



# **Potential for Shoreline Changes Due to Sea-Level Rise Along the U.S. Mid-Atlantic Region**

By Benjamin T. Gutierrez, S. Jeffress Williams, and E. Robert Thieler

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## Contents

Contents .....	iii
Figures .....	iii
Conversion Factors .....	v
Inch/Pound to SI .....	v
A. Abstract .....	1
B. Introduction .....	2
C. The Assessment Process .....	3
D. Geological Characteristics of the Mid-Atlantic Coast .....	4
E. Sea-Level Rise on the U.S. Atlantic Coast .....	5
F. Important Processes Involved in Mid-Atlantic Bight Shoreline Changes .....	6
G. Approaches for Long-Term Assessment and Prediction .....	6
H. Coastal Landforms of the Mid-Atlantic Bight .....	7
Spits .....	7
Headlands .....	7
Wave-Dominated Barrier Islands .....	8
Mixed-Energy Barrier Islands .....	8
I. Potential Responses to Future Sea-Level Rise .....	8
J. Assessment of Question 2 .....	10
Spits (Compartments 4, 9, 15) .....	11
Headlands (Compartments 1, 5, 8, 10, 12, 16) .....	11
Wave-Dominated Barrier Islands (Compartments 2, 6, 11, 13, 17) .....	11
Mixed-Energy Barrier Islands (Compartments 3, 7, 14) .....	12
K. Summary .....	12
L. Acknowledgements .....	13
M. References Cited .....	13
.....	20
Appendix-List of Committee Participants .....	25

## Figures

1. Map of the mid-Atlantic coast of the United States showing the seventeen coastal compartments and their coastal geomorphic type .....	20
2. Paleogeography of the Delaware Bay region inferred from geological investigations of shallow marine sediments. Compiled from Fletcher and others (1990 and 1992). .....	21
3. Map showing the potential sea-level rise responses for each coastal compartment. Colored portions of the coastline indicates the potential response for a given sea-level rise scenario according to the inset table. Numbers indicate the coastal compartments shown in Figure 1. ....	22
4. Schematic diagram of the degrees of likelihood for shoreline change outcomes. ....	23

## Tables

1. Rates of Relative Sea-Level Rise for Selected Long-Term Tide Gauges on the East Coast of the United States (Zervas, 2001). ....	24
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# Conversion Factors

## Inch/Pound to SI

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
<b>Rate</b>		
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

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## A. Abstract

Sea-level rise over the next century is expected to contribute significantly to physical changes along open-ocean shorelines. Predicting the form and magnitude of coastal changes is important for understanding the impacts to humans and the environment. Presently, the ability to predict coastal changes is limited by the scientific understanding of the many variables and processes involved in coastal change, and the lack of consensus regarding the validity of existing conceptual, analytical, or numerical models. In order to assess potential future coastal changes in the mid-Atlantic U.S. for the U.S. Climate Change Science Program (CCSP), a workshop was convened by the U.S. Geological Survey. Assessments of future coastal change were made by a committee of coastal scientists with extensive professional experience in the mid-Atlantic region. Thirteen scientists convened for a two-day meeting to exchange information and develop a consensus opinion on potential future coastal changes for the mid-Atlantic coast in response to sea-level rise. Using criteria defined in past work, the mid-Atlantic coast was divided into four geomorphic compartments: spits, headlands, wave-dominated barriers, and mixed-energy barriers. A range of potential coastal responses was identified for each compartment based on four sea-level rise scenarios. The four scenarios were based on the assumptions that: a) the long-term sea-level rise rate observed over the 20<sup>th</sup> century would persist over the 21<sup>st</sup> century, b) the 20<sup>th</sup> century rate would increase by 2 mm/yr, c) the 20<sup>th</sup> century rate would increase by 7 mm/yr, or d) sea-level would rise by 2 m over the next few hundred years. Potential responses to these sea-level rise scenarios depend on the landforms that occur within a region and include increased likelihood for erosion and shoreline retreat for all coastal types, increased likelihood for erosion, overwash and inlet breaching for barrier islands, as well as the possibility of a threshold state (e.g., dramatic change in barrier evolution, such as segmentation or disintegration) for some barrier island systems. The likelihood of the potential coastal responses is expressed using standard terminology employed in climate change assessments (e.g., as used by the Intergovernmental Panel on Climate Change and CCSP). This assessment was based on the coastal geomorphology in its present condition and does not consider any coastal protection that might be undertaken in the future. The committee recognized that a variety of erosion mitigation measures have been implemented along developed portions of the coast and these are very likely to be applied in the future. It was also acknowledged that economics, political will, and other factors can drive decisions to implement these measures, and that such decisions cannot be predicted with confidence. The results of this assessment are depicted graphically on maps of the study area.

## B. Introduction

Compelling observations have led most scientists to agree that the global climate is changing due to human-induced warming (e.g., Intergovernmental Panel on Climate Change [IPCC] reports released in 2001 and 2007, IPCC, 2001 and IPCC, 2007). The predicted consequences are highly variable, but two that will greatly affect coastal regions are sea-level rise and the potential for more frequent and energetic storms. In the United States, the U.S. Climate Change Science Program (CCSP; <http://www.climatescience.gov/>) has undertaken a synthesis and assessment of the state-of-science regarding climate change and its impacts. As part of this effort, scientists from the USGS, EPA, and NOAA have been tasked with reviewing potential sea-level rise impacts to coastal regions (see <http://www.climatescience.gov/Library/sap/sap4-1/SAP4-1prospectus-final.pdf>). The CCSP synthesis and assessment (SAP) products are typically framed to answer a set of key questions about specific topics relating to climate change and its impacts. For this SAP, the USGS was asked to address several "key questions." The subject of this report is key question 2:

How does sea-level rise change the coastline? Among those lands with sufficient elevation to avoid inundation, which land could potentially erode in the next century? Which lands could be transformed by related coastal processes? (key question 2, page 5 of SAP 4.1 Prospectus)

Sea-level changes over geological time scales have driven large changes in shoreline position, particularly on low-gradient margins lacking significant fluvial systems (e.g., Muhs and others, 2004). While it is widely believed that changes in sea-level over the last century have had some role in shoreline change and land-loss along the coast, it has been difficult to quantify this relationship. The difficulty is due to the range of processes that affect coastal areas, the frequency at which coastal changes occur, and the closely coupled links between sea-level rise and the other processes driving coastal change. For example, over time periods of a century or less, changes in shoreline position have been linked closely to the availability of sand to the coastal sediment transport system (Carter and Woodroffe, 1994; Wright, 1995). In addition, shoreline changes caused by large storms can cause changes in shoreline position that persist for weeks to a decade or more (Morton and others, 1994; Zhang and others, 2004; List and others, 2006; Riggs and Ames, 2007). Shoreline position and beach morphology can vary by tens of meters over periods of a few months to several decades in response to these factors (Morton and others, 1994; Honeycutt and others, 2001; Zhang and others, 2002). Complex interactions with nearshore sand bodies and/or underlying geology (the geologic framework), the mechanics of which are not yet clearly understood, also influence the behavior of beach morphology over a range of time scales (Riggs and others, 1995; Honeycutt and others, 2003; Schuup and others, 2006; Miselis and McNinch, 2006).

Existing shoreline-change prediction techniques such as the Bruun Rule (Bruun, 1962), extrapolation of historic shoreline change rates (NRC, 1987; Leatherman, 1990), and simple inundation of a static topography (Najjar and others, 2000; Titus and Richman, 2001) are based on assumptions that are either difficult to validate or too simplistic to account for the complex processes driving coastal change to be reliable for many real-world applications (Pilkey and Davis, 1987; Wells, 1995; Bird, 1995). As a result, the usefulness of these predictive approaches, and whether it is possible to quantify the link between sea-level rise and shoreline change, has been debated in the coastal science community (Pilkey and others, 1993; Thieler and others, 2000; Leatherman and others, 2000a; 2000b; Pilkey and others, 2000; Sallenger and others, 2000; Cooper

and Pilkey, 2004). Recently, more complex coastal process-based models like the Advanced Circulation Model (ADCIRC) (Luettich and Westerink, 1995), Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005), Delft3D (e.g., Vitousek and others, 2007), Shoreface Translation Model (Cowell and others, 1995) and the Geomorphic Model of Barrier, Estuarine, and Shoreface Translations (GEOMBEST) (Stolper and others, 2005) have sought to incorporate important factors such as the sediment budget and geologic framework into predictions of coastal evolution. Research with these models is underway to advance our understanding of past and present coastal behavior. However, much additional research and testing against both the geologic record and present-day processes are needed to advance scientific understanding and inform management.

A different technique for assessing the potential for future coastal changes, the Coastal Vulnerability Index, uses physical characteristics of the coastal system to classify the potential effects of sea-level rise on open coasts. This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, yielding a quantitative, although relative, measure of the shoreline's natural vulnerability to the effects of sea-level rise. The method has been applied in the U.S. (Gornitz and White, 1992; Thieler and Hammar-Klose, 1999; 2000a; 2000b; Pendleton and others, 2004a; 2004b; 2005), Canada (Shaw and others, 1998), and elsewhere (Argentina -- Diez and others, 2007), and is presently used by the U.S. National Park Service as a planning tool for coastal park units (Thieler and others, 2002). While a rank-based vulnerability assessment allows scientists and decision makers to identify portions of the coast at higher risk, it is not a predictive tool.

Because of the difficulties involved in long-term coastal change projections and the general lack of consensus among coastal scientists regarding appropriate methodologies, the USGS authors of the CCSP SAP 4.1 (Anderson, Cahoon, Gutierrez, Thieler, Williams; see Appendix A) chose to convene a committee of coastal scientists to address key question 2. Given the limited time and resources available to conduct this assessment, more formal group consensus approaches such as expert panel methods (e.g., Fink and others, 1984; Cooke, 1991; Aspinall and Cooke, 1998) were not pursued. In this effort, USGS authors convened a committee of 13 coastal scientists (see Appendix A) to discuss the potential changes that might occur to the ocean shores of the U.S. mid-Atlantic coast in response to predicted accelerations in sea-level rise over the next century. The resulting assessment that is synthesized in this document is based upon the professional judgement of the committee members who participated in this process.

In this report, the results of the two-day meeting are summarized and reviewed. The details of the meeting process are presented in Section C. Section D reviews the geological characteristics of the mid-Atlantic coast. Section E reviews the current understanding of relative sea-level rise for the Atlantic Coast of the United States. Section F summarizes the important factors and processes of shoreline change discussed by the committee. Section G provides a brief summary of assessment and prediction techniques that could be used to assess shoreline changes in response to sea-level rise. Section H summarizes the coastal landforms of the mid-Atlantic coast. Section I describes the potential landform response to sea-level rise, and Section J presents the assessment of coastal changes that may occur due to the future sea-level rise scenarios that were considered in this effort.

## **C. The Assessment Process**

To address key question 2, the USGS authors assembled a committee of coastal scientists to evaluate the potential outcomes of the four sea-level rise scenarios specified in SAP 4.1 and how these might be developed. The members of this group were chosen on the basis of their expertise and long experience in the coastal research community and also their involvement with coastal

management within the mid-Atlantic region. Of the 13 committee members who were contacted, all agreed to participate, but three were unable to attend the meeting due to schedule conflicts (see Appendix A). The two-day workshop was held on April 12-13, 2007 in Beltsville, MD at the USGS Patuxent Wildlife Research Center. Prior to the meeting, the committee members were informed of the meeting objectives and provided with background documents. To orient the participants to the scope of the discussion, members were provided with: a) the SAP 4.1 Prospectus, b) a list of questions and topics that the USGS authors needed to address, and c) a report by a panel of wetlands scientists (Reed and others, 2007) developed for SAP 4.1. This report was provided as an example of a committee-based approach to answer other questions posed by the SAP 4.1 Prospectus.

The sea-level rise impact assessment effort was conducted as an open discussion facilitated by the USGS authors. The group of scientists was tasked with discussing the potential changes that could occur over the remainder of this century based on four sea-level rise scenarios:

1. a continuation of the 20th century rate of sea-level rise,
2. the 20th century rate + 2 mm/yr,
3. the 20th century rate + 7 mm/yr, and
4. a 2-m rise over the next few hundred years.

The 20th century rate refers to the long-term relative sea-level rise rates that have been observed over the last century at east coast tide gauge stations (Table 1; Zervas, 2001). The relative rates include both contributions from the long-term eustatic rate (1.7 mm/yr) and local contributions due to subsidence (See Section E). The second two scenarios assume the acceleration of the local rates will be driven by accelerations in the eustatic rate. The first two scenarios imply changes in sea-level that are within the range of those presented by the recent IPCC report (Bindoff and others, 2007). The third scenario implies a change that could exceed the IPCC model predictions by 0.3 m. These three scenarios are also consistent with a recently conducted wetlands accretion assessment for the mid-Atlantic region between New York and Virginia (Reed and others, 2007). The main topics that the committee discussed were:

1. approaches that can be used to conduct long-term assessments of coastal change;
2. important factors and processes contributing to shoreline change over the next century;
3. key geomorphic settings in the mid-Atlantic Bight;
4. potential responses of these environments to sea-level rise; and
5. likelihood of these responses to the sea-level rise scenarios.

After the meeting, the USGS authors assembled this report to summarize the discussion that occurred during the two day meeting and to synthesize the resulting assessment. Drafts of this report were circulated to the meeting participants soliciting feedback. Participants provided comments and suggested changes to the overall assessment that were incorporated into the final document, which was subsequently approved by all members.

## **D. Geological Characteristics of the Mid-Atlantic Coast**

The mid-Atlantic portion of the U.S. is classified as a trailing edge coast (Inman and Nordstrom, 1971) which is comprised of a low gradient coastal plain that has accumulated over millions of years in response to the erosion and denudation of the Appalachian mountain chain (Walker and Coleman, 1987). The resulting sedimentation has constructed a broad coastal plain and continental shelf that extends up to 300 km seaward of the present coast (Colquhoun and others,

1991). The current morphology of this coastal plain and continental shelf is the product of erosion by rivers that drain the region, the marine regressions and transgressions, and the construction of barrier islands and other coastal landforms on the intervening mainland. Repeated glaciations over the last 3 million years have resulted in sea-level fluctuations of up to 120-140 m (Lambeck and others, 2002; Miller and others, 2005). The major river systems (e.g., Hudson River, Delaware River, Susquehanna River, and Roanoke River) incised large valleys across the continental shelf during periods of low sea level that were subsequently flooded and partly filled with sediments during the Holocene transgression as sea level rose to present levels. At the northern limit of the focus area, Long Island formed from glacial outwash plains and two terminal moraines formed by the Laurentide Ice Sheet, which began to retreat at the end of the last glacial maximum approximately 21,000. The low gradient of the mid-Atlantic landscape in combination with slow rates of sea-level rise over the last few thousand years and the availability of sufficient sand have enabled the formation of the barrier spits and barrier islands along much of the coast.

Presently, the river systems along the mid-Atlantic coast mostly discharge into estuaries and bays and deliver minor amounts of coarse sediment to the open coast (Meade, 1972). As a result, the region is generally considered to be sediment starved (Wright, 1995). The sediments that form mainland beaches and barrier beaches are derived from the erosion of older, pre-existing coastal landforms and the seabed of the continental shelf. Since the largest waves and associated currents that transport sediments and mold landforms occur during storms, the Atlantic margin of the U.S. is often referred to as a storm-dominated coast (Davis and Hayes, 1984).

The majority of the open ocean coast along the mid-Atlantic Bight is comprised of sandy shores that include beach and barrier-island environments. While barriers comprise about 15 percent of the world coastline (Glaeser, 1978), they are the dominant shoreline type along the U.S. Atlantic coast. Along the portion of the mid-Atlantic Bight coast that we consider here, barriers line approximately 90 percent of the study area. Consequently, scientific investigations exploring coastal geology of this portion of North America have largely focused on understanding barrier island systems (Fisher, 1962; Pierce and Colquhoun, 1970; Kraft, 1971; Swift, 1975; Leatherman, 1979; Moslow and Heron, 1979; 1994; Oertel, 1985; Belknap and Kraft, 1985; Hine and Snyder, 1985; Davis, 1994; Oertel and Kraft, 1994; Pilkey and others, 1998).

## **E. Sea-Level Rise on the U.S. Atlantic Coast**

Over the last century, relative sea-level rise rates along the Atlantic coast of the U.S. have ranged between 1.8 mm/yr (Maine) to as much as 4.4 mm/yr (Virginia, Table 1; Zervas, 2001). The lowest rates (~1.8 mm/yr) are nearly equivalent to the average global rate for the 20<sup>th</sup> century of  $1.7 \pm 0.5$  mm/yr (Bindoff and others, 2007) and occur along coastal New England and from Georgia to southern Florida. The highest rates have been observed in the mid-Atlantic region between northern New Jersey and northeastern North Carolina (Table 1; Zervas, 2004). Subsidence of the land surface due to a range of factors contributes to the high rates of relative sea-level rise observed in this region. It is believed that the subsidence is attributable mainly to glacio-isostatic adjustments of the earth's crust in response to the melting of the Laurentide ice sheet, and to the compaction of sediments due to freshwater withdrawal from coastal aquifers (Gornitz and Lebedeff, 1987; Emery and Aubrey, 1991; Peltier, 2001).

With the anticipated acceleration in the rate of global sea-level rise (e.g., IPCC 2001; 2007), local rates of relative sea-level rise will also accelerate. Recently, the Fourth Assessment Report (FAR) of the IPCC has predicted that sea level will rise by 10-59 cm over the next century (Meehl and others, 2007), which is a somewhat smaller rise and range than reported in the Third Assessment Report (TAR; IPCC, 2001; estimate 11-88 cm) (Church and others, 2001). Several

recent criticisms of the FAR estimates of future sea-level changes (Rahmstorf, 2007; Rahmstorf and others, 2007; Hansen and others, 2007) argue that these estimates are conservative and do not incorporate adequately the potential contributions of land-based ice melt from Greenland and western Antarctica to global sea level. The IPCC assessment concludes that the science regarding future acceleration in ice melt and its contribution to sea-level rise is not yet sufficient to include in their sea-level projections.

## **F. Important Processes Involved in Mid-Atlantic Bight Shoreline Changes**

Several important factors influencing the evolution of the mid-Atlantic coast in response to sea-level rise were identified. Among these are: a) the geologic framework, b) physical processes, c) the sediment budget, and d) human activity. The committee agreed that the sediment budget is a critical determinant of how a specific shoreline setting will respond to changes in sea-level, but the response is dependent upon the interactions with the other three variables. At the same time, it was agreed that it is not possible to quantify with high confidence the sediment budget over time periods as long as a century and its precise role in influencing shoreline changes. Another factor is the human impact on coasts. A variety of erosion control practices and alterations of the coast have been undertaken over the last century along much of the mid-Atlantic region, particularly during the latter half of the 20<sup>th</sup> century. In many cases, shoreline engineering structures such as seawalls, revetments, groins and jetties have significantly altered sediment transport processes, often exacerbating erosion on a local to regional scale. At the same time, beach nourishment has been used on many beaches to temporarily mitigate erosion and provide storm protection by adding to the sediment budget. It is uncertain whether or how these engineering measures might impede the ability of natural processes to respond to future sea-level rise. It is also uncertain whether ongoing and planned coastal engineering projects, such as beach nourishment, will be continued into the future due to economic constraints and potentially limited supplies of suitable sand resources. Because of these uncertainties, the committee focused on assessing the vulnerability of the coastal system as it exists today.

## **G. Approaches for Long-Term Assessment and Prediction**

A range of different techniques to predict shoreline change and how these might be applied to assess shoreline change over the next century were discussed. The committee believed that the particular challenges to the application of such techniques are knowledge of how the sediment budget and geologic framework will affect long-term shoreline changes.

The discussion focused primarily on three techniques: a) the Bruun Rule (Bruun, 1962), b) extrapolation of historical shoreline change rates (Leatherman, 1990), and c) the Coastal Vulnerability Index (CVI, Gornitz and White, 1992; Gornitz and others, 1994; Thieler and Hammar-Klose, 1999). The first two approaches were not deemed adequate to form a basis for long-term prediction. The main reason is that there is a lack of consensus in the coastal science community regarding their validity for long-term prediction. In addition, regarding the Bruun model, it was recognized that there is a lack of basic information available over wide stretches of the coast that can be used to adequately define the model input parameters, and that the basic assumptions of the model cannot be satisfied in most real-world applications. Reservations were expressed about shoreline change rate extrapolation due to the quality of historical shorelines that are used and whether these accurately reflect natural processes that contribute to long-term changes. The CVI technique was also discussed but there was no consensus among the group as to whether this tool could be used to inform quantitative long-term assessments.

Given the limited time available for input into the CCSP effort, members of the committee agreed to conduct a qualitative assessment of the potential response of the ocean coast of the mid-Atlantic region to four sea-level rise scenarios described in Section C (page 4, paragraph 2). Using these scenarios, this effort focused on:

1. defining key geomorphic compartments along the mid-Atlantic coast, and
2. specifying potential responses based on knowledge of their behavior that has been established in the coastal science literature and in the experience of the committee members.

Coastal compartments were defined, and the committee assigned a geomorphic designation to each portion of the mid-Atlantic coast. The potential coastal response for each of the specified outcomes for a given sea-level rise scenario were then evaluated. The results of this assessment are explained below.

## **H. Coastal Landforms of the Mid-Atlantic Bight**

A consensus was reached by the committee that coastal landforms along the shores of the mid-Atlantic Bight can best be classified by merging the schemes developed by Fisher (1982), Hayes (1979), and Davis and Hayes (1984). Four distinct geomorphic settings were identified (fig. 1).

### **Spits**

The accumulation of sand from longshore transport has built large spits that extend from adjacent headlands into the mouths of large coastal embayments. Outstanding examples of these occur at the entrances of Raritan (Sandy Hook, NJ) and Delaware Bays (Cape Henlopen, DE). The evolution and existence of these spits result from the interaction between alongshore transport driven by incoming waves and the tidal flow through the large embayments. Morphologically these areas can extend and evolve rapidly. Since 1842, Cape Henlopen (fig. 1, compartment 9) has extended over 1.5 km to the north into the mouth of Delaware Bay as the northern Delaware shoreline has retreated and sediment has been transported north by longshore currents (Kraft 1971; Ramsey and others, 2001).

### **Headlands**

In the mid-Atlantic Bight, coastal headlands typically front drainage divides that separate creeks and rivers from one another in the older landscape (fig. 2). These regions provide a source of sediment that is eroded and incorporated into the longshore transport system that maintains adjacent beaches and barriers. Coastal headlands are present on Long Island, NY (See fig. 1), from Southampton to Montauk (compartment 1), in northern New Jersey from Monmouth to Point Pleasant (compartment 5; Oertel and Kraft, 1994), in southern New Jersey at Cape May (compartment 8), on Delaware north and south of Indian River and Rehoboth Bays (compartments 10 and 12; Kraft, 1971; Oertel and Kraft, 1994; Ramsey and others, 2001), and on the Virginia coast, from Cape Henry to Sandbridge (compartment 16).

## **Wave-Dominated Barrier Islands**

Wave-dominated barrier islands occur as relatively long and thin stretches of sand fronting shallow estuaries, lagoons, or embayments and are bisected by widely-spaced tidal inlets. These barriers are present in regions where wave energy is large relative to tidal energy (Hayes, 1979; Davis and Hayes, 1984). Limited tidal ranges result in flow through tidal inlets that is marginally sufficient to flush the sediments that accumulate from longshore sediment transport. In some cases this causes the inlet to migrate over time in response to a changing balance between tidal flow through the inlet and wave driven alongshore transport. Inlets on wave-dominated coasts often exhibit large flood-tidal deltas and small ebb-tidal deltas as tidal currents are often stronger during the flooding stage of the tide. In addition, inlets on wave-dominated barriers are often ephemeral. They open intermittently in response to storm-generated overwash and migrate laterally in the direction of net littoral drift. In many cases these inlets are prone to filling with sands from alongshore transport (e.g., Riggs and others, 1995; McBride, 1999).

Overwash produced by storms is common on wave dominated barriers (e.g., Morton and Sallenger, 2003; Riggs and Ames, 2007). Overwash cuts through low-lying dunes into the island interior. Sediment deposition from overwash adds to the island's elevation. Washover fans that extend into the back-barrier waterways form substrates for back-barrier marshes and submerged aquatic vegetation. Overwash is critical for the evolution of these barriers over time. The process of overwash is an important mechanism by which some types of barriers migrate landward and upward over time. This process of landward migration has been referred to as "roll-over" (Dillon, 1970; Godfrey and Godfrey, 1976; Fisher, 1982; Riggs and Ames, 2007). Over decades to centuries, the intermittent processes of overwash and inlet formation enable the barrier to migrate over and erode into back-barrier environments such as marshes as relative sea-level rise occurs over time. As this occurs, back-barrier environments such as marshes are eroded and buried by barrier beach and dune sands. Wave-dominated barrier islands and spits are found along Long Island, NY (fig. 1, compartments 2 and 3), the New Jersey coast north of Little Egg inlet (fig. 1, compartment 6), the Delaware and Maryland coasts (fig. 1, compartments 10 and 13), and much of the North Carolina coast that are considered in this assessment (fig. 1, compartment 17).

## **Mixed-Energy Barrier Islands**

The other barrier island type present along the U.S. Atlantic coast, mixed-energy barrier islands, are shorter and wider than their wave-dominated counterparts (Hayes, 1979). They are punctuated by well-developed tidal inlets. The large sediment transport capacity of the tidal currents within the inlets of these systems maintains large ebb-tidal deltas seaward of the inlet mouth. The shoals that comprise ebb-tidal deltas cause incoming waves to refract around the large sand body that forms the delta so that local reversals of alongshore currents and sediment transport occur downdrift of the inlet. As a result, portions of the barrier downdrift of inlets become localized sediment sinks that are manifest as recurved sand ridges, giving the barrier islands a 'drumstick'-like shape (Hayes, 1979; Davis, 1994). Mixed-energy barriers are present along the Virginia coast (fig. 1, compartment 14), and the New Jersey coast between Little Egg Inlet and Cape May (Oertel and Kraft, 1994). Some authors have referred to the mixed-energy barriers as tide-dominated barriers along the Delmarva shoreline (e.g., Oertel and Kraft, 1994).

## **I. Potential Responses to Future Sea-Level Rise**

Three potential responses that could occur along the mid-Atlantic coast in response to sea-level rise over the next century were identified.

**1. Bluff and upland erosion.** Shorelines composed of older geologic units that form headland regions of the coast will retreat landward with rising sea level. As sea level rises over time, the uplands are eroded, and sandy materials are incorporated into the beach and dune systems along the shore and adjacent compartments. It is expected that bluff and upland erosion will persist for all four sea-level rise scenarios. A possible management reaction to bluff erosion is armoring of the shore. This may reduce bluff erosion in the short term, but will probably increase erosion of the beach in front of the armored bluff due to wave reflection as well as increased erosion of adjacent coastal segments by modifying the littoral sediment budget.

**2. Overwash, inlet processes, shoreline retreat, and barrier island narrowing.** Five main processes were identified as agents of change as sea-level rise occurs. First, storm overwash will become more likely. In addition, recent studies suggest that hurricanes have become more intense over the last century (Emanuel, 2005; Webster and others, 2005). Some have argued that there is insufficient data to support this finding (Landsea and others, 2006), but recent work supports this trend for the North Atlantic (Kossin and others, 2007) and the contention that the increased storm activity is linked to 20th century climate and ocean warming (Holland and Webster, 2007).

Tidal inlet formation and migration will also be important components of future shoreline changes. Barrier islands are often subject to inlet formation by storms. If the storm surge produces channels that extend below sea level, an inlet may persist after the storm abates. These inlets can persist for some time until the inlet channels are filled with sediments accumulated from longshore transport, or they may remain open for months to decades. Geological investigations along the shores of the mid-Atlantic Bight have encountered numerous geomorphic features and deposits indicating former inlet positions (Fisher, 1962; Everts and others, 1983; Leatherman, 1985; McBride and Moslow, 1991; Moslow and Heron, 1994; Riggs and others, 1995; McBride, 1999). Historically, most inlets have opened by the storm surge associated with major hurricanes. In the 20th century four of the most important inlets in the mid-Atlantic Bight were formed by storm surges and breaches from the 1933 hurricane (Barden's Inlet, NC; Ocean City Inlet, MD; Indian River Inlet, DE; and Moriches Inlet, NY). Most recently, tidal inlets have formed in the North Carolina Outer Banks in response to Hurricane Isabel in 2003 and on Nauset beach, Cape Cod, MA in response to a spring 2007 storm.

The combined effect of rising sea level and stronger storms potentially acting at higher elevations on the barrier could be expected to **accelerate shoreline retreat** in many locations. Assessments of shoreline change on barrier islands indicate that **barrier island narrowing** has been observed on some islands over the last century (Leatherman, 1979; Jarrett, 1983; Everts and others, 1983; McBride and Byrnes, 1997; Penland and others, 2005). Actual barrier island migration is less widespread, but has been noted at Core Banks, NC (Riggs and Ames, 2007), the Virginia barriers (Byrnes and Gingerich, 1987; Byrnes and others, 1989), and the northern end of Assateague Island, MD (Leatherman, 1984).

**3. Threshold Behavior.** Barrier islands are dynamic environments that are sensitive to a variety of driving forces. Some evidence suggests that changes in some or all of these processes can lead to conditions where a barrier system becomes less stable and crosses a geomorphic threshold. In this situation, the potential for rapid barrier-island migration or segmentation/disintegration is high. It is difficult to precisely define an unstable barrier but indications of instability can be:

- a) rapid landward recession of the ocean shoreline
- b) decrease in barrier width and height
- c) increased overwash during storms
- d) increased barrier breaching and inlet formation
- e) chronic loss of beach and dune sand volume.

Given the unstable state of some barrier islands under current rates of sea-level rise and climate trends, it is very likely that conditions will worsen under accelerated sea-level rise rates. The unfavorable conditions for barrier maintenance could result in barrier segmentation/disintegration as witnessed in coastal Louisiana (McBride and others, 1995; McBride and Byrnes, 1997; Penland and others, 2005; Day and others, 2007; Sallenger and others, 2007). This segmentation/disintegration may result from a combination of 1) limited sediment supply by longshore or cross-shore transport, 2) accelerated rates of sea-level rise, and 3) permanent removal of sand from the barrier system by storms. Changes in sea level coupled with changes in the hydrodynamic climate and sediment supply in the broader coastal environment contribute to the development of unstable behavior. The threshold behavior of unstable barriers could result in: a) landward migration/roll-over, barrier segmentation, or c) disintegration. If the barrier were to disintegrate, portions of the ocean shoreline could migrate or back-step toward and/or merge with the mainland.

During storms, large portions of low-elevation, narrow barriers can be inundated under high waves and storm surge. The parts of the mid-Atlantic coast most vulnerable to threshold behavior can be estimated based on their physical dimensions. Narrow, low-elevation barrier islands are most susceptible to storm overwash, which can lead to landward migration, and the formation of new tidal inlets. The northern portion of Assateague Island and segments of the North Carolina Outer Banks are examples of barrier islands that are extremely vulnerable to even modest storms because of their narrow width and low elevation (e.g., Leatherman, 1979; Riggs and Ames, 2003).

The future evolution of narrow, low-elevation barriers will likely depend in part on the ability of salt marshes in back-barrier lagoons and estuaries to keep pace with sea-level rise (FitzGerald and others, 2003 and 2006; Reed and others, 2007). It has been suggested that a reduction of salt marsh in back-barrier regions could change the hydraulics of back-barrier systems, altering local sediment budgets and leading to a reduction in sandy sediment available to sustain barrier systems (FitzGerald and others, 2003 and 2006). In these cases, even barrier systems that are relatively wide and exhibit well-developed dunes may evolve toward narrow, low-elevation barriers as local sand supplies are reduced.

## **J. Assessment of Question 2**

Seventeen coastal compartments were identified in the SAP mid-Atlantic focus area (fig. 1). The compartments were classified as one of the four geomorphic types described above. The potential coastal responses to the sea-level rise scenarios are described below and the potential responses to the first three sea-level rise scenarios are shown in figure 3. Spits (Compartments 4, 9, 15)

**Three caveats to this approach were identified for this assessment. These are:**

- a) **This is a regional scale assessment and there are local exceptions to these classifications and potential outcomes.**

- b) **Given that some portions of the mid-Atlantic coast are heavily influenced by development and erosion mitigation practices, it cannot be assumed that these will be continued into the future given uncertainties regarding the decision-making process that occurs when these practices are pursued.**
- c) **There are locations where some committee members felt that erosion mitigation will be implemented regardless of cost.**

To express the likelihood of a given outcome for a particular sea-level rise scenario, terminology modified from CCSP (2006) is used to quantify and communicate the degree of likelihood of a given outcome identified by this sea-level rise impact assessment (fig. 4). This represents the degree of confidence that the committee members believe that a specific outcome will be realized. These terms should not be construed to represent a quantitative relationship between a specific sea-level rise scenario and a specific dimension of coastal change, or rate at which a specific process operates on a coastal geomorphic compartment.

### **Spits (Compartments 4, 9, 15)**

For the first three sea-level rise scenarios (the 20<sup>th</sup> century rate, the 20<sup>th</sup> century rate + 2 mm/yr, and the 20<sup>th</sup> century rate + 7 mm/yr) it is **virtually certain** that the coastal spits in the mid-Atlantic Bight will be subject to increased storm overwash, erosion, deposition over the next century. It is **virtually certain** that some of these coastal spits will continue to prograde though the accretion of sediments from longshore transport as erosion of updrift coastal compartments occurs. For a 2 m rise in sea level, it is **likely** that threshold behavior could occur for this type of coastal landform (rapid landward and/or alongshore migration).

### **Headlands (Compartments 1, 5, 8, 10, 12, 16)**

Over the next century, it is **virtually certain** that these headlands will be subject to increased erosion for all four sea-level rise scenarios. It is **very likely** that shoreline and upland (bluff) erosion will accelerate in response to projected increases in sea-level.

### **Wave-Dominated Barrier Islands (Compartments 2, 6, 11, 13, 17)**

Potential sea-level rise impacts on wave-dominated barriers in the mid-Atlantic Bight vary spatially and depend on the sea-level rise scenario (fig. 3).

Assuming that the 20<sup>th</sup> century rate rates of sea-level rise will continue, it is **virtually certain** that the majority of the wave-dominated barrier islands in the mid-Atlantic Bight will continue to experience morphological changes through erosion, overwash, and inlet formation as they have over the last several centuries. The northern portion of Assateague Island (compartment 13) is an exception. Here the shoreline exhibits high rates of erosion and large portions of this barrier are submerged during moderate storms. At times in the past, large storms have breached and segmented portions of northern Assateague Island (Morton and others, 2003). Due to this behavior, it is possible that these portions of the coast are already at a geomorphic threshold. With any increase in sea level, it is **virtually certain** that this barrier island will exhibit large changes in morphology ultimately leading to the degradation of this island. Periodic nourishment and sand bypassing at Ocean City Inlet may reduce erosion on compartment 13, but the long-term sustainability of this practice is uncertain. Small segments within the highly developed portion of the North Carolina Outer Banks (fig. 3) may similarly be nearing a geomorphic threshold (Riggs and Ames, 2003).

For the second sea-level rise scenario, the 20th century rate + 2 mm/yr, it is **virtually** certain that the majority of the wave-dominated barrier islands in the mid-Atlantic Bight will continue to experience morphological changes through overwash, erosion, and inlet formation as they have over the last several centuries. It is also **about as likely as not** that a geomorphic threshold could be reached, resulting in rapid morphological changes in these barrier systems. It is **very likely** that the barrier islands along the shores of northern Assateague Island (compartment 13) and a substantial portion within the center of compartment 17 (Riggs and Ames, 2003) could exhibit threshold behavior (barrier migration, segmentation, or disintegration).

For the second sea-level rise scenario, the ability of wetlands to maintain their elevation through accretion at higher rates of sea-level rise may be reduced (Reed and others, 2007). It is **about as likely as not** that the loss of back-barrier marshes and shallow submarine shoals could lead to changes in hydrodynamic conditions between tidal inlets and back-barrier lagoons affecting the evolution of barrier islands (e.g., FitzGerald and others, 2003 and 2006).

For the third sea-level rise scenario, the 20th century rate + 7 mm/yr, it is **very likely** that the potential for threshold behavior will increase. It is **virtually certain** that a 2 m sea-level rise will lead to threshold behavior for this landform type.

### **Mixed-Energy Barrier Islands (Compartments 3, 7, 14)**

The response of mixed-energy, tide-dominated, barrier islands will vary among coastal compartments.

For the first two sea-level rise scenarios (the 20th century rate and the 20th century rate + 2mm/yr), the mixed-energy, tide-dominated, barrier islands along the mid-Atlantic Bight will be subject to processes much as have occurred over the last century. Storm overwash and shoreline erosion are **very likely** to occur over the next century. Given the degree to which these barriers have been developed, it is difficult to determine the likelihood of future inlet breaches, or whether such breaches would be allowed to persist. In addition, changes to the back-barrier shores are uncertain due to the extent of development.

For the higher sea-level rise scenarios (the 20th century rate + 7 mm/yr or greater), it is **about as likely as not** that these barriers could reach a geomorphic threshold. This threshold is dependent on the availability of sand from the longshore transport system to supply the barrier. It is **virtually certain** that a 2 m sea-level rise will have severe consequences along the shores of this compartment, including one or more of the extreme responses described above.

The ability of wetlands to maintain their elevation through accretion at higher rates of sea-level rise may be reduced (Reed and others, 2007). It is **about as likely as not** that the loss of back-barrier marshes and shallow submarine shoals could lead to changes in the hydrodynamic conditions between tidal inlets and back-barrier lagoons, affecting the evolution of barrier islands (FitzGerald and others, 2003 and 2006).

It is **about as likely as not** that four of the barrier islands along the Virginia coast (Wallops Island, Assawoman Island, Metompkin Island, and Cedar Island) are presently at a geomorphic threshold. Thus, it is **very likely** that further sea-level rise will contribute to significant changes resulting in the landward migration, disintegration, or segmentation of these barrier islands.

## **K. Summary**

A committee of coastal scientists was convened to discuss the potential impacts of future sea-level rise in the mid-Atlantic region of the U.S. Atlantic coast. The committee discussed and deliberated on the nature of a regional assessment of sea-level rise impacts that could occur over

the next century. The group agreed that a high degree of uncertainty exists in predicting long-term shoreline changes because of the variety of factors involved and the complexity of their interaction. Principal unknowns identified by the committee include regional sediment budgets and anthropogenic influences (e.g., erosion mitigation efforts such as beach nourishment).

The committee conducted a qualitative review of potential shoreline changes that could be expected over the next century under different sea-level rise scenarios. Using a combination of criteria defined by Fisher (1982) and Hayes (1979), the shore of the mid-Atlantic study area was divided into four geomorphic compartments: spits, headlands, wave-dominated barriers, and mixed-energy barriers. A range of potential coastal responses was identified for each compartment based on four sea-level rise scenarios. The sea-level rise responses included an increased likelihood for erosion and shoreline retreat for all geomorphic compartments, increased likelihood for erosion, overwash and inlet breaching for barrier islands, as well as the possibility of a threshold state (e.g., segmentation or disintegration) for some barrier island systems.

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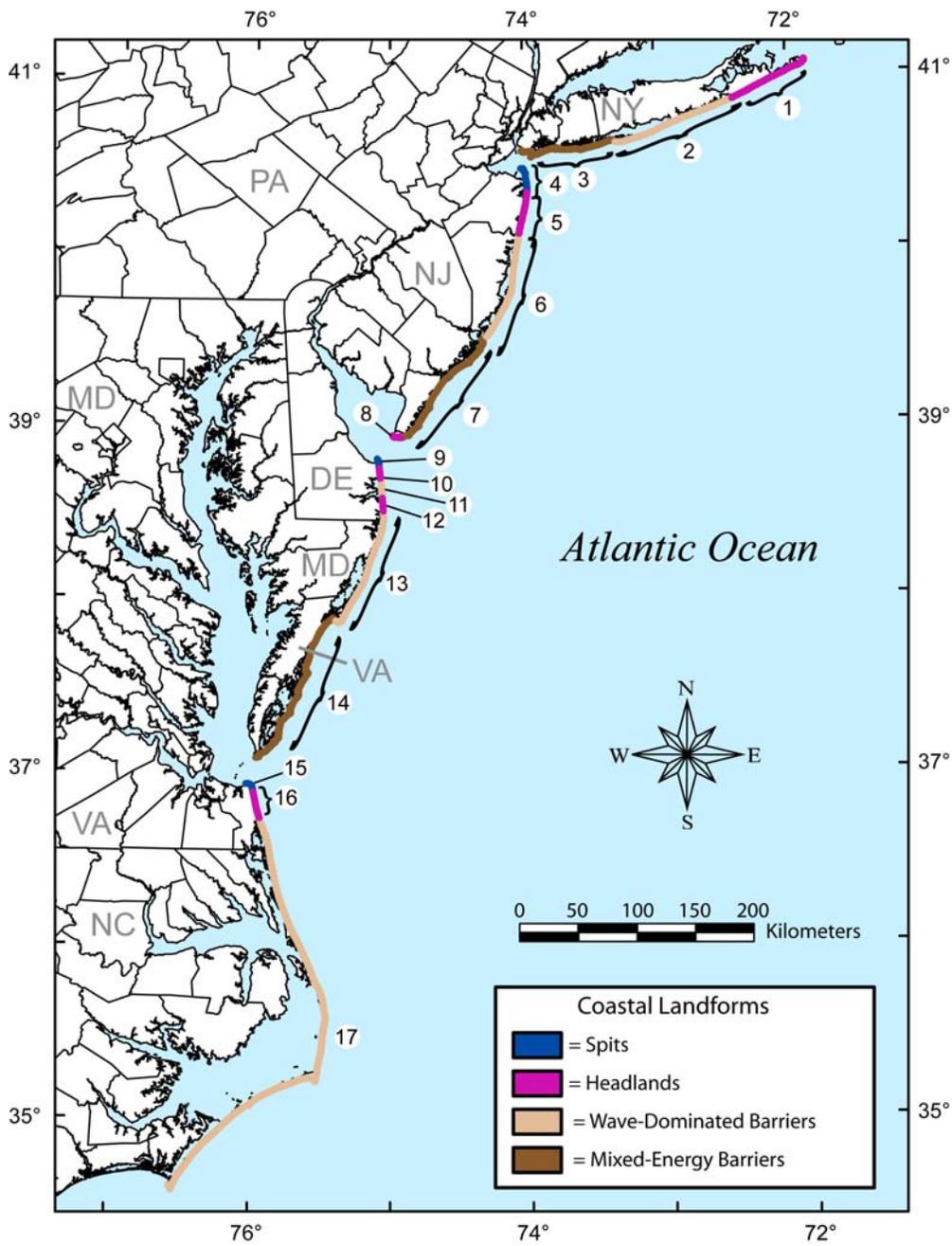
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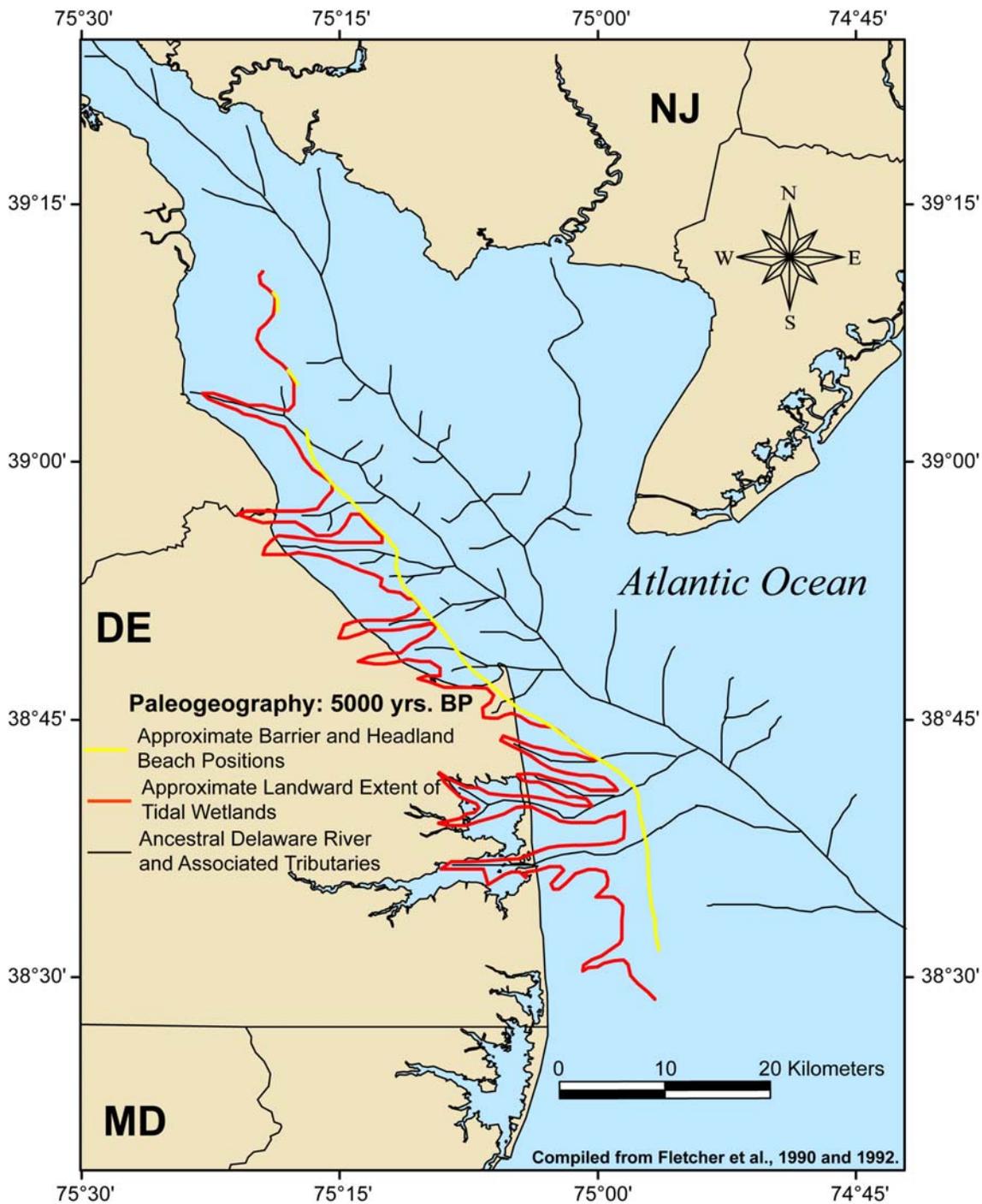
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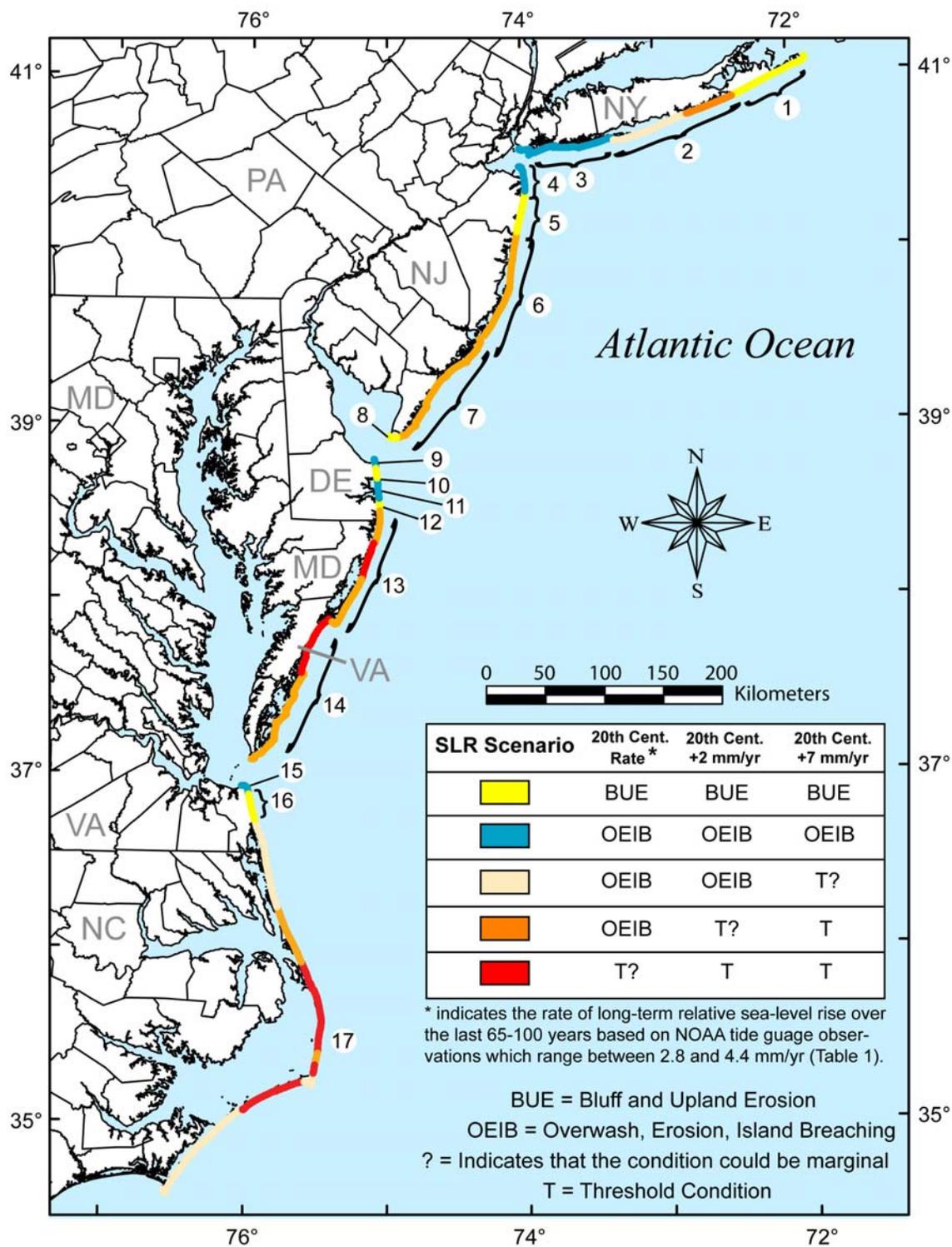
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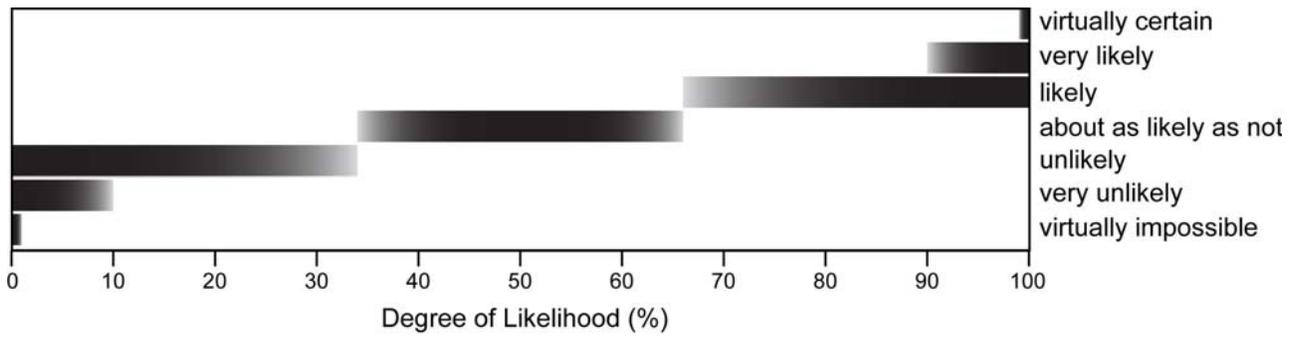
**Figure 1.** Map of the mid-Atlantic coast of the United States showing the seventeen coastal compartments and their coastal geomorphic type.



**Figure 2.** Paleogeography of the Delaware Bay region inferred from geological investigations of shallow marine sediments. Compiled from Fletcher and others (1990 and 1992).



**Figure 3.** Map showing the potential sea-level rise responses for each coastal compartment. Colored portions of the coastline indicates the potential response for a given sea-level rise scenario according to the inset table. Numbers indicate the coastal compartments shown in Figure 1.



**Figure 4.** Schematic diagram of the degrees of likelihood for shoreline change outcomes.

**Table 1.** Rates of Relative Sea-Level Rise for Selected Long-Term Tide Gauges on the East Coast of the United States (Zervas, 2001)

<b>Station</b>	<b>Rate of Sea Level Rise (mm/yr)</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Time Span of Record</b>
Eastport, ME	2.12 ± 0.13	44.9033	-66.9850	1929-1999
Portland, ME	1.91 ± 0.09	43.6567	-70.2467	1912-1999
Seavey Island, ME	1.75 ± 0.17	43.0833	-69.2500	1926-1999
Boston, MA	2.65 ± 0.1	42.3550	-71.0517	1921-1999
Woods Hole, MA	2.59 ± 0.12	41.5233	-70.2222	1932-1999
Providence, RI	1.88 ± 0.17	41.8067	-71.4017	1938-1999
Newport, RI	2.57 ± 0.11	41.5050	-71.3267	1930-1999
New London, CT	2.13 ± 0.15	41.3550	-72.0867	1938-1999
Montauk, NY	2.58 ± 0.19	41.0733	-71.935	1947-1999
Willetts Point, NY	2.41 ± 0.15	40.8000	-72.2167	1931-1999
The Battery, NY	2.77 ± 0.05	40.7000	-74.0150	1905-1999
Sandy Hook, NJ	3.88 ± 0.15	40.4667	-73.9833	1932-1999
Atlantic City, NJ	3.98 ± 0.11	39.355	-74.4183	1922-1999
Philadelphia, PA	2.75 ± 0.12	39.9335	-75.1417	1900-1999
Lewes, DE	3.16 ± 0.16	38.7817	-75.1200	1919-1999
Baltimore, MD	3.12 ± 0.08	39.2667	-76.5783	1902-1999
Annapolis, MD	3.53 ± 0.13	38.9833	-76.4800	1928-1999
Solomons Island, MD	3.29 ± 0.17	38.3167	-76.4517	1937-1999
Washington D.C.	3.13 ± 0.21	38.8733	-77.0217	1931-1999
Hampton Roads, VA	4.42 ± 0.16	36.9467	-76.3300	1927-1999
Portsmouth, VA	3.76 ± 0.23	36.8167	-75.7000	1935-1999
Wilmington, NC	2.22 ± 0.25	34.2267	-77.9533	1935-1999
Charleston, SC	3.28 ± 0.14	32.7817	-79.9250	1921-1999
Fort Pulaski, GA	3.05 ± 0.2	32.3330	-80.9017	1935-1999
Fernandina Beach, FLA	2.04 ± 0.12	30.6717	-81.4650	1897-1999
Mayport, FLA	2.43 ± 0.18	30.3967	-81.4300	1928-1999
Miami, FLA	2.39 ± 0.22	25.7667	-79.8667	1931-1999
Key West, FLA	2.27 ± 0.09	24.5533	-81.8083	1913-1999

## **Appendix-List of Committee Participants**

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*\* denotes participants who could not attend the April 12-13, 2007 meeting, but have provided information and commented on written results and conclusions from the meeting.*