CLIMATE CHANGE AND A GLOBAL CITY: AN ASSESSMENT OF THE THE METROPOLITAN EAST COAST (MEC) REGION

COASTAL ZONE SECTOR REPORT:

SEA LEVEL RISE AND COASTAL HAZARDS

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INTRODUCTION

Anticipated climate changes will greatly amplify risks to coastal populations. By the end of the century, a 2-5-fold increase in rates of global sea level rise could lead to inundation of low-lying coastal regions, including wetlands, more frequent flooding due to storm surges, and worsening beach erosion (IPCC, 1996a,b). Saltwater could penetrate further up rivers and estuaries, and infiltrate coastal aquifers, thereby contaminating urban water supplies.

In the metropolitan New York, Connecticut, and New Jersey (MEC) region, as elsewhere, the coastal zone is squeezed between the hazards of flooding, beach erosion, and sea level rise, on the one hand, and development pressures, on the other hand. In this area, ongoing sea level rise and land subsidence have historically contributed to beach erosion, narrowing of barrier islands, and storm-related damages. These processes will continue and possibly worsen, if projected climate changes materialize.

This report focuses on potential impacts of sea level rise on the Metropolitan East Coast (MEC) region and how natural processes interact with increasing urbanization and land-use changes. We present the results of a suite of sea level projections for several plausible scenarios of climate change in the MEC region. Estimates are also made of future coastal flood heights, return intervals, increases in sand volumes, and costs for beach nourishment under these scenarios at selected case study sites (Fig. 1). Implications of these findings for coastal management will also be discussed.

Global Sea Level Trends

Mean global sea level has been increasing by 0.04 to 0.1 in/yr (1-2.5 mm/yr), for the last 150 years, with 0.07 in/yr (1.8 mm/yr) considered the "best estimate" (Warrick et al., 1996; Gornitz, 1995a). This is the most rapid rate within the last few thousand years (Varekamp and Thomas, 1998; Gornitz, 1995b) and is probably linked to the 20th century global warming of nearly 1°F (0.5°C) (IPCC, 1996a). Additional evidence of warming comes from the world's oceans, where temperatures have risen an average of 0.1°F (0.06°C) between 1955 and 1995, down to a depth of around 10,000 ft (3000 m; Levitus et al., 2000).

Most of the observed sea level rise can be attributed to thermal expansion of the upper ocean layers and melting of mountain glaciers, with nearly zero contributions from polar ice sheets at present (Warrick et al., 1996). Human modification of the hydrologic cycle could also affect sea level rise. Sequestration of water on land in reservoirs and through irrigation losses could exceed amounts transfered seaward by groundwater mining and increased runoff due to urbanization and deforestation. The net effect of these processes could slow sea level rise by 0.04±0.02 in/yr (0.9±0.5 mm/yr) (Gornitz et al., 1997; Gornitz, 2000).

Closely-linked atmospheric-oceanic processes such as the El Nino-Southern Oscillation or the North Atlantic Oscillation generate considerable interannual variability in ocean heights, superimposed on longer-term trends (Nerem, 1999; Hurrell, 1995). Above average sea levels, coastal storms, and cliff erosion are associated with El Nino events on the U.S. West Coast (Komar and Enfield, 1987). While above average sea levels occur in southeastern U.S. and northwestern Europe during the positive phase of the North Atlantic Oscillation, its effects on the MEC region are less clearly-defined (Maul and Hanson, 1991; V. Gornitz, unpubl. data).

The future of the Antarctic ice sheet introduces a major uncertainty into sea level projections. Most global climate models anticipate higher rates of Antarctic snow/ice accumulation than melting. This would remove water from the ocean and reduce sea level (Warrick et al., 1996). On the other hand, a large part of the West Antarctic ice sheet is potentially unstable because it rests on land now below sea level or forms floating ice shelves, which are locally "pinned" or stabilized by submarine ridges. These prevent rapid discharge of ice from fast-moving ice streams. Ocean warming could eventually thin and "unpin" these shelves, which would accelerate the calving of icebergs into the ocean. The melting of this additional ice over several centuries could raise sea level by some 16.4-19.7 feet (5-6 meters). This process, although considered very unlikely, would have devastating consequences on low-lying coastal areas worldwide, if it were to occur (Oppenheimer, 1998).

Regional Sea Level Trends

Sea level has been rising along the U.S. East Coast since the end of the last glaciation. Although most deglaciation ended over 6000 years ago, sea level has continued to change due to the time lag with which the earth's crust has responded to the redistribution of mass on its surface following the removal of the ice (i.e., glacial isostatic changes). These sea level changes are spatially non-uniform over time scales of thousands of years to the present.

The MEC region lies at the southern edge of the last ice sheet. The area to the south was upwarped during the Wisconsinan glaciation 20,000 years ago (the "peripheral bulge"), while land to the north was depressed beneath the weight of the ice. As land formerly under the ice sheet rebounded, most of the Atlantic Coast has subsided. (The zone of subsidence due to the collapsed peripheral bulge has migrated northward over time to the Canadian Maritime Provinces. The area north of the St. Lawrence valley is rebounding). Geophysical models have been used to filter these crustal motions from tide-gauge data in the eastern U.S. (Peltier, 1999; Davis and Mitrovica, 1996).

Tide gauges measure relative sea level change, which includes glacial isostatic and other geologic signals, in addition to the more recent global sea level signal (Gornitz, 1995b). Indicators of former sea level (e.g., mollusks, corals, peats, woods, etc.) going back thousands of years can be used to derive a long-term sea level curve which includes these geologic trends. Subtraction of long-term trends from the recent sea-level data leaves the climate-related absolute sea level change. The absolute average sea level-rise for eastern North America is 0.05±0.03in/yr (1.3±0.7 mm/yr; Appendix 1). (Because the rate of sea level rise has decreased over the last several thousand years, a linear regression fit to the geologic data tends to overestimate the correction, thus lowering the modern sea level trend; Gornitz, 1995a).

At present, the rate of relative sea level rise in the MEC region varies between 0.09 in/yr (2.20 mm/yr; Port Jefferson, Long Island) and 0.15 in/yr (3.85 mm/yr; Sandy Hook, New Jersey, Table 1). In New York City, the rate is 0.11 in/yr (2.73 mm/yr, Table 1). These values lie above the estimated global mean SLR, because of the ongoing regional subsidence, but vary slightly from place to place due to various local factors.

Coastal Stressors Independent of Climate

The coastal zone in the MEC region is subjected to a number of natural and human-induced pressures. Beaches are continually changing as sand is shifted by waves, tides, and currents. In the MEC region, beaches are eroding and barrier islands narrowed or driven landward, in part due to ongoing sea level rise and land subsidence.

The relative vulnerability of different coastal environments to sea level rise has been quantified at regional to national scales using information on coastal geomorphology, rates of relative sea level rise, past shoreline movement, topography, and other factors (Gornitz and White, 1992; Gornitz et al., 1994). These physical variables are then combined into a *Coastal Vulnerability Index* (CVI), which ranks the relative vulnerability of the coast into one of four risk categories (from high to low). This methodology has recently been updated and refined by the U.S. Geological Survey (Thieler and Hammar-Klose, 1999).

As shown in Fig. 2, most of the south shore of Long Island and the New Jersey coast, which consist predominantly of barrier islands, lie in the High to Very High risk categories. On the other hand, the north shore of Long Island and the Connecticut coasts, with more varied landforms, (including rocky headlands in Connecticut), are ranked at a relatively much lower risk.

Some of the highest population growth rates in the United States occur in coastal counties. In the Tri-State area, coastal populations have grown by around 17% between 1960 and 1995, with 7 coastal counties displaying growth rates exceeding 100% (Culliton, 1998). High-rise residential complexes are sprouting at water's edge in Jersey City, Hoboken, Edgewater, New Jersey (Fig. 3; Garbarine, 1999), and Battery Park City, lower Manhattan (Fig. 4). New houses are being built on the dunes of the Hamptons, in eastern Long Island, where many expensive homes were lost during severe nor'easters in the winter of 1992-1993 (Fig. 5; Maier, 1998).

Beaches and other open coastal areas represent a prime recreational resource, which offers the urban population of the MEC region relief from the summer heat, swimming, fishing, boating, and other leisure activities. As population continues to grow and additional land is converted to higher density urban uses, less opportunity remains to expand existing public parks and beaches. Furthermore, many seaside communities, particularly on Long Island, limit beach access to non-residents, thus augmenting utilization pressure on existing public facilities. This raises an important equity issue: to what extent should these coastal towns benefit from beach maintainance which is largely supported by taxpayers who live elsewhere?

The historic regional tendency toward coastal erosion, particularly following major storms as shown below, needs to be periodically counteracted by expensive beach replenishment projects (Dean, 1999; NRC, 1990). A number of such projects have been undertaken by the U.S. Army Corps of Engineers in New Jersey and the south shore of Long Island (Table 2, Valverde et al., 1999).

Although not considered in detail in this report, water pollution is another coastal stressor. Pollution often reaches levels that necessitate closure of beaches. Pollution comes from various sources, such as oil slicks and tar balls from tankers, industrial and urban waste, including contaminated hypodermic needles. Noxious algal blooms (e.g., "red tides") occasionally force beach closings. These events are often triggered by warmer than average sea surface temperatures and high pollutant levels.

POTENTIAL IMPACTS OF SEA LEVEL RISE ON THE COASTAL ZONE

Research Questions

This report investigates impacts of climate change on sea level rise and coastal hazards in the MEC region and how these natural processes interact with shoreline development and land-use changes. Coastal hazards to be examined in this report include sudden, high impact events--storm surges and shoreline erosion, as well as slow-onset hazards--sea level rise and resulting land loss. Consequences of saltwater intrusion will be briefly discussed. Impacts on coastal wetlands are covered in a separate report.

Questions to be addressed are:

1. What is the likely range of sea level rise in the MEC region, taking into account local subsidence effects?

2. What are the maximum flood heights that can be expected, superposed on SLR, and what is their frequency of occurrence?

3. What additional beach nourishment requirements and associated costs are anticipated due to the SLR?

4. How will these changes in natural hazards impact coastal communities?

A set of sea level projections is presented for a number of plausible scenarios of climate change for the MEC region. Estimates are also made of future coastal flood heights, return intervals, and increases in sand volumes and costs for beach nourishment under these scenarios at selected case study sites (Fig. 1). Implications of these findings for coastal management will be discussed below.

Existing Coastal Hazards in the MEC Region

This section reviews current coastal hazards, such as shoreline erosion and flooding caused by tropical and extra-tropical storms (hurricanes and nor'easters, respectively).

Coastal Erosion

The shore is an inherently dynamic environment, shaped by waves, tides, and winds, over days, years, centuries, and longer. The amount of sand on a natural beach is a balance between the amount supplied by rivers, cliff erosion, longshore currents, or overwash during major storms vs the amount removed by longshore currents, transport into tidal inlets, lagoons, and the inner shelf, or wind (Fig. 6; Viles and Spencer, 1995). Man-made interference with transport will disrupt these natural processes.

Overview. Over 70% of the world's sandy beaches are retreating (Bird, 1985). In the MEC region, beaches and barrier islands are narrowing or shifting landward, in part due to ongoing sea level rise and land subsidence (see *Regional Sea Level Trends* and *Historical Erosion Trends*). Accelerated sea level rise may intensify the rate and extent of coastal erosion. While sea level rise is an important factor, beach erosion is frequently exacerbated by human activities, such as trapping of silt and sand in upstream reservoirs, disruption of longshore drift by groins and breakwaters, and sand mining. Examples of such effects in the MEC region are presented below.

Historical erosion trends--Long Island. Long Island formed from glacial outwash plains, stream deposits, and moraines, at the end of the last Ice Age, 18,000 years ago. During the marine incursion following the last Ice Age, glacial sands and gravels were eroded and redeposited into ridges and swales on the inner continental shelf and onshore. Barrier islands have migrated landward and upward more or less continuously during the Holocene by "rolling over", i.e., through dune overwash and inlet formation. The modern barriers are geologically young--not more than ~1000 years old, although the ancestral islands lay lower and seaward of their present locations (Leatherman and Allen, 1985).

The south shore of Long Island is now flanked by a string of barrier beaches and islands extending from the Rockaways in the west to Southampton in the east. Headland beaches and bluffs constitute the remainder of the eastern Long Island shoreline toward Montauk Point. Littoral currents move sand from Montauk Point westward toward New York City, except where intercepted by "hard" structures, such as groins or jetties.

Most of the southern Long Island coastline has been eroding between 1834-1979, on average (Leatherman and Allen, 1985). One exception is the western end of Fire Island which has accreted seaward, especially since construction of the Fire Island inlet jetties in 1941. Major coastal erosion also followed construction of the Moriches Inlet and Shinnecock Inlet jetties (1952-1954), and groins near Westhampton in the late 1960s. These "hard" structures have interrupted the natural westward longshore drift (Kana, 1995).

Recent high-resolution sea-floor mapping of the inner continental shelf off Long Island has revealed important geologic and geomorphologic differences between the inner shelf east and west of Watch Hill (at the middle of Fire Island). The steeper shelf and lower sediment supply east of Watch Hill, Fire Island, have led to relatively rapid landward migration and formation of inlets towards the east, in contrast to the western portion of Fire Island (Schwab et al., 2000). The implications of these physiographic differences for some of our case study sites will be discussed below.

Historical erosion trends--northern New Jersey. The northern New Jersey ocean shoreline extends from Sandy Hook in the north to Asbury Park in the south. Sandy Hook is a spit attached to the mainland near Long Branch. The middle portion of the Sandy Hook spit accreted landward prior to 1900. Serious erosion has occurred at the southern end of the spit near Sea Bright. The area south of Sandy Hook, between Monmouth Beach and Asbury Park, is a cliffed coastline. The historic mean erosion rate for the whole northern New Jersey coast was 2.6 ft/yr (0.8 m/yr) between 1836 and 1985 (Gorman and Reed, 1989). The coast south of Sea Bright has generally retreated over the 149-year period, except between 1932 and 1953. Between 1953-1985, the shoreline of northern New Jersey has remained fairly stable, except for two erosion hotspots, around Asbury Park and north of Sea Bright (Gorman and Reed, 1989).

Major beach nourishment projects were undertaken in Sea Bright and Asbury Park in the early 1990s (Bocamazo, 1991), and at Sandy Hook during the 1980s and early 1990s (Psuty and Namikas, 1991). A seawall/groin complex in the Sea Bright area, south of Sandy Hook, has significantly reduced northward longshore sediment flow to Sandy Hook and steepened the nearshore slope. These factors have enhanced natural erosion due to the long-term sea level rise (0.15 in/yr or 3.85 mm/yr at Sandy Hook). These adverse conditions necessitate periodic beach replenishment (Psuty and Namikas, 1991).

The Raritan Bay estuarine coast has receded landward at an average rate of 7.9 ft/yr (2.4 m/yr), between 1836 to 1855/57 (Jackson, 1996). The shoreline expanded seaward by 1.7 ft/yr (0.53 m/yr), between 1855/57 and 1932/34, due to extensive development, and construction of bulkheads, seawalls, and groins designed to protect the shoreline. The 1932/34-1957 period saw a slight erosion (or negative) trend of 1.05 ft/yr (0.32 m/yr). Since 1957, the shoreline has remained relatively stable, except for some growth near beach nourishment projects.

Coastal storms

Nor'easters (extratropical cyclones) are the dominant type of storm producing major coastal flooding and beach erosion, especially north of Chesapeake Bay (Zhang et al., 2000). Nor'easters are most prevalent between January and March. Although wind speeds are lower than in hurricanes, nor'easters generate considerable damage because of their greater areal extent and duration over several tidal cycles at a particular location (Davis and Dolan, 1993; Dolan and Davis, 1994).

Storm frequencies along the East Coast over the last 50 years peaked in the late 1960s, diminished in the 1970s, and rose again in the early 1990s (Zhang et al., 2000; Dolan and Davis, 1994). However, the number or severity of storms has not increased discernibly over this period. Twentieth century tide-gauge records from Atlantic City, NJ and Charleston, SC show no statistically significant trends in either the number or duration of storm surge events, after removing tidal components and long-term sea level rise (Zhang et al., 2000; 1997). The apparent secular increase in flooding is largely a consequence of the regional sea level rise, beach erosion, and coastal development during this period. Thus, rising ocean levels are likely to exacerbate storm impacts.

Significant nor'easters within the last 40 years include the "Ash Wednesday" storm (March 6-7, 1962), the Halloween storm (October 31, 1991), and two other powerful coastal storms on December 11-12, 1992 and March 13-14, 1993. The "Ash Wednesday" storm, with flood levels over 7 feet at the Battery, lower Manhattan, was particularly destructive over the mid-Atlantic states because it lasted for five tidal cycles. However, the December 1992 storm produced some of the worst flooding seen in the New York Metro area in 40 years. The water level at the Battery tide-gauge peaked at 8.5 feet above NGVD (7.8 ft above mean sea level; U.S. ACOE/FEMA/NWS, 1995), when tides were already above normal due to full moon. Flooding of lower Manhattan and portions of the FDR Drive together with near hurricane-force wind gusts led to the almost complete shutdown of the New York metropolitan transportation system. Coastal flooding also forced evacuation of many seaside communities in New Jersey, Connecticut, and Long Island (New York Times, December 12, 1992; Storm Data, December 1992).

The December 1992 storm provided a "wake-up" call, heralding the vulnerability of the metropolitan New York-New Jersey-Connecticut transportation systems to major nor'easters and hurricanes. Most area rail and tunnel points of entry, and airports lie at elevations of 10 feet or less (U.S. ACOE/FEMA/NWS, 1995). This elevation represents a critical threshold. Flood levels of only 1 to 2 feet (0.3-0.61m) above those of the Dec. 1992 storm could have resulted in massive inundation and loss of life.

The vulnerability of the regional transportation system to flooding was demonstrated again on Aug. 26, 1999, when a brief, but severe thunderstorm dumped 2.5 to 4 inches of rain on the New York metropolitan area, nearly paralyzing the system (see New York Times, August 27, 1999; also **Infrastructure** report). With future sea level rise, even less powerful storms could inflict considerable damage (see **Results--*Storm surges and coastal flooding***).

Hurricanes are major tropical cyclones or low-pressure systems that intensify over the open ocean. The destructive power of hurricanes derives from their very high wind speeds (minimum wind speeds of at least 119 km/hr (74 mi/hr), flooding due to the high storm surge and waves, and heavy rainfall. The storm surge is a dome of water produced by the low barometric pressure and strong wind shear, particularly on the right side of the low-pressure system. The height of the surge is amplified if it coincides with the astronomical tide. Waves add to the flooding.

Atlantic basin hurricane records show no secular trends between 1944 and 1996, although distinct multidecadal variations exist (Landsea et al., 1999). For example, many severe hurricanes (Saffir-Simpson categories 3-5; Table 3) occurred between the 1940s through the 1960s. This period was followed by a relative lull during the 1970s through early 1990s and an upswing in hurricane activity in the late 1990s.

Atlantic hurricanes are influenced by the El Nino-Southern Oscillation. During the El Nino phase, tropical vertical shear increases due to stronger upper-atmosphere westerly winds, which inhibit the development and growth of tropical hurricanes. Therefore, Atlantic tropical storms and hurricanes are 36% more frequent and 6% more intense during the La Nina phase of ENSO than during an El Nino (Landsea et al., 1999). The probability of sustaining at least $1 billion in damages is 77% during a La Nina year, as compared to only 32% in an El Nino year, and 48% in a "neutral" year (Pielke and Landsea, 1999).

While hurricanes are much less frequent than nor'easters in the Northeast, they can be even more destructive. At least 9 hurricanes have struck the metropolitan New York City region within the last 200 years, including major ones in 1938, 1893, and 1821 (Coch, 1994). Effects include severe coastal flooding, damage and destruction of beachfront property, severe beach erosion, downed power lines and power outages, and disruption of normal transportation. A powerful hurricane in August, 1893 completely destroyed Hog Island, a barrier island that once existed seaward of Rockaway Beach (Onishi, 1997).

The worst natural disaster to strike the northeastern United States was the hurricane of September 21, 1938, which claimed almost 700 lives and injured several thousands more. This storm, striking with little warning, raised a wall of water 25 to 35 feet (7.6-10.7 m) high (surge plus waves), which swept away protective barrier dunes, and the buildings behind them, on the shores of eastern Long Island, eastern Connecticut, and Rhode island (Ludlum, 1988).

The right angle bend between the New Jersey and Long Island coasts funnels surge waters toward the apex--the New York City harbor. Surge waters also pile up at the western end of Long Island Sound. Surge levels have been computed using a numerical model (SLOSH) that simulates the effects of a hurricane surge for a worst-case scenario Category 3 hurricane (with wind speeds of 111-130 mph on the Saffir-Simpson scale (Table 3; U.S.ACOE/FEMA/NWS, 1995). Maximum surge levels could reach 25 feet (7.6 m) above the National Geodetic Vertical Datum (Appendix 2), not including astronomical tides, at JFK airport, 21 feet (6.4 m) at the Lincoln tunnel entrance, 24 feet (7.3 m) at the Battery, 23 feet (7.0 m) at Liberty Island, NJ, 18 feet (5.5 m) at West 96th Street, flooding the West Side Highway, and 15.6 feet (4.75 m) at the New York-Connecticut state line. These figures do not include the additional heights of waves on top of the surge.

Hurricane Preparedness. The National Weather Service (NOAA) provides technical data on hurricanes and issues frequently-updated storm bulletins and forecasts. TV and radio news broadcasts (especially the Weather Channel) deliver in-depth storm coverage, including recommendations for individual emergency preparations.

Although NOAA-operated weather satellites routinely track major hurricanes, accurate prediction of the most dangerous path cannot be made more than several hours to half a day in advance. The strongest, most damaging winds occur within a relatively narrow strip to the right of the eyewall. Given the large uncertainty in tracking the path of the danger zone and the huge urban population of the MEC region potentially at risk, evacuation must focus on people living in the most exposed shorefront locations and flood-prone low-lying areas.

State and/or municipality emergency management offices (e.g., the NY/NJ/CT State Emergency Management agencies; New York City Office of Emergency Management) can declare a storm emergency and recommend closing of government offices, private businesses and schools. Selected schools and other safe structures can be designated as emergency shelters for evacuees. Each emergency management office (on whichever level) has its own "command center" where the technical information (e.g., storm track maps) is provided to the emergency management decision-makers, and is then forewarded as operational directives to the police and fire departments, and to the Red Cross. The state and city local government agencies coordinate their disaster mitigation plans with FEMA (Federal Emergency Management Agency).
FEMA assesses damages following a natural disaster and also manages the National Flood Insurance Program, designed to assist communities affected by flood damage (see also *Challenges and Opportunities* below).

Methods and Data

Impacts of climate change on the coastal zone are studied by applying a plausible suite of sea level rise projections to selected localities in New York City, Long Island, and northern New Jersey. U.S. Army Corps of Engineers models are then applied to calculate future coastal flood heights, return intervals, and increases in sand volumes and costs for beach nourishment under these scenarios (see *Storm Surge Heights, Shoreline Changes* and *Beach Nourishment* below).

Data sets utilzed in this study include sea level observations, meteorological data, historic shoreline data, U.S. Geological Survey 7.5'(and higher resolution) Digital Elevation Models, aerial photos, geology. Thematic maps produced by the Geographic Information Systems lab and CIESIN at Lamont-Doherty Earth Observatory show topography, population density, household income levels, and housing values. These maps are overlaid on sea level and flood data to assess areas, populations, and assets at risk.

Sea level rise scenarios

Sea level rise for the MEC region is calculated from historical tide-gauge data and several global climate model (GCM) simulations. U.S. sea level data are available from the NOAA National Ocean Service (website: www.opsd.nos.noaa.gov); international data come from the Permanent Service for Mean Sea Level (Spencer and Woodworth, 1993). Sea level rise scenarios are based on an extrapolation of current sea level trends and on the following GCMs recommended by the U.S. National Assessment of Potential Climate Change Impacts: the Canadian Centre for Climate Modelling and Analysis (CCCMA) (Boer et al., 2000) and the United Kingdom Hadley Centre (Johns et al., 1997).

Climate model outputs are adjusted for local land subsidence. The local subsidence rate is derived by subtracting the relative sea level rise at each station from the regional absolute mean sea level trend (Appendix 1). The difference between decadal mean subsidence (2000s, 2010s,...2090s) and that of the base period (1961--1990) is then added to the projection of sea level rise for each GCM scenario, for the corresponding decade. Sea level projections are for the GCM grid cell(s) enclosing New York City and environs.

The following scenarios are used in this study:

1. **Current trend.** A linear extrapolation of current sea level trends. The *current trend* is the least-squares linear fit through the annual means of sea level from tide-gauge data (Appendix 1, column 1). Mean annual sea levels are averaged in 10-year intervals starting in 1961, to minimize effects of year-to-year variations. Projected sea levels are decadal means above the 1961-1990 mean.

2. **CCGG.** The CCCMA first generation coupled model (CGCM1) transient climate simulation for greenhouse gas warming. Only the steric (temperature/salinity) component of sea level rise is given. Contributions from mountain glaciers and ice sheets are calculated using static sensitivities: 0.063 cm/yr/°C (glaciers), 0.03 cm/yr/°C (Greenland), and -0.03 cm/yr/°C (Antarctica) (Gregory and Oerlemans, 1998).
3. **CCGS.** The same as scenario 2 with sulfate aerosols. In addition to the steric component of SLR, contributions from mountain glaciers and ice sheets are calculated as above, using static sensitivities: 0.063 cm/yr/°C (glaciers), 0.035 cm/yr/°C (Greenland), and -0.03 cm/yr/°C (Antarctica) (Gregory and Oerlemans, 1998).

4. **HCGG.** Hadley Centre HadCM2; the first of an ensemble of 4 greenhouse gas integrations. (The four runs differ only in the year the control integration is used to initialize the first member of the run. Differences among the four runs is relatively small--R. Goldberg, priv. comm.).

5. **HCGS.** Hadley Centre HadCM2; the same as scenario 4 with sulfate aerosol integrations.

Storm surge heights

Plots of flood levels for given return periods (i.e., 2, 5, 10, 25, 50, and 100 years) were prepared for each sea level rise scenario at each site, using the WES Implicit Flooding Model (WIFM) tidal hydrodynamic model (Butler, 1978; Butler and Sheng, 1982). WIFM solves vertically-integrated dynamic, shallow-water wave equations of fluid motion, incorporating information on bathymetry, topography, wave, and meteorological data in order to simulate coastal flooding. An important feature of the model is its ability to stretch the numerical grid, which allows a denser grid resolution in areas of interest.

For this study, flood heights include combined nor'easter and hurricane storm surges, high tide, and sea level rise. In this region, the nor'easter is the most prevalent type of severe storm (Zhang et al., 2000). Wave heights are omitted. Since wave runup can be significant, omission of wave height will lead to a somewhat conservative estimate of flood water levels. Storm climatology is assumed to remain unchanged. (Flood heights are relative to the NGVD datum; see Appendix 2). Projected sea level rise for the Coney Island and Rockaway Beach study sites was based on the New York City (Battery) tide gauge; the northern New Jersey coast between Sea Bright--Asbury Park was referenced to the Sandy Hook gauge; SLR for Long Beach and Westhampton were calculated by linear interpolation between the NYC and Montauk tide gauges (see **Case study sites**). Average flood heights were calculated for each decade between 2000 and 2090. Maximum flood levels (surge + mean high water + sea level rise) for the 100-year storm events were compared with flood levels during major historic storm events, such as the Dec. 1992 nor'easter.

Shoreline response to sea level rise

The shoreline's response to sea level rise is often estimated using the Bruun Rule, which states that a typical concave-upward beach profile erodes sand from the beachfront and deposits it offshore, so as to maintain constant water depth (Fig. 7). Shoreline retreat depends on the average slope of the shore profile. Thus, from Maine to Maryland, a 1 m sea level rise would cause the beach to retreat by as much as 50 to 100 m.

The Bruun Rule assumes no longshore transport of sand into or out of the study area, nor does it account for washover or inlet sedimentation, two important processes shaping barrier islands. It has been modified to account for landward migration and upward growth of a barrier island ("rollover"; Dean and Maurmeyer, 1983). Other shoreline models, such as 3-dimensional sediment budget analysis or dynamic approaches require detailed measurement of local parameters (NRC, 1987). The lack of this information except at a few sites limit the widespread applicability of these models. Alternatively, projections are made from a correlation between historical shoreline erosion trends and local sea level changes (Douglas et al., 1998).

The Bruun Rule remains one of the most widely used methods of estimating shoreline reponse to sea level rise, in spite of above-cited limitations. It has recently received support from long-term observations of coastal erosion on the East Coast (Leatherman et al., 2000). Hence the Bruun Rule is used here to estimate shoreline changes in the absence of sand replenishment for the case study sites.

The Bruun Rule can be stated mathematically as:

$$S = (A*B)/d$$

where:

S Shoreline movement

A Sea level rise

d Maximum depth of beach profile, measured from the berm elevation for each project location to the estimated depth of closure. (A berm is a ridge of sand, produced by wave action, at the upper part of the beach).

B Horizontal length of the profile, measured from the beginning of the berm to the intersection with the estimated depth of closure.

The depth of closure is generally defined as the minimum water depth at which no significant measurable change occurs in sediment motion (NRC, 1995). "Closure" is a somewhat ambiguous term in that it can vary, depending on waves and other hydrodynamic forces. Depth of closure in this study was based on measured beach profiles taken perpendicular to the shore (Appendix 3).

The annual shoreline translation due to sea level rise was calculated from the Bruun Rule and converted to a volumetric change, using the height of the beach profile and the length along the shore.

Beach nourishment

The U.S. Army Corps of Engineers methodology to estimate sand volumes needed to maintain a beach employs physical characteristics, such as measured beach profiles, the average profile depth, and length of shoreline in the project. Sand losses are computed for historic rates (i.e., "Current trends") of sea level rise. Also considered are losses due to long-term erosion and storm-induced erosion over the life of the project. (In the MEC area, project lifetimes range between 25 and 50 years--Appendix 3). The required sand volume is the sum of the volumes for each of these factors. These processes inherently interact with each other. Yet, by separating them, quantifying the results individually and then summing them, one obtains an upper bound estimate of expected renourishment requirements. Such a high estimate provides an adequate safety margin to ensure the maintainance of the project design.

The standard Army Corps procedure has been modified in several ways for this study. Projected shoreline retreat is calculated from the Bruun Rule, using our scenarios of future sea level rise. Long-term erosion losses are based on measurement of beach profiles and volumetric changes. Storm-related losses are determined from damage by a storm event with 50% probability of occurring during the time between renourishment episodes, using the SBEACH model (Larsen and Kraus, 1989). (SBEACH is an empirically-based numerical model used to predict storm-induced beach erosion). Increasing flood heights due to projected sea level rise over this time are also factored into the calculation.

Changes in volumes of beach sand renourishment are tabulated for selected time intervals. Beach replenishment due to sea level rise is compared with that from historic erosion trends and storms for these periods.

Socioeconomic data

Maps of population densities, average housing values, and household income, for 1995 TIGER Census Tracts were overlaid on 5-foot contour plots, using U.S. Geological Survey 7.5 minute Digital Elevation Model (DEM) data for the case study sites (described below). (Horizontal accuracy of the topographic data is within a fraction of an inch [root-mean-square-error]. Vertical accuracy is within 5 feet). The flood risk zone is defined as land lying within the 100-year flood zone. The expansion of this zone inland with sea level rise is discussed.

Case Study Sites

Case study sites differ in degrees of urbanization and biogeophysical characteristics. Nearly all sites lie in the high to very high risk classes of the Coastal Vulnerability Index (compare Figs. 1 and 2). Localities (except for the Battery) lie within boundaries of U.S. Army Corps of Engineers beach nourishment projects (Appendix 3), which are designed to reduce storm damages. Army Corps projects include an initial construction component, as well as scheduled renourishment fill operations. Storm surge elevations, shoreline erosion, and beach nourishment requirements for the given sea level rise scenarios are presented for the following sites:

- The Battery, New York City, NY[1]
- Coney Island, Brooklyn, NY
- Rockaway Beach, Queens, NY
- Long Beach, Long Island, NY
- Westhampton Beach, Long Island, NY
- Sea Bright--Manasquan, NJ

The Battery, New York City, NY

Lower Manhattan covers high-density prime commercial real estate in the heart of the New York City financial district, residential areas, such as Battery Park City (Fig. 4), and major tourist attractions, such as historic Battery Park, and the South Street Seaport. Battery Park City and the Seaport area have been constructed on landfill over the years. Most of the waterfront is bulkheaded and protected by a low sea wall. The tide-gauge, located on a pier at the U.S. Coast Guard Battery Park Building, next to the Staten Island Ferry station, has been in operation since 1856.

Important transportation infrastructure vulnerable to flooding includes the FDR Drive, West Street, the entrances to the PATH tubes, the Brooklyn-Battery Tunnel, approaches to the Brooklyn and Manhattan Bridges, and several subway stations. Portions of this area have been under water during major storms, such as the 1992 nor'easter (New York Times, Dec. 12, 1992; see also old newspaper accounts in Wood, 1986).

Coney Island

Coney Island is representative of an older, high-density urban seashore neighborhood (Fig. 8). The beach lies at the western terminus of littoral drift along the south shore of

[1] Sea level, surge and flood data only.

Long Island (Kana, 1995; Leatherman and Allen, 1985). Coney Island was attached to the mainland during 1870s - 1920s reclamation projects. Serious erosion problems began to occur after the construction of groins at Rockaway Beach, to the east, in the 1920s (Wolff, 1989). Over $25,000,000 has been spent on beach nourishment at Coney Island between 1923 and 1995 (Table 2).

The Coney Island study area extends from the east end of Brighton Beach to Seagate in the west--a total of 2.95 miles (4.75 km). The initial phase of the most recent Army Corps project began in Oct. 1994-Jan. 1995. The project is scheduled to be renourished for a period of 50 years, with periodic renourishment of approximately 990,000 cubic yards (757,350 m^3) of sand every 10 years.

Rockaway Beach

Rockaway Beach, Queens, is a barrier spit (mean elevation 5.5 ft [1.68 m] above sea level) attached to Long Island at its eastern end at Far Rockaway (Fig. 9). The central section of the barrier is another long-established, high-density, urbanized shorefront community. Nearly the entire barrier, including the residential area, lies below 3.3 m (10 ft). A rock jetty built to the east in the 1940s, curtailed littoral drift to the Rockaways and intensified erosion rates there (Wolff, 1989). A total of $134 million has been spent on beach replenishment between 1926 and 1996 (Table 2).

The study area covers a 6.4 mile (10.3 km) stretch of shoreline from Beach 149th Street to Beach 19th Street. This U.S. Army Corps project was initiated in 1975-1977. It may be maintained for an additional 25 years, with beach renourishment operations scheduled every 3 years, requiring approximately 1.75 million cubic yards (1.34 million m^3) of sand per cycle.

Long Beach

Long Beach, Nassau Co., is a medium- to high-density, urbanized residential community located on a barrier island, east of Rockaway Beach (Fig. 10). "Hard" structures include a series of rock groins built in the 1950s and a jetty at Jones Inlet to the east (Wolff, 1989). Lido Beach Town and Pt. Lookout, at the eastern end of Long Beach Island, have attempted to protect and revegetate their dunes, but wave refraction around the jetty has led to further beach erosion. $1.5 million has been spent on beach nourishment in Lido Beach in 1962. A renourishment project over a 7.77 mi (12.5 km) is planned starting in 2002-2003, covering a 50 year period. It would have a 6 year renourishment cycle, using approximately 2.1 million cubic yards (1.6 million m^3) of sand per cycle.

Westhampton Beach

Westhampton Beach is an affluent low-density residential area with prime recreational beaches (Fig. 11). The entire barrier lies below 10 feet except for the narrow strip of dunes. Private houses, beach clubs, and hotels have been built on the dunes. Historically, it has been very vulnerable to storm erosion and washover. Overall, $47 million have been spent between 1962 and 1996 on beach maintaintance (Table 2). Erosion began after stabilization of the Shinnecock Inlet further east, in 1942 (Wolff, 1994). Following extensive flooding and erosion from the "Ash Wednesday" nor'easter in 1962, a series of 15 groins was built between 1965-1970 to protect the shore from further erosion. However, for various reasons, several additional planned groins and beach fill were not constructed.

The barrier was breached in two locations during the Dec. 1992 nor'easter and around 60 homes were destroyed (Fig. 12). The smaller, western opening--Pikes Inlet--closed in Jan., 1993. The larger, eastern opening--Little Pikes Inlet--developed 1000 feet from the westernmost groin (Fig. 12; Terchunian and Merkert, 1995). An 18-foot deep channel formed, allowing tidal currents to erode the inlet and carry sediments bayward, forming a tidal delta and a sand spit that extended northeastward into Moriches Bay. This breach was repaired in late 1993 with sand dredged from offshore sand sources and reinforced with steel sheeting. While the presence of the groin field may have contributed to the 1992 washover, this section of the barrier was already susceptible to storm damage due to lack of bayside salt marshes, sand bars, and overwash lobes (Wolff, 1994). The curved spit extending into Moriches Bay is all that remains of the short-lived Little Pikes Inlet. New homes are being constructed on the site of the former breach (Fig. 5).

In addition to the factors mentioned above, the Westhampton Beach barrier may be especially vulnerable to storm damage, because of particular offshore physiographic characteristics (Schwab et al., 2000). In particular, formation of inlets and bayside sediment accretion following storms induce a more rapid landward migration of the barrier-island system east of Watch Hill, Fire Island, relative to the west. The somewhat steeper offshore bathymetry also exposes the beach to higher energy storm-wave events.

The U.S. Army Corps project covers a stretch of 4 miles (6.4 km). It was initiated in 1997 and is scheduled to run for a period of 30 years. The expected renourishment cycle is 3 years, using approximately 1.18 million cubic yards (0.90 million m^3) of sand per cycle.

Sea Bright-Manasquan, NJ

Sea Bright, a residential community on the narrow, sandy barrier spit south of Sandy Hook at the northern end of the New Jersey shore, has a long history of exposure to storm and wave action (Fig. 13). Starting in 1913, a set of 85 groins was constructed throughout the area, and in 1922 a 120 m breakwater was completed in Sea Bright. In 1898, a sea wall was built along the Highland and Navesink beaches. In the 1950s, additional seawall construction was undertaken between Sea Bright and Monmouth Beach (Gorman and Reed, 1989). By the late 1980s, the seawall had seriously deteriorated and repairs were undertaken in 1990 (Bocamazo, 1991).

The U.S. Army Corps initiated a beach nourishment program between 1994-1998 covering an 11.8 mile (19.0 km) reach between Seabright and Ocean Township. The project has a planned six-year renourishment cycle, over a 50 year period, requiring 3.5 million cu. yds. of sand per cycle. Another project extends over 9 miles (14.5 km) further south, between Asbury Park to Manasquan. It began in 1997-1999 and is expected to continue 50 years, with periodic renourishment every 6 years, consuming 2.6 million cu. yds. of sand per cycle.

Results

Sea level rise

The regional mean relative sea level rise for the East Coast is 0.11±0.3 in/yr (2.7±0.7 mm/yr); the corrected sea level rise, after removal of geologic trends, is 0.05±0.3 in/yr (1.3±0.7 mm/yr; Appendix 1). Tide-gauge stations within the MEC region include: New York City--the Battery, Montauk Point, Sandy Hook, Willets Point, and Port Jefferson (Table 1). Projected sea levels for these stations in the 2020s, 2050s, and 2080s are summarized in Table 4.

Modest rises in sea level of 4.3 to 7.6 inches (11--19 cm) could occur by the 2020s at current rates (Table 4). For the GCM projections, sea level could reach 4.4-11.7 inches (11-30 cm). By the 2050s, sea level could rise by 6.9 to 12.1 inches (18-31 cm) under current trends, or could climb by 8.5 to 23.7 inches (22-60 cm) for the GCM projections. By the 2080s, sea level could rise by 9.5 to 16.7 in (24-42 cm), at current rates, or could exceed 3 feet (>1 m) at some localities in the Canadian Climate Centre model. While sea levels are not expected to rise dramatically within the next 2-3 decades, the rise accelerates sharply after the 2050s, except for the "current trend" scenario (Fig. 14).

Furthermore, sea level rise trajectories diverge widely in the second half of the century.

Coastal managers and planners need information on the likelihood of future sea level rise. Titus and Narayanan (1996) estimate the probability of sea level rise, based on a combination of Monte Carlo statistical techniques and expert opinion review. For New York City, they find a 50% chance that sea level will rise 6 inches over 1990 levels by 2025, 10 inches by 2050 and 22 inches by 2100 (Table 1 in Titus, 1998). A 5% chance exists that sea levels will exceed 9 inches by 2025, 17 inches by 2050 and 38 inches by 2100.

Comparing these probabalistic estimates with our sea level rise projections (Table 4) suggests that the Canadian Climate Centre's CCGG and CCHG scenarios have a likelihood of 5% or less of occurring over the next 100 years. On the other hand, the Hadley Centre's HCGS scenario has better than a 50% chance of occurring in the next 100 years. Extrapolating current trends, a sea level rise of ≥8.6 inches is 74% likely by the 2050s, and a rise of ≥12.9 inches is 87% likely by the end of the century.

Storm surges and coastal flooding

Flood heights are presented for the 100-year storm (combined extratropical and tropical cyclones, Fig. 15). The regional 100-year flood levels could rise from 9.8 to 11.5 feet (3.0-3.5 m) in the 2020s, to 10.1-12.4 feet (3.1-3.8 m) in the 2050s, and up to 13.8 feet (4.2 m) in the worst-case scenario by the 2080s (Fig. 15). Inasmuch as these figures do not include the additional height of waves on top of the surge, these estimates of flood water levels are somewhat conservative. Figure 16 illustrates how flood elevations could evolve over time at each case study site, as a function of sea level rise scenario.

The marked decrease in the flood return period will become a major concern to coastal residents. Among the case study sites, the likelihood of a 100-year flood could become as frequent as once in 43 years by the 2020s, once in 19 years by the 2050s, and once in 4 years by the 2080s, on average, in the most extreme case (Fig. 17).

At present, the 100-year flood in New York City and environs is 9.7 feet (2.96 m)--very close to the area outlined by the 10-foot (3 m) contour (Fig. 18). By the 2080s, the return period for a flood of this magnitude could shrink to 5.5 years in the worst-case scenario (CCGG) and 50 years--extrapolating current trends. More frequent flooding episodes would adversely affect major transportation arteries, including highways, rail and air transportation, not to mention the viability of waterfront structures (see *Infrastructure* sector report).

The projected sea level rise for the MEC region (a maximum of 1 1/2--2 feet [48-60 cm] by the 2050s, and 3--3 1/2 feet [90-108 cm] by the 2080s; Table 4) lies below the 5-ft contour (shown in yellow, Figs. 19a-f). Thus, at most of the case study sites, only a relatively narrow coastal strip would be permanently inundated. However, wetlands could sustain marked reductions in area (see *Coastal Wetlands Sector* report). Furthermore, as shown in the next section, coastal erosion could be an order of magnitude greater than that of simple inundation. For example, while sea level in the New York City area could rise approximately 1-2 feet by the 2050s, the nearby beaches of Coney Island and the Rockaways could retreat landward some 20 to 60 feet (0.6-1.9m) during this decade, if not renourished (Table 4, Figure 19).

In addition, areas at risk to severe flooding would expand considerably. Within two decades, the 100-year flood zone would equal or exceed 10 feet (≥3m) at the case study sites (Fig. 15; Figs. 19a-f. The dark and light blue lines outline the 10 and 15 ft contours, respectively). By the 2080s, the 100-year flood zone could reach 11-14 ft (3.4-4 m). The areas at risk could embrace significant segments of lower Manhattan (Figs. 18, 19a), most of Coney Island (Fig. 19b), Rockaway Beach and Jamaica Bay (Fig. 19c). In addition to the entire Westhampton barrier, nearly the entire bayside shoreline around Moriches and Shinnecock Bays could also become vulnerable to flooding (Fig. 19d). While the flood risk zone near Sea Bright and Asbury Park, New Jersey would lie fairly close to the coast, it could extend much further inland along estuaries (Figs. 19e,f).

Shoreline changes

Figure 20 summarizes rates of shoreline retreat due to sea level rise that would occur at the case study sites, without additional sand replenishment. (The Battery in New York City is omitted here, since it is armored by seawalls). Among these sites, Rockaway Beach experiences the most severe rates of beach attrition, closely followed by Asbury Park, NJ and Westhampton Beach. Coney Island beaches shrink the least under all sea level rise scenarios.

These site-to-site variations reflect differences in underlying geology, geomorphology, sediment particle size distributions, beach profiles, and wave climates. But at any given locality, holding these other variables constant, erosion rates are roughly proportional to sea level rise. Thus, by the 2080s, erosion rates range between 2 to 4 times above those of 2020s, and 4 to 10 times above those of the 2000s. With rising sea level but no sand replacement, Long Island and northern New Jersey beaches could move landward nearly 1.4 to 3.0 ft/yr (0.4--0.9 m/yr) by the 2020s, increasing to as much as 2.8 to 12.0 ft (0.85--3.6 m/yr) by the 2080s (Fig. 20).

An empirical test of the Bruun Rule is a comparison with long-term (~century) erosion trends (Leatherman et al., 2000). The average ratio of erosion rates calculated from the Bruun rule to current rates of sea level rise for our four Long Island test sites is 98.3. This agrees reasonably well with a ratio of 110 for historical data on Long Island that excludes the influence of nearby inlets, coastal engineering, and sediment accretion (Leatherman et al., 2000). But the average calculated ratio for the New Jersey sites is only 83.1 as compared to 181 for the historical data. The discrepancy in northern New Jersey may be due to oversteepened offshore topography and higher wave energies, making the Bruun Rule a less reliable predictor of erosion in New Jersey than in Long Island.

Beach nourishment

In general, estimated sand volumes based on our *current trends* sea level rise scenario differ by only a few percent from those calculated using standard Army Corps methodology, over the design lifetime of the project (25 to 50 years; Appendix 3).

Table 5a summarizes beach renourishment requirements for our case study sites due to sea level rise over selected time intervals. At any given site, volumes of sand pumped onto the beaches increase by factors of 2-7 times during 2050-2080 relative to the 2000-2020 period. Sea Bright, due south of Sandy Hook, lies in an area with the highest rate of relative sea level rise (Table 1) and sand replenishment needs in the MEC region (Table 5a). On average, Sea Bright will consume around double the sand volume as Westhampton Beach (the site with the lowest sand needs) between 2000-2020, and 2-3 times as much between 2050-2080.

To put these figures in perspective, the additional sand needed because of sea level rise remains a relatively small percent of the total beach replenishment due to all factors (long-term erosion, storms, SLR), until the latter half of the century (Table 5b). By the 2020s, the percent due to SLR represents only 2.3% to 11.5% of the overall total. By the 2050s, the percent rises up to 18.7%. But after the 2050s, SLR could be responsible for a significant percent (up to 25.7% at some localities) of the additional sand placement.

Coastal storms and global warming

Estimates of increased storm surge level and coastal flooding have been made for several climate change scenarios, assuming no changes in the characteristics of extratropical and tropical cyclones (Figs. 15-17). How are the number and strengths of such storms likely to change as the world heats up? Climate model simulations of cyclonic behavior under conditions of global warming yield contradictory results.

Nor'easters. Beersma et al. (1997) find a small decrease in the number of strong North Atlantic depressions (<975 hPa) in a CO_2-doubled world, as compared to the present-day control simulation. There is also a tendency toward a greater number of weaker storms. Yet these differences remain small with respect to the natural variability. On the other hand, Lunkeit et al. (1996) observe an intensification of upper troposphere eddy activity--a proxy for storm tracks--and also cyclone frequency over the eastern North Atlantic and Europe, as greenhouse gas concentrations increase by 1.3%/yr. In yet another study, cyclone frequency in a doubled-CO_2 run decreases northeastward of North America and Greenland into northern Europe (Schubert et al., 1998). Cyclone intensity, however, shows little change.

Hurricanes. Henderson-Sellers et al. (1998) review the factors which contribute to the genesis of tropical cyclones. These include sea surface temperatures greater than 26°C (79°F), weak vertical shear of horizontal winds, atmospheric instability, high relative humidity at lower atmospheric levels, and location a few degrees poleward of the equator. Although the area of oceans warmer than 26°C is likely to increase as the earth warms, the minimum temperature at which tropical cyclones develop will increase by 2°-3°C. Therefore, the geographic region in which hurricanes form may not change significantly.

Henderson-Sellers et al. detect no discernable historic trends in tropical cyclone numbers, intensity, or location (see also Landsea et al., 1999). While some climate models suggest increases in the maximum potential intensity of tropical cyclones in a doubled-CO_2 climate, changes in other climatological variables may counteract these increases.

In summary, the extent to which changes in storm behavior will impact coastal regions and wetlands remains unclear, since intensities of weaker storms may not alter significantly. However, a potential exists for the most severe storms to become more intense and frequent, thereby causing greater damage. A detailed analysis of the effects of storm changes under global warming requires further modeling studies. For example, the frequency of storms in the Metro East Coast region could change either as a result of an actual increase in the number of storms generated (increase in cyclogenesis), or simply due to a shift in the mean position of extratropical storm tracks (which would concurrently decrease storm frequency elsewhere).

As yet, no consensus has emerged among climate models. Therefore, we report changes in storm recurrence intervals, flood heights, and beach erosion trends (e.g., Figs. 15-17, 20), under the assumption that storm climatology remains unchanged, for the purposes of this assessment.

Population, coastal property at risk to sea level rise and coastal flooding

Unavailability of high spatial resolution topographic and socio-economic data precludes quantitative assessment of people and property at risk to sea level rise and flooding, at this time. However, vulnerabilities can be be qualitatively outlined by overlaying topography at 5 ft (1.5m) contour intervals with census tract data (Figs. 19a-f), together with sea level and storm flood projections.

Because of the highly developed nature of the coast within the MEC region, a large population and considerable private property and infrastructure will be potentially at risk to inundation and flooding (see also **Infrastructure** sector report). While permanently lost land occupies a relatively narrow coastal strip (generally below the 5-ft contour, yellow line, Figs. 19a-f), flooding due to storms could periodically engulf a much greater area.

Projected 100-year flood zones (Fig. 15) lie between the 10 and 15 ft contours (Figs. 19a-f). High population densities are presently concentrated near water's edge at three urban sites--lower Manhattan, Coney Island, and Rockaway Beach (New York City). Flood risk zones at these sites cut across wide differences in income and housing values. If population growth follows present trends, evacuation of vulnerable populations in these high-risk areas during major storms will pose serious problems, inasmuch as many evacuation routes lie close to present-day storm flood levels (see *Hurricane Preparedness* above, and *Infrastructure* sector report). The greater frequency of severe flooding episodes affecting waterfront residences (e.g., Figs. 3-5, 17) may lead to abandonment of lower floors, as in Venice, or ultimately of entire buildings.

Suburban areas such as Westhampton, NY, Sea Bright and Asbury Park, NJ typically exhibit much lower population densities and higher income levels (Figs. 19d-f). These land-use characteristics could make zoning setbacks and/or relocation to higher ground more feasible options as compared with highly urbanized areas. However, such measures are likely to be controversial and politically unpopular. At least in the short term, continuing defense of the shoreline will be more likely.

CHALLENGES AND OPPORTUNITIES

Strategies for coping with coastal erosion and flood damages associated with a rising sea level include defending the shoreline by means of protective structures, beach restoration, and ultimately, retreat (NRC, 1995; 1990; 1987).

Even at present rates of sea level rise, most of the shoreline of the MEC region is eroding (see **Existing Coastal Hazards**--*Coastal Erosion*). Many beaches must be artificially maintained by the U.S. Army Corps of Engineers (Table 2).

Shoreline armoring is typically applied where substantial assets are at risk. Hard structures include seawalls, groins, jetties, and breakwaters. Seawalls and bulkheads, a common form of shore protection in urban areas, often intercept wave energy, increasing erosion at their bases, which eventually undermines them. Erosion can be reduced by placing rubble at the toe of the seawall. Groins, often built in series, intercept littoral sand moved by longshore currents, but may enhance beach erosion further downdrift, if improperly placed (e.g., at Westhampton Beach). Similarly, jetties, designed to stabilize inlets or to protect harbors, may lead to erosion (as at beaches downdrift (west) of the Moriches, Shinnecock, and Fire Island Inlet jetties).

In response to sea level rise, existing hard structures will need to be strengthened and elevated repeatedly, and beaches will require additional sand replenishment. The increased costs of retrofitting existing structures or armoring selected portions of the coast may be viable in high population density or high property-value areas of MEC, such as Manhattan or Jersey City/Hoboken, NJ (Figs. 3, 4).

In some locations, affluent shorefront property owners or seaside communities may also be willing to incur the additional expenses to save their beaches, as for example in Southampton and East Hampton, Long Island (Figs. 5, 11; Maier, 1998).

Because of erosion problems associated with hard structures, a soft approach involving dune restoration and beach nourishment has emerged as the preferred means of shoreline protection (NRC, 1995). Beach nourishment or restoration consists of placing sand that has usually been dredged from offshore or other locations onto the upper part of the beach. Since erosional processes are continual, beach replenishment must be repeated frequently (see **Results**--*Beach nourishment*).

Beach dunes act as a major line of defense against sea attack. Since many natural dunes in the MEC region have been destroyed by housing construction and sand mining, they have frequently been replaced by artificial dunes. These can be stabilized by replanting natural dune vegetation, building protective fences, and mulching with discarded Christmas trees.

The U.S. Army Corps of Engineers has spent a cumulative total of $2.4 billion[2] nationally and $884 million within the Tri-state region on beach nourishment projects since the 1920s. Over half a billion dollars have been spent in New York State alone (mostly along the south shore of Long Island)--the largest expenditure for any single state (Duke University, Program for Study of Developed Shorelines, 1999). Over $250 million has been spent to date on our case study sites (Table 2).

Estimates of future beach nourishment needs for our suite of sea level rise scenarios (see **Data and Methods**) suggest that sand volumes needed for beach replenishment could increase by 2-11.5% (by volume) over that needed in the absence of SLR through the 2020s, and by another 4 to 19% between 2020-2050. These supplementary sand needs could probably be accommodated during the typical 50-year project lifetime, starting now. However, as shown on Figures 14 and 16, by the latter half of the century, an additional 5 to 26% volume of sand would be necessary (Table 5). Thus, projects may have to design for potentially higher erosion rates and water levels than those experienced until now. The adequacy of onshore/offshore sand resources on Long Island and northern New Jersey to meet future demands may also need to be re-evaluated.

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[2]adjusted to 1996 dollars.

Rising beach nourishment costs could intensify related equity issues. For example, to what extent will taxpayers living elsewhere continue to be willing to support beach nourishment programs from which they benefit indirectly, if at all?

Retreat or pulling back from the shore may become an appropriate option in areas of lower population densities, or land values, or in high risk areas subject to repeated storm damage. The retreat may be a gradual process or a sudden abandonment following a catastrophic storm.

Possible mechanisms of retreat would need to be governed by zoning or land-use regulations and other policies which would:

1. Establish construction setback lines, extrapolating historic erosion rates to future SLR scenarios.

2. Remove buildings or hard structures that are in imminent danger of collapse into the sea.

3. End repeated subsidization to rebuild structures in designated coastal hazard zones.

A number of federal programs affect the coastal zone. These include the Federal Emeragency Management Agency (FEMA) National Flood Insurance Program (NFIP), the NOAA Coastal Zone Management Act (CZMA), U.S. Department of the Interior Coastal Barriers Resource Act (CBRA), and the Army Corps of Engineers' mandate to provide storm protection, stabilize shorelines, and insure navigability of waterways (NRC, 1990). In particular, NFIP provides flood insurance to communities that adopt and enforce measures to reduce future flood risks in hazardous areas (defined as the 100-year flood zone, or A-zone; FEMA, 1997). In coastal areas, the V-zone (seaward of the A-zone) consists of the area subjected to at least a 3-foot breaking wave during a 100-year storm or hurricane. NFIP also calls for designation of erosion zones (or E-zones) and providing setbacks or buffer zones. Several states outside the MEC region have enacted their own setback legislation (Edgerton, 1991).

The Upton-Jones Amendment, enacted in 1987, compensates owners to relocate or demolish buildings in danger of imminent collapse (i.e., located in a zone extending seaward of 10 feet plus 5 times local average annual erosion rate). New construction would only be permitted landward of the area expected to erode within the next 30 years (small houses) or 60 years (larger buildings). The Upton-Jones amendment is a reasonable approach for responding to immediate coastal hazards (NRC, 1990). However, because only several hundred claims had been filed by the mid-1990s, this program was terminated.

Another way of pulling back is the concept of rolling easement, in which human activities are required to yield to the landward migrating shoreline (Titus, 1998). The state could prohibit bulkheads or other hard structures that would interfere with the natural shoreline movement. Alternatively, the state could acquire private land when the sea rises by some specified amount. Several states (e.g., New Jersey, Maryland, and Florida) already have acquisition programs for existing coastal hazard areas (Godschalk et al., 2000). These programs could be modified to include the role of future sea level rise.

Another approach would be notification or disclosure of potential coastal hazards before property purchase. Several states have such disclosure requirements, including Massachusetts, South Carolina and Texas (Godschalk et al., 2000). Here too, the potential effects of sea level rise could be written into the disclosure document. The California Alquist-Priolo Earthquake Fault Zone Act, although applying to earthquake hazard notification, can serve as a useful precedent.

How and when to arrive at the optimal decision in the face of rising ocean levels is explored by Yohe and and Neumann (1997). Several options are given--advanced foresight, wait-and-see, and protect regardless, for three SLR scenarios: 33 cm, 67 cm, and 100 cm by 2100. The first option assumes sufficient advance warning of SLR and fairly rapid market response to the perceived threat. The second option reacts to the imminent loss of property at the time of inundation, while the last option accepts protection as given and simply seeks to minimize its costs. In general, costs for the advanced foresight option are lower than for the wait-and-see option, espcially for the two higher SLR scenarios, but this advantage requires more precise knowledge of the course of SLR and and effective market-based retreat policy. Costs are highest for permanent protection.

Implementing a rational and equitable strategy for coastal retreat from high risk zones will be difficult and politically unpopular. Pressures arising from stakeholders' diverse interests will probably intensify as shorelines shrink and land is inundated (e.g, Figs. 18, 19a-f). Adaptation to changing conditions will require the cooperation and coordination of various disparate groups.

INTEGRATION ACROSS SECTORS

Impacts of sea level rise and exacerbated flooding from storm surges have repercussions on several of the other sectors of the MEC climate change assessment. The findings of the *Coastal Zone* sector intersect with the *Water Resources*, *Infrastructure*, and *Institutional Decision-Making* sectors. Several examples of such overlapping areas of interest are now presented.

Water Resources

An emergency source of water for New York City during periods of drought is the Chelsea Pump Station, located on the Hudson River south of Poughkeepsie (see also *Water Resources* sector). The salt front (defined as 100 mg/L chloride) currently lies south of this station, on average. But its position changes daily with the tides, also seasonally, and due to interannual fluctuations in temperature and precipitation. For example, the salt front reached the Chelsea Pump Station at several times during the drought of 1999, particularly during the months of July and August. The front even reached the Poughkeepsie water-supply intake during late August-early September, 1999. Historic sea level rise may have caused an upstream migration of the salt front, which was apparently located near Tarrytown in 1903, but which since the 1960s ranges between Beacon and Poughkeepsie (Hahl, 1988).

Climate change could affect the location of the salt front in three ways:

1. Reduction (increase) in precipitation can reduce (increase) stream flow, allowing the salt front to move upstream (downstream).

2. Increase in temperature can increase evaporation, reducing freshwater runoff, which in turn would cause the salt front to migrate upstream.

3. Rising sea level may push the mean position of the salt front upstream.

If any of these climate changes, whether singly or in concert, would cause the salt front to reach the Chelsea Pump Station permanently, or even for a significant percent of the year, its continued use as an emergency water resource would be seriously jeopardized.

The U.S. Geological Survey operates five gauges which monitor tide stage, water temperature, and specific conductance (directly correlated to salinity levels). The gauges closest to the Chelsea Pump Station are West Point (south) and near the IBM Center, south of Poughkeepsie (north of Chelsea).

A major research issue will be to model the rise in sea level and its effect on the position of the Hudson River salt front over time, for various climate change scenarios. Results of such modeling studies will help determine which of several options should be adopted, for example, whether to move the intake station upriver, or how to adjust the pumping regime.

Infrastructure and Institutional Decision-Making

Jamaica Bay represents another example of cross-cutting issues involving the *Coastal Zone and Wetlands*, *Infrastructure*, and *Institutional Decision-Making* sectors. JFK Airport, situated on the northeastern shore of Jamaica Bay, is a key global transportation facility. Jamaica Bay Wildlife Refuge, at the Bay's center, forms part of Gateway National Recreation Area. It provides critical habitat for several state and federally recognized endangered species. Planes and birds literally compete for the same airspace. Therefore, coordinated management of aviation safely and protection of wildlife becomes paramount.

Sea level rise will place additional pressures on this delicate coexistence between man, machine, and nature. Preliminary studies by the New York State Department of Energy Conservation finds a loss of 400 acres of former Spartina alterniflora low marshes over a twenty year period (1974-1994). These wetlands have now become coastal shoals. Ongoing sea level rise, together with other factors, such as land subsidence, channel dredging, or boat activity, may be contributing to the marsh losses. If current trends continue, the survival of the Spartina alterniflora wetlands will be in question within the next three decades. JFK Airport, on the other hand, will continue to operate, regardless. Runways and other critical facilities can be raised; dikes and seawalls can protect other areas. These protective measures, however, would prevent landward migration of salt marshes in response to sea level rise.

Comprehensive management of sea level rise impacts in Jamaica Bay would involve a large number of local, state, and federal agencies and stakeholders, often with diverse interests. For example, the National Park Service, the Army Corps of Engineers, U.S. Fish and Wildlife, the Federal Aviation Agency, and the Port Authority of New York and New Jersey would have to cooperate on issues of air safety vs preservation of bird sanctuaries in close proximity to flight runways. The extent and timing of human intervention will become an important consideration. Improved procedures of interagency, communication, coordination and decision-making will become a high priority.

Institutional Decision-making

A large number of local, state, and federal organizations and institutions within the MEC region have mandates that, fully or in part, involve the coastal zone. Their authority or function encompasses infrastructure operations, emergency response actions, and environmental regulation.

Key components of the MEC regional transportation system have been identified as being particularly vulnerable to sea level rise and coastal flooding (see *Infrastructure* sector report). A number of agencies are concerned with management of the regional transportation network (see also *Institutional Decision-Making* sector). Among these are:

The **Port Authority of New York and New Jersey**, which manages bridges, tunnels, PATH railway, shipping and airport facilities; the **New York City Department of Transportation**, which operates city roads and bridges; the **New York State Department of Transportation**, which operates state highways and bridges; the **Metropolitan Transportation Authority**, which runs New York City subways and buses; and the **U.S. Army Corps of Engineers**, which maintains and dredges harbor ship channels.

Emergency responses to severe coastal flooding, along with other weather-related disasters, are handled by a number of agencies, among which are the **New York City Office of Emergency Management**, the **New York York State Office of Emergency Management** and its counterparts in New Jersey and Connecticut. On the Federal level, the **Federal Emergency Management Agency** (Region II) assesses flood and wind damages, and provides relief to affected homeowners through the **National Flood Insurance Program.**

Environmental regulation is the province of diverse state, city, and federal agencies, such as **New York State Department of Environmental Conservation**, **New Jersey Department of Environmental Protection**, which oversee wastewater treatment facilities and regulate construction activity in waterfront locations and coastal wetlands. The **New York City Department of Environmental Protection** manages wastewater treatment plants and sewers, which are located near the waterfront. On the Federal level, the **U.S. Environmental Protection Agency** (Region II) requires water pollution control plants to meet Federal standards regarding release of effluents; manages the NY/NJ Harbor Estuary Project; also has oversight authority under the Clear Water Act, Section 404 for filling/dredging in wetlands. The **U.S. Army Corps of Engineers** (New York District, which includes portions of northern New Jersey) dredges the New York/New Jersey harbor for shipping, replaces sand on eroded beaches, regulates filling of wetlands through its permit program (Clear Water Act, Section 404), and plans restoration of wetlands, as in Jamaica Bay.

Given the fragmentation of coastal zone issues among diverse agencies, at different government levels, with differing jurisdictions and mandates, there will be a pressing need to improve channels of communication and develop institutional arrangements that facilitate the promotion of coherent coastal zone management policies, in the face of rising sea level.

INFORMATION AND RESEARCH NEEDS

This study has raised a number of issues that require further investigation, either because of limitations in data availability, uncertainties in the models used, or incompleteness in our fundamental understanding of the physical and socioeconomic processes at work. Some of the more pressing needs are described below.

A major need exists for higher vertical resolution topographic data. The U.S. Geological Survey 7.5 minute Digital Elevation Models used in this study are inadequate for accurately delineating the land area, infrastructure, and waterfront property at risk to permanent inundation or flooding. Although the New York City Department of Environmental Protection has obtained higher resolution topographic data (1 foot) for New York City, the data were not available in time for this study.

Reducing the uncertainties associated with future sea level rise requires improved understanding of a wide range of diverse climatological and oceanographic processes. For example, we need to know how fast atmospheric warming will penetrate into the oceans (e.g., Levitus et al., 2000) and how much thermal expansion will result, how rapidly mountain glaciers will melt, how human regulation of river runoff and land water storage will affect sea level, and how much the Greenland and Antarctic ice sheets will contribute to sea level rise. In addition, we need to be able to anticipate changes in tropical and extratropical storm frequencies and intensities, and how such changes will affect coastal flooding and beach erosion.

An important issue, not fully treated here, is the migration of the salt front up the Hudson River under various sea level rise scenarios, with potentially adverse consequences to the Chelsea Pump station. A major research task will be to model the relationship between sea level rise and the mean position of the Hudson River salt front over time. Another task will be to model infiltration of saltwater into the Long Island aquifers, which could endanger that region's water supply.

Furthermore, we need to develop more physically-based relationships describing the shoreline's response to sea level rise. Existing models of coastal erosion or beach nourishment requirements have become important tools for investigating coastal processes, for coastal engineering design, and even policy decision-making. However, these models contain a number of shortcomings; for example, they often employ empirical relationships based on oversimplifications of incompletely-understood complex physical processes (Thieler et al., 2000). Thus, further studies are required to gain more insight into the interactions between waves, littoral currents, and movement of sand--their sources and sinks, and how these processes would be modified by sea level rise.

Finally, we need better tools to integrate physical and socioeconomic models. Data needs include improved, higher resolution population projections and economic forecasting. Further work should be undertaken to investigate economic cost/benefit analysis and decision-making under uncertainty. For example, how, when and where to defend the coast and at what cost? At what point in time do higher flood levels and their increasing frequency make it uneconomical to continue beach nourishment, raise seawalls or dikes, etc.? What is the cost threshold in present dollars above which it would be prohibitively expensive to defend the coast? (e.g., Yohe and Neumann, 1997).

POLICY RECOMMENDATIONS

This study raises some concerns over potential increases in future coastal hazards in the MEC region arising out of global climate change, including increased coastal flooding, shoreline erosion, beach nourishment requirements, and land loss (see Tables 4-5, Figs. 14-20). On the positive side, these changes would not increase significantly beyond current rates until several decades from the present. This should allow adequate time to plan future mitigation and adaptation responses. However, educating and informing the public of potential risks, beginning with concerned stakeholders and policy-makers, should start now. This report provides the scientific background which will enable coastal managers, planners, educators, and other concerned stakeholders to develop appropriate policies and make well-informed decisions. Based upon the initial findings of this study, the following are some recommendations for further action.

- Stakeholder groups and appropriate government agencies within the MEC region should be informed on the latest scientific findings on future sea level rise and their implications for coastal managment and planning.

- Agencies involved in coastal management should begin to factor sea level rise into their long-term planning decisions.

- Consider designation of coastal hazard zones, adoptation of erosional setback requirements, rolling easements, and limits to development in high hazard coastal zones.

- Provision should be made to acquire empty space inland for beaches and wetlands to "roll over".

- Purchase remaining open coastal space for future recreational needs.

- Provide educational outreach to inform the general public and concerned stakeholders of the issues raised by this study and various adaptation and mitigation options.

- Develop coherent coastal zone management policies, by promoting increased interagency communication and cooperation.

· Revise NFIP reimbursement policy to limit repeated claims payments to homeowners living within high hazard zones.

SUMMARY AND CONCLUSIONS

The vulnerability of the Metropolitan East Coast Region to coastal hazards, such as more frequent storm flooding, beach erosion, submergence of coastal wetlands, and saltwater instrusion, will intensify as sea level rises. The reduction in flood return period is very sensitive to small increases in sea level, independent of any changes in storm patterns.

Historic storms stiking the Northeast show pronounced interdecadal variability, but no secular trends (Zhang et al., 2000; Dolan and Davis, 1994; Landsea et al., 1999). On the other hand, the soaring coastal flood damages of recent decades reflect increasing development in high-risk areas, rather than any fundamental changes in storm behavior (Changnon and Changnon, 1999; van der Vink et al., 1998). This intense coastal development has occurred during a relatively quiescent period of hurricane activity (e.g., Landsea et al., 1999).

Climate models vary widely in their simulations of future cyclone behavior, pointing to the need for further research. Calculations presented in this report assume a fixed storm climatology.

In the MEC region, sea level has increased steadily by 22 to 39 cm during the 20th century. Projections based on historical trends and climate model simulations (Hadley Centre, U.K. and Canadian Centre for Climate Modelling and Analysis) suggest that sea level rise will remain fairly modest in the next 20 years, ranging between 4.3 to 11.7 in (11-30 cm, Table 4; Fig. 14). However this temporary respite should not induce a false sense of complacency--more pronounced increases could appear by the 2050s (6.9 to 23.7 in [18-60 cm]) and especially by the 2080s (9.5 to 42.5 in [24-

108 cm]).

As a result of sea level rise, storm floods would be higher, cover a wider area, and occur more often. The 100-year floods, ranging between 9.9 and 11.5 ft (3-3.5 m) in the 2020s would rise to 10.1-12.4 ft (3.1-3.8 m) by the 2050s, and 10.4-13.8 ft (3.2-4.2 m) by the 2080s (Fig. 15).

A significant corollary will be the marked reduction in the flood return period. The 100-year flood would have a probability of occurring once in 80 to 43 years, on average, by the 2020s, 68 to 19 years by the 2050s, and 60 to 4 years, by the 2080s (Fig. 17). The area outlined by the 10-foot contour (3 m) in New York City and environs could have a likelihood of flooding once in 50 to as often as every 5.5 years, on average, by the 2080s (Fig. 18).

A narrow strip of shoreline in the case study sites would be permanently under water, particularly by the 2080s (compare Table 4 and Figs. 19a-f). However, projected storm floods would cover a more substantial fraction of these sites after the 2050s (compare Figs. 15, 16, and 19a-f). More frequent floods, even if storminess did not change, would threaten seaside communities, as well as evacuation routes along major transportation arteries, including highways, rail and air routes (e.g., Fig. 18; see also *Infrastructure* sector report).

Rates of beach erosion would double or triple by the 2020s, increasing 3 to 6 times by the 2050s, and 4 to 10 times by the 2080s, relative to the 2000s. To compensate for these losses, we calculate that 2.3 to 11.5% more sand (by volume) would be needed by the 2020s to offset increased erosional losses due to SLR alone, relative to total sand replenishment requirements (Table 5). Sand volumes increase by 4.4-18.7% by the 2050s. Thus, periodic sand nourishment will probably remain a viable option for maintaining the beaches of the south shore of Long Island and northern New Jersey through mid-century. By the 2080s, however, sand replenishment, and associated costs, grow more substantially by 5.4-25.7%.

Another serious impact of rising sea levels could be the northward migration of the salt front up the Hudson River, possibly reaching the Chelsea Pump Station over a major portion of the year; saltwater may also seep into Long Island aquifers, endangering its water supply.

In response to SLR, armoring of the shoreline will be necessary to protect vital infrastructure, such as entrances to bridges and tunnels, airport runways, and also areas of high population density and property value. However, hard or soft defense measures will not be a practical option for the entire MEC coastal zone. In particular, the bay shorelines are potentially even more vulnerable to inundation and storm-related damages, because of their generally low elevation and absense of natural or artificial buffers. Thus, zoning or land-use policies would need to be implemented to enable an orderly and equitable pull-back from the most vulnerable areas.

This could be accomplished by a number of mechanisms, for example: designation of setback lines, removal of buildings or structures in imminent danger of collapse, and acquisition of empty space inland for beaches and wetlands to "roll over", or migrate landward. Other options include the use of rolling easements, in which human activities are required to yield to the landward migrating shoreline (Titus, 1998), or allowing the state to purchase private land when the sea rises by some specified amount.

Although adjustments to sea level rise would be relatively minor within the next 20 years (Fig. 14), this period of grace should utilized to prepare future mitigation and adaptation responses. Educational outreach should begin now, involving concerned stakeholders and policy-makers. This report provides an initial scientific framework to enable coastal managers, planners, educators, and other concerned stakeholders to develop appropriate policies.

Our initial recommendations include the following:

- Inform stakeholder groups and relevant government agencies within the MEC region of the latest scientific findings on future sea level rise and their implications for coastal managment and planning.

- Encourage coastal managers to incorporate sea level rise into their planning decisions.

- Adopt erosional setbacks or rolling easements and limit development in high coastal hazard zones.

- Acquire empty space inland for beaches and wetlands to "roll over".

- Purchase remaining open coastal space for future recreational needs; encourage land conservancy.

- Develop coherent coastal zone management policies, by promoting increased interagency communication and cooperation.

- Require notification of coastal hazard conditions, including sea level rise, in sale or purchase of coastal property.

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Table 1. Relative sea level trends--New York, Connecticut, New Jersey Tri-State region.

STATION	**Relative Sea Level Rise**		
	mm/yr	in/yr	Record length, yr
New London, CT	2.10	0.083	64
Bridgeport, CT	2.57	0.101	32
New Rochelle, NY	2.05	0.081	25
Montauk, NY	**2.27**	**0.089**	**49**
Pt. Jefferson, NY	**2.20**	**0.087**	**32**
Willets Pt., NY	**2.30**	**0.091**	**64**
New York City, NY	**2.73**	**0.107**	**140**
Sandy Hook, NJ	**3.85**	**0.152**	64
Atlantic City, NJ	3.97	0.156	85

Stations lying within the Metro East Coast region are highlighted.

Table 2. Cumulative beach nourishment costs for case study sites.

LOCATION	**TIME PERIOD**	**ADJUSTED COST (1996$)**
Coney Island	1923-1995	$25,220,000
Rockaway Beach	1926-1996	$134,344,956
Lido Beach (Long Beach)	1962	$1,492,010
Westhampton Beach	1962-1996	$47,167,821
SeaBright-Monmouth Beach	1963	$8,212,536
Sandy Hook--Deal (includes Sea Bright)	1995-1996	$35,973,000
TOTAL		$252,410,323

Sources: Duke University Program for the Study of Developed Shorelines; Valverde et al. (1999).

Table 3. The Saffir-Simpson hurricane scale.

The Saffir-Simpson Scale

Category	Central Pressure (millibars)	Winds mph (m/sec)	Surge feet (meters)	Damage
1	≤980	74-95 (32-42)	4-5 (1.4)	Minimal
2	965-979	96-110 (43-49)	6-8 (2.1)	Moderate
3	945-964	111-130 (50-58)	9-12 (3.2)	Extensive
4	920-944	131-155 (59-69)	13-18 (4.7)	Extreme
5	<920	>155 (>69)	>18 (>5.5)	Disaster

Table 4. Sea level rise projections--Metro East Coast Region (inches; cm).

SCENARIO	New York City	Willets Point	Port Jefferson	Montauk	Sandy Hook
2020s					
Current trend	5.4 (13.7)	4.5 (11.5)	4.3 (11.0)	4.5 (11.4)	7.6 (19.3)
CCGG	9.5 (24.1)	8.6 (21.9)	8.4 (21.4)	8.6 (21.8)	11.7 (29.7)
CCGS	8.5 (21.7)	7.7 (19.5)	7.5 (19.0)	7.6 (19.4)	10.7 (27.3)
HCGG	6.3 (16.1)	5.5 (14.0)	5.3 (13.5)	5.4 (13.8)	8.5 (21.7)
HCGS	5.5 (13.9)	4.6 (11.7)	4.4 (11.2)	4.6 (11.6)	7.7 (19.5)
2050s					
Current trend	8.6 (21.8)	7.2 (18.4)	6.9 (17.6)	7.6 (19.2)	12.1 (30.8)
CCGG	20.1 (51.1)	18.8 (47.7)	18.5 (46.9)	18.7 (47.5)	23.7 (60.1)
CCGS	18.7 (47.5)	17.4 (44.1)	17.0 (43.3)	17.2 (43.8)	22.2 (56.5)
HCGG	12.8 (32.5)	11.5 (29.1)	11.1 (28.3)	11.4 (28.9)	16.3 (41.5)
HCGS	10.2 (25.8)	8.8 (22.4)	8.5 (21.6)	8.7 (22.1)	13.7 (34.8)
2080s					
Current trend	11.8 (30.0)	10.0 (25.3)	9.5 (24.2)	9.8 (25.0)	16.7 (42.4)

CCGG	37.5 (95.5)	35.7 (90.8)	35.3 (89.7)	35.6 (90.5)	42.5 (107.9)
CCGS	29.9 (75.9)	28.0 (71.2)	27.6 (70.1)	27.9 (70.9)	34.8 (88.3)
HCGG	21.4 (54.4)	19.6 (49.7)	19.1 (48.6)	19.4 (49.4)	26.3 (66.7)
HCGS	16.7 (42.6)	14.9 (37.9)	14.5 (36.8)	14.8 (37.6)	21.7 (55.0)

Table 5a. Beach nourishment volumes due to sea level rise for the case study sites (in 10^6 cubic yards[3]).

SCENARIO / LOCALITY	CURRENT TRENDS	CCGG	CCGS	HCGG	HCGS
2000-2020					
Coney Island	0.099	0.245	0.206	0.131	0.112
Rockaway Beach	0.240	0.672	0.610	0.292	0.261
Long Beach	0.307	0.783	0.676	0.397	0.342
Westhampton	0.229	0.589	0.514	0.292	0.252
Seabright	0.489	1.053	0.913	0.617	0.538
Asbury Park	0.480	1.034	0.914	0.670	0.602
2020-2050					
Coney Island	0.158	0.483	0.453	0.293	0.218
Rockaway Beach	0.799	2.319	2.140	1.455	1.192
Long Beach	0.702	1.939	1.828	1.236	0.977

[3]To convert to m^3, multiply by 0.765×10^6.

Westhampton 0.473 1. 382 1.230 0 .825
0.569

Seabright 1.279 3. 008 2.790 2. 074
1.655

Asbury Park 0.919 2. 436 2.267 1. 564
1.223

2050-2080

Coney Island 0.164 0. 774 0.517 0. 395
0.320

Rockaway Beach 1.129 4. 683 3.484 2 .138
1.875

Long Beach 0.859 3 .345 2.401 1. 767
1.425

Westhampton 0.658 2 .938 2.327 1. 446
1.175

Seabright 1.885 5. 808 4.473 3. 528
2.679

Asbury Park 1.405 4. 557 3.391 2 .513
2.120

Table 5b. Percent of total beach renourishment volume due to sea level rise.

SCENARIO	**CURRENT TRENDS**	**CCGG**	**CCGS**	**HCGG**	**HCGS**
LOCALITY		**2000-2020**			
Coney Island	4.9	11.4	9.7	6.4	5.5
Rockaway Beach	2.3	6.1	5.5	2.7	2.4
Long Beach	4.8	11.4	10.0	6.1	5.3
Westhampton	3.2	7.9	6.9	4.1	3.5
Seabright	4.6	9.4	8.3	5.8	5.1
Asbury Park	5.7	11.5	10.3	7.8	7.1
		2020-2050			
Coney Island	5.2	14.4	13.6	9.3	7.1
Rockaway Beach	4.9	12.9	12.0	8.5	7.1
Long Beach	6.5	16.0	15.3	10.9	8.8
Westhampton	4.4	11.8	10.6	7.4	5.2
Seabright	8.7	18.3	17.2	13.3	10.9
Asbury Park	8.0	18.7	17.7	12.9	10.4
		2050-2080			

Coney Island	5.4	21.3	15.3	12.1	10.0
Rockaway Beach	7.5	25.2	20.0	13.3	11.9
Long Beach	7.8	24.8	19.1	14.8	12.3
Westhampton	6.0	22.1	18.4	12.3	10.2
Seabright	10.1	25.7	21.0	17.3	13.7
Asbury Park	9.6	25.7	20.4	16.0	13.8

Figure captions

Figure 1. Index map of study site locations.

Figure 2. Map of the Coastal Vulnerability Index for the New York, New Jersey, and Connecticut shoreline (from Thieler and Hammare-Klose, 1999, adapted from Gornitz et al., 1994; Gornitz and White, 1992).

Figure 3. Waterfront development on the Hudson River, Jersey City, NJ.

Figure 4. Battery Park City and the World Trade Towers, looking north.

Figure 5. House on stilts built after the Dec. 1992 nor'easter, on the site of the Little Pikes Inlet breach, Dune Road, Westhampton Beach.

Figure 6. Schematic drawing of sand transport.

Figure 7. Application of the Bruun Rule to erosion.

Figure 8. Aerial view of Coney Island.

Figure 9. Aerial View of Rockaway Beach.

Figure 10. Aerial view of Long Beach.

Figure 11. Aerial view of Westhampton Beach.

Figure 12. Aerial view of Little Pikes inlet, Westhampton Beach, after the December 1992 nor'easter.

Figure 13 Aerial view of Seabright/Asbury Park.

Figure 14. Trajectories of sea level rise for the MEC region.

Figure 15. 100-year flood levels for combined

APPENDIX 1. Sea level trends--eastern North America (mm/yr).

STATION	RSLR (1)	SEOT (2)	AVER. (3)	COR.SLR (4)
Yarmouth, N.S.	2.26	0.81	2.0	0.26
Charlottetown, PEI	2.69	0.20	1.14	1.55
Halifax, N.S.	3.52	0.13	2.83	0.69
St. John, N.B.	2.72	0.23	1.19	1.53
Eastport, ME	1.54	0.42	1.19	0.35
Bar Harbor, ME	2.21	0.27	1.19	1.02
Portland, ME	1.94	0.13	0.92	1.02
Portsmouth, NH	1.80	0.22	1.49	0.31
Boston, MA	2.68	0.15	1.49	1.19
Cape Cod Canal, MA	2.01	1.03	1.75	0.26
Wood's Hole, MA	2.47	0.18	1.75	0.72
Providence, RI	1.73	0.24	1.35	0.38
Newport, RI	2.44	0.16	1.35	1.09
New London, CT	2.10	0.21	1.35	0.75
Bridgeport, CT	2.57	0.67	1.35	1.22
New Rochelle, NY	2.05	1.48	1.35	0.70
Montauk, NY	**2.27**	**0.33**	**1.78**	**0.49**
Pt. Jefferson, NY	**2.20**	**0.56**	**1.78**	**0.42**
Willets Pt., NY	**2.30**	**0.22**	**1.78**	**0.52**
New York City, NY	**2.73**	**0.07**	**2.17**	**0.56**
Sandy Hook, NJ	**3.85**	**0.21**	**1.87**	**1.98**
Atlantic City, NJ	3.97	0.15	1.87	2.10
Lewes, DE	3.09	0.27	2.35	0.74
Baltimore, MD	3.14	0.11	1.81	1.33
Annapolis, MD	3.46	0.18	1.81	1.65
Washington, DC	3.05	0.26	1.81	1.24
Solomons Is., VA	3.36	0.22	1.81	1.55
Gloucester Pt., VA	3.64	0.38	1.20	2.44
Kiptopeake B., VA	3.35	0.36	1.20	2.15
Hampton Roads, VA	4.26	0.20	1.20	3.06
Portsmouth, VA	3.74	0.29	1.20	2.54
Wilmington, NC	2.04	0.27	1.23	0.81
Charleston, SC	3.27	0.18	1.01	2.26
Savannah, GA	3.01	0.23	0.43	2.58
Fernandina, FL	1.97	0.14	0.57	1.40

Mayport, FL	2.23	0.21	0.57	1.66
Daytona Beach, FL	2.01	0.66	0.57	1.44
Miami Beach, FL	2.29	0.26	0.69	1.60
Key West, FL	2.23	0.11	0.69	1.54
Average	2.67	0.32	1.41	
1.26±0.73				
(N=39)	±0.70±0.53			

(1) **RSLR**: raw tide-gauge data (PSMSL, 1998); (2) **SEOT**: standard error of trend; (3) **Aver.**: average trend ≤ 6000 yrs BP, C^{14} data (Gornitz, 1995b); (4) **COR. SLR**: corrected sea level trend, i.e., (1) - (3).

Appendix 2. Tidal datums.

A datum is an arbitrary elevation level used as a reference from which heights or depths are measured. A tidal datum is defined in terms of a particular phase of the tide. Commonly used datums are as follows:

MHHW (Mean Higher High water). The arithmetic mean of the higher of two high tides in a tidal day averaged over a specific 19-year Metonic (lunar nodal) cycle (The National Tidal Datum Epoch).

MHW (Mean High Water). The arithmetic mean of of the high water levels taken over a specific 19-year cycle.

MSL (Mean Sea Level). The arithmetic mean of hourly water levels measured over a specific 19-year cycle.

MTL (Mean Tide Level). The arithmetic mean of MHW and MLW. This value is very close to, but not identical with mean sea level.

MLW (Mean Low Water). The arithmetic mean of the low water levels over a specific 19-year cycle.

MLLW (Mean Lower Low Water). The arithmetic mean of the lower of two low tides in a tidal day, observed over a specific 19-year cycle.

NGVD (National Geodetic Vertical Datum). Formerly known as the mean sea level (MSL) of 1929.

To convert surge or flood levels based on NGVD to MTL, subtract (MTL - NGVD) from the surge (flood) height. Similarly for NGVD to MSL.

SITE	**MTL - NGVD**	**MSL - NGVD**

	feet	cm	feet	cm
Battery Park	0.62	18.9	0.70	21.3
Coney Island	0.58	17.7	0.65	19.8
Rockaway Beach	0.57	17.4	0.63	19.2
Long Beach	0.53	16.2	0.58	17.7
Westhampton	0.52	15.8	0.56	17.1
Montauk	0.48	14.6	0.51	15.5
Sandy Hook	0.76	23.2	0.79	24.1

Appendix 3. Characteristics of study sites

	SITES					
	Coney Island	Rockaway Beach	Long Beach	West. Beach	Seabright-OceanTown	Asbury Park-Manasquan
Length						
mi	2.95	6.4	7.77	4.0	11.8	9.0
km	4.75	10.3	12.5	6.4	19.0	14.5
Initial date	1994-1995	1975-1997	2002-2003	1997	1994-1998	1997-1999
Duration years	50	25	50	30	50	50
Renourish cycle, yr	10	3	6	3	6	6
SLR						
in/yr	0.11	0.11	0.10	0.10	0.15	0.15
mm/yr	2.73	2.73	2.58	2.45	3.85	3.85
Berm ht.[4]						
ft	13.0	10.0	10.0	9.5	10.4	10.4
m	3.96	3.05	3.05	2.9	3.17	3.17
Depth of closure[4]						
ft	13.0	10.0	10.0	9.5	10.4	10.4
ft	-17.0	-17.0	-20.0	-22.0	-21.0	-20.0
m	-5.18	-5.18	-6.10	-6.70	-6.40	-6.10

[4] Referenced to NGVD (see Appendix 2).

Appendix 4. Projected sea level rise scenarios and subsidence, Metro East Coast region (cm).

Site	Decade	Current trend	CCGG	CCGS	HCGG	HCGS	SUBS
NYC	2000	8.2	9.5	9.5	8.6	7.6	4.3
	2010	10.9	15.9	16.4	12.7	11.1	5.7
	2020	13.7	24.1	21.7	16.1	13.9	7.1
	2030	16.4	31.4	25.3	22.1	18.0	8.6
	2040	19.1	44.7	36.7	27.1	23.6	10.0
	2050	21.8	51.1	47.5	32.5	25.8	11.4
	2060	24.6	64.8	54.1	38.9	30.7	12.9
	2070	27.3	82.3	65.4	46.3	36.9	14.3
	2080	30.0	95.5	75.9	54.4	42.6	15.7
	2090	32.8	114.5	98.6	60.6	49.5	17.2
WP	2000	6.9	8.2	8.2	7.3	6.4	3.0
	2010	9.2	14.2	12.2	11.0	9.3	4.0
	2020	11.5	21.9	19.5	14.0	11.7	5.0
	2030	13.8	28.8	22.7	19.5	15.4	6.0
	2040	16.1	41.7	33.7	24.1	20.6	7.0
	2050	18.4	47.7	44.1	29.1	22.4	8.0
	2060	20.7	60.9	50.2	35.0	26.8	9.0
	2070	23.0	78.0	61.1	42.0	32.6	10.0
	2080	25.3	90.8	71.2	49.7	37.9	11.0
	2090	27.6	109.3	93.4	55.5	44.3	12.0
PJ	2000	6.6	7.9	7.9	7.0	6.1	2.7
	2010	8.8	13.8	11.8	10.6	8.9	3.6
	2020	11.0	21.4	19.0	13.5	11.2	4.5
	2030	13.2	28.2	22.1	18.9	14.8	5.4
	2040	15.4	41.0	33.0	23.4	19.9	6.3
	2050	17.6	46.9	43.3	28.3	21.6	7.2
	2060	19.8	60.0	49.3	34.1	25.9	8.1
	2070	22.0	77.0	60.1	41.0	31.6	9.0
	2080	24.2	89.9	70.1	48.6	36.8	9.9
	2090	26.4	108.1	92.2	54.3	43.1	10.8
M	2000	6.8	8.1	8.1	7.2	6.3	2.9

	2010	9.1	14.1 12.1 10.8 9.2 3.9
	2020	11.4	21.8 19.4 13.8 11.6 4.9
	2030	13.6	28.6 22.6 19.3 15.2 5.8
	2040	15.9	41.5 33.5 23.9 20.4 6.8
	2050	19.2	47.5 43.8 28.9 22.1 7.8
	2060	20.4	60.7 50.0 34.7 26.6 8.7
	2070	22.7	77.7 60.8 41.7 32.3 9.7
	2080	25.0	90.5 70.9 49.4 37.6 10.7
	2090	27.2	108.9 93.0 55.1 44.0 11.6
SH	2000	11.6	12.9 12.8 11.9 11.0 7.7
	2010	15.4	20.4 18.4 17.2 15.5 10.2
	2020	19.3	29.7 27.3 21.7 19.5 12.8
	2030	23.1	38.1 32.0 28.8 24.7 15.3
	2040	27.0	52.6 44.6 35.0 31.4 17.9
	2050	30.8	60.1 56.5 41.5 34.8 20.4
	2060	34.7	76.7 66.0 50.8 42.6 24.8
	2070	38.5	93.5 76.6 57.5 48.1 25.5
	2080	42.4	107.9 88.3 66.7 55.0 28.1
	2090	46.2	127.9 112.0 74.1 62.9 30.6
LB	2000	8.0	9.3 9.3 8.4 7.4
	2010	10.6	15.7 15.6 12.4 10.8
	2020	13.3	23.8 21.4 15.8 13.5
	2030	16.0	31.1 25.0 21.7 17.6
	2040	18.6	44.4 36.3 26.7 23.1
	2050	21.4	50.8 47.1 32.0 25.2
	2060	23.9	64.5 53.7 38.4 30.1
	2070	26.6	82.0 65.0 45.7 36.3
	2080	29.2	95.3 75.5 53.9 41.9
	2090	31.9	114.3 98.3 60.0 48.8
WH	2000	7.3	8.6 8.6 7.7 6.8
	2010	9.7	14.7 13.6 11.5 9.9
	2020	12.2	22.6 20.2 14.6 12.4
	2030	14.6	29.6 23.5 20.3 16.2
	2040	17.0	42.6 34.6 25.0 21.5
	2050	20.1	48.8 45.1 30.2 23.4
	2060	29.2	110.9 95.0 57.0 45.9
	2070	24.3	79.3 62.4 43.3 33.9

2080	26.8	92.3 72.7 51.2 39.4
2090	29.2	110.9 95.0 57.0 45.9

Note: All changes are with respect to the 1961-1990 mean. Tide-gauge stations: **NYC** New York City (the Battery), **WP** Willets Point, **PJ** Port Jefferson, **M** Montauk, **SH** Sandy Hook. Other sites: **LB** Long Beach, **WH** Westhampton.

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Table 5. 100-year flood levels for combined extratropical and tropical cyclones, Metro East Coast Region (feet; meters).

SCENARIO	LOCALITY						
	NYC	**CI**	**RB**	**LB**	**WH**	**SB**
			2020s				
Current	10.2 (3.10)	11.2 (3.4)	10.1 (3.08)	10.4 (3.17)	9.9 (3.02)	10.6 (3.23)
CCGG	10.5 (3.20)	11.5 (3.5)	10.4 (3.17)	10.8 (3.29)	10.1 (3.08)	11.0 (3.35)
CCGS	10.4 (3.17)	11.4 (3.5)	10.4 (3.17)	10.7 (3.26)	10.1 (3.08)	10.9 (3.32)
HCGG	10.2 (3.11)	11.2 (3.4)	10.2 (3.11)	10.5 (3.20)	9.9 (3.02)	10.7 (3.26)
HCGS	10.2 (3.11)	11.2 (3.4)	10.1 (3.08)	10.4 (3.17)	9.8 (2.99)	10.6 (3.23)
			2050s				
Current	10.4 (3.17)	11.4 (3.5)	10.4 (3.17)	10.7 (3.26)	10.1 (3.08)	11.0 (3.35)
CCGG	11.4 (3.47)	12.4 (3.8)	11.3 (3.44)	11.7 (3.57)	11.0 (3.35)	12.0 (3.66)
CCGS	11.3 (3.44)	12.3 (3.7)	11.2 (3.41)	11.6 (3.54)	10.9 (3.32)	11.9 (3.63)
HCGG	10.8 (3.29)	11.8 (3.6)	10.7 (3.26)	11.0 (3.35)	10.4 (3.17)	11.4 (3.47)
HCGS	10.6 (3.23)	11.6 (3.5)	10.5 (3.20)	10.8 (3.29)	10.2 (3.11)	11.1 (3.38)
			2080s				
Current	10.7 (3.26)	11.7 (3.6)	10.6 (3.23)	11.0 (3.35)	10.4 (3.17)	11.4 (3.47)
CCGG	12.8	13.8	12.8	13.1	12.4	13.5

	(3.90)	(4.2)	(3.90)	(3.99)	(3.78)	(4.11)
CCGS	12.2	13.2	12.1	12.5	11.8	12.9
	(3.72)	(4.0)	(3.69)	(3.81)	(3.60)	(3.93)
HCGG	11.5	12.5	11.4	11.8	11.1	12.2
	(3.50)	(3.8)	(3.47)	(3.60)	(3.38)	(3.72)
HCGS	11.1	12.1	11.0	11.4	10.7	11.8
	(3.38)	(3.7)	(3.35)	(3.47)	(3.26)	(3.60)

The 100-year flood level includes projected global sea level rise, local subsidence, mean high water, and combined extratropical and tropical storm surge.

NYC New York City (the Battery), **CI** Coney Island, **RB** Rockaway Beach, **LB** Long Beach, **WH** Westhampton Beach, **SB** Sea Bright/Asbury Park.

Table 6. Shoreline erosion--Metro East Coast Region (ft/yr; m/yr).

SCENARIO	**LOCALITY**				
	Coney Island	**Rockaway Beach**	**Long Beach**	**Westhamp. Beach**	**Seabright/ Asbury Park**
			2020s		
Current	1.27 (0.39)	1.69 (0.51)	1.35 (0.41)	1.53 (0.47)	1.61 1.88 (0.49; 0.57)
CCGG	2.24 (0.68)	2.97 (0.90)	2.42 (0.74)	2.53 (0.77)	2.48 2.89 (0.76; 0.88)
CCGS	2.02 (0.62)	2.67 (0.81)	2.18 (0.66)	2.26 (0.69)	2.28 2.65 (0.70; 0.81)
HCGG	1.50 (0.46)	1.98 (0.60)	1.61 (0.49)	1.63 (0.50)	1.81 2.11 (0.55; 0.64)
HCGS	1.29 (0.39)	1.71 (0.52)	1.38 (0.42)	1.39 (0.42)	1.63 1.89 (0.50; 0.58)
			2050s		
Current	2.03 (0.62)	2.68 (0.82)	2.18 (0.66)	2.44 (0.74)	2.58 2.99 (0.79; 0.91)
CCGG	4.75 (1.45)	6.29 (1.92)	5.17 (1.58)	5.46 (1.66)	5.02 5.84 (1.53; 1.78)
CCGS	4.42 (1.35)	5.84 (1.78)	4.80 (1.46)	5.04 (1.54)	4.72 5.49 (1.44; 1.67)
HCGG	3.02 (0.92)	4.00 (1.22)	3.26 (0.99)	3.38 (1.03)	3.47 4.03 (1.06; 1.23)
HCGS	2.40 (0.73)	3.17 (0.97)	2.57 (0.78)	2.62 (0.80)	2.91 3.38 (0.89; 1.03)

2080s

Current	2.79	3.69	2.97	3.36	3.54 4.12
	(0.85)	(1.13)	(0.91)	(1.02)	(1.08; 1.26)
CCGG	8.88	11.75	9.70	10.32	9.01 10.48
	(2.71)	(3.58)	(2.96)	(3.15)	(2.75; 3.19)
CCGS	7.06	9.34	7.69	8.13	7.38 8.58
	(2.15)	(2.85)	(2.34)	(2.48)	(2.25; 2.61)
HCGG	5.06	6.69	5.49	5.73	5.58 6.48)
	(1.54)	(2.04)	(1.67)	(1.75)	(1.70; 1.97)
HCGS	3.96	5.24	4.27	4.41	4.60 5.34
	(1.21)	(1.60)	(1.30)	(1.34)	(1.40; 1.63)