FUTURE SEA LEVEL RISE AND THE NEW JERSEY COAST

Assessing Potential Impacts and Opportunities

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Abstract: Increasing rates of sea level rise caused by global warming are expected to lead to permanent inundation, episodic flooding, beach erosion and saline intrusion in low-lying coastal areas. Sea level rise is a significant and growing threat to the coastal region of New Jersey, USA and this study presents a comprehensive assessment of the expected impacts. We project future sea level rise based on historical measurements and global scenarios, and apply them to digital elevation models to illustrate the extent to which the New Jersey coast is vulnerable. We estimate that 1 to 3 % of New Jersey's land area will be affected by inundation and 6.5 to over 9 % by episodic coastal flooding over the next century. We also characterize potential impacts on the socioeconomic and natural systems of the New Jersey coast focusing on Cape May Point for illustrative purposes. We then suggest a range of potential adaptation and mitigation opportunities for managing coastal areas in response to sea level rise. Our findings suggest that where possible a gradual withdrawal of development from some areas of the New Jersey coast may be the optimum management strategy for protecting natural ecosystems.

1. Introduction

It is estimated that 1.2 billion people, or approximately 23 % of the world's population, live within 100 m of sea level and 100 km from a coast (Nicholls and Small, 2002; Nicholls, 2003). The population densities in coastal regions occur at approximately three times the global average with maximum densities occurring below 20 m in elevation (Nicholls, 2003). At the same time, people continue to migrate to coastal cities and towns where economic opportunities dependent on coastal resources are concentrated. These coastal regions are home to some of the world's most productive and complex systems and support a diversity of plant, fish, and wildlife species.

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has concluded that increasing greenhouse gas concentrations are having a detectable effect on earth's climate system, including an increase in global-mean sea level (IPCC, 2001). These effects are likely to intensify over the course of this century (IPCC, 2001; Church et al., 2001). An increase of global surface temperatures would raise sea level by expanding ocean water, melting glaciers, and increasing melting and calving of the Greenland and potentially West Antarctic ice sheets. Sea level rise would increase the susceptibility of coastal populations and ecosystems through the permanent inundation of low-lying regions, amplification of episodic flooding events, and increased beach erosion and saline intrusion (Mclean et al., 2001). Ultimately, this may lead to the displacement of millions of people, significant damage to property and infrastructure, and a considerable loss of coastal ecosystems by the end of the 21st Century (Nicholls and Lowe, 2004).

Sea level rise is a significant and growing threat to New Jersey. The coastal area spans 204 km along the United States mid-Atlantic coast with an additional 134 km of shoreline along the Raritan and Delaware Bays (Figure 1). Structural development along the coast varies from heavily urbanized centers, such as Atlantic City, to sparsely populated agricultural communities on the Cape May peninsula. New Jersey is the most densely populated state with over 8.6 million people inhabiting 19,210 km^2. The coastal region has experienced significant population growth and development over the past 50 years with the population of New Jersey's coastal counties growing from 3,345,010 in 1950 to 5,281,247 in 2000 (Ocean County Department of Planning, 2002; NJ

Department of Labor and Workforce Development, 2004). Today, the population of the state's coastal counties accounts for approximately 60 % of the total.

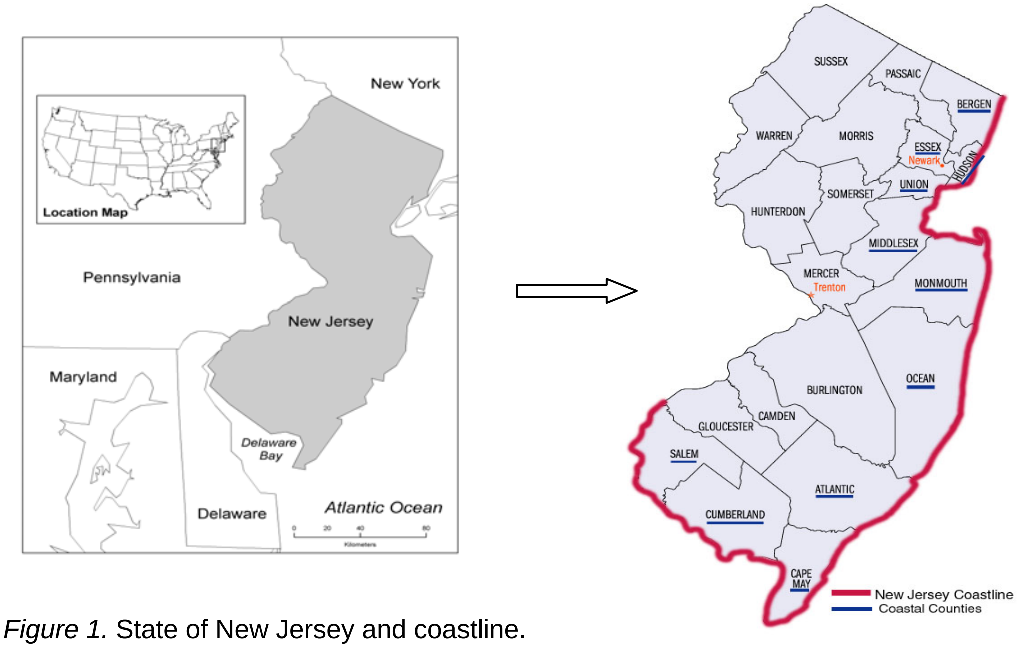

Figure 1. State of New Jersey and coastline.
(Adapted from: U.S. Census Bureau, 2004)

The New Jersey coastal region supports a $16 billion tourism industry which employs hundreds of thousands of state residents (New Jersey Coastal Management Program, 2002a). The coastal urban center of Atlantic City alone draws more than 37 million visitors annually while eco-tourism in coastal natural areas continues to expand (New Jersey Coastal Management Program, 2002a; Atlantic City Regional Chamber of Commerce, 2004). The region sustains a $50 billion maritime industry centered at the Port of New York and New Jersey, and a $100 million commercial fishing industry (New Jersey Coastal Management Program, 2002a; New Jersey Coastal Management Program, 2002b).

The New Jersey coast sustains a diverse range of ecosystems in a series of bays, estuaries, wetlands, sandy beaches, dunes and forests which provides habitat for an abundance of plant species as well as an array of fish and wildlife. The state's coastal ecosystems are home to at least 24 endangered and threatened wildlife species, 11 of which are listed under the federal Endangered Species Act. New Jersey's beaches and coastal wetlands serve 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 (New Jersey Coastal Management Program, 2002a). The coastal counties of Atlantic, Cape May, Monmouth, and Ocean contain nearly 405 km^2 of parkland in addition to over 773 km^2 of State Wildlife Management Areas and National Wildlife Refuges (NJ DEP, 2001a).

A host of descriptive and empirical studies have considered the national or regional impacts of sea level rise in the United States (Titus and Barth, 1984; Titus et al., 1985; Titus, 1989; Gornitz, 1990; Titus et al., 1991; Nicholls and Leatherman, 1996; Najjar et al., 2000; Gornitz et al., 2002;) as well as in New Jersey (Psuty, 1996; Titus, 1990; Wu et al., 2002). Several additional 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). While these studies have proved helpful, the National Assessment of the Potential Consequences of Climate Variability and Change (2000), a report by the U.S. Global Change Research Program, identified the need for further research to evaluate the vulnerability of human and natural systems to sea level rise, land subsidence and storm surges (Field et al., 2000).

This report presents a comprehensive assessment of the potential impacts of sea level rise on the New Jersey coast. Sea level rise is projected for New Jersey and applied to digital elevation models to illustrate the extent to which coastal areas are susceptible to permanent inundation, episodic flooding, beach erosion and saline intrusion. The models integrate current data with increased horizontal and vertical resolution allowing for more accurate modeling. The study then uses the models to characterize the potential impacts of sea level rise on New Jersey's natural and socioeconomic systems. A case study of Cape May Point is highlighted to illustrate the complexity and scale of sea level rise at an important location along the New Jersey coast.

Finally, we articulate a range of adaptation and mitigation possibilities for managing coastal areas in response to future sea level rise. The report offers broad insight into the impacts of sea level rise and possible responses which are applicable to a variety of regional, national and international contexts, and provides a basis from which further research, assessments and action can emanate.

2. Methods

2.1 Sea Level Rise Projections

Changes in sea level are closely related to fluctuations in global temperature. Global sea level has risen over 120 m at some locations from the low stand of the last glacial maximum 20,000 years ago when temperatures were between 5º and 10º C cooler than today (Jouzel et al., 1989; Fleming et. al., 1998; Church et al., 2001). Geologic evidence suggests a global-mean sea level rise rate of 0.1 to 0.2 mm/year over last 3,000 years with a significant acceleration that may have occurred around the mid-nineteenth century (Lambeck and Bard 2000; Church et al. 2001). Based on global tide-gauge data the rate of global-mean sea level rise during the 20th Century is estimated to range from 1.0 to 2.0 mm/year or a total of 10-20 cm (Gornitz and Lebedeff, 1987; Douglas, 1991; Peltier and Jiang, 1997; Douglas, 1997; Church et al., 2001).

When analyzing sea level change at specific coastal locations and over short timeframes two components must be considered. First, there is the global component, arising from thermal expansion of ocean water (the steric contribution) and the transfer of continental water reservoirs to the ocean (the eustatic contribution). The second is the local component reflecting vertical land movement or subsidence due to tectonics, isostatic adjustments and sediment compactions. The sum of the global and local components is referred to as relative sea level rise and reflects the rate of sea level change at a specific location. There often exists considerable variation between global and local components. An analysis of satellite data compiled over the last decade has revealed some regional sea level rise trends at 10 times the global-mean (Cazenave and Nerem, 2004).

Relative sea level rise for New Jersey is calculated from tide-gauge data collected by the National Oceanic and Atmospheric Administration (NOAA) at five locations on the mid-Atlantic 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, 2004b). The average sea level rise rate for each location was calculated as the slope of the least squares line from available tide-gauge data. Averaging the mean values from the tide-gauges provides an approximate 20th Century relative sea level rise trend of 3.53 mm/year, which is double the global-mean. This implies a local component of approximately 2 mm/year for the New Jersey coast which can be partially attributed to land subsidence and sediment compaction (Nicholls and Leatherman, 1996).

The IPCC assessment has predicted that global-mean sea level will rise between 0.09 and 0.88 m between 1990 and 2100, with a central value of 0.48 m (Church et al., 2001). Adding the local component of 2 mm/year suggests a relative sea level rise for the New Jersey coast between 0.31 and 1.10 m, giving a central value of approximately 0.71 m. According to these projections 70 % of future sea level rise for the New Jersey coast can be attributed to the effects of climate change as opposed to local components.

Based on the above sea level rise projections, this study focuses its analyses on two specific contours: **0.61 m** and **1.22 m**. Since digital elevation models measure elevation in integral feet, the 0.61 m (2 ft) and 1.22 m (4 ft) contours most closely match approximations of median and high-end projections. The 0.61 m contour approximates the median-projected sea level rise (50 % probability) for 2050 and 2100, while the 1.22 m contour estimates a high-end projected rise (1 % probability) over the next century.

2.2 Models of Sea Level Rise and Land Use Data

Sea level rise was computed using 7.5 minute digital elevation models with 10 m horizontal resolution. The models were acquired from the New Jersey Department of Environmental Protection Bureau of Geographic Information Systems which were originally obtained from the U.S. Geological Survey (USGS, 2000; NJ DEP BGIS, 2004). The USGS 7.5 minute digital elevation models were created from vectors or digital line hypsographic and hydrographic data projected on the Universal Transverse Mercator and shoreline boundaries are an inherent feature of the data set. The models are referenced horizontally to the North American Datum of 1983 and vertically to the North American Vertical Datum of 1988. The datum represents current geodetic controls as published by the National Geodetic Society (National Geodetic Society, 2004). The digital elevation models have an undefined horizontal and vertical accuracy.

Applying projected sea level rise to simple digital elevation models has limitations. First, the models characterize a fixed representation based on land elevation and are not able to represent future shorelines. They do not consider land subsidence, erosion, accretion and other natural adaptations. Nor are they able to incorporate future development or human response to sea level rise such as seawalls or beach nourishment projects. Second, due to digital elevation model and data limitations, including poor benchmarks and vertical resolution, and the “concave up” profile of the coastal zone, elevation grids may overestimate land elevations and therefore underestimate the susceptibility of coastal areas (Titus and Richman, 2000). Despite the limitations, the models illustrate the position of land areas susceptible to sea level rise and allow for plausible characterization of the potential impacts on the New Jersey coast.

The land use data used in this study was acquired from the New Jersey Department of Environmental Protection (NJ DEP BGIA, 2004). The specification of land areas was determined using 1986 baseline data and updated using 1995 and 1997 color infrared imagery. The land area and coastal waterways are delineated based on the Anderson Classification System as developed by the U.S. Geological Survey (NJ DEP, 2001b; USGS, 2003).

3. Coastal Vulnerability to Sea Level Rise

Several studies have examined the vulnerability of coastal areas to sea level rise (Gornitz, 1990; Gornitz et al., 1994; Thieler and Hammer-Klose, 1999). Vulnerability is defined as the degree to which a natural or social system is at risk to damages or losses due to natural phenomenon. Vulnerability can be discussed as a function of exposure (i.e. duration or intensity of change), sensitivity (i.e. extent to which a system will respond to change) and adaptive capacity (i.e. extent to which a system can moderate or take advantage of change). In this characterization, a vulnerable coastal area is susceptible to the effects, and incapable to adapting to, even modest increases in sea level.

Gornitz (1990) constructed a coastal hazards database to assess the vulnerability of the U.S. East Coast to the impacts of sea level rise. The database integrated seven variables known to influence the vulnerability of coastal areas to the impacts of sea level rise. These variables included elevation, coastal rock type, geomorphology, relative sea level rise, erosion and accretion, tidal ranges and wave heights (Gornitz, 1990). These variables were assessed for their relative risk potential and combined into an overall coastal vulnerability index. Based on the criteria much of coastal New Jersey, especially the barrier beaches and coastal wetlands on the Atlantic coast were characterized as at “high risk” to the impacts of sea level rise.

Thieler and Hammer-Klose (1999) have completed the most recent and extensive assessment of coastal vulnerability along the U.S. Atlantic coast. Based on the work of Gornitz (1990), Thieler and Hammer-Klose integrated six physical coastal variables: geomorphology, coastal slope, relative sea-level rise, shoreline erosion/accretion rate, mean tide range, and mean wave height. These variables were ranked according to their potential contribution to shoreline change and analyzed to produce a vulnerability index expressing the relative sensitivity of coastal areas to sea level rise. The results suggest that over 80 % of the New Jersey coast is highly or very highly vulnerable to the effects of sea level rise (Thieler and Hammer-Klose, 1999) (Figure 2).

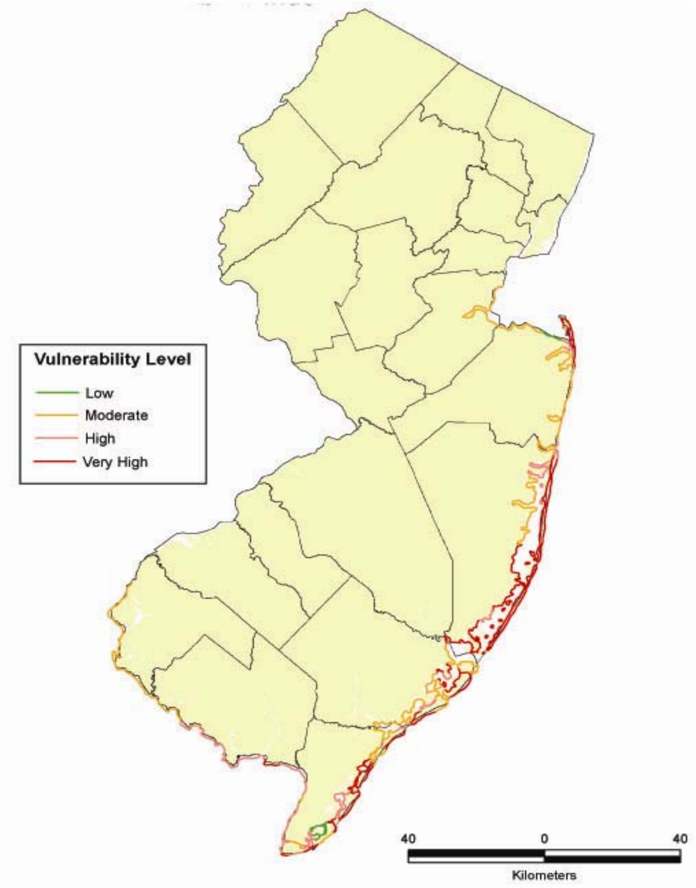

Figure 2. Coastal vulnerability of New Jersey to the impacts of sea level rise. (Adapted from Thieler and Hammer-Klose, 1999)

4. Effects of Sea Level Rise

4.1 Coastal Inundation

The most obvious outcome of sea level rise is the permanent inundation of coastal areas. Inundation refers to shoreline retreat as low-lying areas are gradually submerged by ocean waters. Over time inundation changes the position of the coastline and drowns natural habitats and human structures. Inundation can also exacerbate coastal erosion by transporting submerged sediment offshore, and extending the effects of coastal flooding by allowing storm waves to act further inland. Inundation is determined by a host of factors including the rate of sea level rise, sediment availability and the slope and geomorphology of the shoreline.

Several factors make the New Jersey coast highly susceptible to inundation. It is characterized by a flat coastal plain, gently sloping shoreline and barrier islands, sandy beaches and salt marshes, which produce extensive shoreline displacement with relatively small rises in sea level. Further, it lacks a consistent natural sediment delivery from onshore and offshore sources to nourish coastal areas and curtail inundation. This is due to an absence of river systems in which to transport inland sediment, existing seawalls which block sediment transfer, and a lack of offshore sediment (Psuty and Ofiara, 2002). Together with the increasing rates of sea level rise these factors increase the likelihood of inundation.

New Jersey coastal areas susceptible to inundation are illustrated using an inundation model (Figure 3). All coastal areas below selected elevations are assumed to be permanently inundated if sea level rises by 0.61 m or 1.22 m, respectively. It is estimated that a 0.61 m rise would inundate approximately 170 km², representing nearly 1 % of the total land area of New Jersey. A projected 1.22 m rise in sea level would drown approximately 442 km², or more than 3 % of the state.

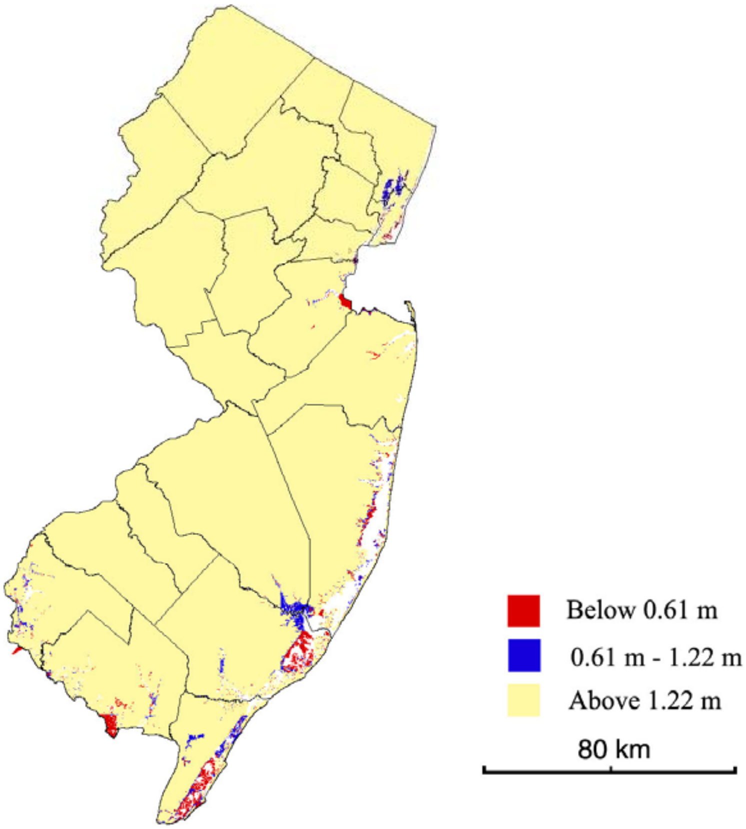

Figure 3. Estimated coastal land area susceptible to permanent inundation applying sea level rise projections of 0.61 m and 1.22 m in New Jersey.

4.2 Coastal Flooding

Storms are a natural force which has inflicted long-term change on the New Jersey coast for millennia (Psuty and Ofiara, 2002). During storm events, high winds and low-pressure work to push water swells toward the coastline. This increase in water level is known as a storm surge and combines with normal tides to create a 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).

Northeasters and offshore hurricanes are key events which shape and erode the New Jersey coast. Elevated sea levels and wave action associated with these storms can produce greater erosion in a few hours than may have occurred during the previous half century (Leatherman et al., 2000). These storm events, when compared to previous decades, have increased in frequency and intensity since 1980 (Psuty and Ofiara, 2002). From 1980 to 1998, the New Jersey coast was impacted by 12 major northeasters (Psuty and Ofiara, 2002). These storms typically produce winds ranging from 32 to 80 km/hour and can produce significant wave heights and storm surges due to their long wind fetch and several-day duration. For example, the “Ash Wednesday” northeaster that struck New Jersey in March of 1962 had storm surges which overtopped barrier islands and penetrated back-bay marshes (Donnelly et al., 2001).

High water levels and waves associated with offshore hurricanes can inflict considerable damage at the coast through flooding, strong winds and beach erosion. The last intense hurricane to make landfall in New Jersey was in 1821 (Donnelly et al., 2001). Active hurricane seasons are often beneficial to the New Jersey shore as well. As hurricanes pass off the coast, swells are produced that can transport sediment to onshore areas. In fact, the large swell preceding Hurricane Fabian in 2003 broadened New Jersey’s beach areas to the widest of the year (New Jersey Marine Sciences Consortium et al., 2004).

Storm water levels have been measured to allow for the construction of frequency curves in order to determine the probability of coastal flooding. The U.S. 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 that there is a 1 % probability that water level will equal or exceed 2.90 m, respectively. 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.

FEMA Tidal Surge Frequency	**Flood Water Level in Meters** (relative to NGVD 1929)
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

Table 1. FEMA tidal surge frequency and flood water levels for Atlantic City, New Jersey. (Adapted from: Psuty and Ofiara, 2002)

Sea level rise increases flood levels by providing a higher base for a storm surge to build upon. Figure 4 illustrates this effect at Atlantic City, New Jersey adapting the work of Najjar et al., (2000) and Psuty and Ofiara (2002). Four historic storm events are adjusted to the year 2000 assuming a historic 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 et al., 1996, Psuty and Ofiara, 2002). The events and current 5-, 10-, 20-, 30-, and 50-year flood water levels are then projected assuming sea level rises of 0.61 m and 1.22 m. For example, the northeaster in January 1987 created a flood water level of 1.80 m. This same event would have produced a water level of 1.85 m in the year 2000 and a water level of 3.07 m after a 1.22 m rise in sea level.

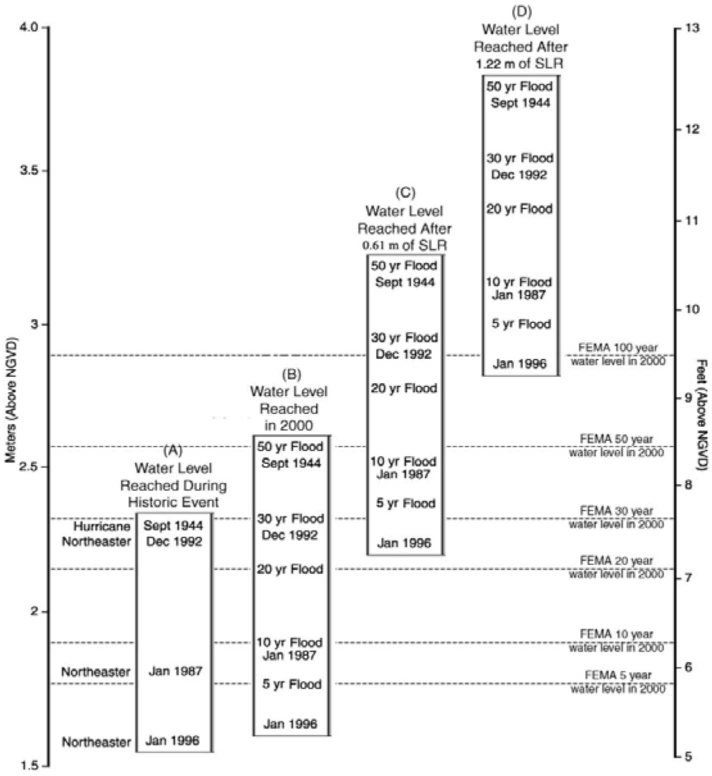

Figure 4. Potential impact of sea level rise on tidal surge frequency and flood water levels in Atlantic City, New Jersey.

Sea level rise will allow current water levels to be exceeded and low-lying lands to be flooded with increased frequency. Based on the data in Figure 4, following a 0.61 m rise in sea level, the current 30-year storm will produce a flood water level of 2.96 m, which exceeds the current 100-year level. After a 1.22 m rise in sea level, the current 5-year storm will produce water levels well above the current 100-year flood water level. The result suggests that the current 100-year flood water level of 2.90 m to be exceeded 3 to 4 times more frequently after a 0.61 m rise in sea level and approximately 20 times more frequently after a 1.22 m rise. Other factors being equal, New Jersey’s current 100-year flood water level could become the 30-year flood level after a 0.61 m sea level rise and the 5-year flood level after a 1.22 m rise.

Utilizing an inundation model the coastal areas vulnerable to episodic flooding are illustrated based on flood water levels and sea level rise projections (Figure 5). The 2.90 m contour represents the current 100-year flood water level while the 3.50 m contour represents the estimated 100-year level after a 0.61 m rise in sea level. The current 100-year flood water level is estimated to temporarily inundate an area of 1,251 km², representing approximately 6.5 % of the state's total land area. With a projected 0.61 m rise in sea level approximately 1,787 km² would be impacted by episodic flood waters, representing over 9 % of the state's total land area.

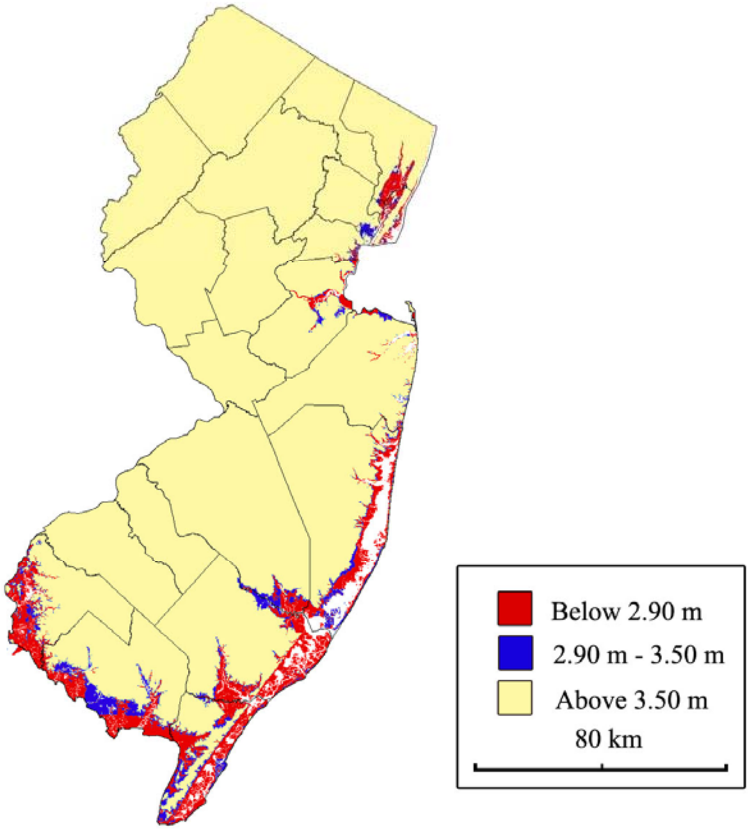

Figure 5. Estimated coastal land area susceptible to episodic flooding applying current 100-year flood water level (2.90 m) and 0.61 m rise in sea level (3.50 m) in New Jersey.

4.3 Coastal Beach Erosion

Approximately 70 % of the world's sandy beaches have been identified as eroding (Bird, 1985). On the east coast of the United States, roughly 80-90 % of beaches are undergoing long-term erosion in areas not modified by engineering projects or affected by lateral spit accretion (Galgano et al., 1998). Accordingly, such widespread beach erosion has been attributed to several factors including sea level rise, changes in storm frequency and severity, and human interference.

Although coastal regions are densely populated, it is generally accepted that human interference has been neither uniform nor extensive enough to produce the amount of beach erosion taking place worldwide (Zhang et al., 2004). Nor can changes in storm frequency and severity account for global erosion rates. For example, storm frequency demonstrates large inter-annual and inter-decadal variability and there was no significant secular increase in storm activity during the 20th Century (Zhang et al., 1997; Landsea et al., 1999, Zhang et al., 2004). Moreover, evidence suggests that coastal beaches recover their long-term trend positions regardless of storm severity which demonstrates that storms are not responsible for the pervasive beach erosion (Zhang et al., 2004). Therefore, sea level rise has been isolated as the most probable cause of widespread beach erosion occurring worldwide (Leatherman, 1991; Zhang et al., 2004).

While coastal inundation and beach erosion hasten shoreline retreat they are related but distinct processes (Zhang et al., 2004). Unlike inundation, which drowns land areas, erosion redistributes sediment from the onshore to offshore areas. Sea level rise does not directly erode beaches and coastal areas. Rather, rising sea levels act as a swelling tide that allows waves to act further up the beach profile and permits larger waves to reach the coast (Zhang et al., 2004). Beach erosion is intensified in areas affected by inlets or where the construction of groins and breakwaters disrupts long-shore drift (Gornitz et al., 2002).

Bruun (1962) constructed a simple geometric model which predicted that coastlines will retreat at a rate 50 to 100 times greater than the rate of sea level rise. The Bruun model is limited in that it considers only the movement of sand perpendicular to the shoreline (cross-shore) and does not account for movement of sand parallel to the shore (long-shore). Both Zhang et al. (2004) and Cooper and Pilkey (2004) note that at the current rate of sea level rise the cross-shore effects expressed in the Bruun rule will often be subordinate to a variety of other physical processes including sediment supply.

Zhang et al. (2004) found that U.S. east coast beaches have retreated an estimated 23.8 m on average for each 0.3 m of sea level rise over the last century. This value is in agreement with the Bruun rule. It is important to note that Zhang et al. only considered beach segments not influenced by inlets, spits, and stabilization structures when calculating long-term erosion rates and included only about 18 % of the state's coastline. The New Jersey shoreline change rate was estimated by Zhang et al. (2004) at 36.6 m per 0.3 m of sea level rise assuming a sandy beach environment. This rate is larger than the average along the U.S. east coast and the highest from New York to South Carolina. Given sea level rise projections of 0.61 m and 1.22 m, future shoreline change rates may increase to between 73 m and 146 m over the next century.

A range of studies have assessed the susceptibility of the New Jersey coast to erosion. (United States Army Corps of Engineers, 1971; Nordstrom et al., 1977; NJ DEP, 1981, Kyper and Sorenson, 1985; Phillips, 1986; Gornitz, 1990, Zhang et al., 2004). A 1971 study conducted by the U.S. Army Corps of Engineers considered economic, ecological, and other variables along with physical measures of shoreline change to determine the severity of New Jersey coastal erosion (United States Army Corps of Engineers, 1971). The study classified 81 % of the coastline as critically eroding, 9.7 % as non-critically eroding, and 8.8 % as non-eroding or stable. A successive study by the New Jersey Department of Environmental Protection (1981) calculated the severity of shoreline erosion (considering only physical factors) and categorized 32.9 % as critically eroding, 18 % as significantly eroding, 38.5 % as moderately eroding and 10.6 % as non-eroding.

At present it is difficult to build a definitive relationship between sea level rise and erosion at specific locations due to the considerable variability in slope, beach width and geomorphology along the New Jersey coast. This is further complicated by the unpredictability of periodic storm effects, land subsidence, coastal stabilization and beach nourishment projects, and the influence of inlets. Despite these limitations, the available evidence suggests that the vast majority of New Jersey beach environments are eroding and acceleration of this trend should be anticipated.

4.4 Saline Intrusion

As sea level continues to rise the associated effects of permanent inundation, erosion and episodic flooding is likely to increase the salinity of surface and groundwater near coastal areas (Hull and Titus, 1986). The gradual flow of freshwater toward the ocean prevents low-lying continental water systems from having the same salinity as the ocean. As sea-level rises, saltwater can penetrate upstream into coastal watersheds making it too saline for residential, agricultural and industrial uses. This issue is especially notable under drought conditions when freshwater flow decreases and the salt front can move inland.

Sea level rise can enable saltwater to penetrate coastal aquifers. Aquifer salinization may be compounded during droughts or in regions with significant overdraft (when water is extracted from the aquifer faster than it can be naturally replaced), because the aquifer may lack sufficient water pressure to prevent the ocean from backing up into groundwater. The Potomac-Raritan-Magothy aquifer system in particular is an important water source for residential and industrial centers in the coastal region of southern New Jersey (Luzier, 1980). During a drought in 1961-66, the salt front (defined as 100 milligrams/liter chloride) moved 50 km inland and salt water recharged the Potomac-Raritan-Magothy aquifer, increasing chloride concentrations in wells 10 to 70 mg/liter above background levels (5-10 mg/liter) (Camp Dresser and Mckee, 1982; Hull and Titus, 1986). These chloride levels remained elevated for more than 10 years.

Increased salinity levels associated with sea level rise could have a significant impact on drinking water quality along the Delaware River (Hull and Titus, 1986; Major and Goldberg, 2001). Hull and Titus (1986) estimated that after a 0.73 m rise in sea level (1965 baseline), the 1960's drought would have increased chloride concentrations from 135 mg/liter to 305 mg/liter on the Delaware River near Philadelphia exceeding New Jersey's chloride drinking water standard of 200 mg/liter. Sea level rise of this level would also allow sodium concentration in excess of 50 mg/liter (New Jersey's sodium drinking water standard) to be present in aquifer recharge water past river mile 100 close to Philadelphia. In this case, the salt front would still be below Philadelphia's Torresdale water supply intake at river mile 110. However, a rise in sea level considerably greater than 0.73 m would likely invade Philadelphia's water supply intake at Torresdale and leave water too saline for human consumption or industrial uses (Hull and Titus, 1986).

Saline intrusion associated with sea level rise can have considerable impact on coastal ecosystems. As sea level rises and estuarine and wetland salinity increases, coastal vegetation will likely undergo changes in community composition as more salt tolerant species dominate and salt intolerant species are forced further inland. These changes in vegetation will likely modify fish and wildlife populations adapted to specific plant associations (USGS, 1997b).

5. Potential Impacts on the New Jersey Coast

5.1 Impact on Socio-economic Systems

Sea level rise is predicted to have pronounced impacts on New Jersey's socioeconomic systems. A surge in residential, industrial and tourism-related development has accompanied the recent influx of new residents to the New Jersey coast. Property and land values in Monmouth, Ocean, Atlantic and Cape May counties alone was estimated to total over $100 billion in 2002 (NJ Division of Taxation, 2004). The population of New Jersey's coastal counties is estimated to climb to over 6 million by 2020 and property values will likely rise in tandem (New Jersey Department of Labor, 2002). Sea level rise will make coastal development, infrastructure and residents increasingly susceptible to inundation, erosion, and storm-induced flooding.

It is estimated that from 12,950 km² to 25,900 km² of coastal land is in danger of permanent inundation in the United States assuming a 1 m rise in sea level (Titus, 1989). Based on the inundation models and sea level rise projections of 0.61 and 1.22 m it is estimated that 1 to 3 % of the land area of New Jersey, or between 170 - 442 km², will be inundated over the next century. Approximately 19.5 km² of developed shoreline (defined in this study as residential/urban, industrial, and agricultural) lie below 0.61 m of current sea level and 60 km² lie within 1.22 m (Table 2). Assuming no natural or human adaptation, it is estimated there is a 50 % chance that nearly 20 km² of developed shoreline will be appreciably impacted by permanent inundation during the 21st Century.

Land use class	Land below 0.61m contour (km²)	Land below 1.22m contour (km²)	Land below 2.90m contour (km²)
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
Agricultural	0.3	0.7	44.0
Total	170.7	442.1	1251.0

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

FEMA estimates that U.S. land area susceptible to 100-year flood water levels will increase from 50,500 km² to 56,200 km² after a 0.3 m rise in sea level and cause an increase of National Flood Insurance Program insured property values by 36-58 % (FEMA, 1991). A sea level rise of 0.91 m would expand flood prone U.S. land area to 67,330 km² and increase insured property values by 100-200 % (FEMA, 1991). The number of flood prone households in the U.S. is estimated to increase from approximately 2.7 million to 5.7 million and 6.8 million by the year 2100 assuming a 0.3 m and 0.91 m rise in sea level, respectively (FEMA, 1991).

Flooding associated with storm events has produced devastating effects along the U.S. eastern and gulf coasts. The "Ash Wednesday" northeaster of 1962 produced over $500 million in damage (Gaul and Wood, 2000). The "Halloween" northeaster of 1991 caused over $1.5 billion in damage along the mid-Atlantic coast and Hurricane Andrew hit the U.S. east and south coasts in 1992, leaving 52 people dead and resulting in $32 billion in damage (Dean, 1999; Field et al., 2000). Figure 6, adapted from Psuty et al., (1996), illustrates the dramatic impact storm events can have on tide-water elevations. On December 11, 1992 a northeaster hit the New Jersey coast. The strongest period of the storm coincided with the spring tide, when standing water elevations reached 2.32 m above datum with maximum wave heights of 3.05 m (Psuty et al., 1996). The storm persisted over 12 tidal cycles and caused $341 million in damages (Gaul and Wood, 2000).

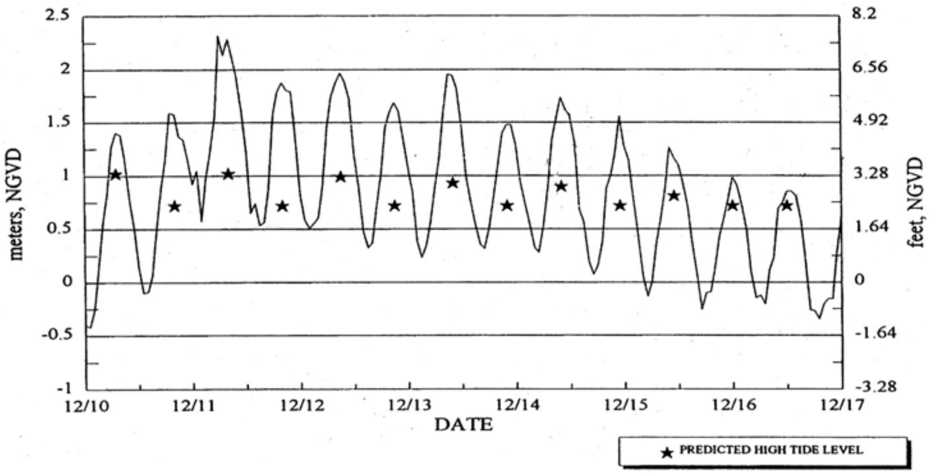

Figure 6. Hourly flood water level elevations at Atlantic City, New Jersey, December 10-16, 1992. (Adapted from: Psuty et al., 1996).

In New Jersey it is estimated that 269 km² of developed coastal areas lie within the current 100-year flood level of 2.90 m, the majority of which is occupied by residential and urban development (Table 2). As noted earlier, these areas may be flooded three to four times more frequently after a 0.61 m rise in sea level and around 20 times more frequently after a 1.22 m rise. New Jersey's highly developed barrier islands, which have an average height of about 2 m above sea level, are particularly susceptible to inundation and flooding episodes (Psuty and Ofiara, 2002). Moreover, coastal communities currently safe from even the most severe flooding events will be impacted as sea level rise causes impacts beyond the current 100-year flood water level. For instance, a 0.61 m rise in sea level would raise the 100-year flood water level to 3.35 m, resulting in the flooding of an estimated 414 km² of developed coastal area. This would add nearly 145 km² of previously unaffected developed shoreline to the 100-year flood water level.

Nationally, it is predicted that 25 % of homes and other structures within 152 m of the U.S. coast and the shores of the Great Lakes will be taken by the effects of coastal erosion during the next century (Heinz Center, 2000). Intense storm events can cause dramatic shoreline erosion on the order of tens of meters. Although evidence suggest that beaches return to long-term erosion rates after storm episodes this recovery process can last multiple decades leaving property and residents of New Jersey's coastal areas more susceptible to the impacts of inundation and flooding.

New Jersey surface and ground water resources are highly strained by the competing demands of population growth, agriculture, industry, and recreation. Sea level rise will exacerbate current problems and further limit available water supplies. Aquifers provide the sole or principle source of water for at least 14 of New Jersey's 21 counties and the Coastal Plain Aquifer System covers all of central and southern New Jersey (U.S. EPA, 1988). In addition, much of New Jersey is dependent on coastal watersheds for water. A 0.61 m or 1.22 m rise in sea level over the next century would allow the salt front to advance further upstream in watersheds and permit saline waters to penetrate coastal aquifers. The increasing salinity may contaminate drinking water supplies and limit the water available for agricultural and industrial uses. In response, New Jersey's would be required to regulate and drastically reduce water usage or find alternative supplies of water at substantial cost (Hull and Titus, 1986).

5.2 Impacts on Natural Systems

Worldwide coastal natural systems are highly susceptible to the effects of sea level rise and the loss of the coastal wetlands and beaches will likely produce significant ecological impacts (Titus et al., 1988; Hoozemans et al., 1993; Nicholls et al., 1999; McLean et al., 2001; Nichols, 2003). Nicholls et al. (1999) predict that sea level rise alone could cause the loss of up to 22 % of the world's coastal wetlands over the next century. The combination of sea level rise, and direct human impacts during this same timeframe, could result in a 70 % loss (Nicholls et al., 1999). The U.S. mid-Atlantic coast contains some of the most valuable estuarine and wetland ecosystems in the U.S. and is also among the most threatened due to human activity.

The New Jersey coast sustains a diverse range of productive ecosystems including bays, estuaries, wetlands, beaches, dunes and forests. These environments provide habitat for a diversity of plant, fish and wildlife species. The coastal wetlands and beaches 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 also provide essential spawning ground for the world's largest population of horseshoe crabs. The state's coastal ecosystems support at least 24 endangered and threatened wildlife species, 11 of which are listed under the federal Endangered Species Act (Table 3).

Species	**Scientific Name**	**Taxonomic Group**	**Status**	**Listing (NJ State/ U.S. Federal)**
Least Tern	*Sterna antillarum*	Bird	Endangered	State/Federal
Roseate Tern	*Sterna dougallii*	Bird	Endangered	State/Federal
Northern Goshawk	*Accipiter gentilis*	Bird	Endangered	State
Northern Harrier	*Circus cyaneus*	Bird	Endangered	State
Short-eared Owl	*Asio flammeus*	Bird	Endangered	State
Piping Plover	*Charadrius melodus*	Bird	Endangered	State
Upland Sandpiper	*Batramia longicauda*	Bird	Endangered	State
Black Skimmer	*Rynchops niger*	Bird	Endangered	State
Sedge Wren	*Cistothorus platensis*	Bird	Endangered	State
Bald Eagle	*Haliaeetus leucocephalus*	Bird	Threatened	State/Federal
Black Crowned Night Heron	*Nycticorax nycticorax*	Bird	Threatened	State
Yellow Crowed Night Heron	*Nyctanassa violaceus*	Bird	Threatened	State
Red Knot	*Calidris canutus*	Bird	Threatened	State
Osprey	*Pandion haliaetus*	Bird	Threatened	State

Black Rail	*Laterallus jamaicensis*	Bird	Threatened	State
Red-headed Woodpecker	*Melanerpes erythrocephalus*	Bird	Threatened	State
Atlantic Ridley Turtle	*Lepidochelys kempi*	Reptile	Endangered	State/Federal
Hawksbill Turtle	*Eretmochelys imbricata*	Reptile	Endangered	State/Federal
Atlantic Leatherback Turtle	*Dermochelys coriacea*	Reptile	Endangered	State/Federal
Atlantic Loggerhead Turtle	*Caretta caretta*	Reptile	Threatened	State/Federal
Atlantic Green Turtle	*Chelonia mydas*	Reptile	Threatened	State/Federal
American Burying Beetle	*Nicrophorus mericanus*	Insect	Endangered	State/Federal
Northeastern Beach Tiger Beetle	*Cincindela d. dorsalis*	Insect	Endangered	State/Federal
Bronze Copper	*Lycaena hyllus*	Insect	Endangered	State
Shortnose Sturgeon	*Acipenser brevirostrum*	Fish	Endangered	State/Federal

Table 3. Threatened or endangered species of New Jersey coastal region.
(NJ DEP, 2003; U.S. FWS, 2004).

New Jersey’s coastal systems suffer from a variety of factors associated with human development. Between the 1780’s and 1980’s 39 % of the state’s original 6,000 km^2 of wetlands (coastal and interior) were lost to human reclamation for farming, roads, and development (Dahl, 1990). Approximately 20 % of this loss occurred in the 20 years between 1950 and 1970 (NJ DEP, 2002). Subsequent state and federal laws and regulations appear to have slowed the rate of reclamation with 7 km^2 wetlands being lost annually from 1986 to 1995 (NJ DEP, 2002). In 1995, coastal wetlands covered approximately 811 km^2, representing 25 % of the state’s total wetland area (NJ DEP, 2002).

Human activity along the New Jersey coast has greatly compromised coastal ecosystems independent of any climate change and sea level rise impacts. Coastal bays and wetlands have been heavily impacted by an influx of chemical pollution released from agricultural, industrial, and municipal point and non-point sources. Trace metals, polyaromatic hydrocarbons, polychlorinated biphenyls, and other toxins have contaminated sediments and bio-accumulated into the flora and fauna (U.S. EPA, 1998). Moreover, the anthropogenic release of nitrates, phosphates, and other compounds has lead to increased nutrient levels producing phytoplankton blooms and hypoxic conditions in estuaries throughout the U.S. Atlantic coast (U.S. EPA, 1998).

New Jersey’s coastal wetlands are highly susceptible to the effects of sea level rise. Coastal wetlands can adapt and keep pace with sea level rise through vertical accretion and inland migration but must remain at the same elevation relative to the tidal range and have a stable source of sediment. Vertical accretion occurs through sediment deposition and subsurface accumulation of organic plant matter. Coastal wetlands risk permanent inundation if sea level rises faster than the rate by which they can accrete. The degree of wetland loss is directly related to the rate of sea level rise compared to the accretion rate (Najjar et al., 2000). The combination of sea level rise and vertical accretion forces coastal wetlands to migrate inland causing upslope transitional brackish wetlands to convert to saline marshes and the saline marshes on the coastline to drown or erode.

Evidence suggests that wetland accretion processes along the U.S. mid-Atlantic coast have stagnated (Gornitz, 1995; Hartig et al., 2001). Coastal wetland accretion rates on the U.S. mid-Atlantic coast ranges from no net accretion to approximately 8 mm/year but exhibit large regional 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. Although accretion rates for New Jersey are highly variable and data insufficient, average accretion rates for New Jersey are estimated to be approximately 2 mm/year (Erwin, 2003). This suggests that coastal wetlands in New Jersey will generally be unable to accrete at a pace greater or equal to relative sea level rise (3.53 mm/year) and are extremely susceptible to permanent inundation.

Even coastal wetlands with vertical accretion rates thought to be able to keep pace with sea level rise inland migration may be obstructed by bluffs, development, or shoreline protection structures. In this process, wetlands migrate inland until they are 'squeezed' against natural or human barriers. In fact, a significant portion of New Jersey's coastal wetlands are adjacent to human development or seawalls that block natural wetland migration paths and increase the likelihood of wetland loss from inundation.

It is important to note that work by the U.S. Geologic Survey (1997a) found that at several sites along the U.S. coast, the rate of wetland elevation increase was less than the rate of vertical accretion. One illustrative example from a four year study in Louisiana found a vertical accretion average of 2.07 cm/year, yet the elevation at the site remained virtually unchanged. In effect there appears to be processes that create shallow subsidence, offsetting the elevation gain (USGS, 1997a). These findings suggest that relying on accretion data alone, where it exists, is not sufficient for projecting wetland dynamics.

The delineation of the wetland areas is based on the Anderson Classification System (USGS, 2003). The saline marsh land class is associated with waters with salinities greater than one part per thousand and dominated by growth of two forms of *Spartina alterniflora* in the regions of highest salinity. Freshwater tidal wetlands are co-dominated by annual and perennial herbaceous vegetation and are associated with tidal waters with salinities less than one part per thousand. The interior wetland class includes all non-tidal lowlands associated with primary, secondary and tertiary watercourses, and isolated wetlands. The interior wetland class also includes all forested wetlands, regardless of tidal influences.

Wetland Class	**Land Area Below 0.61m contour (km²)**	**Land Area Below 1.22 m contour (km²)**	**Total Land Area in New Jersey (km²)**
Saline Marsh	134.7	251.2	771.8
Freshwater Tidal Marsh	2.6	10.4	38.8
Interior Wetlands	5.2	18.1	1763.8*
Total	142.4	279.7	2574.4

Table 4. Wetland land use classes below 0.61m and 1.22 m sea level in New Jersey. *(represents only interior wetlands located in New Jersey coastal watersheds)

Inundation statistics for three wetland classes were calculated (Table 4). It is estimated that a 0.61 m rise in sea level could permanently inundate approximately 15 % of the saline marshes in New Jersey, while a 1.22 m rise in sea level could inundate about 30 %. These estimates assume a fixed position for all wetlands and do not account for the ability of wetland complexes to adapt through vertical accretion. The increase in flooding associated with sea level rise will also affect wetland habitats. In total, approximately 906 km² of wetlands lie within the current 100-year flood level of 2.90 m. This area includes virtually all 772 km² of New Jersey's saline marshes and 95 % of freshwater marshes.

The effects of sea level rise may result in the loss of coastal ecosystems like sandy beaches, wetlands, and dunes which sustain a diversity of plant and animal species. As noted previously, increased salinity levels will alter community composition of wetland vegetation, potentially modifying fish and wildlife communities. In addition, the sandy beaches of southern New Jersey, which are highly susceptible to sea level rise, play a vital role in the lifecycle of the horseshoe crab (*Limulus polyphemus*) and literally millions of migratory birds. Any alternation of these beach areas would likely result in declining horseshoe crab densities and bird populations. Galbraith et al. (2002) estimates that even under conservative sea level rise projections, a 60 % loss of inter-tidal beach areas in Delaware Bay alone may occur and could severely impair the ability of these locations to support current numbers of migratory birds. The loss of vulnerable coastal dune forests, of which less than 12 km² remain in New Jersey, would endanger the threatened black-crowned night heron (*Nycticorax nycticorx)*. Furthermore, the federally listed seabeach amaranth (*Amaranthus pumilus*), a plant found in the foredunes of New Jersey's barrier beaches, is highly susceptible to the effects of rising seas and likely to be irreversibly damaged (U.S. FWS, 2004).

6. Case Study: Cape May Point, New Jersey

A case study of Cape May Point at the southern tip of New Jersey was conducted to assess how sea level rise may potentially impact interconnected ecological and socioeconomic systems. The study area was selected for its combination of ecological, social, and economic value and its extensive, unprotected beach area which adequately illustrates coastal processes and shoreline change. The case study builds on similar studies which have assessed the potential impact of sea level rise at particular locations along the U.S. mid-Atlantic coast (Najjar et al., 2000; Gornitz et al., 2002).

The case study area is located at the tip of Cape May in southern New Jersey (Figure 7). The study area (excluding the sandy beach zone) covers approximately 1.5 km² and is composed of approximately 40 % freshwater and saline marsh, 40 % wooded wetland, and 20 % forest. The western third of the case study area lies within the Cape May Point State Park administered by the New Jersey Division of Parks and Forestry. The eastern portion constitutes the Cape May Migratory Bird Refuge administered by the Nature Conservancy. Residential development surrounds a majority of the study area.

Cape May Point and the Delaware Bay region in particular contain important bird, fish and wildlife habitat most notably for horseshoe crab spawning and migratory shorebird foraging. Each year during May and June, the region serves as the stopover point for over a million birds migrating northward from wintering grounds as far south as the tip of South America. Key bird species include red knots (*Calidris canutus*), sanderlings (*Calidris alba*), ruddy turnstones (*Arenaria interpres*), and semipalmated sandpipers (*Calidris pusilla*). During an 8-12 day stopover the birds rapidly increase their body weight in order to fly to breeding grounds in the Canadian Arctic (NJ DEP, 2004). The migratory bird stopover coincides with the spawning period for the world's largest population of horseshoe crabs (Shuster, 1982; Shuster and Botton, 1985; Castro and Myers, 1989). The crabs arrive from the deep ocean to breed and lay eggs on the area's beaches and mudflats. The migratory birds feed on these eggs as a principle food source (Andres et al., 2003).

Figure 7. Cape May Point, New Jersey.

The shoreline and natural lands on Cape May Point were surveyed by the authors in March 2004. The study area is characterized by a sandy beach of approximately 2.5 km in length (Figure 8). The shallow beach is backed by a dune of varying elevation, with a maximum height of approximately 3 m above the back saline wetland. Between 500 m and 750 m of saline and low-lying forested areas are found between the dune and outlying residential developments.

Figure 8. Case study area, Cape May Point.

Portions of Cape May Point susceptible to inundation were determined using an inundation model (Figure 9). All land area lying below selected elevations are assumed to be permanently inundated if sea level rises by 0.61 m or 1.22 m, respectively. It is estimated that a 0.61 m rise in sea level could inundate approximately 20 % of the study area and a 1.22 m rise would inundate approximately 45 % of the study area. The illustrated contours do not take into account the effects of shoreline displacement, wetland accretion or human alteration.

Figure 9. Estimated land area susceptible to inundation at case study area, Cape May Point, New Jersey.

A more complete characterization of the future condition of study area and its susceptibility to sea level rise can be estimated by determining the shoreline displacement rate. Shoreline displacement data complements the inundation model and can effectively capture the coastal processes at work in the study area. This is especially important at Cape May Point where the combination of shallow slope and adjoining shoreline protection structures indicate a rapid rate of shoreline displacement.

Historical shoreline positions from 1879 to 1977 were determined for Cape May Point with data provided by the New Jersey Department of Environmental Protection Bureau of Geographic Information Systems (NJ DEP, 1991; NJ DEP BGIS, 2004) (Figure 10). Historic map sheets and aerial photographic images were digitized and analyzed to estimate shoreline positions. According to this data, the shoreline of Cape May Point receded at its maximum distance approximately 500 m since 1879. This suggests a rapid shoreline displacement rate of around 4 m/year. The tide-gauge at Cape May gives an average sea level rise of 3.98 mm/year since 1965 which is higher than the historic New Jersey sea level rise trend. Applying 3.98 mm/year, it appears that the shoreline has receded approximately one meter for each millimeter of sea level rise. This value represents the maximum rate of displacement observed over the last 125 years on the shoreline of Cape May Point. If shoreline displacement continues in the same manner, a 0.61 m rise would erode the central beach by 610 m, removing approximately 70 % of the study area. A 1.22 m rise in sea level would erode 1,200 m displacing the entire study area, in addition to adjoining agricultural and residential development located nearest to the coastline.

It is important to note that the maximum rate of shoreline displacement observed at Cape May Point is several magnitudes greater when compared to average shoreline change rates for New Jersey (Bruun, 1962; Kyper and Sorenson, 1985; Zhang et al., 2004). According to Zhang et al. (2004) the shoreline change rate for Cape May Point would be approximately 36.6 m per 0.3 m of sea level rise. If the study area is displaced at this rate it is expected to recede approximately 73 m to 146 m given sea level rise projections of 0.61 m and 1.22 m, respectively. These estimates would remove an estimated 12-17 % of the study area. Therefore, it is expected that the loss of the study area due to shoreline displacement is highly variable and will depend on both the rate of relative sea level rise and on a variety of local factors such as subsidence, sediment availability and human alternation of adjacent coastal areas.

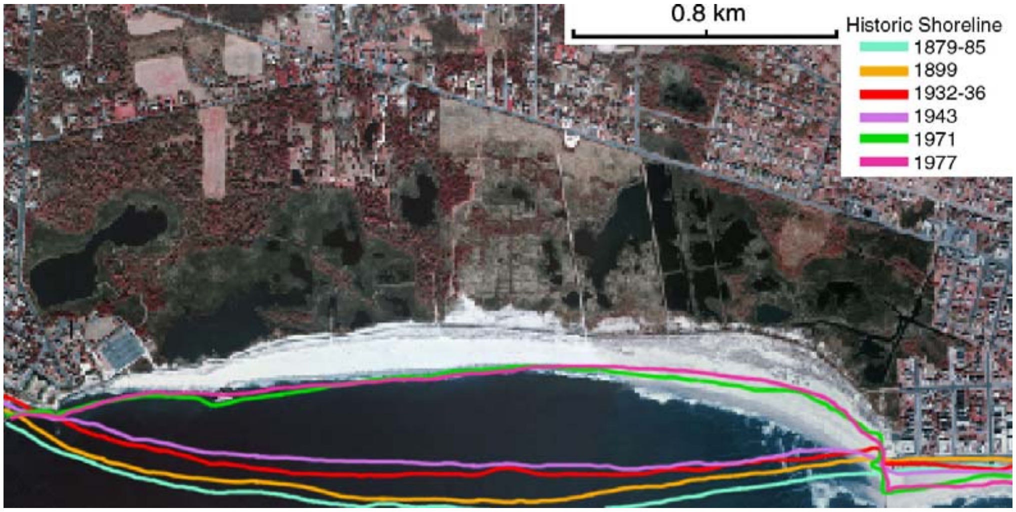

Figure 10. Historic shoreline positions at case study area, Cape May Point, New Jersey, 1879-1977.

The shallow slope of the study area also makes it highly vulnerable to storms and episodic flooding. The study area lies entirely within the 100-year flood water level of 2.90 m. It is estimated that a sea level rise of 0.61 m would flood the case study area about 3 to 4 times more frequently and a 1.22 m rise approximately 20 times more frequently. These findings are supported in a recent study by Wu et al. (2002) which points out that Cape May Point is an area at “very high risk” of substantial flooding.

The exact rate of shoreline retreat and the future ecological composition of the study area cannot be precisely estimated. However, a loss of land area by 2100 on the order of 12-100 % due to the combined influence of inundation, flooding and erosion is expected. There is little doubt this would result in substantial saltwater intrusion into low-lying wetlands behind the current beach area and compromise the role of Cape May Point as habitat for migratory birds, horseshoe crabs and other wildlife. The increasing salinity would adversely affect established plant and animal communities. It is possible that the wetlands and beach areas in the study area can accrete and naturally migrate inland during the next century, decreasing the land lost to sea level rise. However, at present, the study area is backed by residential and agricultural development. If sea level rise estimates are accurate and the wetlands are blocked from accreting and migrating inland, it appears that during the next century the current study area will slowly attenuate, change in composition and potentially disappear.

The dense residential development surrounding the study area also would likely be compromised, although precisely to what extent is uncertain. Property nearest the study area and coast would be exposed directly to the mounting effects of inundation, flooding and erosion increasing the frequency of property damage. If the past is any guide, coastal stabilization structures will be erected at a cost to taxpayers to protect susceptible properties. While this may postpone the ultimate impacts of sea level rise on residential development it will exacerbate the loss of study area's coastal habitat.

7. Adaptation and Mitigation Potential

During the 20th Century, a range of coastal management techniques have been employed to protect the economic, cultural, and natural resources present along the coast. When faced with rising sea level, there are two general categories of response: defend the existing coastline or allow the coastline to naturally migrate inland.

New Jersey has one of the most managed coastlines in the U.S. The state's coastal protection projects alone account for approximately 14 % of the national total and costs over $25 million annually (Gaul and Wood, 2000). The initial state and national response to sea level rise relied extensively on 'armoring' the shore using coastal stabilization structures such as revetments, bulkheads, seawalls, breakwaters, groins, and jetties (Psuty and Ofiara, 2002). These 'hard' defenses attempt to maintain the existing shoreline position by serving to dissipate the energy of waves, protect coastal property from flooding and inundation, and reduce erosion by slowing littoral sand drift or trapping sand. Stabilization structures are present on over 165 km of New Jersey's 204 km Atlantic coastline and can be found in 41 of 45 of the state's shorefront communities (Psuty and Ofiara, 2002). Along the New Jersey coast there are over 480 groins and over 37 km of seawalls and bulkheads (Gaul and Wood, 2000). The construction of stabilization structures can effectively protect coastal property in the short-term; however the negative impact of many of these structures on local and neighboring sediment transport and beach profiles has been well documented (National Research Council, 1995; Dean, 1999; Psuty and Ofiara, 2002).

During the later part of the 20th Century, New Jersey shifted its coastal management efforts to nonstructural approaches, such as beach nourishment, and dune construction and stabilization (NJ DEP, 1981; Psuty and Ofiara, 2002). Beach nourishment requires the trucking or pumping of sand onto an eroded or disappearing beach. This approach addresses the central problem of inadequate sediment supply but with a significant price tag. Nationally, nearly 40 million cubic meters of sand has been placed in beach fill projects, at a cost to taxpayers of over $3.2 billion over the last 80 years, adjusted for inflation (Gaul and Wood, 2000; Gornitz et al., 2002). The continual erosion and displacement of nourished beach areas requires that sand continually be replenished to maintain the shoreline position, generally with a 3- to 5- year maintenance cycle, not accounting for storm and flood events. Future sea level rise notwithstanding, it has been estimated that the state will need approximately $5 billion over the next 50 years to meet its beach nourishment demands (Gaul and Wood, 2000).

Land use planning and building codes can play in important role in coastal hazard management. In New Jersey, and the U.S. at-large, there remains a significant lack of public understanding of the predictability of coastal hazards and hazard mitigation. Episodic flooding events due to storm surges are often perceived as 'natural disasters', not failures in land use planning and building code requirements. The presidential declaration of 'federal disaster areas' and the release of millions of dollars in state aid following major storm events may help foster the perception of storms as unpredictable 'disasters' resulting in unpreventable damage. Some property damage is unavoidable in the coastal zone from large storm systems, particularly along the oceanfront near a hurricane landfall. However, current research suggests that the total property damage related to coastal hazards is highly dependent on the design and elevation of the homes, buildings and other structures near the shoreline (Rogers and Tezak, 2004).

FEMA requires that all new coastal structures be built with the 100-year flood water level as their basis in order to qualify for insurance through the National Flood Insurance Program. New Jersey, in conjunction with national and local agencies, has approved numerous grants for the purpose of elevating residential dwellings in high risk areas. A disturbing trend, however, is that significant development continues to take place in hazardous coastal regions (NJ DEP, 2001a). The current coastal management regulations do include provisions to direct new development away from high hazard areas but the in-place reconstruction and expansion of existing development (including storm damaged property) remains largely unaffected (NJ DEP, 2001a).

A gradual withdrawal of development from the shoreline could limit the value of at-risk property and allow natural systems to migrant inland. However, abandoning coastal property or property in wetland migration paths is not a step many property owners are willing to take by choice. Withdrawing from the coastline could be achieved through "rolling easement" policies, through which human activities are required to yield to naturally migrating shorelines (Titus, 1991; Titus et al., 1991; Titus, 1998). Rolling easement policies, as articulated by Titus (1991), shift the risk of sea level rise primarily to property developers by institutionalizing the accretion and inland migration of coastal wetlands. Developers must then weigh the risk of sea level rise with the risk of the eventual abandonment of structures. Over time, according to Titus (1991), structures built in coastal areas will be viewed in terms of "limited lifetimes" and new structures will be constructed which can be moved. Ultimately, through the gradual withdrawal of development from the coast, construction on property in areas susceptible to sea level rise will be curtailed, gradually allowing coastal wetlands to adapt. Such policies pose a myriad of political and legal challenges due to the nature of current regulatory takings doctrine especially given that most coastal wetlands are privately owned (Titus, 1998). Furthermore, the New Jersey Department of Environmental Protection has been largely unsuccessful in defending coastal development permit denials when litigation has been brought by private parties (NJ DEP, 2001a).

Several states, including Maryland and Florida, currently have programs in place for acquiring vulnerable coastal areas (Godschalk et al., 2000). In southern New Jersey, the New Jersey Department of Environmental Protection has succeeded in preserving approximately 11 km^2 of wetlands and an additional 11 km^2 of upland areas in the wetland migration path through direct collaboration with local industries (NJ DEP, 2001a). In 1999, New Jersey enacted the Garden State Preservation Trust Act which allows for the preservation of one million acres of open space, farmland, and historic land by 2009 through the use of $98 million annually from sales tax revenues and up to $1 billion in revenue bonds (NJ DEP, 2001a). The Green Acres Program has used state funding to acquire more than 81 km^2 of land in Atlantic, Cape May, Monmouth, and Ocean counties including almost 1 km^2 of beachfront, dune, and wetlands along Delaware Bay (NJ DEP, 2001a). However, neither the Garden State Preservation Trust Act nor the Green Acres Program has funding specifically dedicated for the acquisition of coastal wetland or shoreline areas.

In 2001, the New Jersey Department of Environmental Protection evaluated the state's current coastal management strategy as required under Section 309 of the federal Coastal Zone Management Act (NJ DEP, 2001a). The report notes that:

> "As more shoreline protection structures are built, shorelines become more defined and static, and the ability of wetland systems to migrate upland in response to sea level rise will be inhibited. This will likely result in the increased inundation and drowning of wetlands" (NJ DEP, 2001a).

The report goes on to note that the maintenance and establishment of large undeveloped buffers between wetlands and shoreline protection structures would help address this concern. Despite the outright acknowledgement of the susceptibility of New Jersey's wetlands to sea level rise, the report makes no mention of current policy initiatives to address this critical issue. Instead the current regulatory framework continues to allow a net loss of wetlands due to human reclamation and clearly fails to protect the areas where wetlands and other coastal ecosystems would naturally migrate as sea level rises (NJ DEP, 2002).

The decision of when and how to respond to sea level rise in a particular coastal area will depend on the balance of economic, environmental, and societal factors. Studies have attempted to quantify the direct economic costs associated with sea level rise; however such analyses continue to face significant uncertainty (Titus et al., 1991; Yohe and Schlesinger, 1998; Darwin and Tol, 2001; Hitz and Smith, 2004). However, the work of Yohe and Neumann (1997) suggests in the face of climate uncertainty, measures which only protect the current shoreline and do not anticipate sea level rise will likely result in the highest adaptation costs in the long-run.

An important, and often underemphasized, strategy for decreasing the adaptation costs to sea level rise would be to decrease global greenhouse gas emissions. The release of anthropogenic greenhouse gases, notably CO_2, exacerbates global warming which accelerates the rate of sea level rise. Several studies have attempted to determine response of sea level rise to different greenhouse gas emission scenarios (Wigley, 1995; Smith et al., 2000; Nicholls and Lowe, 2004; Wigley, 2005). Although substantial quantitative uncertainties exist in this research, and the uncertainties increase with time, the general modeled trends provide valuable insight.

It is expected that sea level will to continue to rise at an almost a constant rate for centuries after climate stabilization is achieved. This "commitment" to sea level rise resulting in part from thermal expansion in the oceans (leading to an increase in ocean volume and increased sea level) will continue in the deep ocean layers long after temperature stabilization (Wigley, 1995). As a result, current models suggest that greenhouse gas mitigation will have a limited impact on sea level rise rates during the next 50 years. However, decreasing the stabilization concentrations of greenhouse gases could produce decreases in the rate of sea level rise by the year 2100, particularly with the assumption of mid to high climate sensitivity (Smith et al., 2000; Nicholls and Lowe, 2004). The benefits of decreased stabilization concentrations would likely be even more significant during the 22nd century and beyond (Wigley, 1995; Nicholls and Lowe, 2004).

Greenhouse gas emission mitigation can decrease the rate of sea level rise and its associated impacts on the coastal zone under all realistic scenarios. The work of Nicholls and Lowe (2004) suggests that unmitigated emissions could lead to the inundation of vast additional coastal wetland areas and the flooding of millions of people each year by the end of this century. The trend emerging from the current literature is that lowering the stabilization concentration of greenhouse gases will significantly impact future rates of sea level change. As such, national and international action is needed in the near-term to ensure that greenhouse gas concentrations are minimized in order to mitigate the deleterious impacts of sea level rise and other components of

8. Summary and Conclusions

Sea level rise has altered the physical and ecological composition of the New Jersey coast for millennia. Shorelines have long accreted and eroded, barrier islands have disappeared and reformed, and wetlands have migrated inland. Despite short-term and at times dramatic changes to the physical and ecological nature of the coast, the basic forms and habitats have been present for over 2,500 years (Psuty, 1996; Psuty and Ofiara, 2002). Accelerated sea level rise, driven by global climate change, will continue to affect the New Jersey coast through permanent inundation, episodic flooding, beach erosion and increased saline intrusion of low-lying areas. As a result, a wide range of impacts on socioeconomic and natural systems is anticipated, including increased damage of property and infrastructure, net loss of coastal wetlands and beaches, declines in coastal bird and wildlife populations and the contamination of groundwater supplies.

Faced with the impacts of a rising sea, the state of New Jersey has responded with a variety of structural and non-structural approaches, with a recent focus on beach nourishment. The primary components of New Jersey's hazard mitigation strategy consist of the acquisition of vulnerable property, beach and dune enhancement, elevating and retrofitting flood-prone structures, and public education. Due to the high value of coastal property and tourism revenues, the use of further structural devices and beach replenishment projects in certain regions may be cost-effective in the near-term. However, management policies that emphasize the permanent protection of the current shoreline will likely result in increased costs and environmental damage when compared to management strategies that require the gradual withdrawal of development from the coast (Yohe and Newmann, 1997).

Management programs focused on protecting the current shoreline will likely lead to the elimination of wetlands and natural beaches in most developed regions (Titus et al., 1988; Titus et al., 1991; Titus, 2000). New Jersey's Garden State Preservation Trust Act provides the statutory framework and funding base needed to implement a plan for purchasing threatened wetland areas and undeveloped buffers between wetlands and development. However, most coastal wetlands are privately owned and the government can only protect a minority through an acquisition program (Titus, 1991; McCrery and Adams, 1995; Titus, 2000). It is more likely that significant portions could be protected through the implementation of a regulatory program requiring the gradual withdrawal of development from the coast. Policies, such as rolling easements, focused specifically at the preservation of coastal ecosystems could prove useful. If future coastal management policies do not accommodate the natural inland migration of beaches and wetlands, these natural systems may disappear beneath the rising sea and the ecological, economic, and social benefits they provide will be lost.

The balance of scientific evidence suggests that the emission of greenhouse gases is associated with increases in global average temperature and the acceleration of sea level rise (IPCC 2001; Cazenave and Nerem, 2003). Current modeling states that limiting the stabilization concentrations of greenhouse gas emissions will reduce the rate of sea level rise and overall cost of sea level adaptation over the next one hundred years, with significant benefits predicted by the 22nd Century and beyond (Wigley, 1995; Smith et al., 2000; Nicholls and Lowe, 2004; Hitz and Smith, 2004; Wigley, 2005). Limiting the emission of greenhouse gases could also significantly decrease the number of additional people flooded each year and the rate of coastal wetland loss both in New Jersey and around the globe (Nicholls, 2004). The significant impacts associated with accelerated sea level rise, along with the deleterious impacts associated with global warming, should inspire efforts to decrease greenhouse gas emissions.

While limitations of the data and other sources of uncertainty remain we do not believe that resolving these uncertainties would alter the general patterns of sea level rise and the susceptibility of natural and socioeconomic systems presented in this study. The impacts of sea level rise can be estimated with relative confidence when compared with effects associated with increasing global temperature on sectors such as terrestrial biodiversity, marine ecosystem productivity, or the spread of vector born diseases (Hitz and Smith, 2004; Rosenzweig and Solecki, 2001). Sea level rise is among the more avoidable consequences of global warming.

The study of sea level rise and its impact on coastal systems throughout the United States and the world remains limited due to the low resolution of digital elevation models for coastal regions. However, higher resolution elevation data, such as that produced with InSAR and LIDAR technologies, is being developed and will permit more accurate mapping of the coastal zone. This high resolution data will be used in the future to identify regions sensitive to inundation and flooding and to monitor long term and episodic patterns of coastal beach erosion (NOAA, 2004a). Further research is necessary to identify how individual flora and fauna will respond to the impacts of sea level rise. In the case study area of Cape May Point we discussed in general terms how rising sea levels may impact vulnerable migratory species. More detailed studies are needed to determine which species are most vulnerable and to identify the most ecologically sensitive regions for protection. In addition, research into the effect of sea level rise on groundwater contamination will help mitigate potential problems and assure adequate drinking water sources in the future.

The past and current affect of sea level rise on the New Jersey coast are apparent. What is much less obvious and more difficult to predict is the future impact of increasing rates of sea level rise and climate change on the state's valuable socioeconomic and natural systems. This study, based on plausible projections, has assessed the susceptibility of the state's coastal areas to the effects of inundation, flooding, erosion and saline intrusion and articulated a range of adaptation and mitigation opportunities. What is evident from the findings is that action needs to be taken immediately and at many levels. Strategies and initiatives which address coastal management at the state and national level are vital. Effective mitigation of the impacts of sea level rise also requires a concerted and long term effort aimed at climate stabilization.

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References

Andres, B.A. et al.: 2003, *Delaware Bay Shorebird – Horseshoe Crab Assessment Report*, U.S. Fish and Wildlife Service, Division of Migratory Bird Management.

Atlantic City Regional Chamber of Commerce: 2004, *What to see and do in Atlantic City?* http://www.atlanticcitychamber.com/.

Bird, E.C.F.: 1985, *Coastline Changes*, Wiley and Sons, New York.

Bruun, P.: 1962, ‘Sea Level Rise as a Cause of Shore Erosion’, *Journal of Waterways and Harbors Division* **88**, 117-130.

Camp Dresser and McKee, Inc.: 1982, *Groundwater Management Plan for Study Area 1: Coastal Plain Formations*, Delaware Bay Basin Commission, Trenton, NJ.

Castro, G. and Myers, J.P.: 1989, ‘Flight Range Estimates for Shorebirds’, *Auk* **106**, 474-476.

Cazenave, A. and Nerem, R.S.: 2004, ‘Present Day Sea Level Change: Observations and Causes’, *Review of Geophysics* **42**, 1-20.

Church, J.A. et al.: 2001, ‘Changes in Sea Level’, in Houghton et al., (eds), *Climate Change 2001, the Scientific Basis*, Cambridge University Press, Cambridge, pp. 639-693.

Clark, K.E. et al.: 1993, ‘Abundance and Distribution of Migrant Shorebirds in Delaware Bay’, *Condor* **95**, 694-705.

Cooper, J.A.G. and Pilkey O.H.: 2004, ‘Sea level Rise and Shoreline Retreat: Time to Abandon the Bruun Rule’, *Global and Planetary Change* **43**, 157-171.

Dahl, T.E.: 1990, ‘*Wetland Losses in the United States 1780’s to 1980’s’*, U.S. Fish and Wildlife Service, Washington DC.

Darwin, R.F. and Tol, R.S.J.: 2001, ‘Estimates of the Economic Effects of Sea Level Rise’, *Environmental and Resource Economics* **19**, 113-129.

Dean, C.: 1999, ‘*Against the Tide: The Battle for America’s Beaches’*, Columbia University Press, New York.

Donnelly, J.P. et al.: 2001, ‘Sedimentary Evidence of Intense Hurricane Strikes from New Jersey’, *Geology* **29**, 615-618.

Douglas, B.C.: 1991, ‘Global Sea Level Rise’, *Journal of Geophysical Research* **96**, 6981-6992.

Douglas, B.C.: 1997, ‘Global Sea Level Acceleration’, *Journal of Geophysical Research* **97**, 12699-12706.

Erwin, R.M.: 2003, *Atlantic Sea Level Rise, Lagoonal Marsh Loss and Wildlife Habitat Implications*, USGS Patuxent Wildlife Research Center, http://www.pwrc.usgs.gov/resshow/erwin1rs/erwin1rs.htm

Federal Emergency Management Agency: 1991, *Projected Impact of Sea Level Rise on the National Flood Insurance Program*. FEMA, Washington DC.

FEMA: *See* Federal Emergency Management Agency.

Field, J.C. et al.: 2000, ‘Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources’, in National Assessment Synthesis Team (eds.), *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.

Fleming, K. et al.: 1998, ‘Refining the Eustatic Sea Level Curve since the Last Glacial Maximum using Far- and Intermediate Field Sites’, *Earth and Planetary Science Letters* **163,** 327-342.

Galbraith, H. et al.: 2002, ‘Global Climate Change and Sea Level Rise, Potential Losses of Inter-tidal Habitat for Shorebirds’, *Waterbirds* **25**, 173-183.

Galgano et al.: 1998, ‘Trends and Variability of Shoreline Position’, *Journal of Coastal Research* **26**, 282-291.

Gaul, G.M. and Wood, A.R.: 2000, ‘Crisis on the Coast, the Risky Development of America’s Shores’, *Philadelphia Inquirer,* March 1-6.

Godschalk, D.R. et al.: 2000, ‘Avoiding Coastal Hazard Areas, Best State Mitigation Practices’, *Environmental Geosciences* **7**, 13-22.

Gornitz, V.M. and Lebedeff, S.: 1987, ‘Global Sea Level Changes during the Past Century’, in Nummendal, D. et al. (eds.), *Sea Level Fluctuation and Coastal Evolution*, Society for Economic Paleontologists and Mineralogists **41**, 3-16.

Gornitz, V.M.: 1990, 'Vulnerability of the East Coast, USA to Future Sea Level Rise', *Journal of Coastal Research,* Special Issue **9**, 201-237.

Gornitz, V.M. et al.: 1994, 'The Development of a Coastal Risk Assessment Database: Vulnerability to Sea Level Rise in the U.S. Southeast', *Journal of Coastal Research*, Special Issue **12**, 327-338.

Gornitz, V.M.: 1995, 'Monitoring Sea Level Rise', *Climatic Change* **31**, 515-544.

Gornitz, V.M.: 2001, 'Sea Level Rise and Coasts', in Rosenzweig, C. and Solecki, W.D. (eds.), *Climate Change and the Global City: The Potential Consequences of Climate Variability and Change, Metro East Coast*. Columbia Earth Institute, Columbia University, New York, 21-46.

Gornitz, V.M. et al.: 2002, 'Impacts of Sea Level Rise in the New York City Metropolitan Area', *Global and Planetary Change* **3**, 61-88.

Hartig, E.K. et al.: 2001, 'Wetlands', in Rosenzweig, C. and Solecki, W.D. (eds.), *Climate Change and the Global City: The Potential Consequences of Climate Variability and Change, Metro East Coast*. Columbia Earth Institute, Columbia University, New York, 67-86.

Heinz Center: 2000, *Evaluation of Erosion Hazards*, FEMA, Washington DC.

Hitz, S. and Smith, J.: 2004, 'Estimating Global Impacts from Climate Change', *Global Environmental Change Part A* **14**, 201-218.

Hoozemans, F.M.J. et al.: 1993, *A Global Vulnerability Assessment for Population, Coastal Wetlands and Rise Production on a Global Scale*, Delft Hydraulics, Netherlands.

Hull, C.H.J. and Titus, J.G.: 1986, *Greenhouse Effect, Sea Level Rise, and Salinity in the Delaware Estuary*, Environmental Protection Agency (EPA 230-05-86-010), Washington DC.

Intergovernmental Panel on Climate Change: 2001, 'Summary of Policymakers, A report of Working Group 1of the Intergovernmental Panel on Climate Change', in *Climate Change 2001, the Scientific Basis*, Cambridge University Press, Cambridge, pp 1-20.

IPCC: *See* Intergovernmental Panel on Climate Change.

Jouzel, J et al.: 1989, 'A Comparison of Deep Antarctic Cores and their Implications for Climate between 65,000 and 15,000 Years Ago', *Quaternary Research* **31**, 135-150.

Kyper, T. and Sorenson, R.: 1985, 'Potential Impacts of Selected Sea Level Rise Scenarios on the Beach and Coastal Works of Sea Bright, New Jersey', in Magoon, O.T. et al. (eds.), Coastal Zone '85, American Society of Engineers, New York.

Lambeck K. and Bard, E.: 2000, ‘Sea Level Change along the French Mediterranean Coast for the Past 30,000 Years’, *Earth and Planetary Science Letters* **175**, 203-222.

Landsea, C.W. et al.: 1999, ‘Atlantic Basin Hurricanes: Indices of Climatic Changes’, *Climate Change* **42**, 89-129.

Leatherman, S.P.: 1991, ‘Modeling Shore Response to Sea Level Rise on Sedimentary Coasts’, *Progress in Physical Geography* **14**, 447-464.

Leatherman, S.P. et al.: 2000, ‘Sea Level Rise Shown to Drive Coastal Erosion’, *EOS Transactions* **81**, 55-57.

Luzier, J.E.: 1980, *Digital Simulation and Projection of Head Changes in the Potomac-Raritan-Magothy Aquifer System, Coastal Plain, New Jersey*, U.S. Geological Survey Water Resources Investigations 80-11, Washington DC.

Major, D.C. and Goldberg, R.: 2001, ‘Water Supply’, in Rosenzweig, C. and Solecki, W.D. (eds.), *Climate Change and the Global City, The Potential Consequences of Climate Variability and Change, Metro East Coast*, Columbia Earth Institute, Columbia University, New York, pp 87-101.

McCrery, S.T. and Adams, M.B.: 1995, ‘Managing Wetlands through Advanced Planning and Permitting: The Columbia River Estuary Task Force’, in Porter, D.R. and Salvesen, D.A. (eds.), *Collaborative Planning for Wetlands and Wildlife: Issues and Examples*, Island Press, Washington DC, pp 103-138.

Mclean, R.F. et al.: 2001, ‘Coastal Zones and Marine Ecosystems’, in McCarthy, J.J. et al. (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge University Press, Cambridge, pp 343-379.

Najjar, R.G. et al.: 2000, ‘The Potential Impacts of Climate Change on the mid-Atlantic Coastal Region’, *Climate Research* **14**, 219-233.

NOAA: *See* National Oceanic and Atmospheric Administration.

National Geodetic Society: 2004, *Frequently Asked Questions about the National Geodetic Survey*, http://www.ngs.noaa.gov/faq.shtml

National Oceanic and Atmospheric Administration: 2004a, *An Evaluation of Hurricane-Induced Erosion along North Carolina Coast using Airborne LIDAR surveys*, NOAA Coastal Services Center, Charleston.

National Oceanic and Atmospheric Administration: 2004b, *Mean Sea Level Trends for Stations in New Jersey,* http://coops.nos.noaa.gov/sltrends/sltrends_states.shtml?region=nj

National Research Council: 1990, *Managing Coastal Erosion*, National Academy Press, Washington DC.

National Research Council: 1995, *Beach Nourishment and Protection*, National Academy Press, Washington DC.

New Jersey Coastal Management Program: 2002a, *What is the New Jersey Coast? Fact Sheet 2*. NJ Department of Environmental Protection, Trenton, http://www.state.nj.us/dep/cmp/fact2.pdf

New Jersey Coastal Management Program: 2002b, *Ocean Resources Management in New Jersey: Fact Sheet 3*, NJ Department of Environmental Protection, Trenton, http://www.nj.gov/dep/cmp/fact3.pdf

New Jersey Department of Environmental Protection: 1981, *New Jersey Shore Protection Master Plan*, Department of Environmental Protection, Trenton.

New Jersey Department of Environmental Protection: 1991, *Shoreline Position Dataset*, Department of Environmental Protection, Trenton, http://www.state.nj.us/dep/gis/digidown/metadata/statewide/histshore.htm.

New Jersey Department of Environmental Protection: 2001a, *Coastal Management Program Section 309 Assessment*, New Jersey Department of Environmental Protection, Office of Coastal Planning, Trenton.

New Jersey Department of Environmental Protection: 2001b, *Anderson Classification System*, http://www.state.nj.us/dep.gis/digidownload/metadata/lulc95/anderson.html

New Jersey Department of Environmental Protection: 2002, *Creating Indicators of Wetland Status: Freshwater Wetland Mitigation in New Jersey*, Department of Environmental Protection, Trenton.

New Jersey Department of Environmental Protection: 2004, *Imperiled Shorebirds on Delaware Bay: What Can You Do To Help?* Department of Environmental Protection, Trenton.

New Jersey Department of Environmental Protection: 2003, *New Jersey's Threatened and Endangered Wildlife*, Department of Environmental Protection. http://www.nj.gov/dep/fgw/tandespp.htm

New Jersey Department of Environmental Protection: 2004, *Beach Nourishment*, Department of Environmental Protection, Shoreline Protection and Coastal Engineering. http://www.nj.gov/dep/shoreprotection/nourishment.htm.

New Jersey Department of Environmental Protection: Bureau of Geographic Information Systems, 2004, http://www.nj.gov/dep/gis/

NJ DEP: *See* New Jersey Department of Environmental Protection.

NJ DEP BGIS: *See* New Jersey Department of Environmental Protection, Bureau of Geographic Information Systems.

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*, Trenton. http://www.nj.gov/labor/lra/

New Jersey Division of Taxation: 2004, 2003 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, http://www.njmsc.org/

Nicholls, R.J. and Leatherman, S.P.: 1996, 'Adapting to Sea Level Rise: Relative Sea Level Trends to 2100 for the United States', *Coastal Management* **24**, 301-324.

Nicholls, R.J. et al.: 1999, 'Increasing Flood Risk and Wetland Loss Due to Global Sea Level Rise: Regional and Global Analysis', *Global Environmental Change* **9,** 69-87.

Nicholls, R.J. and Small, C.: 2002, 'Improved Estimates of Coastal Population Exposure to Hazards Released', *Eos* **83**, 303-305.

Nicholls, R.J.: 2003, *Case Study on Sea Level Rise Impacts*. Prepared for OECD workshop on the Benefits of Climate Policy: Improving Information for Policy Makers: December 12-13, 2002, Working Party on Global and Structural Policies, Organization for Economic Cooperation and Development, Paris.

Nicholls, R.J. and Lowe, J.A.: 2004, 'Benefits of Mitigation of Climate Change for Coastal Areas', *Global Environmental Change* **14**, 229-244.

Nordstrom, K.F. et al.: 1977, *Coastal Geomorphology of New Jersey*, in Technical Report 77-1, Volumes I and II, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, NJ.

Ocean County Department of Planning: 2002, *Historical Population Trends in New Jersey, 1930-2000*, http://www.co.ocean.nj.us/planning/databook.

Peltier, W.R. and Jiang, W.: 1997, 'Mantle Viscosity, Glacial Isostatic Adjustment and Eustatic Sea Level of the Sea', *Surveys in Geophysics* **18**, 239-277.

Phillips, J.D.: 1986, 'Spatial Analysis of Shoreline Erosion, Delaware Bay, New Jersey', *Annals of the Association of American Geographers* **76**, 52-62.

Psuty, N.P. et al.: 1996, *Coastal Hazard Management Report*, Final Report to NJ DEP, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ.

Psuty, N.P.: 1996, 'A White Paper on the Measurements of Sea Level Rise in New Jersey and a Perspective on the Implications for Management', Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ.

Psuty, N.P. and Ofiara, D.D.: 2002, *Coastal Hazard Management, Lessons and Future Directions from New Jersey*, Rutgers University Press, New Brunswick, NJ.

Rogers, S.P. and Tezak, E.S.: 2004, 'Hurricane Isabel Damage to North Carolina Buildings', *Shore and Beach* 72, 38-47.

Rosenzweig, C. and Solecki, W.D.: 2001, *Climate Change and the Global City, The Potential Consequences of Climate Variability and Change, Metro East Coast*, Columbia Earth Institute, Columbia University, New York.

Shuster, C.N.: 1982, 'A Pictorial Review of the Natural History and Ecology of the Horseshoe Crab *Limulus polyphemus*, with Reference to other Limulidae', in Boneventura, J. et al. (eds.), *Physiology and Biology of Horseshoe Crabs, Studies on Normal and Environmentally Stressed Animals*, Alan Liss, New York.

Shuster, C.N. and Botton, M.L.: 1985, 'A Contribution to the Population Biology of Horseshoe Crabs *Limulus polyphemus* in Delaware Bay'*, Estuaries* **8**, 363-372.

Smith, S.J. et al.: 2000, 'Climate Implications of Greenhouse Gas Emissions Scenarios', Technology Forecasting and Social Change, **65**, 195-204.

Steetzel, H.J.: 1991, 'A Model for Profile Changes during Storm Surges, *Coastal Sediments* **1991**: 618-630.

Thieler, E.R. and Hammer-Klose, E.S.: 1999, National Assessment of Coastal Vulnerability to Future Sea Level Rise: Preliminary Results for the U.S. Atlantic Coast, U.S. Geological Survey Open-File Report 99-593. http://woodshole.er.usgs.gov/epubs/openfiles/ofr99-593/

Titus, J. G. and Barth, M.C.: 1984, 'An Overview of the Causes and Effects of Sea Level Rise', in Barth, M.C. and Titus, J.G. (eds.), *Greenhouse Effect and Sea Level Rise, A Challenge for this Generation*, Van Nostrand Reinhold Company, New York.

Titus, J.G. 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.

Titus, J.G. et al.: 1988, *Greenhouse Effect, Sea Level Rise and Coastal Wetlands*, U.S. Environmental Protection Agency, Washington DC.

Titus, J.G.: 1989, 'Sea Level Rise', in *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.

Titus, J.G.: 1990, 'Greenhouse Effect, Sea Level Rise and Barrier Islands, Case Study of Long Beach Island, New Jersey', *Coastal Management* **18**, 65-90.

Titus, J.G. et al.: 1991, 'Greenhouse Effect and Sea Level Rise, the Cost of Holding

Back the Sea', *Coastal Management* **19**, 171-204.

Titus, J.G.: 1991, 'Greenhouse Effect and Coastal Wetland Policy: How Americans Could Abandon an Area the Size of Massachusetts at Minimum Cost', *Environmental Management* **15**, 39-58.

Titus, J.G.: 1998, 'Rising Seas, Coastal Erosion and the Takings Clause, How to Save Wetlands and Beaches without Hurting Property Owners', *Maryland Law Review* **57**, 1279-1399.

Titus, J.G.: 2000, 'Does the U.S. Government Realize that the Sea is Rising? How to Restructure Federal Programs to so that Wetlands and Beaches Survive', *Golden Gate University Law Review* **30**, 717-778.

Titus, J.G. and Richman, C.: 2000, 'Maps of Lands Vulnerable to Sea Level Rise, Modeled Elevations along the U.S. Atlantic and Gulf Coasts', *Climate Research* **18**, 205-228.

United States Census Bureau: 2004, Map of New Jersey, http://www.census.gov/geo/www/maps/CP_MapProducts.htm

United States Army Corps of Engineers: 1971, *National Shoreline Study, Regional Inventory Report for the North Atlantic Region*, Vol. 1-2, North Atlantic Division, New York.

United States Environmental Protection Agency: 1988a, *Sole Source Aquifer Determination for the New Jersey Coastal Plain Aquifer System*, Federal Register Notice 53(122), U.S. Environmental Protection Agency, Washington DC. http://www.epa.gov/region02/water/aquifer/coast/coastpln.htm

United States Environmental Protection Agency: 1998, *Condition of the Mid-Atlantic Estuaries*,
U.S. Environmental Protection Agency (600-R-98-147), Washington DC.

United States Fish and Wildlife Service: 2004, *Federally Listed Endangered and Threatened Species in*
New Jersey, United States Fish and Wildlife Service, Washington DC. http://njfieldoffice.fws.gov/Endangered/eslist.htm#candidate

United States Geological Survey: 1996, *U.S. Geological Survey Programs in New Jersey*, USGS Fact Sheet FS-030-96, United States Geological Survey, Washington DC.

United States Geological Survey: 1997a, *Global Warming, Sea Level Rise and Coastal Marsh Survival*, USGS Fact Sheet 091-97, United States Geological Survey, Washington DC.

United States Geological Survey: 1997b*, Global Change and Submerged Aquatic Vegetation Research*, USGS Fact Sheet 090-97, United States Geological Survey, Washington DC.

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

United States Geological Survey: 2003, Land Cover Class Definitions, United States Geological Survey, Washington DC. http://landcover.usgs.gov/classes.asp

United States Geological Survey: 2004, *Vulnerability of Production Wells in the Potomac-Raritan-Magothy Aquifer System to Saltwater Intrusion from the Delaware River in Camden, Gloucester and Salem Counties, New Jersey*, USGS Scientific Investigations Report 2004-5096, United States Geological Survey, Washington DC.

U.S. EPA: *See* United States Environmental Protection Agency.

U.S. FWS: *See* United States Fish and Wildlife Service.

USGS: *See* United States Geological Survey.

Weiss, J. and Overpeck, J.T.: 2003, *Climate Change and Sea Level: Maps 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

Wigley, T.M.L.: 1995, ‘Global-Mean Temperature and Sea Level Consequences of Greenhouse Gas Concentration Stabilization’, *Geophysical Research Letters* **22**, 45-48.

Wigley, T.M.L.: 2005, ‘The Climate Change Commitment’, *Science* **307**, 1766-1769.

Wu, S.Y. et al.: 2002, ‘Vulnerability of Coastal Communities to Sea Level Rise, a Case Study of Cape May County, New Jersey, USA’, *Climate Research* **22**, 255-270.

Yohe, G.W. and Neumann J.: 1997, ‘Planning for Sea Level Rise and Shore Protection under Climate Uncertainty’, *Climatic Change* **37**, 243-270.

Yohe, G.W. and Schlesinger, M.E.: 1998, ‘Sea Level Change, the Expected Economic Cost of Protection or Abandonment in the United States’, *Climatic Change* **38**, 447-442.

Zhang K. et al.: 1997, ‘U.S. East Coast Storm Surges Provide Unique Climate Record’, *EOS Transactions* **78**, 389, 396-397.

Zhang, K. et al.: 2001, ‘Beach Erosion Potential for Severe Nor’easters’, *Journal of Coastal Research* **17**, 309-321.

Zhang K. et al.: 2004, ‘Global Warming and Coastal Erosion’, *Climate Change* **64**, 41-58.