Preface

The U.S. Climate Change Science Program (CCSP) was launched in February 2002 as a collaborative interagency program, under a new cabinet-level organization designed to improve the government-wide management of climate science and climate-related technology development. The mission of the CCSP is to "facilitate the creation and application of knowledge of the Earth's global environment through research, observations, decision support, and communication." As part of this mission, this report is one of twenty-one synthesis and assessment products (SAPs) identified in the *Strategic Plan for the U.S. Climate Change Science Program* (CCSP, 2003). The SAPs are intended to support informed discussion and decisions by policymakers, resource managers, stakeholders, the media, and the general public. The products help meet the requirements of the Global Change Research Act of 1990, which directs agencies to "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" and to undertake periodic scientific assessments. This SAP (4.1) on *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* provides a detailed assessment of the effects of sea-level rise on coastal environments and presents some of the challenges that will need to be addressed to adapt to sea-level rise while protecting environmental resources and sustaining economic growth.

A large and expanding proportion of the U.S. population and associated urban development is located along the coasts of the United States and is increasingly affected

by the natural processes associated with coastal change from storms and sea-level rise. Recent international assessments of climate change and related impacts indicate that the rate of sea-level rise is increasing in association with a warming ocean and melting ice caps and glaciers. Future sea-level rise is expected to increase at rates exceeding those observed over the last century, and the rise could be exponential rather than linear as it has been (Bindoff *et al.*, 2007; Meehl *et al.*, 2007). Rising sea levels will potentially affect large portions of the U.S. coast, presenting challenges to those residing at and using the coast, as well as to the sustainability of critical coastal habitats and ecosystems.

P.1 SCOPE AND APPROACH OF THIS REPORT

The focus of this report is to review and identify the potential impacts of future sea-level rise based on the state of our present scientific understanding. To do so, this report evaluates several aspects of sea-level rise impacts to the natural environment and also examines the impact to human development. In addition, the report addresses the interplay between sea-level rise impacts and human adaptation measures, and assesses the role of the existing coastal management infrastructure in identifying and responding to potential challenges.

The report focuses on the mid-Atlantic coast of the United States which consists of the region between Montauk, New York and Cape Lookout, North Carolina. While other regions in the U.S. such as the Gulf coast are potentially as or more vulnerable to sea-level rise, the Mid-Atlantic is also a region where high population density and extensive coastal development could be at risk. In addition, there is substantial scientific research

on the mid-Atlantic coast, as well as recent studies of this region by EPA and NOAA, as listed in the *Strategic Plan for the U.S. Climate Change Science Program* (CCSP, 2003).

The development of this report was guided by ten prospectus questions, focusing on different aspects of future sea-level rise and the impact to the coastal environment. The first four prospectus questions focus on evaluating the impact to and vulnerability of the natural environment. Specifically, these questions are:

1. Which lands are currently at an elevation that could lead them to be inundated without shore protection measures? (Chapter 1)
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? (Chapter 2)
3. What is a plausible range for the ability of wetlands to vertically accrete, and how does this range depend on whether shores are developed and protected, if at all? That is: will sea-level rise cause the area of wetlands to increase or decrease? (Chapter 3)
4. Which lands have been set aside for conservation uses so that wetlands will have the opportunity to migrate inland; which lands have been designated for uses requiring shore protection; and which lands could realistically be available for either wetland migration or coastal development requiring shore protection? (Chapter 5)

The remaining prospectus questions focused on the societal impacts expected with future sea-level rise. These questions are:

5. What are the potential impacts of sea-level rise on coastal floodplains? What issues would FEMA, coastal floodplain managers, and coastal communities face as sea level rises? (Chapter 8)

6. What are the population, infrastructure, economic activity, and value of property within the area potentially inundated by rising sea level given alternative levels of shore protection? (Chapter 6)

7. How does sea-level rise affect the public's access to, and use of, the shore? (Chapter 7)

8. Which species depend on habitat that may be lost due to sea-level rise given various levels of shore protection and other response options? (Chapter 4)

9. Which decisions and activities (if any) have outcomes sufficiently sensitive to sea-level rise so as to justify doing things differently, depending on how much the sea is expected to rise? (Chapter 9)

10. What adaptation options are being considered by specific organizations that manage land or regulate land use for environmental purposes? What other adaptation options are being considered by federal, state or local governments? What are the specific implications of each option? What are the institutional barriers to preparing for sea-level rise? (Chapters 10 and 11)

The first four questions are addressed for the entire mid-Atlantic study area, whereas our answers to most of the latter questions are focused on sub-regions, based on site-specific

examples, direct observations, stakeholder input, or case studies. During the preparation of this report, three regional stakeholder meetings were held between the author team and representatives from local, county, and state agencies, other federal agencies and non-governmental organizations. Many of the prospectus questions were discussed in detail with the audience and the feedback was incorporated into the report.

Many of the findings expressed in this report are expressed using common expressions of likelihood as in the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment. These likelihood determinations were established by the report authors and modeled after other CCSP SAPs (*e.g.* Karl *et al.*, 2006) (Figure P1). These determinations are based on the judgment of authors and the published uncertainties in literature cited.

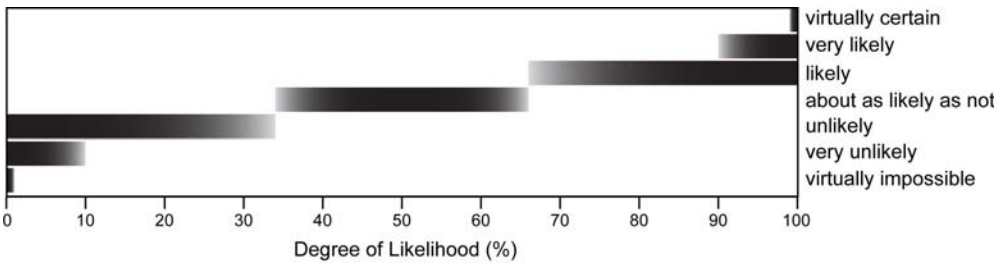

Figure P.1 The likelihood terms and related probabilities that were used for this report.

In some cases, specific chapters may incorporate more quantitative assessment of uncertainty related to a specific analysis conducted to address a specific question in the report.

P.2 FUTURE SEA LEVEL SCENARIOS ADDRESSED IN THIS REPORT

In this report, the term "sea level" refers to mean sea level or the average level of tidal waters, generally measured over a 20-year period (See Glossary). These measurements generally indicate the water level relative to the land, and thus incorporate changes in the elevation of the land as well as absolute changes in sea level (*e.g.*, relative sea level). For clarity, scientists often use two different terms:

- "Global sea-level rise" is the worldwide increase in the volume of the world's oceans that occurs due to a range of factors with the most significant being 1) the thermal expansion of the oceans surface layers and 2) the melting of land-based ice sheets, ice caps, and glaciers.
- "Relative sea-level rise" refers to the change in sea level relative to the elevation of the land, which can also rise or subside. Relative sea-level changes include both global sea-level rise and changes in the vertical position of the land surface.

In this report, the term "sea-level rise" refers to "relative sea-level rise."

This report does not provide a forecast of future rates of sea-level rise. Instead, it evaluates the implications of three sea-level rise scenarios:

- Scenario 1: the 20th century rate, which is generally 3-4 mm/yr in the mid-Atlantic region
- Scenario 2: the 20th century rate + 2 mm/yr acceleration (up to 50 cm by the year 2100)

- Scenario 3: the 20th century rate + 7 mm/yr acceleration (up to 100 cm by 2100)

The 20th century rate of sea-level rise refers to the local long-term rate of sea-level rise that has been observed at tide gauges in the mid-Atlantic study region. Scenario 1 thus assesses the impacts if future sea-level rise occurs at the same rate as was observed over the last century at a particular location. Scenarios 1 and 2 are within the range of those reported in the recent IPCC report (Bindoff *et al.*, 2007), while Scenario 3 exceeds this range by up to 40 cm by 2100. Scenario 3 reflects concerns that the IPCC values might be conservative and are less than high estimates suggested by more recent publications. In addition to these three scenarios, some chapters refer to higher sea-level rise scenarios, such as a 2 m rise over the next few hundred years (a conservative estimate if ice sheet melting on Greenland and Antarctica exceeds IPCC model estimates).

P.3 REPORT ORGANIZATION

This report first provides context and then presents the results of our synthesis and assessment in six parts and eight appendices:

Part I analyzes the effects of sea-level rise on the physical environment. Chapters in Part I discuss (1) the extent of low-lying land that occurs below future sea-level rise scenarios (Chapter 1); (2) the physical changes at the coast that will result in changes to coastal landforms (*e.g.* barrier islands) and shoreline position in response to sea-level rise (Chapter 2); (3) the ability of wetlands to accumulate sediments and survive in response

to rising sea level (Chapter 3); and (4) the habitat and species that will be vulnerable to sea-level rise related impacts (Chapter 4).

Part II describes the societal impacts and implications of sea-level rise. Chapter 5 provides a framework for assessing shoreline protection options in response to sea-level rise. Chapter 6 discusses the extent of vulnerable population and infrastructure, and Chapter 7 addresses the implications for public access to the shore. Chapter 8 reviews the impact of sea-level rise to flood hazards.

Part III examines strategies for coping with sea-level rise. Chapter 9 outlines key considerations when making decisions to reduce vulnerability. Chapter 10 discusses what organizations are doing now to adapt to sea-level rise, and Chapter 11 examines possible institutional barriers to adaptation.

Part IV introduces and highlights some mid-Atlantic local case studies of coastal elevations and sensitivity to sea-level rise, which are then explored further in Appendices A-G.

Part V discusses sea-level rise impacts and implications at a national scale and briefly highlights how coasts in other parts of the U.S. are vulnerable to sea-level rise.

Part VI presents some recommendations for future effort to reduce uncertainty and close gaps in scientific knowledge and understanding.

Appendices A-G provide maps and tables showing coastal elevations, scenarios of flooding and erosion mitigation, and discussions of particular areas of environmental significance that may be vulnerable to sea-level rise. **Appendix H** reviews some of the basic approaches that have been used to conduct shoreline change or land loss assessments in the context of sea-level rise and some of the difficulties that arise in using these methods.

While the authors strove to limit technical jargon in the report, technical and scientific terms occur throughout the report. To aid readers with some of these terms, a **Glossary** is included at the end of this Report.

PREFACE REFERENCES

Bindoff, N.L. *et al.* (2007) Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

CCSP, 2003: Strategic Plan of the U.S. Climate Change Science Program. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research. CCSP Coordination Office, Washington, DC, 202.

Karl, T.R., S.J. Hassol, C. D. Miller, and W. L. Murray, eds, 2006:*Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*.

A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Meehl, G.A. et al. (2007) Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Executive Summary

Authors: K. Eric Anderson, USGS; Donald R. Cahoon, USGS; Stephen K. Gill, NOAA; Benjamin T. Gutierrez, USGS; E. Robert Thieler, USGS; James G. Titus, EPA; S. Jeffress Williams, USGS

Editor: Anne M. Waple, STG Inc.

1. SEA-LEVEL RISE IN THE MID-ATLANTIC

Global sea level is rising and is expected to accelerate. Global sea level is primarily affected by the proportion of water that exists in ocean basins and the amount that is held in glaciers and ice sheets. Sea level has risen and declined as the climate has cooled (producing ice ages) and warmed (melting ice sheets) over the past several million years. Sea level has risen about 120 m (390 ft) since the peak of the last ice age approximately 21,000 years ago. During the last 10,000 years, by contrast, global sea level has been relatively stable, enabling development of human civilization along the coasts.

Recent assessments have indicated that the rate of sea-level rise increased between the mid-19th and mid-20th centuries. Global sea level rose at an average rate of 1.7 mm/yr over the 20th century, with an increased rate of 3.1 mm/yr from 1993 to 2003. In the mid-Atlantic region from New York to North Carolina, tide gauge observations indicate that relative sea-level rise rates have exceeded the global rate due to a combination of land