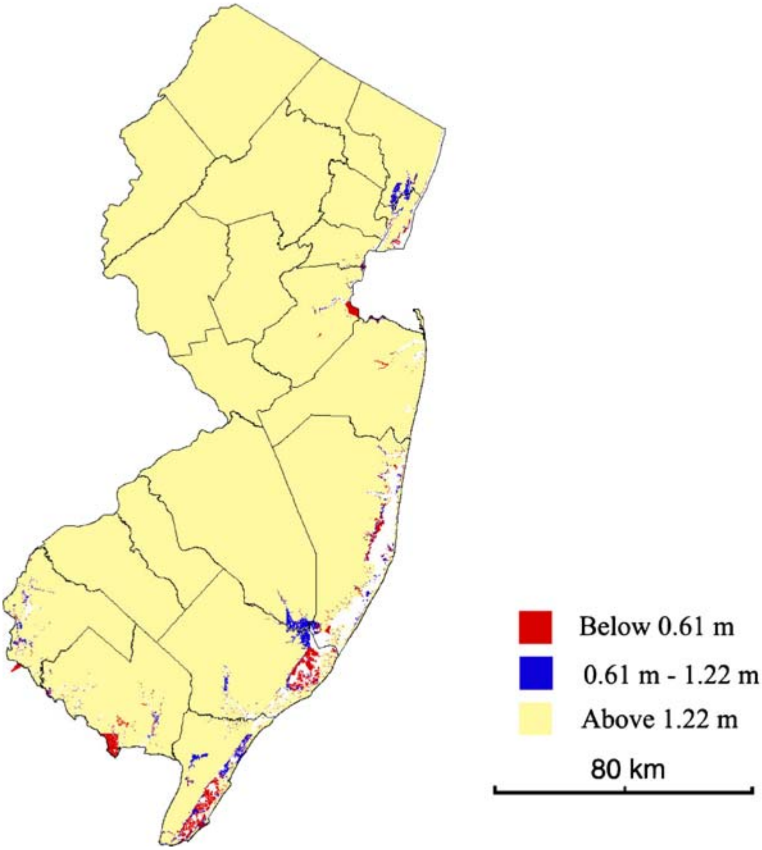

Fig. 2 Estimated coastal land area susceptible to direct inundation applying sea level rise projections of 0.61 and 1.22 m

storm tide. The storm tide elevation largely determines the magnitude of the erosional effect of the waves, the penetration of dunes and potential overwash, and the flooding of barrier islands and coastal regions (Steetzel 1991; Zhang et al. 2001; Psuty and Ofiara 2002). The elevation of the storm tide above an established datum is often referred to as the flood-water level. The flood-water level is perhaps the best single descriptor of the impact a storm will have on the coastal environment (Psuty and Ofiara 2002).

Flood-water levels have been measured that allow for the construction of frequency curves to determine the probability of coastal flooding. The US Federal Emergency Management Agency (FEMA) has evaluated historic storm flood levels at Atlantic City, New Jersey and calculated the expected probability that certain water elevations will be reached each year. FEMA estimates a 1% probability that the water level will equal or exceed 2.90 m annually (FEMA 1991). Accordingly, a water level of 2.90 m is referred to as the 100-year flood-water level. The FEMA tidal surge frequency for 5, 10, 20, 30, 50 and 100-year flood-water levels for Atlantic City, New Jersey are listed in Table 1.

Sea level rise increases flood levels by providing an elevated base for a storm surge to build upon. Figure 3 illustrates this effect at Atlantic City, New Jersey adapting the work of Najjar et al. (2000) and Psuty and Ofiara (2002). Flood levels for four historic storm events

Table 1 Federal Emergency Management Agency (FEMA) tidal surge frequency and flood-water levels for Atlantic City, New Jersey (adapted from: Psuty and Ofiara 2002)

FEMA tidal surge frequency	Flood-water level (m)
5-year tidal surge	1.76
10-year tidal surge	1.92
20-year tidal surge	2.16
30-year tidal surge	2.34
50-year tidal surge	2.58
100-year tidal surge	2.90

are adjusted to the year 2000 assuming the observed twentieth century sea level rise rate in New Jersey of 3.53 mm/year. These events include the Great Atlantic "hurricane" of September 1944 and northeasters in January 1987, December 1992, and January 1996 (Psuty and Ofiara 2002).

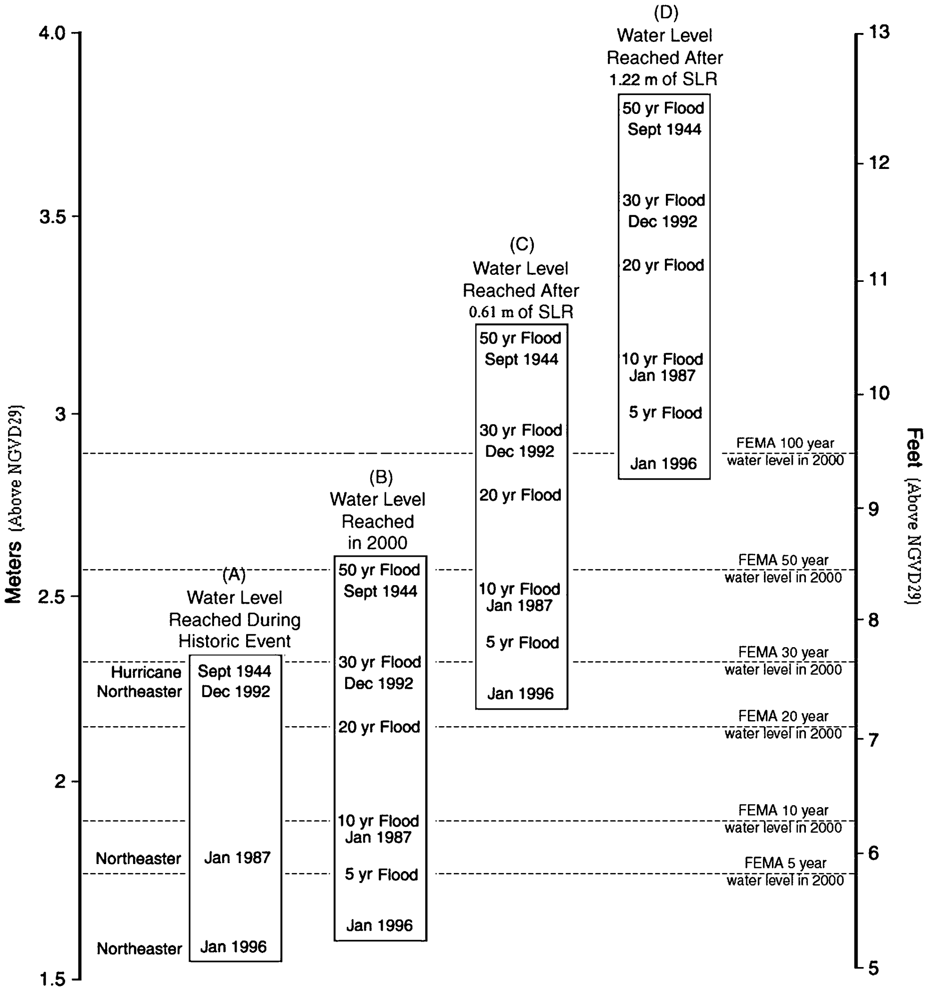

Fig. 3 Potential impact of sea level rise on flood-water levels associated with four historic storm events in Atlantic City, New Jersey

Using this approach, we estimated the shift in current 5, 10, 20, 30, and 50-year flood-water levels assuming projected sea level rise of 0.61 and 1.22 m, keeping all other factors, including storm intensity, constant. For illustration, the northeaster in January 1987 created a flood-water level of 1.80 m. This same event would have produced a flood-water level of 1.85 m in the year 2000. Using a projected sea level rise of 0.61 m, the flood level of the January 1987 storm would have exceeded 2.50 m and after a 1.22 m rise in sea level the flood-water level would have been approximately 3.07 m. Of course, year-to-year sea level rise is highly variable so these estimates based on only a few years of sea level rise are only illustrative.

Sea level rise will also allow current flood-water levels to be exceeded and low-lying lands to be flooded with increased frequency. The current 100-year flood water level will be exceeded three to four times more frequently after a 0.61 m rise in sea level and approximately 20 times more frequently after a 1.22 m rise. In other words, New Jersey's current 100-year flood-water level could become the 30-year flood level after a 0.61 m rise and the 5-year flood level after a 1.22 m rise.

The results are illustrated in Fig. 4. The 2.90 m projection represents the current 100-year flood-water level. By contrast, the 3.50 m projection represents the estimated 100-year level after adding sea level rise of 0.61 m. Assuming coastal storms temporarily inundate all land below the selected elevations, the results suggest that the current 100-year flood water level affects nearly 1,251 km^2, representing approximately 6.5% of the state's land area. With a 0.61 m rise in sea level approximately 1,787 km^2 would be impacted by episodic flooding, representing over 9% of the state's total land area.

The models illustrate the potential effect of future sea level rise on episodic flooding associated with coastal storms, and point to areas that may be most vulnerable. We assumed that coastal storms would be unchanged with regard to strength and duration, and we ignored the effect of processes other than sea level rise, including possible human adaptations.

6 Vulnerability assessment

6.1 Vulnerability of coastal development

Accelerated rates of sea level rise are predicted to have pronounced impacts on New Jersey's socio-economic systems due to the combination of inundation and episodic flooding. While future sea level rise trends must be viewed as superimposed on dynamic and varying shoreline processes, features and adaptations, the models suggest that the ocean will generally penetrate further inland and act to alter shorelines and low-lying areas.

Predicted future rates of sea level rise would be of much lesser concern if not for the high population density of the New Jersey coast. A majority of the coastline is crowded with residential, industrial and tourism-related development. The rate of New Jersey's coastal development has increased in tandem with the influx of residents moving to the shore and increasing popularity of the coast as a tourist destination. In fact, the population of New Jersey's coastal counties is expected to climb to over 6 million by 2020 and property values are expected to increase as well (NJ Department of Labor 2002; NJ Department of Labor and Workforce Development 2004). Property and land values in four coastal counties alone were estimated to total well over \$100 billion in 2002 (NJ Division of Taxation 2004).

Since the New Jersey coast is gently sloping, the population, development and infrastructure are very susceptible to coastal hazards. Many low-lying areas are identified

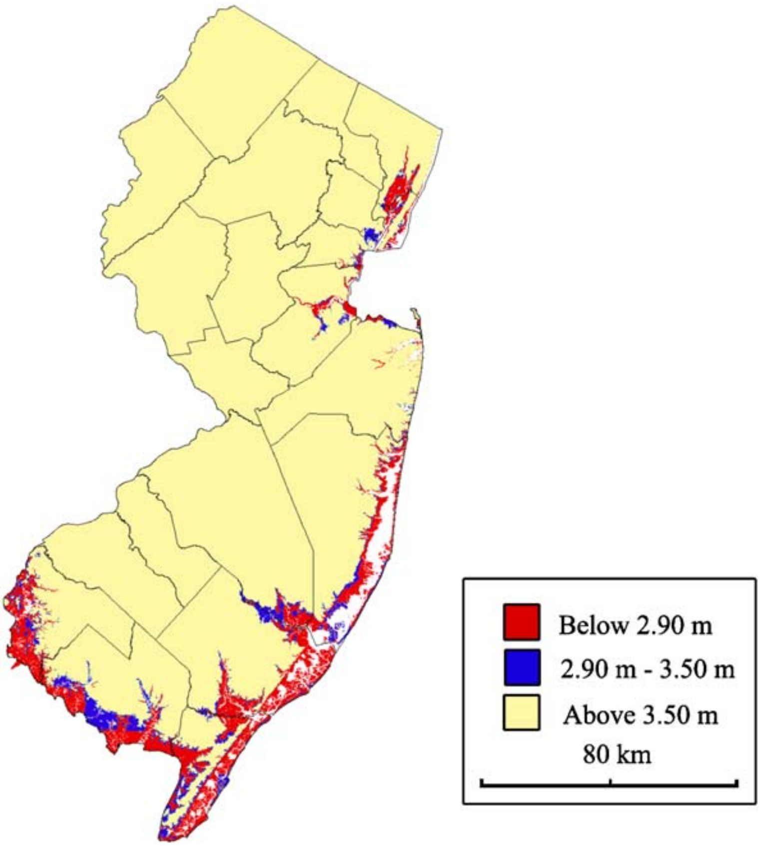

Fig. 4 Estimated coastal land area susceptible to episodic flooding applying current 100-year flood water level (2.90 m) and projected 0.61 m rise in sea level (3.50 m)

as “high risk”, and suffer damage from erosion and flooding in nearly every storm event (Psuty and Ofiara 2002). Given the fact that the average height of New Jersey’s highly developed barrier islands is only 2 m above sea level (Psuty and Ofiara 2002), as sea level rises, the coastline will be progressively more susceptible to inundation, erosion, and storm-induced flooding.

Using the previous method, we estimate that the extent of developed coastal area, defined as residential/urban, industrial and agricultural land uses, susceptible to inundation (NJ DEP BGIS 2004) would range from 19.5 to 50.3 km^2, for the two benchmark projections, respectively (Table 2). We can also estimate the extent of developed coastal area vulnerable to episodic flooding. Table 2 indicates that 269 km^2 of developed coastal areas lie within the current 100-year flood-water level of 2.90 m, a majority of which is occupied by residential and urban development. Our calculations suggest that approximately 414 km^2 of developed coastline would be susceptible to episodic flooding as a result of a 0.61 m sea level rise. This would add nearly 145 km^2 of previously unaffected developed coastline to the 100-year flood water level over the next century. The ultimate impact to coastal development and the population due to inundation and episodic flooding depends on the details of local coastal processes and future adaptations.

Table 2 New Jersey land use classifications below 0.61, 1.22 and 2.90 m sea level

Land use classification	Land area below 0.61 m contour (km^2)	Land area below 1.22 m contour (km^2)	Land area below 2.90 m contour (km^2)
Wetlands	141.9	367.6	906.5
Forest	3.9	10.1	57.0
Beach	5.4	14.1	18.1
Residential/urban	17.4	44.9	196.8
Industrial	1.8	4.7	28.5
Agriculture	0.3	0.7	44.0
Total	170.7	442.1	1,251.0

A comprehensive analysis of the socio-economic affects of future sea level rise on coastal New Jersey is beyond the scope of this study. However, based on the social and economic impacts of past storm events as well as the continuous fiscal resources allocated to “protect” the population and development, it is apparent that amplified inundation and episodic flooding may bring substantial additional costs. Indeed, a range of other consequences become apparent from our projections and models. For instance, the increasing cost of insuring property, the intrusion of salt water into groundwater supplies, the inundation of roads and municipal infrastructure, the limited capacity of storm discharge systems and the presence of hazardous waste along the coast are just a few of the critical issues that need to be considered in the face of rising seas.

6.2 Vulnerability of coastal ecosystems

Future sea level rise is predicted to have a marked impact on New Jersey’s coastal ecosystems due to the combination of inundation and episodic flooding. While future sea level rise represents only one aspect of dynamic shoreline processes, increasing water levels have the potential to penetrate inland, modify shorelines and tidal flats, transform the extent and distribution of coastal wetlands, and alter estuarine habitats. These ecosystem impacts can change the size and composition of plant communities and modify particular fish and wildlife populations.

Coastal wetlands are the ecosystems most vulnerable to the effects of sea level rise and changes in them are likely to produce other, significant ecological impacts (Titus 1988; Hoozemans et al. 1993; Nicholls et al. 1999; McLean et al. 2001; Nicholls 2003). New Jersey’s coastal wetlands, including saline, brackish and freshwater wetlands (and to a lesser extent wetland forests) are productive and hemispherically important. Specifically, the wetlands of Cape May and Delaware Bay in southern New Jersey serve as a globally significant resting and feeding stopover for millions of shorebirds along the Atlantic bird migration flyway. These same areas provide essential spawning ground for the world’s largest population of horseshoe crabs.

Coastal wetlands are constantly being modified and rearranged by complex processes interacting at the land–ocean interface. The configuration of New Jersey’s coastal wetlands developed over time in conjunction with the long term sea level rise, the accumulation of plant matter and the accretion and erosion of sediment. These wetlands formed between 4,000–7,000 years ago as post-ice age sea level rise began to slow (Thomas and Varekamp 1991). Historically, they extended almost the entire length of the coast and into Raritan and Delaware Bays (Thomas and Varekamp 1991).

Coastal wetlands adapt and keep pace with sea level rise through vertical accretion, which occurs by sediment deposition and subsurface accumulation of organic plant matter. The process of vertical accretion is dynamic and characterized by significant spatial and temporal variability. Over shorter time intervals, from months to years, coastal wetlands migrate back and forth along the shoreline and adapt to changing water levels, and sediment and biomass budgets. Over longer intervals, decades to centuries, the combination of sea level rise and vertical accretion generally forces coastal wetlands to migrate inland causing upslope brackish wetlands to convert to saline marshes and the saline marshes on the coastline to drown or erode. Coastal wetlands risk inundation if sea level rises faster than the rate by which they can vertically accrete or migrate inland.

It is difficult to forecast precisely how wetlands would respond to future sea level rise given the unpredictability of local coastal changes. Studies indicate that coastal wetland accretion rates on the US Mid-Atlantic coast in the vicinity of New Jersey ranges from no net accretion to approximately 8 mm/year but exhibit significant temporal and spatial variation (Gornitz 1995; Hartig et al. 2001). Values in this range imply that wetlands in certain areas are presently outpacing current sea level rise while in other areas wetland loss is occurring. Mean accretion rates for New Jersey are estimated to be approximately 2 mm/year (Erwin 2003) based on limited data. Assuming no change in accretion rates over the next century, this suggests that a majority of coastal wetlands in New Jersey will be unable to accrete at a pace greater or equal to future sea level rise and are extremely susceptible to permanent inundation.

It is important to note a US Geologic Survey study (1997), which found that at several sites in the USA the rate of wetland elevation increase was less than the rate of vertical accretion. Unknown processes appear to create shallow subsidence that can offset the elevation gain (USGS 1997). These findings suggest that relying on accretion data alone, where it exists, is not sufficient for estimating the vulnerability of wetlands.

Even for coastal wetlands with vertical accretion rates sufficient to keep pace with future sea level rise, inland migration may be obstructed by bluffs, development, or shoreline protection structures. Increasing rates of sea level rise combined with limited sediment and biomass can be expected to “squeeze” wetlands against natural or human barriers. In fact, a significant number of New Jersey’s coastal wetlands are adjacent to development or structures that block wetland migration paths. This greatly increases the probability of coastal wetland loss from inundation.

To assess the impacts of future sea level rise on these coastal ecosystems, we estimated the extent to which coastal wetlands are susceptible to permanent inundation, ignoring accretion. Land use data for New Jersey’s coastal watersheds was acquired from the NJ Department of Environmental Protection using 1986 baseline data and updated with 1995 and 1997 color infrared imagery (NJ DEP BGIS 2004). Our calculations suggest that sea level rise of 0.61 m would permanently inundate nearly 17% of the state’s saline and freshwater tidal marshes while a 1.22 m rise would inundate over 32% (Table 3). Similarly, we calculated the extent of coastal wetlands susceptible to episodic flooding, finding that 906 km^2 of wetlands lie within the current 100-year flood level of 2.90 m (Table 2). This area includes virtually all 772 km^2 of New Jersey’s saline and tidal marshes and 95% of freshwater tidal marshes.

As noted above, we estimate coastal wetlands will be periodically flooded up to 20 times more frequently over the next century. This increase in episodic flooding is potentially sufficient to alter plant composition or shrink plant communities as more salt tolerant species come to dominate and salt intolerant species move further inland. These changes

Table 3 Wetland classifications below 0.61 and 1.22 m sea level in New Jersey

Wetland Classification	Land Area below 0.61 m Contour (km^2)	Land Area Below 1.22 m Contour (km^2)	Estimated Total Land Area in New Jersey (km^2)
Saline marsh	134.7	251.2	771.8
Freshwater tidal			
Marsh	2.6	10.4	38.8
Interior wetland	5.2	18.1	1,763.8[a]
Total	142.4	279.7	2,574.4

[a] Represents only interior wetlands located in New Jersey coastal watersheds

may modify fish and wildlife populations and have far reaching ecological consequences (Mclean et al. 2001; see also Walther et al. 2002).

A complete analysis of the impacts of future sea level rise on the diversity of New Jersey's coastal ecosystems is beyond the limits of this study. However, juxtaposing the projected extent of inundation and episodic flooding from our models with the locations of vitally important coastal ecosystems suggests the ecological costs may be dramatic. For example, the sandy beaches and wetland areas of southern New Jersey are highly susceptible to sea level rise and play a fundamental role in the lifecycle of the horseshoe crab (*Limulus polyphemus*) and millions of migratory shorebirds (Shuster 1982; Shuster and Botton 1985). Any systemic alternation of these coastal areas would likely result in the significant decline of horseshoe crab densities and bird populations (Galbraith et al. 2002). Furthermore, New Jersey's coastal areas sustain a number of endangered and threatened species that are considered highly vulnerable to even small alterations in habitat and would likely be unable to adapt to the consequences of future sea level rise.

7 Potential for adaptation

The objective of this study has been to illustrate methodologies that may provide useful and important information for policy makers despite the large uncertainties inherent in analysis of local impacts of climate and sea level change. Based on our projections and models, and absent human adaptation, future sea level rise is expected to have substantial consequences for New Jersey due to permanent inundation and episodic flooding. Since our approach only estimates future coastline displacement and its consequences based on direct inundation, it may provide a lower bound on total coastline displacement.

Even if stabilization of global-mean temperature is achieved quickly, it is expected that sea level will continue to rise for centuries (Wigley 1995, 2005). Faced with the impacts of rising sea levels discussed here, the next critical step is to determine the potential for adaptation. Policy makers, coastal managers and researchers should consider appropriate adaptation options based on local and regional vulnerabilities and work to effectively implement and sequence policy, planning and management choices (see Titus 1991, 1998; Titus et al. 1991; Biljsma et al. 1996; Bray et al. 1997; Klein et al. 2000; Mclean et al. 2001; Nicholls and Lowe 2004; Moser 2005).

We have noted the limitations of current models of future sea level rise. Development of new models that employ higher resolution elevation data and permit more accurate mapping of the coastal zone should be a priority. Furthermore, studies that illustrate how coastal processes and increased rates of sea level rise interact may prove vital to realizing effective and efficient adaptation options. In addition, more detailed analyses of the potential economic and social costs of sea level rise are warranted to identify localities that are particularly vulnerable. Research is also necessary to identify how individual flora and fauna will respond to the changing coastal environment.

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References

Atlantic City Regional Chamber of Commerce (2004) What to see and do in Atlantic City? http://www.atlanticcitychamber.com/. Accessed November 2004

Biljsma L, Ehler CN, Klein RJT et al (1996) Coastal zones and small islands. In: Watson RT, Zinyowera MC, Moss RH (eds) Climate change 1995. Impacts, adaptations and mitigation of climate change, second assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 289–324

Bray M, Hooke J, Carter D (1997) Planning for sea level rise on the south coast of England: advising the decision makers. Trans Inst Br Geogr 22:13–30

Bruun P (1962) Sea level rise as a cause of shore erosion. J Waterw Harb Div 88:117–130

Bruun P (1988) The Bruun rule of erosion by sea level rise: a discussion on large-scale two and three dimensional usages. J Coast Res 4:627–648

Cazenave A, Nerem RS (2004) Present day sea level change: observations and causes. Rev Geophys 42:1–20

Church JA, Gregory JM, Huybrechts P et al (2001) Changes in sea level. In: Houghton JT, Ding Y, Griggs DJ et al (eds) Climate change 2001, the scientific basis. Cambridge University Press, Cambridge, pp 639–693

Cooper JAG, Pilkey OH (2004) Sea level rise and shoreline retreat: time to abandon the Bruun rule. Glob Planet Change 43:157–171

Donnelly JP, Roll S, Wengren M et al (2001) Sedimentary evidence of intense hurricane strikes from New Jersey. Geology 29:615–618

Douglas BC (1991) Global sea level rise. J Geophys Res 96:6981–6992

Douglas BC (1997) Global sea level acceleration. J Geophys Res 97:12699–12706

Emery KO, Aubery DG (1991) Sea level, land levels and tide gauges. Springer, New York

Erwin RM (2003) Atlantic sea level rise, lagoonal marsh loss and wildlife habitat implications. USGS patuxent wildlife research center and Department of Environmental Sciences, University of Virginia. http://www.pwrc.usgs.gov/resshow/erwin1rs/erwin1rs.htm. Accessed January 2005

Farrell SC, Hafner S, Constantino C et al (2003) New Jersey beach profile network: report covering 15 years of study on shoreline changes in New Jersey. Richard Stockton College of New Jersey, Trenton

Federal Emergency Management Agency (FEMA) (1991) Projected impact of sea level rise on the National Flood Insurance Program. FEMA, Washington DC, USA

Field JC, Boesch DF, Scavia D et al (2000) Potential consequences of climate variability and change on coastal areas and marine resources. In: Climate change impacts on the United States: The potential consequences of climate variability and change, Report for the U.S. Global Change Research Program. Cambridge University Press, Cambridge, pp 461–483

Galbraith H, Jones R, Park R et al (2002) Global climate change and sea level rise, potential losses of inter-tidal habitat for shorebirds. Waterbirds 25:173–183

Gornitz VM (1990) Vulnerability of the east coast, USA to future sea level rise. J Coast Res 9:201–237

Gornitz VM (1995) Monitoring sea level rise. Clim Change 31:515–544

Gornitz VM, Lebedeff S (1987) Global sea level changes during the past century. In: Nummendal D, Pilkey OH, Howard JD (eds) Sea level fluctuation and coastal evolution. Society for economic paleontologists and Mineralogists 41:3–16

Gornitz VM, Couch S, Hartig EK (2002) Impacts of sea level rise in the New York City metropolitan area. Glob Planet Change 3:61–88

Gregory JM, Church JA, Boer GJ (2001) Comparison of results from several AOGCMs for global and regional sea level change 1900–2100. Clim Dyn 18:225–240

Hartig EK, Kolker A, Fallon D et al (2001) Wetlands. In: Rosenzweig C, Solecki WD (eds) Climate change and the global city: the potential consequences of climate variability and change, metro east coast. Columbia University Earth Institute, New York, pp 67–86

Hoozemans FMJ, Marchand M, Pennekamp HA (1993) A global vulnerability assessment for population, coastal wetlands and rice production on a global scale. Delft Hydraulics, Netherlands

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: The physical science basis, Summary for Policymakers. IPCC, Geneva, 1–18

Klein RJT, Buckley RJ, Nicholls S et al (2000) Coastal adaptation. In: Metz B, Davidson OR, Martens JW et al (eds) Methodologies and technological issues in technology transfer, a special report of IPCC working group III. Cambridge University Press, Cambridge, pp 349–372

Kyper T, Sorenson R (1985) Potential impacts of selected sea level rise scenarios on the beach and coastal works of sea bright, New Jersey. In: Magoon OT (ed) Coastal zone ’85. American Society of Engineers, New York

Landsea CW, Pielke RA, Mestas-Nunez AM et al (1999) Atlantic basin hurricanes: indices of climatic changes. Clim Change 42:89–129

Leatherman SP (1991) Modeling shore response to sea level rise on sedimentary coasts. Prog Phys Geogr 14:447–464

Leatherman SP, Zhang K, Douglas BC (2000) Sea level rise shown to drive coastal erosion. EOS Transactions 81:55–57

Lombard A, Cazenave A, Le Traon PY et al (2005) Contribution of thermal expansion to present day sea-level change revisited. Glob Planet Change 47:1–16

Mclean RF, Tsyban A, Burkett V et al (2001) Coastal zones and marine ecosystems. In: McCarthy JJ, Canziani OF, Leary NA et al (eds) Climate change 2001: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, pp 343–379

Moser SC (2005) Impact assessment and policy responses to sea level rise in three US states: an exploration of human-dimension uncertainties. Glob Environ Change 15:353–369

Najjar RG, Walker HA, Anderson PJ et al (2000) The potential impacts of climate change on the mid-Atlantic coastal region. Clim Res 14:219–233

National Geodetic Survey (NGS) (2004) National geodetic survey frequently asked questions. http://www.ngs.noaa.gov/faq.shtml. Accessed August 2005

National Oceanic and Atmospheric Administration (2004) Mean sea level trends for stations in New Jersey. http://coops.nos.noaa.gov/sltrends/sltrends_states.shtml?region=nj. Accessed April 2005

New Jersey Coastal Management Program (2002a) What is the New Jersey coast? Fact sheet 2. Department of Environmental Protection, Trenton

New Jersey Coastal Management Program (2002b) Ocean resources management in New Jersey: Fact sheet 3. Department of Environmental Protection, Trenton

New Jersey Department of Environmental Protection (NJ DEP) (1981) New Jersey Shore Protection Master Plan. Department of Environmental Protection, Trenton

New Jersey Department of Environmental Protection (2003) New Jersey’s threatened and endangered wildlife. Department of Environmental Protection, Trenton. http://www.nj.gov/dep/fgw/tandespp.htm. Accessed March 2005

New Jersey Department of Environmental Protection, Bureau of Geographic Information Systems (NJ DEP BGIS) (2004) New Jersey statewide GIS data. http://www.nj.gov/dep/gis/. Accessed April 2005

New Jersey Department of Labor (2002) County population and labor force projections for New Jersey 2000–2020. Division of Labor Market and Demographic Research, Trenton

New Jersey Department of Labor and Workforce Development (2004) New Jersey’s many faces: demographic data. New Jersey Department of Labor, Trenton. http://www.nj.gov/labor/lra/. Accessed March 2005

New Jersey Division of Taxation (2004) Annual report, total taxable value, land and improvements in New Jersey, 2002 county values. New Jersey Department of Treasury, Trenton

New Jersey Marine Sciences Consortium et al (2004) New Jersey: State of the Shore Report. National Sea Grant Program and NOAA, Fort Hancock. http://www.njmsc.org/. Accessed December 2004

Nicholls RJ (2003) Case study on sea level rise impacts. Prepared for OECD workshop on the benefits of climate policy: improving information for policy makers, Organization for Economic Cooperation and Development, Paris, 12–13 December 2002

Nicholls RJ, Leatherman SP (1996) Adapting to sea level rise: relative sea level trends to 2100 for the United States. Coast Manage 24:301–324
Nicholls RJ, Lowe JA (2004) Benefits of mitigation of climate change for coastal areas. Glob Environ Change 14:229–244
Nicholls RJ, Hoozemans FMJ, Marchand M (1999) Increasing flood risk and wetland loss due to global sea level rise: regional and global analysis. Glob Environ Change 9:69–87
Nordstrom KF, Fisher S, Burr M et al (1977) Coastal geomorphology of New Jersey. In: Center for coastal and environmental studies technical report 77-1, volumes I and II. Rutgers University, New Brunswick
Ocean County Department of Planning (2002) Historical Population Trends in New Jersey, 1930–2000. http://www.co.ocean.nj.us/planning/databook. Accessed March 2005
Peltier WR, Jiang W (1997) Mantle viscosity, glacial isostatic adjustment and eustatic sea level of the sea. Surv Geophys 18:239–277
Phillips JD (1986) Spatial analysis of shoreline erosion, Delaware Bay, New Jersey. Ann Assoc Am Geogr 76:52–62
Psuty NP (1986) Holocene sea level in New Jersey. Phys Geogr 7:156–167
Psuty NP (1996) A white paper on the measurements of sea level rise in New Jersey and a perspective on the implications for management. Rutgers University, New Brunswick
Psuty NP, Ofiara DD (2002) Coastal hazard management, lessons and future directions from New Jersey. Rutgers, New Brunswick
Rahmstorf S (2007) A semi-empirical approach to projecting future sea-level rise. Science 315:368–370
Rosenzweig C, Solecki WD (2001) Climate change and the global city, the potential consequences of climate variability and change, metro east coast. Columbia University Earth Institute, New York
Shuster CN (1982) A pictorial review of the natural history and ecology of the horseshoe crab *Limulus polyphemus*, with reference to other Limulidae. In: Boneventura J, Boneventura C, Tesh S (eds) Physiology and biology of horseshoe crabs, studies on normal and environmentally stressed animals. Alan Liss, New York
Shuster CN, Botton ML (1985) A contribution to the population biology of horseshoe crabs *Limulus polyphemus* in Delaware Bay. Estuaries 8:363–372
Stanley A, Miller KG, Sugarman PJ (2004) Holocene sea-level rise in New Jersey: an interim report. New Jersey Department of Environmental Protection, Trenton, NJ, USA
Steetzel HJ (1991) A model for profile changes during storm surges. Coast Sediments 1991:618–630
Stive MJF (2004) How important is global warming for coastal erosion. Clim Change 64:27–39
Thomas E, Varekamp JC (1991) Paleo-environmental analysis of marsh sequences (Clinton, Connecticut): evidence for punctuated rise in relative sea level during the latest Holocene. J Coast Res 11:125–158
Titus JG (1988) Greenhouse effect, sea level rise and coastal wetlands, U.S. Environmental Protection Agency, Washington DC, USA
Titus JG (1989) Sea level rise. In: U.S. Environmental Protection Agency. The potential effects of global climate change on the United States, Report to Congress. U.S. Environmental Protection Agency (EPA 230-05-89-052), Washington DC, USA
Titus JG (1990) Greenhouse effect, sea level rise and barrier islands, case study of Long Beach Island, New Jersey. Coast Manage 18:65–90
Titus JG (1991) Greenhouse effect and coastal wetland policy: how Americans could abandon an area the size of Massachusetts at minimum cost. Environ Manage 15:39–58
Titus JG (1998) Rising seas, coastal erosion and the takings clause, how to save wetlands and beaches without hurting property owners. MD Law Rev 57:1279–1399
Titus JG, Barth MC (1984) An overview of the causes and effects of sea level rise. In: Barth MC, Titus JG (eds) Greenhouse effect and sea level rise, a challenge for this generation. Van Nostrand Reinhold, New York
Titus JG, Narayanan VK (1995) The probability of sea level rise. U.S. Environmental Protection Agency (EPA 230-R-95-008), Washington DC, USA
Titus JG, Richman C (2000) Maps of lands vulnerable to sea level rise, modeled elevations along the U.S. Atlantic and gulf coasts. Clim Res 18:205–228
Titus JG, Leatherman SP, Everts CH et al (1985) Potential impacts of sea level rise on the beach at Ocean City, Maryland. U.S. Environmental Protection Agency (EPA 230-10-85-013), Washington DC, USA
Titus JG, Park RA, Leatherman SP et al (1991) Greenhouse effect and sea level rise, the cost of holding back the sea. Coast Manage 19:171–204
United States Army Corps of Engineers (1971) National shoreline study, regional inventory report for the North atlantic region, vol. 1–2. U.S. Army Corps of Engineers, New York
United States Census Bureau (2004) Map of New Jersey. http://www.census.gov/geo/www/maps/CP_MapProducts.htm. Accessed February 2005

United States Fish and Wildlife Service (US FWS) (2004) Federally listed endangered and threatened species in New Jersey. U.S. Fish and Wildlife Service, Washington DC, USA http://njfieldoffice.fws.gov/Endangered/eslist.htm#candidate. Accessed December 2005

United States Geological Survey (USGS) (1997) Global warming, sea level rise and coastal marsh survival, USGS Fact Sheet 091-97. U.S. Geological Survey, Washington DC, USA

United States Geological Survey (2000) I.S. Geodata Digital Elevation Models, U.S. Geological Survey. http://erg.usgs.gov/isb/pubs/factsheets/fs04000.html. Accessed January 2005

Walther GR, Post E, Convey P et al (2002) Ecological responses to recent climate change. Nature 416:389–395

Weiss J, Overpeck JT (2003) Climate change and sea level: map of susceptible areas. Department of Geosciences Environmental Studies Laboratory, University of Arizona, Tucson http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level.htm. Accessed March 2005

Wigley TML (1995) Global-mean temperature and sea level consequences of greenhouse gas concentration stabilization. Geophys Res Lett 22:45–48

Wigley TML (2005) The climate change commitment. Science 307:1766–1769

Wu SY, Yarnal B, Fisher A (2002) Vulnerability of coastal communities to sea level rise, a case study of Cape May County, New Jersey, USA. Clim Res 22:255–270

Zhang K, Douglas BC, Leatherman SP (1997) U.S. East Coast storm surges provide unique climate record. EOS Trans 78:396–397

Zhang K, Douglas BC, Leatherman SP (2001) Beach erosion potential for severe nor'easters. J Coast Res 17:309–321

Zhang K, Douglas BC, Leatherman SP (2002) Do storms cause long-term beach erosion along the U.S. East Barrier Coast? J Geol 110:493–502

Zhang K, Douglas BC, Leatherman SP (2004) Global warming and coastal erosion. Clim Change 64:41–58