SEA LEVEL RISE AND COASTAL INFRASTRUCTURE

PREDICTION, RISKS, AND SOLUTIONS

Edited by Bilal M. Ayyub, Ph.D., P.E. and Michael S. Kearney, Ph.D.

Note: Regions 11, 12, and 13, representing Alaska, Hawaii, and Puerto Rico, respectively, are not shown.

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Preface

Scientists are estimating that by the end of this century at least 100 million people worldwide will be affected by rising sea levels. This number, large as it may be, hinges on the relatively conservative upper end of scenarios for future sea level rise of the Fourth Assessment of the Intergovernmental Panel on Climate Changes (IPCC 2007). Among many climate scientists there exists considerable disquiet that this top end estimate could prove too low, as the contribution from polar ice melting still remains highly uncertain. The resulting impacts on global sea levels could be a rise on the order of 19.6 feet. An increase in the global trend is very likely, and this increase will be on the order of two to two-and-a-half times what occurred in the 20th century, historically a period of the highest rate of sea level rise in the last 1000 years (Kearney 1996). The challenge of such a sea level rise is indeed formidable and requires immediate attention in order to examine associated risks and to assess the socioeconomic impacts for the purpose of developing appropriate long-term measures and mitigation strategies. With advance planning, the impacts while formidable are not insurmountable.

The objective of this workshop was to utilize a risk framework to define requirements and next steps for developing timely and socioeconomically acceptable solutions to accommodate the challenges posed by rising sea level and climate change. Among the topics that the workshop will address are (1) modeling of impacts to coastal infrastructure from rising sea levels and increased intensity of tropical and extratropical storms, (2) developing strategies for the phase-in of new construction and how to target existing infrastructures for retrofitting, and (3) developing risk models that can be linked with overall regional socioeconomic policies. The workshop will consider the mid-Atlantic region as a case study to produce generic outcomes applicable to other regions.

Bringing scientists, engineers, and policy-makers together to discuss recent research findings will help identify research needs and directions. Convening such a workshop was considered to be timely and necessary, and is not being undertaken at the time of holding this workshop by key professional societies.

This effort was sponsored by the Council on Disaster Risk Management of the American Society of Civil Engineers (ASCE); the Coasts, Oceans, Ports, and Rivers Institute (COPRI) of ASCE; and three colleges at the University of Maryland at College Park—the College of Computer, Mathematical and Physical Sciences; the College of Engineering; and the College of College of Behavioral and Social Sciences.

The editors would like to acknowledge the workshop's steering committee:

- Alfredo H. Ang, NAE, Professor, University of California, Irvine
- Margaret Davidson, Director, Coastal Services Center, National Oceanic and Atmospheric Administration (NOAA)
- Glenn Higgins, Northrop Grumman Corporation
- Maria Honeycutt, Coastal Services Center, NOAA
- Dave Kreibel, Professor, U.S. Naval Academy
- Shun Ling, Head, Environmental Office, NAVFAC ESC, U.S. Navy
- Court Stevenson, Center for Environmental Science, University of Maryland
- Dan Walker, Chief, Climate Assessment and Services Division, Climate Program Office, NOAA

The steering committee's guidance contributed greatly to the workshop's success. The editors also acknowledge the assistance of Alex Riter, Ph.D., and Kristen Markham in recording and summarizing the discussion at the workshop and that of Clara Popescu in preparing the Web site for facilitating the discussion at *www.TheElicitor.com*.

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Chapter 1. Quantifying Regional Risk Profiles Attributable to Sea Level Rise

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Abstract

This paper introduces a quantitative risk analysis methodology for regions that might be affected by rising sea level. The methodology is intended to offer a basis for quantifying risk profiles to assist decision- and policy-makers and has the characteristics of being analytic, quantitative, and probabilistic. The hazard is quantified using a probabilistic framework to obtain hazard profiles as sea elevation-exceedance probabilities as a function of time. The risk is quantified in the form of loss-exceedance probabilities as a function of time based on a spectrum of sea level rise scenarios and increased storm activity. The proposed methodology will enable decision- and policy-makers to evaluate alternatives for managing these risks, such as providing increased protection, suggesting population relocation measures, changing land uses, enhancing protection system operations, and enhancing preparedness for increased storm frequency and intensity.

Background

By the end of this century, some estimates suggest at least 100 million people worldwide will be affected by rising sea levels. This number, large as it may be, hinges on the relatively conservative upper end of scenarios for future sea level rise of the *Fourth Assessment of the Intergovernmental Panel on Climate Changes* (IPCC 2007). Many climate scientists are concerned that this top end estimate could prove too low, as the contribution from polar ice melting still remains highly uncertain. The resulting impacts could be a rise of about 19.6 ft. for global sea levels. The likely increase will be on the order of 2 to 2.5 times the rate of sea level rise in the 20th century, historically a period of the highest rate of sea level rise in the last 1,000 years (Kearney 2008).

The challenge of such a sea level rise is indeed formidable and requires immediate attention to examine associated risks and to assess the socioeconomic impacts so that appropriate long-term measures and mitigation strategies (Ayyub 2003) can be developed. The potential impacts on some parts of the globe, such as southern Asia, could be total devastation for some countries.

An important economic consequence of sea level rise requiring immediate attention is the impact on ports and the transportation arteries that support them. For example in recent years, the Chesapeake Bay Port of Baltimore has experienced a 28 percent growth in foreign cargo, amounting to 32 million tons in 2004. The port is generates 19,000 direct jobs ($2.4 billion in personal wages and salary), $2 billion in business revenue, and $278 million in state, county, and municipal taxes. The total economic impact is well beyond these estimates. Comparable figures are available for the ports of Norfolk and Portsmouth in Virginia. In addition, with the nation's largest naval installation, the added impact on national security and the ability to project national power to areas across the world must be considered.

Sea Level Rise and Associated Risks

Fairbridge (1950, 1958, 1960, 1961) documented that the ocean levels rose and fell over long-time scales producing what has become known as the Fairbridge Curve of the Holocene Eustatic Fluctuations, based on detailed observations off Western Australia and later from elsewhere in the world. Its author, R.W. Fairbridge, formulated the hypothesis that sea levels had been rising for the last 16,000 years and that the rise showed regular periodic oscillations of rise and fall during this period with oscillations continuing throughout the last 6,000 years to the present time, but with diminishing amplitude. The oscillations include a relatively short periodicity component of relatively rapid rises and falls of up to 4 m, although up to 3 m is more common, taking place over periods of no more than 10 or 20 years. This short-periodicity component would now have catastrophic consequences for the world. Over the next 100 years and possibly within our lifetime such an occurrence is likely. The periodicities are revealed in a rich variety of sources, including geology, geomorphology, glaciations, sediments, sand dunes, beach rock, ocean circulation, geomagnetic records, and the records of the isotopes of carbon, oxygen, beryllium, chlorine, and hydrogen in tree rings, ice cores, biota, rocks, air, and water (Mackey 2007, Finkl 1995 and 2005).

Changes in the average sea level involve several primary categories of variables that are interdependent with nonlinear associations: (1) temperature and salinity levels of oceans, (2) worldwide carbon inventory, (3) the shape of the basins that contain the oceans, (4) the volume of water in these basins, and (5) local variations in land adjacent to the ocean basins. Global warming causes the oceans to warm up, which in turn causes thermal expansion of the oceans leading to rising sea level. Global warming also warms the poles leading to the melting of land-based ice sheets, glaciers, and ice caps. For example, most of the eastern and western U.S. coastlines are observing a steady rise. The Gulf Coast is experiencing a more concerning steady sea level rise rate, whereas some locations in Alaska are actually observing a fall in sea level. This fall is due to uplifting of land as a result of coalitions between tectonic plates—the uplifting rate is greater than the sea level rise rate, making it appear as if sea levels are dropping when in fact land is moving upward more rapidly. In addition to volumetric expansion of oceans and melting of ice sheets, ocean salinity can cause oceans to expand or contract, changing the sea level both locally and globally. Ocean salinity is primarily caused by the amount of carbon present in water: Human beings are redistributing carbon around the globe. Oceans absorb this carbon and become more saline, increasing their capacity to store heat and therefore expanding further. Carbon concentrations are greatest in the North Atlantic Ocean near industrialized nations (CCSP 2009, Dean 1987, IPCC 2007). These variables can be used to define scenarios with associated probabilities as recommended by the IPCC (2007).

Defining risk as the potential of losses for a system resulting from an uncertain exposure to a hazard or as a result of an uncertain event (Ayyub 2003) offers a basis for quantifying risk for identified risk events or event scenarios along with associated rates, system vulnerabilities, and potential consequences. This definition offers a basis to quantify risk as the rate (measured in events per unit time, such as a year) or probability that human, economic, environmental, and social/cultural losses will occur due to an event including the non-performance of an engineered system or component. The non-performance of the system or component can be quantified as the probability that specific loads (or demands) exceed respective strengths (or capacities) causing the system or component to fail. Losses are defined as the adverse impacts of that failure if it occurs. Risk can be viewed as a multi-dimensional quantity that includes event-occurrence rate (or probability), event-occurrence consequences, consequence significance, and the population at risk. It is commonly measured as a pair of the rate (or probability) of occurrence of an event and the outcomes or consequences associated with the event's occurrence that account for system weakness (or vulnerabilities). Another common representation of risk is in the form of an exceedance rate (or exceedance probability) function of consequences. In a simplified notional (or Cartesian) product, it is commonly expressed as

$$\text{Risk} = \text{Event rate} \times \text{Vulnerability} \times \text{Consequences} \tag{1-1}$$

This equation not only defines risk but also offers strategies to control or manage risk by making the system more reliable through vulnerability reduction or by reducing the potential losses resulting from a failure or impacting event rates. Engineers can influence the probability of failure part of the equation by strengthening existing structures or by adding additional protection; however, the consequence portion is highly dependent on actions and decisions of residents, government, and local officials, including land-use changes, protection measures for coastal areas, response, and population relocation plans and practices. Event rates can be affected through policies relating to global warming and carbon reduction, for example. In densely populated areas, simply increasing the reliability of a protection system may not reduce risks to acceptable levels, and increasing consequences through continued development of flooding-prone areas can offset any risk reductions.

Risk Model

Probabilistic risk analysis as described by Ayyub (2003), Kumamoto and Henley (1996), and Modarres et al. (1999) can be used to develop the overall risk analysis methodology suitable for quantifying and managing risks associated with sea level rise. Risk assessment is a systematic process for quantifying and describing the nature, likelihood, and magnitude of risk associated with some substance, situation, action, or event, including consideration of relevant uncertainties (Ayyub 2003). Its objective is to provide to the maximum extent practical a scientific basis for answering the following questions (adapted after Kaplan and Garrick 1981, Haimes 1991):

- What could happen?
- How can it happen?
- How likely is it to happen?
- What are the consequences if it happens and the associated uncertainties?
- What can be done to reduce the risks in a cost-effective manner?
- What effects would these risk management decisions have on subsequent risks and options?

In an all-hazard context, risk analysis answers these questions by defining an exhaustive set of hazard or threat scenarios and assessing the likelihoods, vulnerabilities, and consequences of existing threat or hazard reduction countermeasures, vulnerability reduction actions, and consequence mitigation actions. The combination of these three fundamental elements (hazard or threat, vulnerability, and consequence) gives the familiar expression for risk, R, as provided in Eq. 1-1.

The process of risk management entails identifying actions, including countermeasures, planning options, land-use changes, consequence mitigation strategies, and such aimed at reducing or minimizing these risks in an efficient and cost-effective manner with limited impact on future options. The selection of risk reduction alternatives depends on two factors—their cost to implement and relative cost-effectiveness. A common measure of cost-effectiveness for a given investment alternative is its benefit-to-cost ratio. In general, the computation of defensible benefit-to-cost ratios requires consideration of all aspects of risk, including consequence (economic loss, public health and safety, etc.), vulnerability (security and physical), and threat likelihood within a unified probabilistic framework. The rationale behind this assertion is that a probabilistic paradigm permits rational and coherent comparisons among decision alternatives that affect multiple assets to determine the most cost-effective risk reduction strategies. Furthermore, knowledge of the quantitative risks under various investment alternatives facilitates a rational comparison with other societal risks (such as fire, earthquake, disease, flood, and other natural hazards) to assist in establishing acceptable risk levels and achieve all-hazard risk reduction objectives (Ayyub et al. 2007, McGill et al. 2007).

Ayyub et al. (2007) developed an approach called the critical asset and portfolio risk analysis (CAPRA) methodology. In general, CAPRA is a five-phase process. CAPRA consists of several steps as shown in Figure 1-1 and discussed below:

- **Scenario Identification:** This step characterizes the missions applicable to an asset, portfolio, and region and identifies hazard and threat scenarios that could cause significant regional losses should they occur. For natural hazards, this phase considers the estimated annual rate of occurrence and screens out infrequent scenarios. The outcome of this phase is a complete set of hazard and threat scenarios that are relevant to the region under study.
- **Hazard Likelihood Assessment:** This step produces estimates of the annual rate of occurrence for each threat or hazard scenario including the time-variant hazard profile associated with sea level rise for a region. For natural hazards, the results from this phase yield an annual rate or probability of occurrence for a hazard affecting the asset or a region and the intensity of the hazard as a function of time.
- **Vulnerability Assessment:** This step estimates the effectiveness of measures to protect, reduce hazard intensity, detect, delay, respond to, and eliminate a hazard that might cause harm to a region. This phase provides estimates of the probability of success for each hazard scenario, and if combined with estimated losses, yields an estimate of conditional risk.
- **Consequence and Criticality Assessment:** This step estimates the loss potential for each scenario identified for the region by considering the maximum credible loss, fragility of the target elements, effectiveness of mitigation strategies, and effectiveness of consequence-mitigation measures to respond to and recover. The results of this phase provide estimates of potential loss for each hazard and threat scenario, which are used to screen scenarios and determine those that warrant further analysis.
- **Benefit-Cost Analysis:** This step assesses the cost-effectiveness of proposed countermeasures and consequence mitigation strategies produced by developing strategy tables. The results from this phase provide benefit-to-cost ratios for each proposed risk reduction alternative, which are used to inform resource allocation decisions.

Risk associated with sea level rise is quantified using a regional sea-level rise (S) probability distribution f_S at time t, scenarios of underlying variables (i) defining S and respective probabilities P_i, regional storm rate (λ) that is dependent on S and i, scenarios of underlying variables (j) defining λ_j and respective probabilities Q_j, and the conditional probability $P(C>c)$ with which a consequence valuation (C) exceeds different levels (c) for $i, j,$ and coastal state at time t. A loss-exceedance probability at time t can be expressed as follows:

$$P(C > c;t) = \sum_i P_i \left(\int_s f_S \left(\sum_j \lambda_{ij} Q_j P(C > c \mid i, j) \right) ds \right) \quad (1\text{-}2)$$

where f_S is probability density function of sea level (S) at time t; P_i is the probability of a scenario of underlying variables (i) defining S; λ is regional storm rate that is dependent on S and i; Q_j is the probability of a scenario of underlying variables (j) defining λ; and $P(C>c|i, j)$ is the probability that the consequence C exceeds c under a state defined by the pair (i, j) and the corresponding state of the coast at time t. Summations are over all scenario types i and j using a suitable discretization. The increased storm activities would include wave run-up. This model is consistent with recently developed and used risk model for natural hazards, such as the risk model for developing protection strategies of hurricane-prone regions (Ayyub, et al. 2009a and 2009b, USACE 2006).

Figure 1-2 defines a logic and computational flow diagram for the proposed risk methodology for seal-level rise at a particular region starting with hazard identification and definition, followed by inventory definition to estimate losses based on inundation mapping, and finally constructing risk profiles and estimating associated uncertainty. Figure 1-3 provides the corresponding probability and risk tree based on the discretization of the underlying variables and system states according to Eq. 1-2.

One of the objectives of the risk analysis is to quantitatively assess the uncertainties associated with resulting risk profiles. A generalized treatment of uncertainty is available as provided by Ayyub and Klir (2006); however, the methodology proposed in this paper utilizes a simplified treatment that is familiar to practitioners in which two fundamentally different sources of uncertainty affecting an estimated risk profile are considered. The first is attributed to the inherent randomness of events in nature. These events are predicted for their likelihood of occurring (e.g., the chance of storm occurrence). This source of uncertainty is known as aleatory uncertainty and is, in principle, irreducible with the present and foreseeable state of knowledge. The second source of uncertainty is attributed to our lack of knowledge or data. For example, the ability to determine the likelihood of an event (i.e., its rate of occurrence) requires that certain data be available. Depending on the volume of available data, the accuracy of the estimate of the rate of occurrence will vary. If limited data are available, the estimated rate may be quite uncertain (i.e., with a wide interval for a prescribed confidence level). A second type of knowledge uncertainty is attributed to our lack of understanding (e.g., knowledge) about the physical processes that must be modeled (e.g., the meteorological processes that generate hurricane events). Often scientists and engineers have interpretations of existing data and models of physical processes of interest that often competing in the sense they lead to different results, while at the same time are consistent with observations. In these instances expert evaluations are often required to assess the current state of knowledge and to quantitatively evaluate the level of uncertainty. These sources of uncertainty are referred to as epistemic (knowledge-based) uncertainty. The distinction between what is aleatory and what is epistemic uncertainty can often seem arbitrary. For example, the distinction depends on the models used in a particular analysis. In addition, their estimates can change over time. Nonetheless, making a distinction between the sources of uncertainty in a logical manner helps ensure that all uncertainties are quantified, and those that can be reduced with additional data or knowledge are identified. In principle, epistemic uncertainties are reducible with the collection of additional data or the use/development of improved models. However, for a given project, it is typically not possible to reduce these uncertainties. It should be noted that epistemic uncertainties in each part of the analysis lead to uncertainty in the final risk results. Propagating the uncertainties of the individual parts of the analysis through to the final result produces a probability distribution on the risk profile as provided in Figure 1-2.

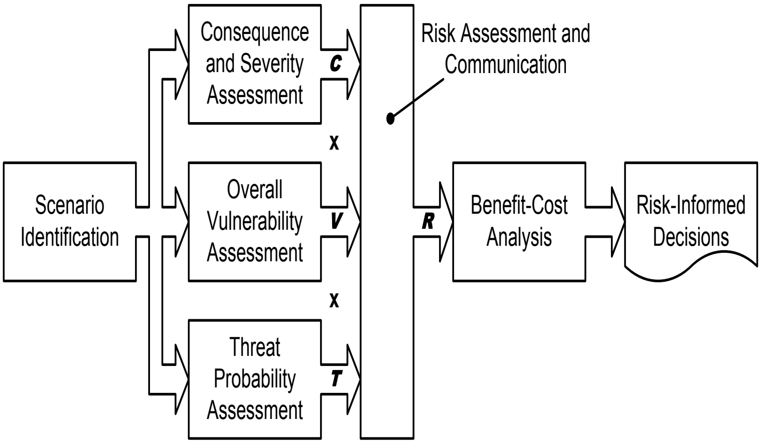


Figure 1-1. The critical asset and portfolio risk analysis (CARRA) methodology

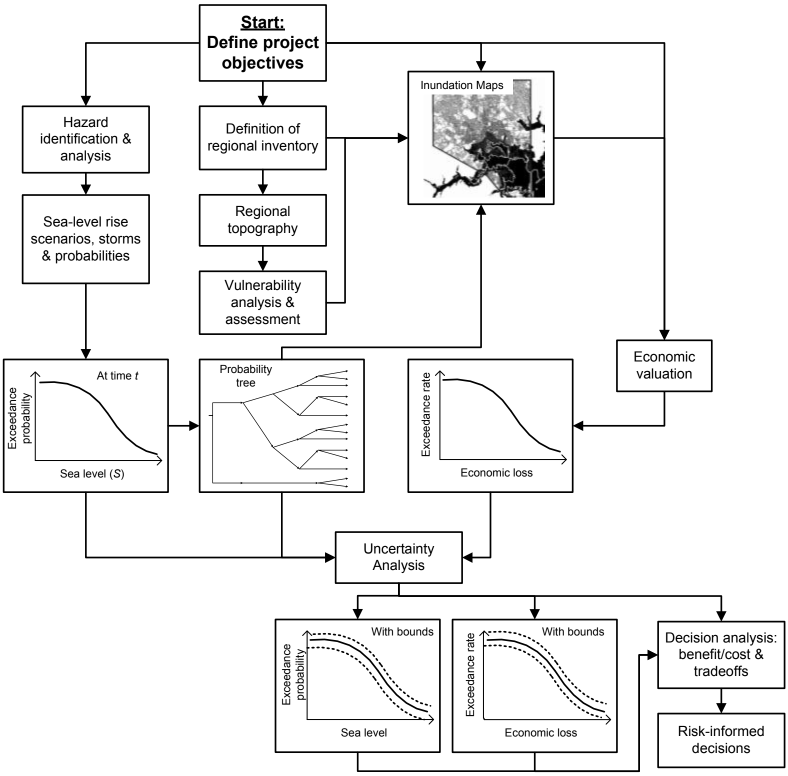


Figure 1-2. A risk methodology for seal-level rise at a particular region

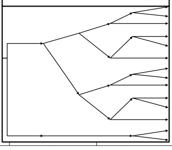
Regional hazard analysis (sea-level rise and probabilities)		Regional hazard analysis (storms and rates)		Vulnerabilities (conditional inundation per event)			Consequence severity valuation		Risk profiles
Scenarios and probabilities (P_i)	**Sea-level at time t**	**Scenarios and probabilities (Q_j)**	**Rate (λ_{ij})**	**Regional inventory (GIS)**	**Regional topography**	**Underground water levels**	**Assumed measures**	**Economic loss ($)**	**Economic risk ($)**
($Scenario_1,p_1$) ($Scenario_2,p_2$) ⋮ ($Scenario_i,p_i$) ⋮ ($Scenario_N,p_N$)	Probability distribution of sea-level f_S	($Scenario_1,q_1$) ($Scenario_2,q_2$) ⋮ ($Scenario_i,q_i$) ⋮ ($Scenario_N,q_N$)	Storms with varying intensities and associated rates Sample probability tree 	Property Population Environ.	Inundation maps Impacted property Impacted population Impact on environ.	Fresh water maps Salinity levels Impact on water resources	Regional planning & policies Shoreline protection Asset protection Global policies	Valuation of land use changes, land loss, property, environ., meeting water needs, etc.	Loss exceedance rates & probabilities as a function of time Benefits of measures Benefit/cost analysis Point estimates with epistemic uncertainty estimates

Figure 1-3. A probability and risk tree for sea level rise at a particular region

Risk Management

The risk management phase assesses the cost-effectiveness of proposed countermeasures and consequence mitigation strategies for reducing the risk associated with an asset or portfolio of assets or a region. In the context of sea level rise, countermeasures aim to reduce vulnerabilities of coastal lines, property and asset exposure, impact on resources and populations, and land use changes. Consequence mitigation strategies aim to reduce the potential consequences given the occurrence of a successful scenario. Risk management entails decision analysis for a cost-effective reduction of risk given finite available resources. The benefit of a risk mitigation action can be assessed as the difference between the risk before and after implementation (Ayyub 2003):

$$\text{Benefit} = \text{Unmitigated Risk} - \text{Mitigated Risk} \qquad (1\text{-}3)$$

The benefit-to-cost ratio can be calculated as

$$\text{Benefit-to-Cost Ratio (B/C)} = \text{Benefit/Cost} \qquad (1\text{-}4)$$

where ratios greater than one are desirable. The cost in Eq. 1-4 is the cost to implement and sustain the risk mitigation action. In general, larger benefit-to-cost ratios indicate better risk mitigation actions from a cost-effectiveness standpoint. However, selection of the optimal risk mitigation action must also consider the absolute cost to implement relative to available resources as well as whether the strategy achieves risk reduction objectives.

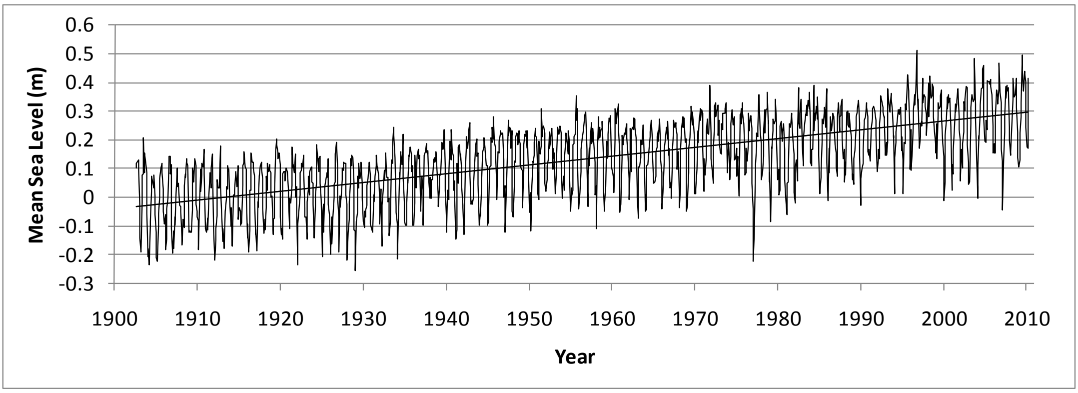


Figure 1-4. Mean sea level trend for Baltimore, MD

The probability that a favorable benefit-to-cost ratio will be realized can be represented as

$$P\left(\frac{\text{Benefit}}{\text{Cost}} \geq 1\right) = 1 - P(\text{Benefit} - \text{Cost} \leq 0) \qquad (1\text{-}5)$$

The model in Eq. 1-5 is analogous to the familiar stress-strength model used in reliability engineering (Ayyub 2003, Modarres et al. 1999). In general, both benefit and cost in Eq. 1-5 are random variables that can assume any parametric distribution. With knowledge of these distributions, the probability of realizing a favorable benefit-to-cost ratio can be computed using techniques such as the second order reliability model (Ayyub 2003).

The City of Baltimore as a Case Study

This section provides a preliminary demonstration of the proposed methodology using publically available information on the city of Baltimore.

Hazard Analysis

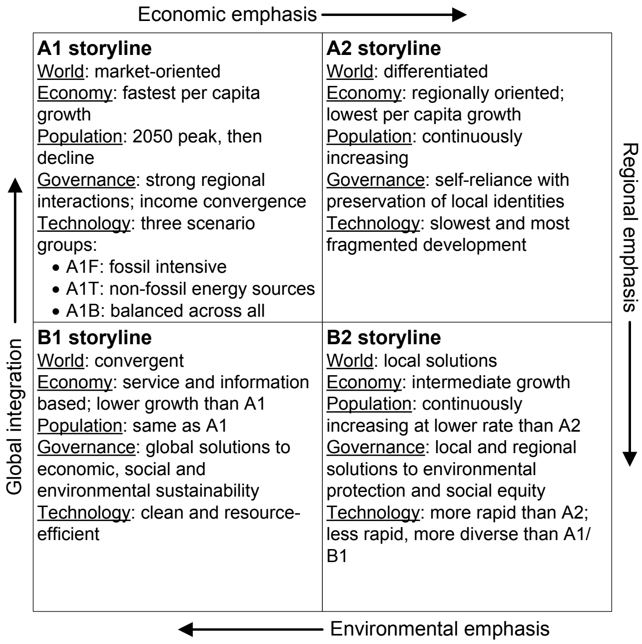
The first step is to estimate the sea level rise as a function of time. Data obtained from the National Oceanic and Atmospheric Administration (NOAA) Web site was used as the lower bound on the estimates. The data includes current sea level rise trends for the city of Baltimore recorded for more than 100 years at a Baltimore NOAA station (# 8574680), and its record goes back to 1902. Figure 1-4 shows current sea level trends for Baltimore along with a trend line. This trend line is used to estimate future sea level elevations using a linear trend for the purpose of demonstration, and it is specific for the station location. The resulting linear trend is

$$\text{Sea level} = 0.0031y - 5.8699 \qquad (1\text{-}6)$$

where y is the year, such as 1992. Using this model, the predictions of Table 1-1 can be obtained for 200 years. It should be noted that the results displayed in this table are solely based on current sea level rise trends and do not include predictions made by the 2007 Intergovernmental Panel on Climate Change (IPCC) 2007 based on scenario A1B (see Figure 1-5) defining economic, energy, and population trends, and not accounting for other effects reported in other studies, such as the melting of any ice masses (Vermeera and Rahmstorf 2009) where the following model was proposed:

$$\frac{dH(t)}{dt} = a(T - T_0) + b\frac{dT}{dt} \tag{1-7}$$

where H is sea level as a function of time t; T is temperature above the baseline temperature T_0 at which sea level is in equilibrium with climate. The first term in this equation models the long-term trend, and the second term accounts for the short-term effect since some components of sea level adjust quickly to temperature changes (e.g., the heat content of the oceanic surface mixed layer). The temperature T requires some time to achieve its full effect on the sea level rise, called the time lag τ (i.e., T should be the temperature value at $\tau + t$). The model parameters a, b, τ, and T_0 can be empirically estimated from data. Using A1B IPCC scenario with temperature range above the 1980 to 2000 temperature of 2.3°C to 4.3°C, the sea level rise above the 1990 level in the year 2100 is on the average of 124 cm with the range 97 to 156 cm—about three orders of magnitude compared to the IPCC predictions.



A1 storyline World: market-oriented Economy: fastest per capita growth Population: 2050 peak, then decline Governance: strong regional interactions; income convergence Technology: three scenario groups: • A1F: fossil intensive • A1T: non-fossil energy sources • A1B: balanced across all	**A2 storyline** World: differentiated Economy: regionally oriented; lowest per capita growth Population: continuously increasing Governance: self-reliance with preservation of local identities Technology: slowest and most fragmented development
B1 storyline World: convergent Economy: service and information based; lower growth than A1 Population: same as A1 Governance: global solutions to economic, social and environmental sustainability Technology: clean and resource-efficient	**B2 storyline** World: local solutions Economy: intermediate growth Population: continuously increasing at lower rate than A2 Governance: local and regional solutions to environmental protection and social equity Technology: more rapid than A2; less rapid, more diverse than A1/B1

Figure 1-5. The IPCC storylines, i.e., scenarios (Adapted from IPCC 2007)

Table 1-1. Sea Level Prediction for the City of Baltimore
(for illustration purposes only)

Year	Mean Sea Level (m)	Sea Level Rise (m)	Sea Level Rise (ft)
2000	0.3301	0	0
2010	0.3611	0.031	0.101706037
2020	0.3921	0.062	0.203412074
2030	0.4231	0.093	0.305118111
2040	0.4541	0.124	0.406824148
2050	0.4851	0.155	0.508530184
2060	0.5161	0.186	0.610236221
2070	0.5471	0.217	0.711942258
2080	0.5781	0.248	0.813648295
2090	0.6091	0.279	0.915354332
2100	0.6401	0.31	1.017060369
2110	0.6711	0.341	1.118766406
2120	0.7021	0.372	1.220472443
2130	0.7331	0.403	1.32217848
2140	0.7641	0.434	1.423884517
2150	0.7951	0.465	1.525590554
2160	0.8261	0.496	1.62729659
2170	0.8571	0.527	1.729002627
2180	0.8881	0.558	1.830708664
2190	0.9191	0.589	1.932414701
2200	0.9501	0.62	2.034120738

Land, Asset, and Resource Inventory

Much information about Baltimore is available in geographical information system (GIS) format, thus in an effort to most efficiently and effectively analyze this information and how it can be potentially affected by sea level rise, it is important to first identify the type of information needed to sufficiently capture the key assets to define the consequences of greatest concern. The key assets of concern identified in this case study include the following main categories:

1. **People.** Three methods were identified to estimate the population affected: One method uses the Census data; the other two use Real Property data.
    - *2000 Census Tract data and population counts for each tract.* For each census that the United States conducts every 10 years, population counts are tallied and divided into small areas within each county called tracts. Free GIS data files are published for public use that include the size of the tract and the number of people. This data can be used to compute population density based on census tracks and multiply the population density by the affected areas.

- *Real Property "Dwelling Units" data.* Information on the number of dwelling units is available for each property listed in Baltimore City. Totaling all the affected dwelling units within the area of concern and then multiplying this by an average number of people per household is another possible method of counting population.
- *Real Property "Zoning Code" data.* Each property is also coded by its intended use (such as commercial, residential, or industrial). For each residential zoning code, minimum and maximum numbers of units per square acre allowed by city laws are provided. This third method of counting people affected estimates the number of dwellings based on the area of the property and the zoning code and then multiplies this number by the estimated number of people per dwelling.

The first method is used for the case study of the city of Baltimore. The last two methods are also useful; however, they involve uncertainty due to reliance on several assumptions. Under this category are populations affected due to sea level rise and populations affected due to policy relating to land use changes.

2. **Land and Environment**. Inundation of land and its impact on the environment is another primary loss component. Using estimated areas of inundation and land-use types, environmental impacts can be assessed to facilitate a proper valuation.

3. **Property.** Of greatest importance is the property loss (using valuations in dollars) that could result from a sea level rise. The Real Property dataset provides a wide variety of information about each property. Of greatest importance is the approximate cost of the property in dollars. While this may not perfectly represent the cost of the buildings on the property, it has a strong enough correlation to make the assumption that high property values typically indicate that the building(s) located on that property also have higher value and thus higher replacement cost of replacement if damaged. In addition, values for the approximate square footage can be obtained that can be and used with valuation unit prices to estimate replacement and content values. Using zoning classification offers the means to estimate residential, commercial, industrial, and other property values.

4. **Roadways and Railways.** The length of roadways and railways within inundation areas can be estimated with respective daily traffic volumes and movement of goods. The City of Baltimore provided many files including all roads (small alleyways to large highways) and railways. These two variables offer strong bases for valuation.

5. **Other Specific Assets.** There are many other buildings and other structures throughout the city along the coastal lines, many of which would be of particular importance to know about for consequence estimation. These include
   - ports and shipyards
   - manufacturing plants
   - water intakes
   - government structures
   - stadiums
   - religious institutions
   - commercial and retail structures
   - historical and cultural landmarks
   - government structures
   - schools
   - assisted living, nursing homes
   - hotels

The properties of each of these specific assets include the relevant information that would enable consequence estimation including the approximate number of people that could be affected.

Inundation Mapping and Risk Profile

Assuming that the City of Baltimore does not have a coastal protection system in place and therefore is vulnerable to sea level rise, the development of inundation maps requires topographical maps of the city. These maps were obtained from the U.S. Geological Service (USGS) Web site. The GIS data are represented by pixels containing the average elevation of a portion of land in Baltimore with an approximate area of 10 m^2. The sea level rise trends of Table 1-1 were used in combination with the topographical data to define the inundated areas as provides in Figure 1-6. Using an inventory summary of affected land, assets, and resources with hypothetical valuations and a loss intensity, a risk profile was produced as provided in Figure 1-7.

A time line for the risk profile for the City of Baltimore is shown in Figure 1-8 by focusing and zooming in on the coastal areas provided in Figures 1-6 and 1-7. Figure 1-9 shows the trends of the inventory components affected by inundation. The counts and measures shown in Figure 1-9 are summarized in Tables 1-2 and 1-3. The tables also show other asset details.

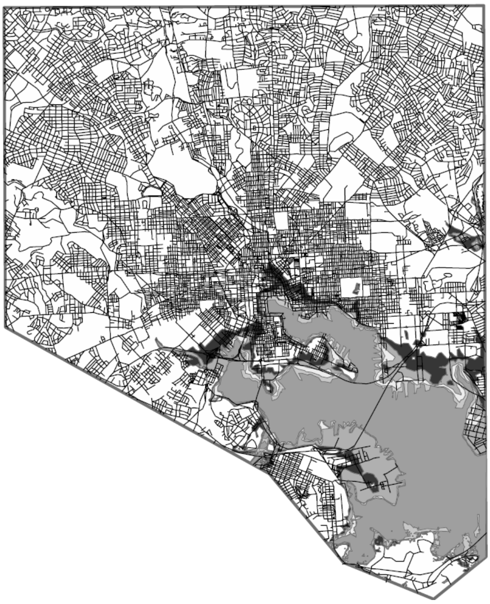


Figure 1-6. An illustrative inundation of the City of Baltimore in the year 2200 based on three times the values in Table 1-1 with a roads overlay.
Source: U.S. Geological Service

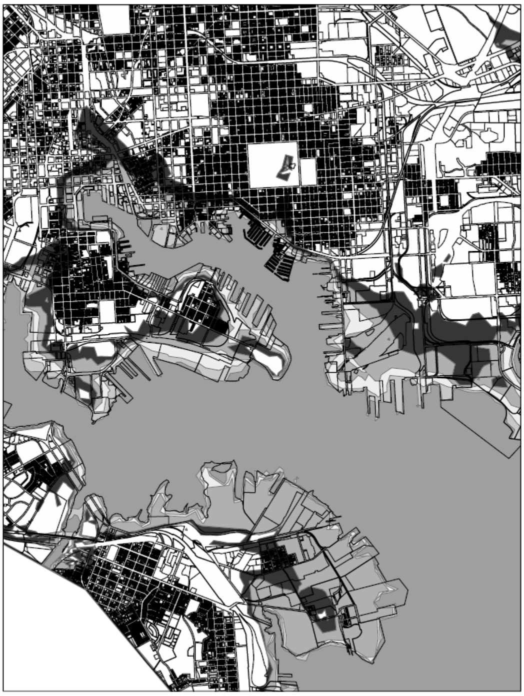


Figure 1-7. An illustrative inundation of the harbor area of the City of Baltimore in the year 2200 based on three times the values in Table 1-1 with a real property overlay. Source: U.S. Geological Service

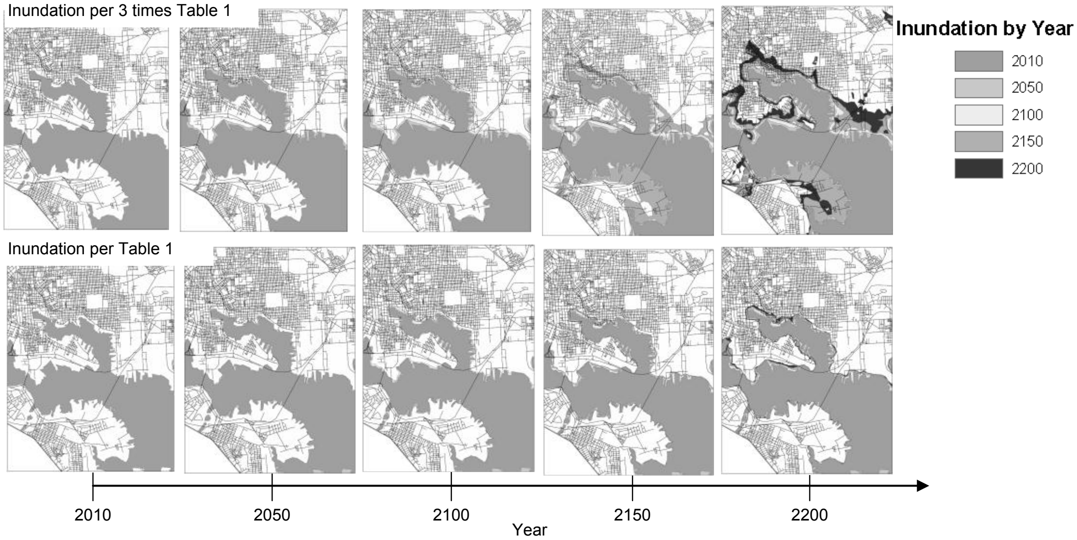


Figure 1-8. A demonstration of the format of the timeline of the risk profile of the City of Baltimore due to sea level rise

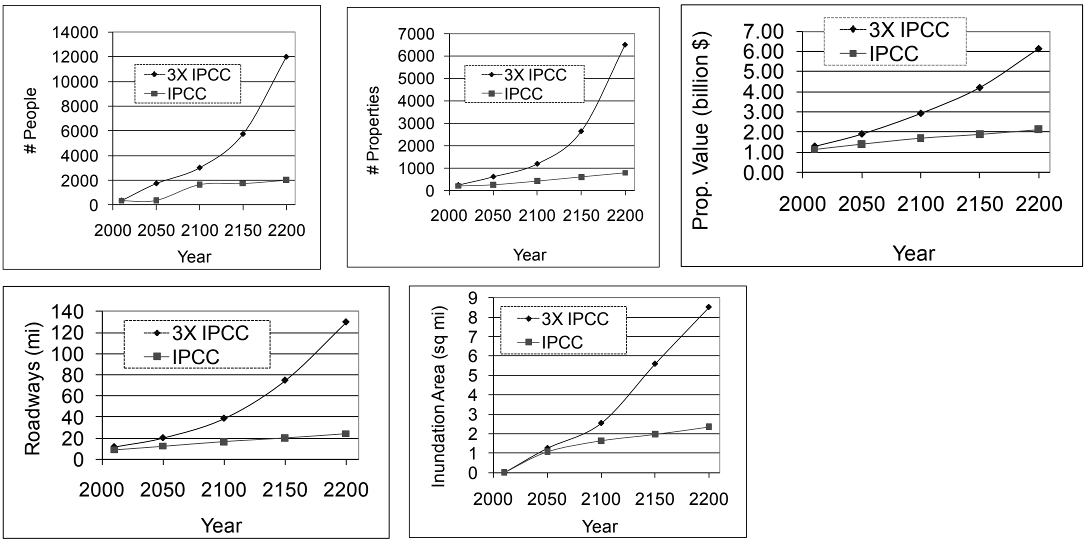


Figure 1-9. Inundation inventory components to quantify the risk profiles

Table 1-2. Affected Inventory of the City of Baltimore as a Result of Sea Level Rise Based on the Predictions of Table 1-1

*(for illustration purposes only)**

Year		2010	2050	2100	2150	2200
Property Affected	**#**	345	370	1663	1751	2022
Real Property	**#**	200	252	417	605	786
	$	$1,131,150,680.00	$1,397,601,330.00	$1,695,078,040.00	$1,884,009,160.00	$2,120,259,760.00
	$ billions	$1.13	$1.40	$1.70	$1.88	$2.12
Roads	**#**	68	95	148	199	271
	LMile	8.98 mi	12.34 mi	16.79 mi	20.22 mi	24.21 mi
Inundation area	**ft^2**	280619651	310636672	326552487.9	335726967.8	346353528.2
	mi^2	10.066	11.143	11.713	12.043	12.424
	Increase	0.000	1.077	1.648	1.977	2.358
Rails		123.26 mi	123.26 mi	131.15 mi	131.15 mi	131.15 mi
Assets		6 Bridges	8 Bridges	10 Bridges	12 bridges	18 Bridge
			2 Cultural Landmarks	7 Cultural Landmarks	10 Cultural Landmarks	14 Cultural Landmarks
			6 City Facilities	1 Federal Buildings	1 Federal Buildings	1 Federal Buildings
				3 Hotels	5 Hotels	6 Hotels
				16 City Facilities	21 City Facilities	1 Pub School
				26 Restaurants	36 Restaurants	27 City Facilities
						69 Restaurants

* These tables do not include ports and shipyards, manufacturing plants, water intakes, stadiums, and coastal improvements.

Table 1-3. Affected Inventory of the City of Baltimore as a Result of Sea Level Rise Based on Three Times the Predictions of Table 1-1

*(for illustration purposes only)**

Year		2010	2050	2100	2150	2200
Property Affected	**#**	370	1751	3024	5753	12001
Real Property	**#**	233	605	1180	2636	6508
	$	$1,271,676,870.00	$1,884,009,160.00	$2,909,132,970.00	$4,190,346,750.00	$6,127,220,880.00
	$ billions	$1.27	$1.88	$2.91	$4.19	$6.13
Roads	**#**	82	199	471	1006	1904
	LMile	11.71 mi	20.22 mi	38.67 mi	74.75 mi	129.97 mi
Inundation area	**ft^2**	300596434	335726967.8	371629070.8	456686145.8	538137459.6
	mi^2	10.782	12.043	13.330	16.381	19.303
	Increase	0.000	1.260	2.548	5.599	8.521
Assets		8 Bridges	12 Bridges	22 Bridges	33 Bridges	61 Bridges
		1 Cultural Landmarks	10 Cultural Landmarks	16 Cultural Landmarks	29 Cultural Landmarks	6 Churches
		1 City Facilities	1 Federal Buildings	3 Federal Buildings	4 Federal Buildings	1 Court House
			5 Hotels	7 Hotels	11 Hotels	41 Cultural Landmarks
			21 City Facilities	1 PrivSrHouseSubsid	2 PrvSrHouseSubsid	7 Federal Buildings
			36 Restaurants	1 Comm College	1 Comm College	3 Grocery Stores
				1 Pub School	1 Pub School	15 Hotels
				45 City Facilities	1 Priv School	1 Comm College
				109 Restaurants	128 City Facilities	1 College
					200 Restaurants	1 Priv School
						1 Pub Midd
						1 Pub Elem
						1 Pub School
						208 City Facilities
						297 Restaurants

* These tables do not include ports and shipyards, manufacturing plants, water intakes, stadiums, and coastal improvements.

Concluding Remarks and Next Steps

Quantifying risk using a probabilistic framework produces hazard (elevation) and loss-exceedance probability curves based on a spectrum of sea level rise scenarios according the mean sea level as a function of time and increased storm rates with associated surges, waves, and precipitation with uncertainty quantification. The methodology provides a process for evaluating the loss potential for a region covering land use changes, population affected, and property at risk by considering the topography and asset inventory for the region. The quantification of risk will enable decision-makers to consider various alternatives to manage risk through setting appropriate policy relating to land use, land use changes, infrastructure planning, building requirements and permits, water resource planning, and the enhancement of consequence mitigation measures.

This preliminary, conceptual framework for quantifying risks associated sea level rise requires refinement and development of computational details. Moreover, the state of the inventory requires further developing by focusing on the coastal areas of the City of Baltimore and other areas with the United States. The inventory used in this paper was developed for rail safety studies and is incomplete and/or inaccurate along the coastal lines. The increase in storm activity with wave run-up intensity escalation due to the rising sea level requires further investigation. The impacts of such increased activities at coastal lines would lead to interdependence with changes in land use and human activity.

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Chapter 2. Seal Level Changes Results from the IPCC 2007 Report and Subsequent Results

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Abstract

This paper presents results describing sea level change from the Inter-governmental Panel on Climate Change (IPCC) (2007) report as well as some subsequent published results. The sea level budget has been balanced for the 2003-08 period. One crucial point learned is that the Gravity Recovery and Climate Experiment (GRACE) gravity mission data need to be corrected over the world ocean for glacial isostatic adjustment (GIA), just as ocean satellite altimeter data need to be corrected. Also important is that the sea level balance has changed. In recent years it seems that melting of glaciers and ice caps have increasingly added to the rise in sea level while the thermosteric contribution has been reduced.

Introduction

It is obvious that an increase in relative sea level can have enormous global economic and social consequences. For example, a large percentage of earth's population lives in coastal cities. McGranahan et al. (2007) define the low elevation coastal zone (LECZ) as the contiguous area along the coast that is less than 10 m above sea level. They also note that this zone contains 2 percent of the world's land area but 10 percent of the population and 13 percent of urban population.

The public, coastal engineers, and planners need to know about the frequency and duration of inundation and sea level rise. Questions include the following:

1. How often will local land surfaces be inundated and how high will the water levels get?
2. How long will these surfaces be inundated, regardless of elevation?
3. Is there a relation between the elevation and the duration of an inundation event?
4. How will inundation profiles change with sea level rise?

Coastal infrastructure and resources have already been adversely affected in some areas due to an increase in relative sea level (RSL). Land has been lost due to encroaching ocean water and structures have been lost or damaged. This is only the briefest of lists of possible effects of relative sea level rise.

IPCC 2007 Results

Projecting future climate conditions and sea level change depends of course on many assumptions including future human activity. The *IPCC Special Report on Emission Scenarios* (Nakicenovic et al. 2000) has constructed 40 different scenarios, each making assumptions for future greenhouse gas emissions, land-use, and other forcing functions. In addition, assumptions about future technological development as well as the future economic development are made for each scenario. The emissions scenarios are organized into families, which contain scenarios that are similar to each other in some respects. Most scenarios include an increase in the consumption of fossil fuels.

The IPCC (2007) report projected a range of possible global average sea level increases by the year 2100 of 220 to 500 mm (9 to 20 in.). These estimates were based on projections from atmosphere-ocean general circulation models forced by estimates of greenhouse gases in earth's atmosphere during the next 100 years. These projections did not include the effect of possible contributions due to increases in ice sheet flow due to a lack of published data. Ice sheet modeling is in its infancy. The ranges of sea level increase predictions were based on a variety of model runs of atmosphere-ocean-general circulation models using the IPCC "A1B" scenario.

This scenario is characterized by
1. a more integrated world;
2. rapid economic growth;
3. a global population that reaches 9 billion in 2050 and then gradually declines;
4. the quick spread of new and efficient technologies;
5. a convergent world—income and way of life converge between regions; and
6. extensive social and cultural interactions worldwide.

There are subsets to the A1 family based on their technological emphasis:
- A1FI—an emphasis on fossil-fuels
- A1B—a balanced emphasis on all energy sources
- A1T—emphasis on non-fossil energy sources

The biggest uncertainty about future projections of sea level rise is the possibility of substantial amounts of meltwater entering the world ocean from the Greenland and/or Antarctic ice sheets.

IPCC projections included a contribution due to increased ice flow from Greenland and Antarctica at the rates observed from 1993 to 2003, but these flow rates could increase or decrease in the future.

For the period 1961 to 2003, IPCC estimated the average rate of global sea level rise from tide gauge data to be 1.8±0.5 mm/year. The report also stated that the average thermal expansion contribution for this period was 0.42±0.12 mm/year with significant decadal variations, while the contribution from glaciers, ice sheets is estimated to have been 0.7±0.5 mm/year. The report concluded that "the sum of these estimated climate-related contributions for about the past four decades thus amounts to 1.1±0.5 mm/year, which is less than the best estimates from the tide gauge observations. Therefore, the sea level budget for 1961 to 2003 has not been closed satisfactorily."

Some Definitions

Mean sea level" (MSL) is determined as an average over a long enough period to reduce or eliminate short period fluctuations associated with storms, tides, and surface waves. Changes in MSL can be measured with reference to nearby land (termed relative sea level (RSL) or a fixed reference frame.

The eustatic component of sea level change represents a change in sea level due to fresh water added to or removed from a water column.

The thermosteric component of sea level change (TCSL) represents the change of sea level due to warming or cooling of a column of seawater. Warming of a seawater column results in higher sea level and cooling of a seawater column results in lower sea level.

Similar to the thermosteric component of sea level change the halosteric component of sea level change represents the change of sea level due to freshening or salinification of a column of seawater. Freshening of a seawater column results in higher sea level, and salinification of a seawater results in lower sea level. This is different from the eustatic component and results from changes in the values of the coefficient of haline contraction due to changes in salinity.

How Do We Measure Sea Level and Its Component Terms?

Tide gauges represent the oldest quantitative method for measuring sea level. Gauges are located along the land-sea boundaries of continents and adjacent seas and on islands. The oldest tide gauge record dating from 1711 is from a tide gauge location at Brest, France. Pugh (1989) provides a thorough summary of technologies to measure sea level.

Since 1993 satellite altimetry from joint U.S./French satellite missions have the best precision for measuring global sea level, mainly TOPEX/Poseidon (T/P) and Jason 1 and Jason 2. Other satellite altimeter missions (e.g., GeoSat, which preceded T/P) were not as accurate.

The joint U.S./German GRACE satellite mission measures gravity from a pair of satellites well enough to provide information about the earth's geoid and post-glacial rebound (PGR). These are important measurements for studies of sea level change.

The term PGR is being replaced by the term global isostatic adjustment (GIA) in recognition that the solid earth flows horizontally.

Tide station records provide information on relative sea level trends and need to be properly adjusted for vertical land motion to be used for global (absolute) sea level applications. Local relative sea level trends are extremely important to coastal communities because they represent sea level variations at the land-water interface, regardless of cause. Local relative sea level trends can be combined with future estimates of global sea level trends to investigate projected changes in frequency and duration of inundation.

Inundation analyses performed relative to tidal benchmark elevations can provide accurate information on present day conditions, can be used to express impacts of RSL on local land surfaces, and can provide accurate ground truth points for digital elevation models.

To estimate the halosteric and thermosteric components of sea level change, oceanographers depend on instruments that measure temperature and salinity as a function of depth. Historically such instruments have been lowered by ships. During the past several years, much of the upper part (0-2000 m) of the world ocean is now being monitored by an array of approximately autonomous underwater profiling floats. A description of the various instrument types used to monitor temperature and salinity in the world ocean is given by Boyer et al. (2007).

Some Processes Contributing to Sea Level Change

Several processes affect sea level. These include transfer of meltwater between continental ice caps and/or mountain glaciers and the world ocean. However, adding or removing water from a column of seawater also changes its salinity and affects sea level via haline contraction (expansion). Changes in the temperature of a water column affect sea level via thermal expansion (contraction). Changes in the shape of a basin (land subsidence or uplift due to GIA), local changes in land subsidence or uplift due to sediment loading or dredging, and impoundment of water by reservoirs or other storage on land all affect sea level. Changes in wind and ocean circulation as well as the transfer of ground water between continents and oceans also affect sea level.

Estimate of the Thermosteric Component of Sea Level Change, 1955-2009, Since IPCC 2007

Instrumental errors have been found in temperature measurements from expendable bathythermograph instruments (XBTs) after the publication of the IPCC (2007) assessment (Gouretski and Koltermann 2007). When these errors (and others) are corrected for, the increase in the TCSL is larger than previously estimated for the past 50 years. This is because the instrumental errors were responsible for unrealistic decadal-scale variability in the ocean temperature record. The linear trend of TCSL is determined by a least-squares fit, which leads to an increase in the estimates of the TCSL. In addition, most of these earlier measurements were only for the 0-700 m layer of the ocean. Based on data from Boyer et al. (2009) and using the method of calculation described by Antonov et al. (2002) we have computed the global yearly distributions of 0-2000 TCSL. Figure 2-1 shows an estimate of the global integral of yearly TCSL for 1955-2009 for the 0-2000 m layer of the world ocean. Based on linear trends as determined by least square fits, the rate of increase of TCSL for the 1955-2009 period and 1969-2009 periods respectively are 0.54 and 0.68 mm/year. The pre-1969 period contains fewer data so we present estimates for each of these periods. From 1997 through 2004, there was a relatively large increase in TCSL, which was then followed by a substantial reduction in the rate of increase. The reason for this is not well known but may be related to a phenomenon known as the El Niño/Southern Oscillation (ENSO). Similarly, the interannual variability of this record is not well understood. Is this variability real? If so, is it due to sampling issues including interpolation error or more likely is it a combination of all of these factors?

Balancing the Sea Level Budget

Several papers have attempted to balance the sea level budget. Most notable are the works of Peltier (2009) and Cazenave et al. (2009). Both of these studies have balanced the sea level budget for the 2003-2008 period. One crucial point learned in these two studies is that the GRACE gravity mission data need to be corrected for GIA just as the altimeter data needs to be corrected.

These works show that that the sea level balance has changed. In recent years there seems to have been an increase in the contribution to sea level increase from the melting of glaciers and ice caps and a decreased contribution from the thermosteric contribution.

Figure 2-2 shows global mean sea level from the TOPEX/Poseidon and Jason satellite altimeters for the 1993-2010 period. The trend exceeds 3 mm/year, which substantially exceeds global mean sea level for the 20th century (1.8 mm/year) as determined from tide gauges.

Future Projections of Relative Sea Level Change Since IPCC 2007

Rahmstorff (2007) developed a technique to provide estimates of RSL that have been published with projections through 2100. His approach is semi-empirical and relates RSL to global average sea surface temperature. He estimates a rise of global mean RSL of 50 to 140 cm by 2100 above the 1900 level using IPCC scenarios. Jevrejeva et al. (2010a) estimated a 60 to 160 cm rise by 2100 above the 1900 level using IPCC scenarios. Jevrejeva et al. (2010b) used reconstructed sea level from paleo and projected data to estimate a sea level rise of 90 to 130 cm for the IPCC A1B scenario.

Discussion

Perhaps the most remarkable observation is the recent increase in RSL rise and the fact that glaciers and ice caps are increasing their relative contributions to increasing sea level change, while the component due to ocean warming has remained relatively constant during the past several years.

The measurement and understanding of global sea level is in a state of rapid flux. New observing systems such as satellite altimetry and gravity measurement missions and the deployment of profiling floats to measure vertical profiles of ocean temperature and salinity will lead to improved understanding of regional and global sea level variability. This will lead to improved projections of sea level variability.

Acknowledgments

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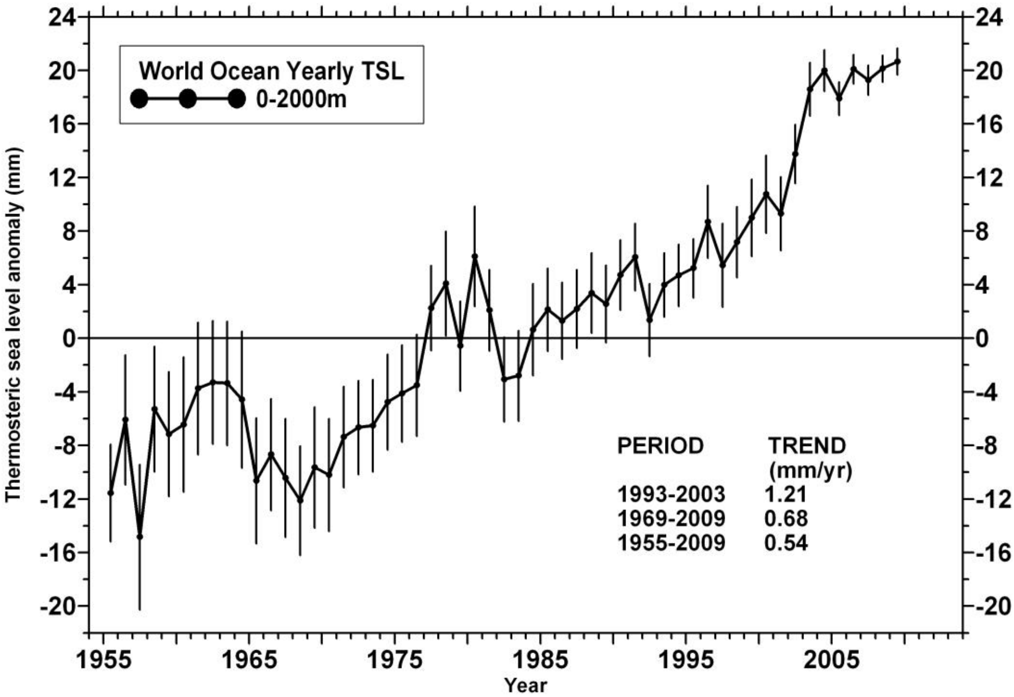

Figure 2-1. Global integral of the yearly thermosteric component of sea level change (mm/year) for 1955-2009 for the 0-2000 m layer of the World Ocean.

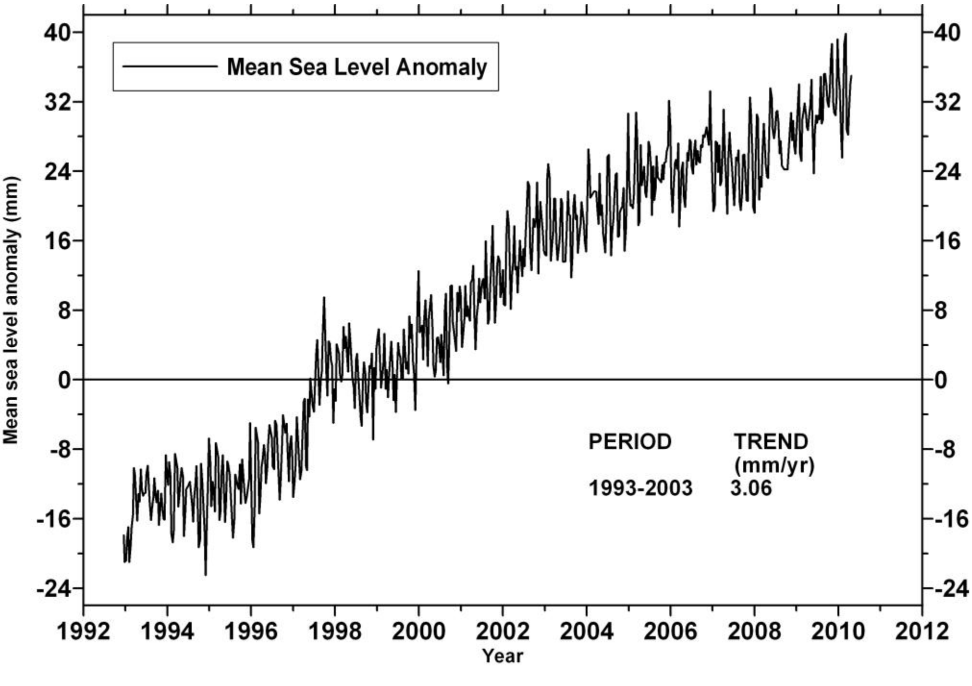

Figure 2-2. Global (60ºS-60ºN) total mean sea level from TOPEX/Poseidon and Jason satellite altimetry measurements for 1993-2009 (Nerem et al. 2006). Original data online at http://sealevel.colorado.edu/results.php

Chapter 3. Is the Rate of Sea Level Rise Increasing? An Analysis Based on U.S. Tide Gauges

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Abstract

Climate models predict future increases in the rate of sea level rise, yet the literature is divided on whether accelerations are now detectable. We examine 57 U.S. tide gauge records with a record length of at least 60 years to address this issue. Data are analyzed for both linear and quadratic trends.

Introduction

Climate models predict future increases in the rate of global sea level rise, yet the literature is divided on whether acceleration is now detectable. We adopt the definition of acceleration given by Douglas (1992) that acceleration is "… the deviation of sea level from a linear trend over the data span in question that is modeled by an algebraic term of the second degree in time."

Determining the rise and acceleration of global sea level is complicated by the small number of long-term tidal records and their concentration in the northern hemisphere, strong spatial world-wide variations in sea level rise, vertical land movements, and seasonal to decadal temporal variations that can be large compared to sea level rise and accelerations. Following Sturges and Hong (2001), we use the term "decadal" to refer to low-frequency variations that are longer than a year and extending out beyond 10 years and are caused in part by wind and atmospheric pressure variations and the Rossby and Kelvin waves they produce. Acceleration is a second-order effect that is influenced by all of these complications except vertical land movements, which are considered linear over long periods, such as glacial isostatic adjustment and sediment consolidation. Short-term tectonic movements, such as those arising from earthquakes, can affect both the apparent sea level trend and acceleration.

In the Third Assessment of the Intergovernmental Panel on Climate Change (IPCC), Church et al. (2001) summarize the results of several tidal gauge analyses and report that the global sea level rise for the 20th century was between 1 and 2 mm/year. In the fourth IPCC assessment report, Bindoff et al. (2007) estimate that global sea level rose about 1.7 mm/year in the 20th century. A range of rates have been determined based on regional data. For example, Woodworth and Blackman (1999) estimated a sea level rise of about 1 mm/year for the North Sea region. Davis and Mitrovica (1996) estimated a rise of 1.5 mm/year along the east coast of North America. Lambeck (2002) estimated a rise of 1.16 mm/year at Sydney, Australia, and a 1.65 mm/year rise at Perth. Hunter et al. (2003) found a sea level rise taking into account land uplift of 1 mm/year at Port Arthur, Tasmania, which has recorded sea level rise for 160 years, although with considerable record gaps. Church et al. (2001) report that sea level in China is rising at about 2 mm/year in the south but less than 0.5 mm/year in the north. Church et al. (2004) note that regional differences in sea level rise are to be expected due to global differences in heat, momentum, and salinity fluxes. Global sea level rise recorded by the TOPEX/Poseidon and Jason-1 satellite altimeters show strong regional sea level rise differences as vividly displayed in Wunsch et al. (2007).

There have been a limited number of studies focusing on the acceleration of sea level. Wordworth (1990) analyzed long records from European tide gauges and found overall a slightly negative acceleration of mean sea level from 1870 to 1990, although he found positive accelerations in individual gauge records. He also analyzed the four oldest European gauge records from Brest, Sheerness, Amsterdam, and Stockholm starting in 1807, 1834, 1799, and 1774, respectively, and found a small positive acceleration on the order of 0.004 mm /yr^2 that appeared typical of European Atlantic coast and Baltic mean sea level acceleration over the last few centuries. He noted that this small apparent acceleration was an order of magnitude less than anticipated from global warming. Jevrejeva et al. (2008) perform a similar analysis based on the long-term tide gauge recordings at Amsterdam, Liverpool, and Stockholm. They conclude that sea level has accelerated an average of about 0.01 mm/yr^2 over the past 300 years with the fastest rise between 1920 and 1950.

Douglas (1992) analyzed 23 tide records of 75 years or greater from around the world and determined an apparent global deceleration of -0.011 ± 0.012 mm/yr^2 for the 80-year period from 1905 to 1985. He further analyzed 37 records that were less uniform but had an average length of 92 years and determined that from 1850 to 1991 the acceleration was 0.001 ± 0.008 mm/yr^2. Noting that global warming models forecast acceleration over the next five to six decades in the range of 0.1-0.2 mm/yr^2, he concluded there was no evidence of acceleration in sea level rise in the past 100 or more years that was significant statistically or consistent with values predicted by global warming models. Holgate and Woodworth (1994) analyzed 177 tide gauge records from 1948 to 2002 and compared global mean sea level trends for 10-year overlapping periods. This gave them a 45-year record, which they split in half and obtained a trend of 1.3 mm/year for the first half of the record and 2.2 mm/year for the second half. However, in a subsequent study that considered a longer period, Holgate (2007) obtained the opposite result. He analyzed nine long and representative gauge records and found that the rate of sea level rise was greater from 1904 to 1953 (2.03 ± 0.35 mm/yr^2) than from 1954 to 2003 (1.45 ± 0.34 mm/yr^2). He noted that these results were consistent with "… a general deceleration of sea level rise during the 20th century," which he noted were suggested in analyses by Woodworth (1990), Douglas (1992), and Jevrejeva et al. (2006).

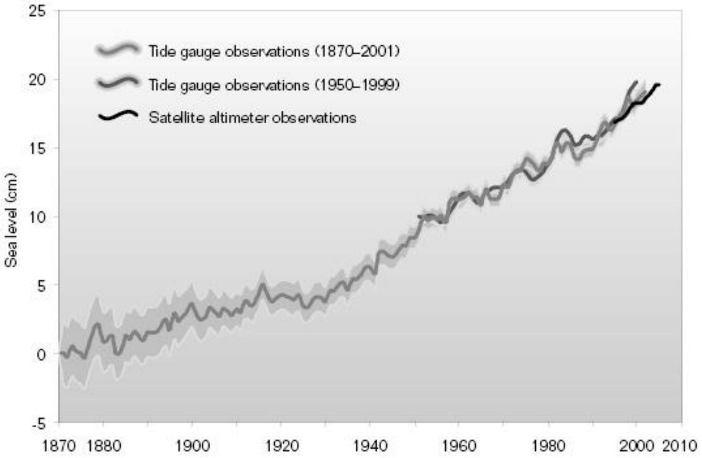

Figure 3-1. Sea level rise from Church and White (2006), Holgate and Woodworth (2004), Leuliette et al. (2004)

Church et al. (2004) used TOPEX/Poseidon satellite altimeter data to estimate global empirical orthogonal functions (EOF) that were then combined with historical tide gauge data to estimate global sea level rise from 1950 to 2000. They concluded that "… there is no detectable secular increase in the rate of sea level rise over the period 1950-2000." Church and White (2006) used the same EOF method but extended the analysis back to 1870. They concluded that from January 1870 to December 2004 there was a sea level rise acceleration of 0.013 ± 0.006 mm/yr^2 and a smaller acceleration of 0.008 ± 0.008 mm/yr^2 in the 20th century. They note that there is an increase in the rate of the sea level rise at about 1930. It appears that the increase in sea level rise rate shown in their Figure 3-1 is linear from 1930-2004, but they do not perform an analysis for this period.

A review paper on sea level rise acceleration by Woodworth et al. (2009) notes that the analysis by Church and White (2006) shows a positive acceleration, or "inflexion" point, around 1920 to 1930 and a similar deceleration inflexion point around 1960. They do not use the mathematical definition of an inflexion point as the point where the curvature (second derivative) changes. Instead, they define inflexion point as a change in trend of sea level rise, so the trend in sea level rise increases some time during the period 1920 to 1930 and decreases at about 1960. They note that the inflexion point at about 1920 to 1930 is the main contributor to acceleration from 1870 to 2004. Woodworth el al (2009) conclude that "if one restricts discussion from the latter part of the 19th century (e.g., 1870) to the end of the 20th century, then there is a reasonable consensus between the analysis of various authors as to global average accelerations." However, the acceleration from 1870 to 2004 seems to have occurred at or before the "inflexion" point around 1920 to 1930 with no apparent acceleration after 1930. Since Marland et al. (2007) show that about 90 percent of global fossil carbon emissions have occurred since 1930, the apparent absence of an acceleration of sea level rise since about 1930 is a conundrum.

The TOPEX/Poseidon satellite altimeter recorded sea level from August 1992 to 2005 and Jason-1 satellite altimeter from late 2001 to the present. Altimeter measurements are quite valuable because they measure elevations over the huge area of the oceans from +66 to -66 degrees rather than at the limited number of coastal gauge locations. In addition, altimeter measurements are not affected by fresh water runoff and other processes that contaminate shallow water tide gauge records. On the other hand, Ablain et al. (2009) note the many uncertainties and sources of error in satellite altimeter measurements.

From 1992 to the present, these altimeters measured a global sea level rise of 3.26 mm/year (Aviso 2010). Based on this and other evidence, Fletcher (2009) concludes that global sea level rise has accelerated. Indeed, the rise might be the leading edge of an acceleration predicted by climate change models. However, as noted by Douglas (1992) low-frequency variations of sea level "heavily corrupt the computation of an acceleration parameter for records less than about 50 years in length." He shows that analyzing records as short as the 22-year altimeter record can produce large spurious apparent accelerations of ± 1mm/yr^2 that exceed accelerations of 0.1 to 0.2 mm/yr^2 predicted by climate change models. Moreover, Domingues et al. (2008) note that the altimeter and tide gauge measurements were in good agreement until 1999 and then began to diverge with the altimeters recording a significantly higher rate of sea level rise, adding an element of uncertainty in the altimeter measurements. Moreover, Ablain et al. (2009) show that 3- and 5-year moving averages of the altimeter measurements have trended downward with the 3-year average having recently dropped as low as 1 mm/year and the 5-year average approaching 2 mm/year When compared to decadal oscillations shown in Figure 3-2 of Holgate (2007), the trend recorded by the satellite altimeters is similar to the trends as great as 5 to 6 mm/year that occurred at the peaks of a half dozen decadal oscillations since 1905.

The sea level rise measured by satellite altimeters from August 1992 to the present is not uniquely high. Bindoff et al. (2007) note that sea level rise similar to that measured by the altimeters have occurred in the past. Holgate (2007) calculated consecutive, overlapping 10-year mean sea level rise rates for nine representative long-term tide gauges and found that the altimeters measured the third highest of six peaks in rate since about 1910. The highest rates were 5.31 mm/year centered on 1980 and 4.68 mm/year centered on 1939. Church et al. (2004) report that from 1950 to 2000 there have been periods with sea level trends greater than those measured by the satellite altimeters. Similarly, White et al. (2005) noted sea level rates varying from 0 to 4 mm/year during the period 1950-2000. Jevrejeva et al. (2006) analyzed 1023 gauge locations and showed that global sea level rise is highly dependent on the time period chosen, and the sea level rise that occurred from 1920 to 1945 is similar to the rise measured by satellite altimeters.

Merrifield and Merrifield (2009) argue that the increase in the rate of sea level measured by the satellite altimeters is a sign of an acceleration that is distinct from decadal variations. They note that the rate of sea level rise recorded by northern ocean (25° to 65°) gauges is trendless, being approximately constant since about 1925. However, southern (-65° to -25°) and tropical (-25° to 25°) ocean gauges are typically 180° out of phase, so that when one experiences an increase in sea level rise, the other experiences a decrease. After the mid-1980s, the two became in phase, and their rise dominates the increase in the sea level measured by the satellite altimeters. Thus, Merrifield and Merrifield (2009) believe that this recent increase in sea level rise represents a long-term change rather than a fluctuation and is caused by ice melt and a subduction of heat below the upper layers of the ocean. However, significant numbers of sea level measurements from the tropical and southern oceans have only been taken since about 1955 and 1965, respectively. Only two cycles of the variation in sea level rise occur during these periods with the tropical and southern oceans being out of phase three of the half cycles and in phase the latest half cycle. It is not possible to discern whether the current half cycle is a long-term change or a normal fluctuation. Moreover, Jevrejeva et al. (2008) in their analysis of sea level rise over the past 300 years note that the main contribution to sea level rise acceleration comes from a 60- to 70-year cycle of sea level rise accelerations and that they follow a 70-year cycle in sea surface temperature and sea level pressure fluctuations determined by Delworth and Mann (2000). They show there have been four multi-decadal rises since about 1780 with the current one starting in about 1975 and being at a lesser rate than the previous three and due to peak at about 2005 to 2015. The rise measured by the altimeters may be part of this 70-year cycle.

Woodworth et al. (2009) show that by extending the empirical orthogonal function method of Church and White (2006) back in time, they can produce a global map of the quadratic term of 0.013 ± 0.006 mm/yr^2 determined by Church and White (2006) for 1870 to 2004. They note this term displays an El Niño-like global spatial distribution over this period with high values on the west coast of North America and low values in western Pacific just east of the Philippines. Further, they say that this pattern is consistent with an increase in the frequency and intensity of El Niño events that is predicted by climate models and shown by Tsonis et al. (2005) to accompany a warming climate. However, as shown in Figure 3-2, the rapid increase in sea level measured by the altimeters displays a pattern that is the opposite of an El Niño pattern, a La Niña pattern with high rates of sea level rise in the western Pacific just east of the Philippines and low rates on the west coast of North America. Again, it is not clear whether the rise measured by the altimeters is a long-term change or a global adjustment to the climate shift that Woodworth et al. (2009) note occurred around 1976 and is related to a normal phase change of the Pacific Decadal Oscillation.

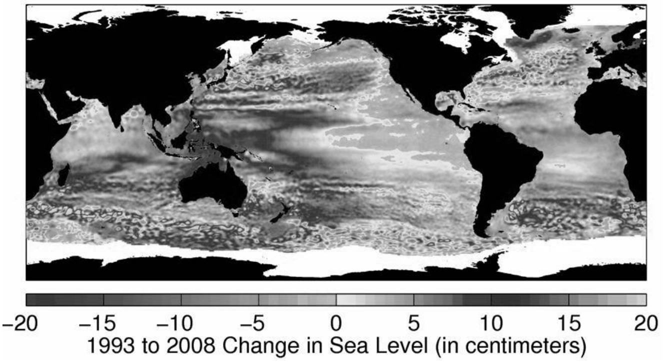

Figure 3-2. Satellite altimeter measurements from Ablain et al. (2009)

Methodology

Douglas (1992) notes that it is well established that sea level trends obtained from tide gauge records of less than about 50 to 60 years are significantly corrupted by decadal variations. Zervas (2001) estimates that 50 to 60 years of data are required to obtain mean sea level trends having a precision of 1 mm/year with a 95 percent statistical confidence interval. In this study, we analyze data from U.S. gauges having at least 60 years of data recorded at single locations and without significant tectonic activity that has caused vertical datum shifts. A total of 57 tide gauge stations met these criteria after we eliminated two Alaska tide gauge stations, Seward and Kodiak Island, because the 1964 earthquake significantly changed their datums. Data were obtained from the National Oceanic and Atmospheric Administration (NOAA) database at *www.co-ops.nos.noaa.gov/station_retrieve.shtml?type=Historic+Tide+Data*. Data extend back to 1900. The 57 tide gauge stations are listed below by city, NOAA location identifier, and the period of the record.

For each of the 57 tide gauge records, we obtained monthly sea level values from the NOAA database. Each record was first divided in half, and we determined the linear slope, a_1 in mm/yr, for each half record using the best least squares fit to the equation.

$$y(t) = a_0' + a_1' t \tag{3-1}$$

For entire records, we determined the slope, a_1 in mm/yr, and quadratic term acceleration, a_2 in mm/yr^2, using the quadratic equation

$$y(t) = a_0 + a_1 t + \frac{a_2}{2} t^2 \tag{3-2}$$

We determined 95 percent confidence limits for a_1', a_1, and a_2.

Table 3-1. Tide Gauge Stations with 60 Years of Data

Station	Years
Adak Island AK 9461380	1943-2009
Alameda CA 9414750	1939-2009
Annapolis MD 8575512	1928-2009
Apra Harbor 1630000	1948-2009
Astoria OR 9439040	1925-2009
Atlantic City NJ 8534720	1911-2009
Baltimore MD 8574680	1902-2009
Bar Harbor ME 8413320	1947-2009
Battery NY 8518750	1900-2009
Boston MA 8443970	1921-2009
Cedar Key FL 8727520	1914-2009
Charleston SC 8665530	1903-2009
Crescent City CA 9419750	1933-2009
Eastport ME 8410140	1929-2009
Fernandina FL 8720030	1900-2009
Fort Pulaski FL 8670870	1935-2009
Friday Harbor WA 9449880	1934-2009
Galveston TX 8771450	1908-2009
Hilo HI 1617760	1947-2009
Honolulu HI 1612340	1911-2009
Juneau AK 9452210	1936-2009
Ketchikan AK 9450460	1919-2009
Key West FL 8724580	1913-2009
Kwajalein 1820000	1946-2009
La Jolla CA 9410230	1924-2009
Lewes DE 8557380	1919-2009
Los Angeles CA 9410660	1924-2009
Mayport FL 8720220	1928-2000
Montauk NY 8510560	1948-2009
Neah Bay WA 9443090	1934-2009
New London CT 8461490	1938-2009
Newport RI 8452660	1930-2009
Pago Pago 1770000	1948-2009
Pensacola FL 8729840	1925-2009
Philadelphia PA 8545240	1922-1994
Port Isabel TX 8779770	1944-2009
Portland ME 8418150	1912-2009
Port San Luis CA 9412110	1945-2009
Providence RI 8454000	1938-2009
San Diego CA 9410170	1906-2009
Sand Is Midway 1619910	1947-2009
Sandy Hook NJ 8531680	1932-2009
San Francisco CA 9414290	1900-2009
Santa Monica CA 9410840	1933-2009
Seattle WA 9447130	1900-2009
Seavey Island ME 8419870	1926-2001
Sewells Point VA 8638610	1927-2009
Sitka AK 9451600	1938-2009
Skagway AK 9452400	1944-2009
Solomons Is MD 8577330	1938-2009
St Petersburg FL 8726520	1947-2009
Wake Island 1890000	1950-2009
Washington DC 8594900	1931-2009
Willets Point NY 8516990	1931-2001
Wilmington NC 8658120	1935-2009
Woods Hole MA 8447930	1932-2009
Yakutat AK 9453220	1940-2009

Results

Woodworth et al. (2009) notes that many papers on sea level rise lack transparency. Often the particular gauges being analyzed are not identified specifically and details of the analysis are not provided so that the results can be independently duplicated. Therefore, we are providing detailed results for each of the 57 gauges in Table 3-2 in addition to summary results. The term “1st” below designates the linear slope term in mm/year for the first half of the record and “2nd” for the second half. Delta is the second half slope minus the first half slope and has units of mm/year A negative value for delta indicates the second half slope is less than the first. The final term, a_2, shows the acceleration in mm/yr^2 based on the entire record with a negative value being a deceleration.

The average of the delta values for the 57 gauges is -0.10 mm/year with a standard deviation of the mean of ± 0.29 mm/year That is, the average linear rise was less in the second half of the records than the first, indicating a slight deceleration of sea level rise. Thirty of the gauge stations show a deceleration, 24 show acceleration, and three show no change. We expect a significant standard deviation of the mean because we are analyzing half records, so some records may be as short as 30 years. There are two data outliers, Agra with a delta of 7.37 mm/year and Yakutat with a delta of -7.38 mm/year. If these two stations are removed from the analysis, the average value is the same, -0.10 mm/yr, but the standard deviation decreases to ± 0.21 mm/year. Other gauge stations showing large deltas include Adak, -3.84; Skagway, -3.7; Port Isabel 3.94; and Sand Island, Midway, 4.76 mm/year. Interestingly, the outliers are balanced between positive and negative values, so if all six outliers are removed from the analysis, the average value is -0.13 ± 0.16 mm/year.

The average acceleration is -0.0017 ± 0.0082 mm/yr^2. That is, the average is a slight deceleration. Thirty-one of the gauges show a deceleration, 25 an acceleration, and one has a zero value. Again, Agra and Yakutat are outliers, and if they are eliminated from the analysis, the average is -0.0014 ± 0.0058 mm/yr^2. If Adak, Skagway, Port Isabel, and Sand Island, Midway, are also eliminated, the average is -0.0014 ± 0.0042 mm/yr^2. Eliminating outliers decreases the standard deviation of the mean, but has little effect on the average because of a balance of negative and positive accelerations.

Church and White (2006) showed an acceleration from January 1870 to December 2004 of 0.013 ± 0.006 mm/yr^2 and a smaller acceleration of 0.008 ± 0.008 mm/yr^2 in the 20th century. They note that the trend in sea level rise changed around 1930 but do not analyze data after that date to check for an acceleration in sea level rise. We analyzed 26 gauge stations with records extending back to 1930 and found that from 1930 to 2009 the average acceleration was -.0127 ± 0.0040 mm/yr^2. Of the 26 gauge stations, 19 displayed a deceleration and only seven an acceleration.

Discussion

Our analysis of 57 gauge stations in the United States shows slight average decelerations in sea level rise when comparing the rise in the second half of each record to the first and also when using a quadratic equation to determine acceleration. More gauges showed decelerations then accelerations. However, the large standard deviations make it impossible to be definitive on whether the rate of sea level rise has accelerated or decelerated.

Table 3-2. Results of 57 Gauge Station in the United States

Station	1st a_1	2nd a_1		Delta a_2
Adak Island AK	0.70	-3.14	-3.840	-0.1374
Alameda CA	0.51	0.50	-0.005	-0.0050
Annapolis MD	4.17	3.07	-1.100	-0.0292
Apra Harbor	-1.17	6.20	7.366	0.2580
Astoria OR	0.02	-0.57	-0.592	-0.0158
Atlantic City NJ	4.13	4.61	0.484	0.0078
Baltimore MD	3.32	2.81	-0.510	-0.0030
Bar Harbor ME	3.31	1.67	-1.640	-0.0438
Battery NY	3.01	2.83	-0.180	0.0014
Boston MA	3.59	2.42	-1.170	-0.0242
Cedar Key FL	2.01	1.70	-0.310	-0.0114
Charleston SC	3.75	3.00	-0.750	-0.0160
Crescent City CA	-0.59	-0.75	-0.160	-0.0132
Eastport ME	3.35	0.77	-2.580	-0.0506
Fernandina FL	1.86	2.06	0.200	0.0092
Fort Pulaski FL	2.53	2.98	0.450	0.0092
Friday Harbor WA	0.91	0.06	-0.850	-0.0174
Galveston TX	6.02	6.52	0.500	0.0074
Hilo HI	3.34	1.30	-2.040	-0.0636
Honolulu HI	1.45	1.45	0.000	-0.0020
Juneau AK	-12.95	-15.08	-2.130	-0.0404
Ketchikan AK	-0.41	-0.96	-0.550	-0.0100
Key West FL	2.42	2.60	0.180	0.0012
Kwajalein	1.76	4.35	2.590	0.1000
La Jolla CA	1.95	2.17	0.220	0.0022
Lewes DE	3.00	3.94	0.940	0.0122
Los Angeles CA	0.88	1.29	0.410	0.0036
Mayport FL	3.13	3.34	0.210	0.0062
Montauk NY	2.20	5.04	2.840	0.0772
Neah Bay WA	-0.98	-2.30	-1.320	-0.0382
New London CT	2.79	3.94	1.150	0.0344
Newport RI	3.38	3.43	0.050	-0.0086
Pago Pago	1.88	4.15	2.270	0.0688
Pensacola FL	2.48	2.07	-0.410	-0.0146
Philadelphia PA	4.26	2.75	-1.510	-0.0400
Port Isabel TX	3.01	7.00	3.990	0.0976
Portland ME	2.36	1.19	-1.170	-0.0190

Station	**1st**	**2nd**		**Delta**
Port San Luis CA	0.94' a_1	-0.21' a_1	-1.150	-0.0426 a_2
Providence RI	1.92	3.43	1.510	0.0258
San Diego CA	1.94	1.84	-0.100	-0.0024
Sand Is Midway	-0.86	3.90	4.760	0.1338
Sandy Hook NJ	4.59	3.92	-0.670	-0.0116
San Francisco CA	1.65	1.73	0.080	0.0008
Santa Monica CA	2.04	0.93	-1.110	-0.0392
Seattle WA	1.42	1.80	0.380	0.0082
Seavey Island ME	2.98	1.06	-1.920	-0.0488
Sewells Point VA	**4.45**	**4.83**	**0.380**	**0.0068**
Sitka AK	-2.07	-2.02	0.050	0.0108
Skagway AK	-16.93	-20.63	-3.700	-0.0974
Solomons Is MD	3.17	5.66	2.490	0.0450
St Petersburg FL	1.52	2.37	0.850	0.0314
Wake Island	1.54	2.08	0.540	0.0222
Washington DC	2.78	2.75	-0.030	-0.0006
Willets Point NY	2.89	1.84	-1.050	-0.0316
Wilmington NC	2.09	1.84	-0.250	-0.0046
Woods Hole MA	3.42	3.23	-0.190	0.0000
Yakutat AK	-4.72	-12.10	-7.380	-0.1946

Church and White (2006) use the acceleration 0.013 ± 0.006 mm/yr^2 that they determined for the period January 1870 to December 2004 to project sea level rise to 2100, despite the fact that much of the acceleration occurred prior to 1900. As previously noted, they calculated an acceleration of only 0.008 ± 0.008 mm/yr^2 for the 20th century. Moreover, they noted an increase in the rate around 1930, which appears to account for the entire acceleration of the 20th century. Our analysis indicates that there has not been an acceleration since 1930. Indeed, there is evidence of a deceleration in sea level rise after 1930, with almost three times as many gauges showing a deceleration rather than an acceleration. Our results are consistent with Holgate (2007), who noted that his and other studies have shown a deceleration of sea level rise in the 20th century.

The satellite altimeters show an increased rate of sea level rise since 1993. However, this is too short a time to determine if sea level rise started accelerating from its steady rise since 1930. Interestingly, 54 of the 57 gauge stations that we analyzed had recordings during the complete 1993 to 2009 period, and 29 of the 54 showed net decreases in sea level. Most gauges on the West Coast of the United States document a decrease in sea level since 1993. For example, the San Francisco gauge, which has had a rate of sea level rise of 1.92 mm/year from 1900 to 2009, had a rate of sea level decline of 3.42 mm/year from 1993 to 2009. During this 17-year period, mean sea level at San Francisco decreased 58 mm. As seen in Figure 3-2, the decline in mean sea level shown by West Coast gauges is a result of a strong La Niña pattern from 1993 to 2009, resulting in cold waters off the West Coast of the United States.

Conclusions

The 57 U.S. gauges from 1900 to 2009 show no evidence of sea level rise acceleration. This result is in agreement with a number of studies cited in the introduction that considered tide gauge records worldwide and showed no acceleration of sea level in the 20th century. Woodworth et al. (2009) noted that there is general consensus that sea level accelerated from 1870 to 2000. However, Figure 3-1 suggests that all of the acceleration occurred before about 1930. Indeed, Church and White (2006) note that much of the acceleration occurred in the first half of the 20th century, but they still use the acceleration prior to 1930 to project sea level in 2100. Our results also show that U.S. tide gauge records do not show an acceleration in sea level from 1930 to 2009. It is possible that the increase rate of sea level rise displayed by satellite altimeters since 1993 foreshadows the beginning of an expected acceleration of sea level rise. However, since there have been accelerations of a similar magnitude in the past (typically followed by decelerations), it may be a number of years before we will know if this latest acceleration is a trend or a fluctuation.

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Chapter 4. The U. S. Navy's Approach to Climate Change and Seal Level Rise

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Abstract

Climate change and its associated effects such as sea level rise, ice sheet melting, and changing storm and precipitation patterns are being observed on global and regional scales around the world and will influence the way the U.S. Navy operates in the 21st century. In response to the overwhelming scientific evidence that climate change is occurring, and recognizing that climate change is a national security threat with strategic implications for the Navy, the Navy's Task Force Climate Change and Task Force Energy are executing Navy arctic and climate roadmaps and a Navy energy strategy. The *Climate Change Roadmap* outlines the Navy's approach to assessing, predicting, and adapting to climate change to ensure that the Navy is mission ready to meet the challenges of the future.

Introduction

Melting Arctic sea ice, the stability of developing and resource-poor nations, changing fish stocks in Asia, and more intense hurricanes in the Atlantic Ocean may seem like unrelated scenarios, but in fact, all are caused or affected by changing climate. There is broad scientific consensus that climate change is occurring on a variety of scales around the world with economic, human health, societal, and national security implications. This paper examines the national security implications of climate change and their impacts on U.S. Navy missions, force structure, and infrastructure.

Observations

To understand how climate change will affect the U.S. Navy requires first comprehending the science. Extensive observations of the Earth's atmosphere, oceans, biosphere, and cryosphere confirm that the planet's climate is changing.

Temperature and Greenhouse Gases

Global average temperature since 1990 has risen about 1.5°F (USGCRP 2009). In a recent paper submitted to *Reviews of Geophysics*, James Hansen, Ph.D., observes that global warming on decadal time scales is continuing, concluding that there has been no reduction in the global warming trend of 0.15°C to 0.20°C per decade that began in the late 1970s (Hansen 2010). Figure 4-1 illustrates this point, displaying the global temperature anomaly with correlation to the Niño (El Niño and La Niña index) and large volcanic eruption cooling effects that last approximately two years. While the graph demonstrates these short-term fluctuations in temperature, the observed trend of steadily increasing global temperatures since the 1970s is clear.

The link between increasing global average temperature and greenhouse gas emissions should not be as contentious as it has become. The greenhouse effect is a well-understood physical phenomena governed by the radiative transfer equation by which greenhouse gases such as methane and carbon dioxide absorb short wavelength radiation from the sun and reflected from the earth's surface, and re-radiate this energy back to the atmosphere and earth's surface at longer wavelengths (Cicerone 2009). Without the greenhouse effect, the Earth's average global surface temperature would be -18°C, instead of around +13°C. However, increasing concentrations of greenhouse gases in the atmosphere beginning in the Industrial Revolution have led to corresponding increases in global temperature. The 2007 Intergovernmental Panel on Climate Change (IPCC) Report of the Fourth Working Group (AR4) states with very high confidence that the global average net effect of human activities since the 1750s has been one of warming (IPCC 2007).

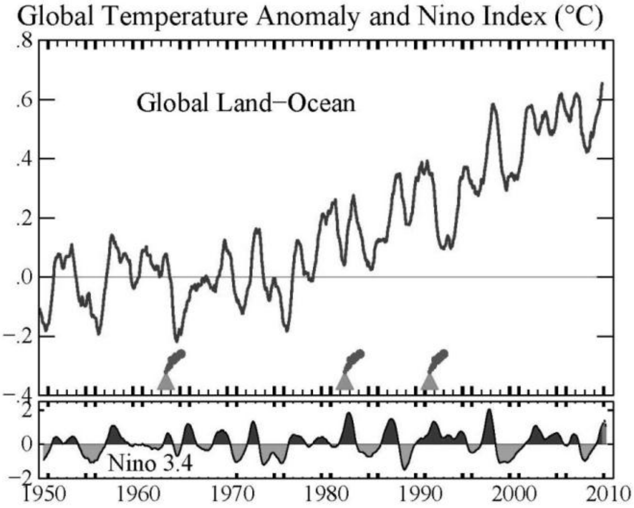

Figure 4-1. Top curve: 12-month running-mean global temperature. Niño index at the bottom (dark gray = El Niño, light gray = La Niña). Large volcanoes (shown in the middle graph with volcano icons) have a cooling effect for about 2 years. Source: James Hansen 2010.

The world's oceans and land absorb significant amounts of this heat and energy. In fact, about 45 percent of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation. Other effects of the rising global temperatures observed today include an increasing frequency of heat waves, changing precipitation patterns, and shifting plant and animal habitat (USGCRP 2009).

Sea Ice and Ice Sheets

Because the Arctic is warming twice as fast as the rest of the globe, the region is experiencing declining sea ice extent and volume, increasing glacial and ice sheet melt, and shrinking snow areas (Kallen 2009). Sea ice extent in the Arctic has decreased steadily since the 1950s and in September 2007 reached a record low 39 percent below the 1979-2000 mean. September sea ice in 2008 and 2009 reached the second and third lowest recorded extent, respectively (NSIDC 2009). The overall sea ice extent for the 2009/2010 winter season remains below the National Snow Ice and Data Center 30 average, and multi-year ice extent has decreased by 5 to 10 percent from 2006 to 2009 (see Fig. 4-2) (NSIDC 2010). Moreover, in 2010, March Arctic sea ice volume observed by the University of Washington's Applied Physics Lab was 20,300 km^3, the lowest for the 1979-2009 period and 38 percent below the 1979 maximum. September ice volume was lowest in 2009 at 5,800 km^3 or 67 percent below its 1979 maximum (APL-UW PSC 2010). Reduction in ice volume means that thicker, multi-year sea ice is being replaced by first-year or seasonal ice in the Arctic, which is thin and much more susceptible to melting or being influenced by wave and wind action.

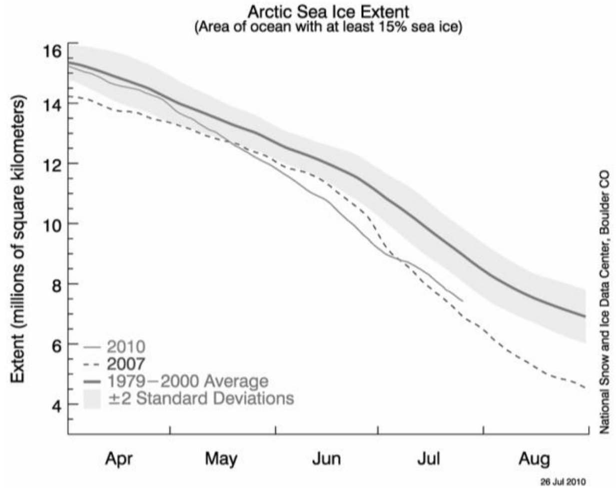

Figure 4-2. March and April 2010 sea ice extent was above the 2007 measurement, and remains above the 2007 extent for July 2010, despite a sharp dip below 2007 levels in May and June 2010. The 2010 extent remains below the 1979-2000 average. Source: National Snow Ice and Data Center, July 2010.

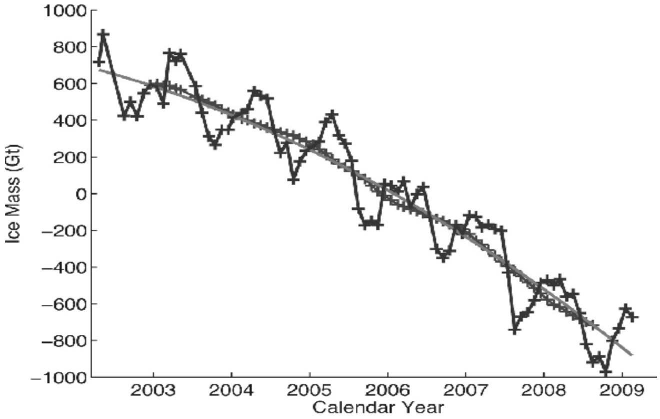

Figure 4-3. Greenland ice sheet mass loss is accelerating. Source: I. Velicogna, Geophysical Research Letters, 2009. (Reproduced/modified by permission of the American Geophysical Union.)

Also exhibiting significant decline is the mass of the Greenland ice sheet (GRIS), and this trend has recently been observed to be accelerating (see Fig. 4-3) (Allison et al. 2009). Observations indicate a large increase in summer 2007 ice melt at 60 percent more than the previous high in 1998 (McMullen 2009). Antarctica's ice sheet has exhibited a similar trend (Allison et al. 2009).

Sea Level Rise

Ice sheet melting is one of two processes that contribute to global sea level rise. The net GRIS ice loss is contributing as much as 0.7 mm per year to sea level rise due to expanded melting and accelerated ice flow, and the Antarctic ice melt is contributing to sea level rise at a nearly equal rate (Allison et. al 2009). Rising global ocean temperature also contributes to increased global sea level rise through thermal expansion of warming ocean water. Both ice sheet melting and global ocean warming contributed to the historic sea level rise, which has been carefully reconstructed dating back to the last ice age by geologists using the dates and depths of coral reefs (NRC 2010). Their data show that changes in sea level were punctuated by sharp, unsteady increases attributable to melting ice; 6,000 years ago the global average sea level was roughly equivalent to its present-day level and remained relatively steady from the first century AD to 1800 (NRC 2010).

For the 19th and 20th centuries, sea level has been recorded using tide gauge measurements, which date back approximately 140 years. These observations indicate that sea level has been rising since the mid-19th century at approximately 2 mm/year (Douglas 1997).

More recent and accurate satellite altimeter measurements have been used to record global sea level since 1993, indicating a 3.4 mm per year increase, 80 percent faster than the best estimate of the IPCC Fourth Assessment Report (AR4) for the same period. This disparity is almost certainly due to the omission of ice sheet contributions used in the IPCC AR4 (Allison et. al 2009, NRC 2010).

Extreme Events and Variability

While observed trends in global averages are significant, variability and extremes relative to these averages are expected to have mostly adverse impacts on natural and human systems, altering the time available for humans to recover and adapt (IPCC 2007, USGCRP 2009). The U.S. Global Change Research Program (USGCRP) notes that the cumulative effects of these events is compounded in that they usually occur concurrently and have more severe impacts; for example, heat waves, droughts, air stagnation, and wildfires in California can feed off of one another and cause greater damage than if they occur singularly.

Examples of changes in extreme event patterns are many. The last 10 years have seen fewer cold waves than any other 10-year period in the historical record, extreme precipitation episodes have become more frequent and intense, and droughts are becoming more severe in some regions (USGCRP 2009).

On the other hand, the data for tropical cyclones are mixed. No link between climate change and the number of tropical cyclones has been identified (IPCC AR4), and the Accumulated Cyclone Energy Index from 1950 to 2009 showed no clear trends in cyclone frequency (U.S. EPA 2010). However, the EPA does note that intensity has risen noticeably over the past 20 years, and six of the 10 most active years occurred since the mid-1990s (U.S. EPA 2010).

Understanding climate variability is even more elusive. Recent data released by the National Oceanic and Atmospheric Administration (NOAA) illustrates that despite a severe and cold winter for much of the United States this year, combined land and ocean temperatures for April 2010 were the warmest on record at 58.1°F, which is 1.37°F above the 20th century average. Snow cover extent was also the fourth-lowest on record (since 1967) and below the 1967-2010 average for the Northern Hemisphere for the seventh consecutive April (NOAA 2010). This type of vacillation from one extreme to the next will make it very challenging for populations around the world to adapt to a changing climate in a safe and timely manner. Improved understanding of predicted events is integral to the climate change planning and adaptation process.

Predictions

Climate change scientists use physical models and historic and observed trends to predict future change. While significant uncertainties remain in modeling possible outcomes of global change, these predictions are essential to the Navy and other organizations as they provide a foundation of scientifically based projections for adapting to and planning for likely situations.

Temperature

While scientists observe that global emissions of carbon dioxide and other greenhouse gases are accelerating, it is impossible to predict the exact rise in future temperature due to the uncertainty in predicting future emission scenarios. However, under a "business as usual" global emission scenario, the average-annual temperature increase in the United States is likely to reach 4°F to 6°F by 2050 and 7°F to 11°F by 2090 (USGCRP 2009). While the increase of a few degrees over decades may not seem like an immense problem, consider that the climate observations discussed in the sections above have occurred in a world that has warmed on average only about 1.5°F since 1990 (Holdren 2009). Indeed the IPCC states that global average temperature is projected to rise by 2°F to 11.5°F by the end of this century based on scenarios that do not assume explicit climate policies to reduce greenhouse gas emissions.

Even if greenhouse gas emissions stabilize, however, the time lag in climate response will cause warming to continue for many years. The effects of increased warming on other climate processes must be considered when projecting future scenarios.

Sea Ice and Ice Sheets

Warmer global temperatures will continue to have a significant effect on the coldest regions of the world, including sea ice and ice sheets. Holland et al. (2006) suggest that the Arctic could experience an ice-free summer in the late 2030 period. Rapid melting of Arctic sea ice likely will trigger permafrost melting and warming on land (Allison et al. 2009). The Greenland and West Antarctic Ice Sheets have the potential to trigger massive sea level rise around the world if they experience continued melting. The *Copenhagen Diagnosis* states that if completely melted, the Antarctic Ice Sheet would raise global sea level by 52.8 m, and a loss of only the most vulnerable parts of West Antarctica would still raise sea level by 3.3 m. Greenland would add another 6.6 m.

Sea Level Rise

Based on the exclusion of melting ice sheets from the IPCC *AR4 Report*, recent scientific observations and modeling efforts like those cited above have concluded the that prediction of 18 to 59 cm of sea level rise by 2100 in the IPCC *AR4 Report* is too conservative (Allison et al. 2009). Based on a number of new studies, the synthesis document of the 2009 Copenhagen Climate Congress (Richardson et al. 2009) concluded that "updated estimates of the future global mean sea level rise are about double the IPCC projections from 2007" (Allison et al. 2009). According to Vermeer and Rahmstorf (2009), the higher emission scenario, under which we are currently tracking, yields a global sea level rise by 2100 of about 1.4 m. This figure is countered by other scientists who state that this figure represents a linear relationship between global temperature and sea level rise that is not entirely acceptable because there is the risk of the climate reaching "tipping points" (for example, Arctic sea ice, ice sheet melt, and Amazon deforestation) that could trigger rapid, non-linear change in sea level rise.

Another component of sea level rise is regional change. Regional sea level change is affected by a number of factors including local atmospheric pressure, alongshore wind stress, integrated water column density and thermocline depth, and short-term effects from processes such as El Niño. The effects of global sea level rise will be exacerbated by regional changes, making it necessary to understand these processes on both global and regional scales.

As with global temperature, sea level will continue to rise for many centuries after global temperature is stabilized. If the UNFCCC negotiations are successful and global greenhouse gas emissions are capped within the next few years, the world will still have to contend with rising sea levels as the oceans and ice sheets fully respond to a warmer climate.

Extreme Events

Despite the lack of an observed relationship between climate change and risks of extreme weather events, the IPCC report identifies a higher confidence in the projected increases of drought, heat waves, and floods in many regions around the world. Increased storminess, sea level rise, and associated storm surge will continue to accelerate over the 21st century and will have dramatic impacts on low-lying areas where subsidence and erosion problems already exist (Boesch et al. 2000).

The lethal storms and subsequent floods in Nashville, Tennessee, in May 2010 demonstrate the severity and suddenness with which extreme events will occur. In one weekend, Nashville experienced its heaviest one- and two-day rains on record, receiving 7.25 in. of rain on Sunday, killing 15 people, closing highways, causing unprecedented flooding of rivers, and damaging homes (Masters 2010). These types of events are predicted in the USGCRP's 2009 *U.S. Climate Impact Report*. The report observes, "The amount of rain falling in the heaviest downpours has increased approximately 20 percent on average in the past century, and this trend is very likely to continue, with the largest increases in the wettest places." The storms in Tennessee illustrate on a small-scale the kind of extreme events that can wreak havoc on communities, states, and countries. With increasing frequency, there will be the call for help from regions around the world. The U.S. Navy must be prepared to operate under shifting conditions as extreme events related to climate change increase.

Navy Concerns

What implications does a changing climate have for the Navy? The 2010 Department of Defense (DoD) Quadrennial Defense Review identified two broad ways in which climate change will affect the DoD. First, climate change "will shape the operating environment, roles, and missions" that DoD undertakes. The projected effects of climate change will have geopolitical impacts around the world that may, in addition to other factors, contribute to poverty, environmental degradation, further weakening of fragile governments, and resource scarcity (QDR 2010).

The second consideration identified in the QDR is the ways in which DoD will have to adjust to the affects of climate change on military capabilities and facilities. The Navy in particular locates the majority of its installations along coasts that will be increasingly vulnerable to the impacts of extreme events and sea level rise.

Continental U.S. Installations

In its recent report entitled *Advancing the Science of Climate* (part of its America's Climate Choices project), the National Research Council notes that many U.S. military bases are located in areas likely to be affected by sea level rise and tropical storms, and that future military operations may take place in areas subject to drought or extreme high temperatures (NRC 2010). A 2008 report by the National Intelligence Council noted that more than 30 U.S. military installations were already facing elevated levels of risk from rising sea levels. As the QDR states, DoD's operational readiness hinges on continued access to land, air, and sea training and test space. A 2010 Letter Report to the Chief of Naval Operations from the National Academies' Naval Studies Board suggests that the Navy conduct a detailed analysis and action plan to address vulnerabilities of coastal installations identified as being high risk or very high risk, taking into account risk factors such as regional weather history, shifts in storm tracks, changes in ocean circulation, and the impact of groundwater drawdown and recharge on subsidence (NSB 2010). This kind of work will help inform larger risks to Navy installations and ensure that the Navy understands and can adapt to changes that will occur on its Continental U.S. (CONUS) installations.

Overseas Installations

Overseas installations are also of extreme importance to the Navy. In addition to the basic climate change concerns discussed for CONUS installations that also need to be addressed overseas, bases such as Guam and Diego Garcia provide a strategic advantage to the Navy because of their location, ease of access to different regions around the world, and logistics support. The U.S. Navy frequently engages other nations via port visits, and climate change threats to these foreign bases will stymie the Navy's ability to maintain friendly relations and access to the global commons.

Water Resources

As the climate changes, both the quantity and quality of water resources will become increasingly scarce due to the changing precipitation patterns and amounts discussed above.

The IPCC *2007 Synthesis Report* states that "climate change is expected to exacerbate current stresses on water resources from population growth and economic and land-use change."

Alterations in freshwater systems will also present challenges for flood management, drought preparedness, and water supply (NRC 2010). In regions such as the Southwest and Southeast United States, drought is already a problem and will need to be continually addressed for Navy installations as climate change intensifies. Additionally, shifting water resources are one small piece of likely increasing humanitarian assistance and disaster relief missions for the Navy.

Humanitarian Assistance and Disaster Relief

About 160 million people around the world live less than 1 m above sea level, and these people are at risk from more intense coastal storms, flooding, and erosion (Allison et al. 2009). While the exact estimates of increases in extreme events are uncertain, the National Intelligence Council estimates that demand for food will rise by 50 percent by 2030 as a result of growing world population, rising affluence, and a shift to Western dietary preferences, resulting in greater stresses on resources already under pressure from climate change effects (NIC 2008). Combined, these factors may increase the potential for humanitarian assistance/disaster relief (HA/DR) requirements. However, further study is needed to examine the complex interplay between climate, resources, and regional and national economic, political, and security considerations that influence decisions to perform HA/DR missions.

Wild Card Scenarios

The Navy is concerned with climate change "wild cards," or those aspects of climate change for which little is known or has been addressed by the climate science community. One such wild card is abrupt climate change set off by tipping elements. Tipping elements are defined as Earth system components vulnerable to abrupt change, such as the Indian summer monsoon, Atlantic ocean thermohaline circulation, and the Amazon rainforest. Tipping elements do not follow linear paths of change and, thus, present a challenge to climate scientists and modelers in observing and predicting future events; the significance of tipping points in the climate system being reached means that the observations and climate phenomena discussed earlier will likely become even more unpredictable, causing greater need for military response (McMullen 2009).

A second wild card is ocean acidification. The world's oceans have absorbed approximately 40 percent of fossil fuel emissions, currently totaling about one-third of the total emissions from the past 200 years (Barry 2010). The uptake of CO_2 into the world's oceans is the basis for unprecedented modifications to ocean chemistry, which in turn causes a domino effect of changes to a myriad of ocean organisms, including fisheries that millions of people around the world depend on as a food source (NRC 2010). Of concern is that the current episode of acidification is taking place more rapidly than at any other time in the past, leaving oceanic species little time to adapt (Doney 2006). While changes in temperature, salinity, and oxygen content alone can affect the distribution of fisheries, it is expected that ocean acidification may exacerbate these changes in some parts of the world. For example, leading fishery scientists estimate decreases of up to 40 percent in overall catch potential for most major fisheries near the tropics during the next four decades due to warming and changes in ocean chemistry, while the Arctic region may see a 30 to 70 percent increase in overall catch potential (Cheung et al. 2010). The impacts of ocean acidification on the marine food chain may have significant implications for emerging coastal economies and could cause severe food shortages for millions of people that depend upon it for sustenance. This, in turn, could cause civil disturbances on a variety of scales.

The third climate change wild card is geoengineering. Defined as "deliberate large-scale intervention in the Earth's climate system to moderate global warming," geoengineering methods fall into two main categories: carbon dioxide removal and solar radiation management. The latter reflects a small percentage of the sun's light and heat back into space (U.K. Royal Society 2009). Geoengineering is fast gaining attention in mainstream science discussion as a way to mitigate the warming effects of climate change in addition to regulating greenhouse gases. Joint work by the U.S. House Science and Technology Committee and the U.K. House of Commons Science and Technology Committee is being conducted to explore this topic in greater detail, and the U.S. Government Accountability Office is currently gathering research for a report of federal government actions with respect to geoengineering, which is expected to be released in late summer 2010. As the subject of geoengineering gains attention, there are many questions raised about its effects and outcomes on global and local scales. For example, the unintended consequences of geoengineering, regulation on an international scale, and the effects to surrounding countries if another decides to conduct geoengineering are all scenarios that require the Navy to monitor climate intervention techniques and research for implications to its own missions.

Wild-card climate scenarios do not occur linearly and require greater monitoring and international collaborative research. These and the other near- and mid-term climate change impacts discussed will shape the Navy's approach to climate change and energy security and help it adapt to a changing climate by reducing risk associated with changing environments.

Navy and Department of Defense Initiatives

Guidance

To address climate change, the Navy is responding to guidance issued by the federal government and DoD, as well as its own strategic guidance that calls out climate change adaptation. On the national level, Executive Order 13514, *Federal Leadership in Environmental, Energy, and Economic Performance,* requires federal agencies to set goals for improving energy efficiency, conserving resources, reducing greenhouse gas (GHG) emissions, increasing water efficiency, and utilizing green procurement. Within the DoD, the *2010 QDR* identifies climate change as one of several key geopolitical trends that may influence future conflict and directs the DoD to craft a strategic approach to energy and climate that considers the influence of climate change in shaping the operating environment, roles, and missions of the DoD, and the impact of climate change on military facilities and capabilities. With respect to the influence of climate change on installations, the *QDR* recognizes the significant level of environmental stewardship exercised by the DoD and directs it to foster efforts to assess and adapt to the impacts of climate change.

Primary Navy guidance includes the Secretary of the Navy's (SECNAV) Energy Goals and the Cooperative Strategy for 21st Century Seapower (CS21). CS21 identifies climate change impacts in the Arctic as a strategic challenge and defines Navy strategic imperatives, including the prevention or mitigation of disruptions or crises and the fostering and sustainment of cooperative relationships with more international partners. Additionally, the *Navy Strategic Plan* in support of POM 12 lists the effects of climate change as a key uncertainty in developing alternative futures. Increasing the predictability of climate change impacts will improve alternative futures planning processes and strategic guidance documents.

Navy Task Forces

To address its climate change adaptation and energy security charge, the U.S. Navy formed two task forces that are leveraging DoD's technology and research capabilities to address climate change—Task Force Climate Change (TFCC) and Task Force Energy (TFE). Task Force Energy is responding to the *SECNAV Energy Goals* through energy security initiatives that reduce the Navy's carbon footprint and is implementing this direction through the Navy energy strategy (Paige 2009).

The Chief of Naval Operations, Admiral Gary Roughead, formed Task Force Climate Change in May 2009 to assess implications of climate change for national security and naval operation, to answer the question *"when"* in terms of Navy decisions about climate change, and to ensure the Navy is ready and capable to meet all mission requirements in the 21st century. The Navy's *Arctic* and *Climate Change Roadmaps* respond to this direction.

Arctic Roadmap

Because of the rapidly changing and complex environment in the Arctic and the implications for increased maritime security presence as laid out in National Security Policy Directive-66/Homeland Security Policy Directive-25, which requires that naval forces be prepared to operate in the Arctic, the Navy chose to make the Arctic a near-term priority. As a result, the *Arctic Roadmap* was released in November 2009 to guide Navy policy, investment, action, and public discussion in the Arctic region and to build on the Navy's extensive experience in the region. A five-year plan, the *Arctic Roadmap,* places emphasis on cooperative partnerships in joint surveys, research, search and rescue operations, maritime domain awareness, and incident response.

Key components of the *Arctic Roadmap* are already underway or completed, including a mission analysis and capabilities-based assessment of current readiness for Arctic operations. Tabletop exercises and war games are examining future scenarios in the Arctic, and collaborative partnerships with joint, interagency, and international stakeholders are being established for hydrographic survey operations and increased environmental understanding.

Climate Change Roadmap

Intended as a companion document to the Navy *Arctic Roadmap* and released in May 2010, the Navy *Climate Change Roadmap* is similar in structure to the *Arctic Roadmap* in that it is a five-year action plan with a focus on partnerships and using the best available science to support decision-making and future planning. The *Climate Change Roadmap* takes a broader view of global climate change outside the Arctic and seeks to achieve five desired effects:

- The Navy is fully mission-capable through changing climatic conditions while actively contributing to national requirements for addressing climate change.
- Naval force structure and infrastructure are capable of meeting combatant commander requirements in all probable climatic conditions during the next 30 years.
- The Navy understands the timing, severity, and impact of current and projected changes in the global environment.
- The media, public, government, joint, interagency, and international community understand how and why the Navy is effectively addressing climate change.
- The Navy is recognized as a valuable joint, interagency, and international partner in responding to climate change.

Significant actions in the *Climate Change Roadmap* fall into three broad categories: assessment and prediction, adaptation, and mitigation.

Assessment and Prediction

In light of the complex and evolving climate change science and predictions, the Navy seeks to provide its leadership and decision-makers a science-based, comprehensive understanding of the timing, severity, and impact of current and predicted global change on tactical, operational, and strategic (climatic) scales to inform its strategies, policies, and plans. TFCC has leveraged partnerships to engage more than 400 individuals from more than 120 organizations around the world, including premier scientific, academic, and analytical organizations.

Near-term assessment and prediction efforts include fielding networked climate observation systems, such as satellite and underwater remote sensors, the development of a next generation coupled air-ocean-ice operational prediction system, and the deployment of a fleet of ocean gliders to contribute to national climate observation systems. The U.S. Navy is scheduled to perform cooperative hydrographic and oceanographic surveys in the Bering Strait and environmental assessments in the Arctic and in U.S. areas affected by changing precipitation patterns.

To achieve proper investments and ensure that they are delivered at the right time and the right cost, the Navy will initiate a climate change capabilities based assessment (CBA), identify climate change science and technology needs, and incorporate climate change-related guidance from the *Navy Strategic Plan* into sponsor program proposals (SPPs). Assessment and prediction efforts will ensure that the Navy's missions are adaptable to the variety of climate changes predicted to occur over the next century.

Adaptation

Adaptation to climate change requires incorporation of climate change science and strategic considerations into fleet training and planning and formal naval training and education at the Naval Academy, Naval War College, and Naval Postgraduate School. Wargames, tabletop exercises, and limited objective experiments are being conducted to examine projected climate change impacts. For example, the Navy conducted a July 2010 war game at the Naval War College that examined climate change as one of several dimensions shaping security environments in different regions of the world. This summer, the Navy also participated in Operation NANOOK, a Canadian national Arctic training exercise.

In addition to Navy missions, impacts to military infrastructure must also be considered, both within and outside of the Continental United States because global and regional sea level changes will render coastal infrastructure particularly vulnerable, especially as it is coupled with storm surge and/or severe storm events.

Loss of coastal infrastructure can alter access to foreign ports, inhibiting theater security cooperation and regional security. To address concerns about sea level rise, the Strategic Environmental Research and Development Program (the DoD's environmental science and technology program) is leading a QDR-directed, comprehensive assessment of military installations to assess the potential impacts of climate change on DoD's missions. The project will result in impact and vulnerability assessment tools designed for military installations, regionally applicable climate change information, and adaptation strategies appropriate for DoD requirements.

Additionally, the Navy is informing media, public, government, defense, interagency, and international audiences and other interested stakeholders about its policy, strategy, investments, intentions, and actions in response to climate change. It continues to advocate for U.S. accession to the United Nations Convention on the Law of the Sea (UNCLOS). UNCLOS allows countries to claim jurisdiction past their exclusive economic zones based on undersea features that are considered extensions of the continental shelf. This advocacy can be viewed as adaptation because UNCLOS is of particular importance in the Arctic; the 2008 Illulissat Declaration recognizes that "the Law of the Sea is the relevant legal framework in the Arctic" and protects the national security, environmental, and economic interests of all nations.

Mitigation

The Navy is dedicated to showing leadership in conserving energy by reducing its carbon footprint and increasing its reliance on alternative fuels. U.S. Secretary of the Navy Ray Mabus has committed the Navy to making sizable progress in the next decade and directed Task Force Energy to carry out specific goals to decrease the Navy's dependence on foreign oil and increase energy security. His goals include sailing a "great green fleet," reducing petroleum use, and increasing alternative energy ashore and Navy-wide. To achieve these goals Task Force Energy is implementing tactical initiatives, such as maritime and aviation incentivized energy conservation, improved hydrodynamics, smart voyage planning and efficient aircraft and ship systems, and efficient aircraft and ship propulsion. On shore, net zero installations, advanced metering, auditing, smart grid technology, and improved building design and efficiency upgrades all contribute to an energy-efficient Navy. These initiatives are supported by training and awareness to educate all Navy personnel about the importance of reducing energy usage.

Initiatives under both the *Arctic* and C*limate Change Roadmaps* and the Navy energy strategy will contribute to meeting the overall Navy objective of ready and capable in the 21st century.

Navy Science Needs

Significant improvements have been made over the past few decades in the collection, analysis, and interpretation of basic climate data (CNAS 2010). However, as evidenced in the *2007 IPCC Report*, considerable uncertainties still exist. The National Research Council notes that even as actions are taken to limit the magnitude of future climate change and adapt to its effects, it is imperative to make continued progress in observing all aspects of the climate system to understand climate system processes and to project future evolution of the climate system and interactions with other environmental and human systems (2010). The Navy has developed its own list of science and technology requirements that will enable it to increase its ability to assess the impacts of climate change on national security and the effects of adaptation and mitigation actions.

Model Resolution

Implementation of any plan is executed at the local level. Navy planners and decision-makers require knowledge of future changes on scales from hours to decades at spatial resolution on the order of meters. Therefore, the Navy needs corresponding climate projection and resolution.

Model Physics

There is a need to improve the understanding of the basic physics (including solar physics) associated with climate and the ability to model important variables (for example, temperature, aerosol content, precipitation, winds, sea ice, and sea level) at a full coupled, regional scale, including the complexities that arise from the interaction of global, regional, and local processes. This will yield a greater understanding of the phenomena that can cause the most stress for natural and human systems. For example, the feedback mechanisms and dynamics of polar ice sheets are poorly understood, yet their contribution to sea level rise is significant. Models for glacier melt, sea level rise, and other water systems require the same accuracy as regional climate modeling capabilities across the same decadal time scales. Models for extreme weather events should provide data for a given location on expected frequency, intensity, and duration of these events (tropical storms, tornados, severe rains, high winds, and such) to predict damage to valuable infrastructure and threats to human habitat. While the physics of carbon absorption into the ocean for ocean acidification are well modeled and verified, the impact on ecosystems and the marine food web is poorly understood. Improvement in our understanding of the biological impacts of ocean acidification are required to understand future climate change effects on coastal communities, nations, and their fisheries.

Quantifying Uncertainty

To properly assess risk, decision-makers require uncertainties in climate models (for temperature, precipitation, sea ice, and sea level) to be quantified and model outputs to be statistically realistic—with known confidence levels—across a decade of time. Model output should be available in probability distribution functions that can determine the risk for deviations from average values. Models should incorporate and be able to realistically represent sources of long- and short-term variation that are relevant for representing regional variability. Through quantification of uncertainty, decision-makers can begin to understand where these uncertainties arise and how that may affect future decisions and investments. By reducing scientific uncertainty in model resolution and physics, the nation will be able to make the most effective and efficient investments in climate change adaptation and mitigation methods and, thereby, reduce risks to national security.

Conclusion

The U.S. Navy is committed to understanding and preparing for a changing climate. With direction from the federal government and the Department of Defense, the Navy's Task Force Climate Change is implementing the Navy's *Arctic* and *Climate Change Roadmaps* to guide policy, strategy assessments, investments, and outreach to ensure that the Navy is ready and capable throughout the 21st century.

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Chapter 5. The Impact of Climate Change on the National Flood Insurance Program

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Abstract

An assessment of the likely impact of climate change on the National Flood Insurance Program was undertaken at the request of the U.S. Government Accountability Office (GAO). All major flooding sources were considered, both coastal and riverine. The coastal assessment discussed here included both changes in storm intensity and frequency and the additional contribution of sea level rise. Sea level rise was estimated for 13 coastal regions selected to exhibit an approximately uniform sea level rise character. Owing to the relatively moderate changes anticipated through 2100 for both storm frequency and storm intensity, sea level rise was found to be a major contributor to the potential growth of the coastal special flood hazard area, although that growth would be partly offset by a loss of flood plain area caused by shoreline erosion.

Introduction[1]

Background

In March 2007, the GAO released a report to the U.S. Senate Committee on Homeland Security and Governmental Affairs titled “Climate Change: Financial Risks to Federal and Private Insurers in Coming Decades are Potentially Significant.” The report recommended that the Federal Emergency Management Agency (FEMA) analyze the potential long-term implications of climate change on the National Flood Insurance Program (NFIP) and report its findings to Congress. The recommendation further stated that FEMA should use assessments from the U.S. Climate Change Science Program (U.S. CCSP) and the Intergovernmental Panel on Climate Change (IPCC) in conducting the analysis.

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[1] The views expressed in this paper are those of the authors and do not necessarily represent those of the Federal Emergency Management Agency.

The GAO recommendation addressed climate change in general terms, indicating that FEMA should perform a comprehensive analysis of potential changes in precipitation intensity and patterns, coastal storms, sea level rise, and other natural processes affecting both riverine and coastal flooding. This is in contrast with a 1991 study conducted by FEMA in which the agency investigated the NFIP implications of sea level rise but not other aspects of climate change.

The NFIP is administered by FEMA through its Federal Insurance and Mitigation Administration. The NFIP is an insurance, mapping, and land use management program that makes federally backed flood insurance available to home and business owners in communities that participate in NFIP. Currently there are more than 20,000 participating U.S. communities. Three interconnected activities are central to NFIP: (1) insurance—making flood insurance available to help individuals and small businesses recover following a flood; (2) floodplain management—minimizing the economic impact of flood events using a combination of mitigation efforts and community-adopted floodplain ordinances; and (3) floodplain analysis and mapping—identifying and mapping community areas that are subject to flooding (Pasterick 1998). These activities are supported by the production of flood insurance studies (FIS) and flood insurance rate maps (FIRM) based on engineering evaluations of the flood hazards in each community.

FIS provide the basis for determining flood hazard areas. In particular, they establish the elevation of the 1 percent annual chance flood, which is a flood that has a 1 percent chance of being equaled or exceeded during any given year. Since a 1 percent annual chance flood will occur on average every 100 years, it is sometimes referred to informally as the 100-year flood.

Surface water elevations of the 1 percent annual chance flood are called base flood elevations (BFE) and are referenced to either the National Geodetic Vertical Datum of 1929 (NGVD29) or the National American Vertical Datum of 1988 (NAVD88). FEMA intends to convert all flood maps from NGVD29 to NAVD88 within the next several years. Areas subject to 1 percent annual chance floodwaters are called special flood hazard areas (SFHA). The boundaries and lateral extent of SFHA and other flood zones are established when BFE are overlain on topographic data. This information is then used to produce FIRM. FIRM depict the ground extent of SFHA and other flood hazard boundaries, as well as associated BFE. FIRM are now produced using digital methods and are referred to as DFIRM (Crowell et al. 2007).

History

FEMA's Mitigation Directorate and its predecessor directorates have a long history of investigating and planning for certain aspects of climate change with respect to NFIP—specifically long-term coastal erosion and to a lesser extent sea level rise (although long-term coastal erosion is primarily a consequence of long-term sea level rise).

In addressing sea level rise, FEMA completed a congressionally mandated study in 1991 on the impact of sea level rise on NFIP (FEMA 1991). The study concluded that NFIP would not be significantly affected by a 1-ft. rise in sea levels by the year 2100 because "the aspects of flood insurance ratemaking already account for the possibility of increasing risk, and the tendency of new construction to be built more than 1 ft. above BFE." The study also concluded that given "[F] or the high projection of a 3-ft. rise, the incremental increase of the first foot would not be expected until the year 2050." Given this 60-year timeframe for the first foot of sea level rise, the study concluded that there would be "ample opportunity for the NFIP to consider alternative approaches to the loss control and insurance mechanisms of the NFIP and to implement those changes that are both effective and based on sound scientific evidence." Nonetheless, the study noted that because of uncertainties in projected sea level rise and the ability of the insurance rating system to easily respond to a 1-ft. rise, the possibility exists for significant sea level rise (SLR) impacts in the long-term, and therefore, FEMA should (1) continue to monitor progress in the scientific community about SLR and consider future studies that provide more detailed information on potential impacts of SLR on NFIP; (2) consider the formulation and implementation of measures that would reduce the impact of relative SLR along the Louisiana coast; and (3) strengthen efforts to monitor development trends and incentives of FEMA's Community Rating System (CRS) that encourage measures that mitigate the impacts of sea level rise.

As discussed in more detail later, the current climate change study discussed here uses more recent information and data than was available for the 1991 study, including the 2007 IPCC Fourth Assessment Report (AR4) reports and the Climate Change Science Program reports released between 2007 and 2009. Moreover, the current study also considers aspects of climate change beyond just sea level rise. In fact, all major factors affecting both coastal and riverine flooding throughout the nation were considered.

FEMA's efforts to deal with long-term coastal erosion, a consequence of long-term sea level rise, follow a long convoluted history. The National Flood Insurance Act (NFIA) of 1968, which was responsible for the creation of the National Flood Insurance Program, did not contain language on the peril of erosion. Five years later passage of the 1973 Flood Disaster Protection Act strengthened many of the regulatory aspects of NFIP, and it was with this act that damages caused by flood-related erosion were specifically made eligible for coverage under NFIP. Importantly, long-term, gradual, erosion was not considered in the 1973 act, and it was not until the 1988 Upton-Jones Amendment to NFIA that long-term erosion was considered under NFIP. Under Upton-Jones, flood insurance claims were payable for structures imminently threatened by coastal (and riverine) erosion prior to any damages actually occurring. Insureds could receive claims payments if their structures were located within what was termed the zone of imminent collapse. FEMA defined the zone of imminent collapse as the area located between an applicable shoreline erosion reference feature, such as a bluffline or eroding dune line and a landward distance equal to 5 times the erosion rate at the site plus 10 ft. Insureds could receive up to 110 percent of the value of the structure to demolish it or 40 percent of the value of the structure to relocate it landward of a 30- or 60-year (depending on the size of the structure) erosion-based setback line. The Upton-Jones program was considered to be a temporary program that would stay in place until a more comprehensive long-term, erosion-based program could be developed and initiated (Crowell et al. 1999).

In the late 1980s, FEMA commissioned the National Research Council (NRC) to examine the broader public policy and scientific issues for administering a coastal erosion program under NFIP (Buckley 1999). In 1990 NRC released a report (NRC 1990) titled ‘Managing Coastal Erosion,” which recommended that long-term erosion mapping and land-use management requirements should be incorporated into NFIP. The NRC report stimulated congressional interest in this issue, and in 1990 several bills were introduced in Congress that would have required FEMA to consider long-term coastal erosion through NFIP (Buckley 1999). Opposition by various interest groups led Congress to abandon the proposed bills, but ultimately, a compromise bill was formulated that directed FEMA to study the issue of long-term coastal erosion rather than mandate immediate change to the program. The compromise bill was inserted as Section 577 of the National Flood Insurance Reform Act (NFIRA) of 1994, and it required that the FEMA director submit a report to Congress that evaluated the economic impact of erosion and erosion mapping on coastal communities and NFIP (Crowell et al. 1999).[2]

In 1995 FEMA began the first phase of an erosion study to meet the requirements of the 1994 NFIRA, and it contracted with 18 coastal and Great Lakes states (or their designees) to conduct erosion hazard mapping for a total of 26 counties. In 1997 the H. John Heinz Center for Science, Economics and the Environment, initiated the second, economic/insurance phase of the study, (which utilized the erosion hazard mapping conducted during the first phase).

In 2000 the Heinz Center released its report, *Evaluation of Erosion Hazards* (H. John Heinz III Center 2000), which made two recommendations. The first was that Congress should instruct FEMA to map coastal erosion hazard areas. The second was that Congress should require FEMA to include the cost of expected losses from long-term coastal erosion when setting flood insurance rates. After the release of the Heinz Center report, FEMA formed an internal workgroup to determine what actions could be taken to implement the report’s recommendations under the laws and regulations governing NFIP. The workgroup concluded that because of the politically sensitive nature of the erosion issue, the implementation of either of the Heinz Center recommendations would require direct authorization from Congress (Crowell et al. 2007). To date, Congress has not acted on these recommendations. However, under existing regulatory and statutory authority, FEMA has increased insurance rates for policies in V Zones

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[2] NFIRA also terminated the Upton Jones program.

close to 10 percent (the maximum allowed by current statutory law) most years between 2001 and present. An important reason for this increase was recognition of the results obtained by the Heinz Center study (Crowell et al. 2007).

Since the release of the 2000 Heinz Center report, there have been sporadic attempts by elected officials or governing bodies to act on the recommendations made to Congress about long-term coastal erosion, but none of these attempts have been successful. In summary, because of the past highly charged political nature of the long-term erosion debate, FEMA believes that a Congressional mandate is required for the agency to map, manage, and ensure against long-term erosion through NFIP.

FEMA's Current Climate Change Adaptation Measures

Current measures taken by FEMA to adapt to climate change include actions related to its *Coastal Construction Manual* and to the NFIP's Community Rating System. These actions are explained below.

FEMA publishes a coastal construction manual (FEMA 2000) that documents state-of-the-art and best practices in coastal construction in accord with information and recommendations contained in several pertinent publications. These publications include the *International Residential Code*, the *International Building Code*, NFIP regulations and technical bulletins, and other relevant publications. The last major update to the *Coastal Construction Manual* was published in 2000. This version (as with previous versions) contained limited information about the direct effects of sea level rise on coastal construction design and siting. However, the update did include substantive information about the hazards of long-term coastal erosion (again, a specific consequence of sea level rise) and provided recommendations for coastal construction siting and design standards that reflect this long-term hazard. Currently FEMA's Mitigation Directorate is in the preliminary stages of substantially revising the manual. This revision will include a new section (or subsection) that addresses climate change. It is anticipated that this section/subsection will summarize current knowledge about the effects of climate change on our coastal regions and will make recommendations for coastal construction siting and design within the context of potential effects of climate change.

FEMA's Community Rating System, a component of NFIP, provides financial incentives for implementing practices beyond the minimum NFIP floodplain management standards. In this program, the CRS provides discounts on flood insurance premiums ranging from 5 to 45 percent, with the size of the discount determined by tallying credit points that are assigned to various community floodplain management activities. Currently, no CRS credits are specifically described as climate-change activities. There are, however, flood-protection activities, such as requiring additional freeboard or long-term coastal erosion-based setbacks that, while not described as specific to climate change, do mitigate aspects of sea level rise and concomitant long-term coastal erosion. Nevertheless, it is likely that the next revision of the CRS manual, which will probably be issued in 2011, will contain new climate change-specific language describing certain CRS activity credits.

Finally, it should be noted that FEMA is providing a $5 million congressionally earmarked grant to the State of North Carolina to conduct a sea level rise risk management study. The study will assess the long-term fiscal implications of climate change as it affects the frequency and impacts of natural disasters. Although the study focuses only on North Carolina, the results of this study will provide FEMA with additional findings and conclusions that should assist the agency in formulating climate change adaptation strategies.

Engineering Methods

Coastal Storm Methodology

Storm Frequency

The approach used in the coastal portions of the study was based on consideration of three primary factors: changes in storm frequency as influenced by climate change, associated changes in storm intensity, and projected sea level rise. Before beginning the discussion of sea level rise, which is of primary interest here, the storm aspects will be briefly reviewed.

The first key idea is that a change in storm frequency, λ, simply rescales the existing stage-frequency curves as established in prior coastal flood insurance studies. Using hurricane storm surge as an example, the rate of exceeding a surge level η, is given by

$$F(\eta) = \lambda \Pr\{\eta_x > \eta\} = \lambda \int \ldots \int_{x \in X} f_X(x) H(\eta_x > \eta)\, dx \tag{5-1}$$

where the integral on the right is over the probability densities *f(x)* of all of the several storm parameters, *x*, describing the hurricane, and *H* is a step function. The parameters include the central pressure depression, the radius to maximum winds, and others describing the storm track and certain characteristics of the wind and pressure fields. As seen from this expression, the storm frequency is a simple multiplicative factor, so that

$$F_2(\eta) = \frac{\lambda_2}{\lambda_1} F_1(\eta) \tag{5-2}$$

is the rate after a change in λ, holding all other parameters constant. This can be visualized as a change of the existing stage-frequency curve as shown in Figure 5-1.

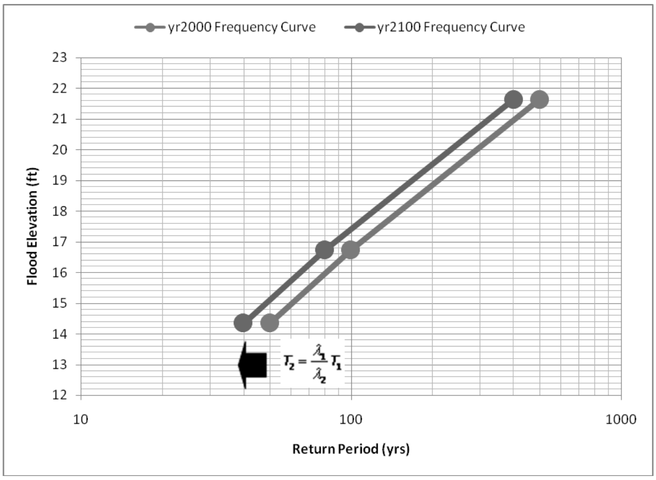

Figure 5-1. Illustration of rescaling an existing flood frequency curve (right) to account for a future change in storm frequency, λ. T is the recurrence interval equal to the reciprocal of the rate F.

Information about projected changes in storm frequency was obtained primarily from the recent comprehensive review by Knutson et al. (2010) and more specifically from Bender et al. (2010) for tropical storms and hurricanes, and from Lambert and Fyfe (2006) for extratropical storms. The projections used were based on three emissions scenarios commonly adopted for comparisons in the climate change literature—A2, A1B, and B1. In general, the projections through the year 2100 show a slight decrease of storm frequency for both tropical and extratropical storms, implying a lessening of coastal flood hazard from this source.

Storm Intensity

Projected changes in storm intensity were approximated in a similarly simple manner, where with hurricanes as the example, storm intensity is measured by the central pressure depression or deficit, ΔP. It is known that storm surge scales almost linearly with central pressure deficit, as shown in Figure 5-2, taken from the recent FEMA study of coastal Mississippi.

In view of this linearity, an expression for a change of surge amplitude analogous to the prior expression for a change of frequency is

$$\eta_2 = \eta_1 \frac{\Delta P_2}{\Delta P_1} \tag{5-3}$$

This permits an existing surge-frequency curve to be scaled by intensity as shown in Figure 5-3, all else held constant.

Projections of changes in storm intensity through 2100 were based on Bender et al. (2010) for tropical storms, and Bengtsson et al. (2009) for extratropical storms.

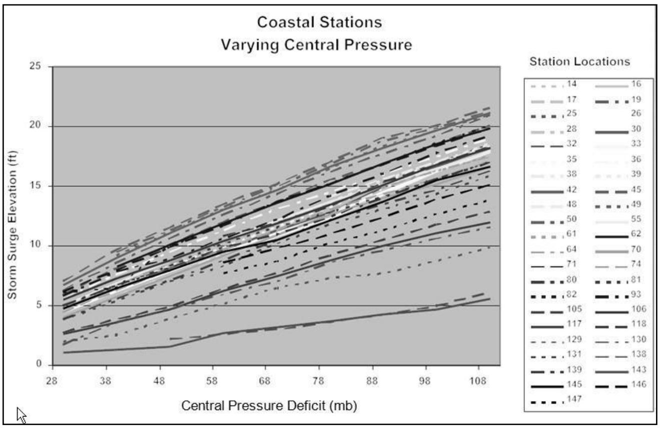

Figure 5-2. Illustration of the linearity of storm surge with central pressure depression of a tropical storm. Each line shows surge response vs. pressure deficit at a single point in the flooded zone.

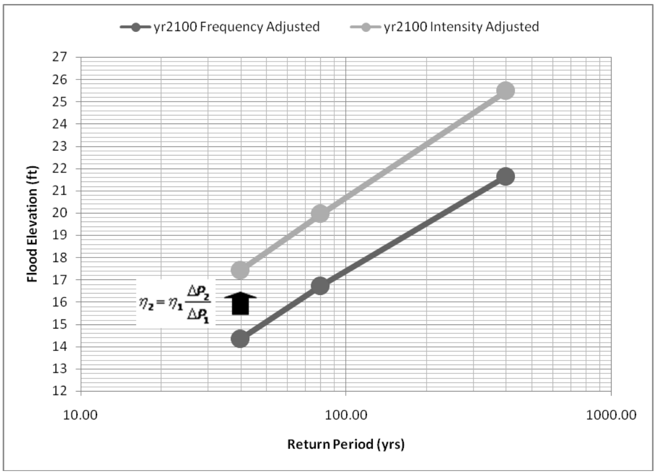

Figure 5-3. Illustration of rescaling an existing flood frequency curve (right) to account for a future change in storm intensity.

Again, the three basic emissions scenarios, A2, A1B, and B1 were adopted. A modest increase in storm intensity is forecast through 2100.

Sea Level Rise

Sea level rise was accounted for as a simple add-on to the flood levels. That is, coastal flood levels at a future epoch were assumed to increase by an amount equal to the projected change of sea level, in addition to any changes associated with storm frequency and intensity. As with the storm factors, the global sea level rise projections were based on climate change modeling using the same three basic emissions scenarios.

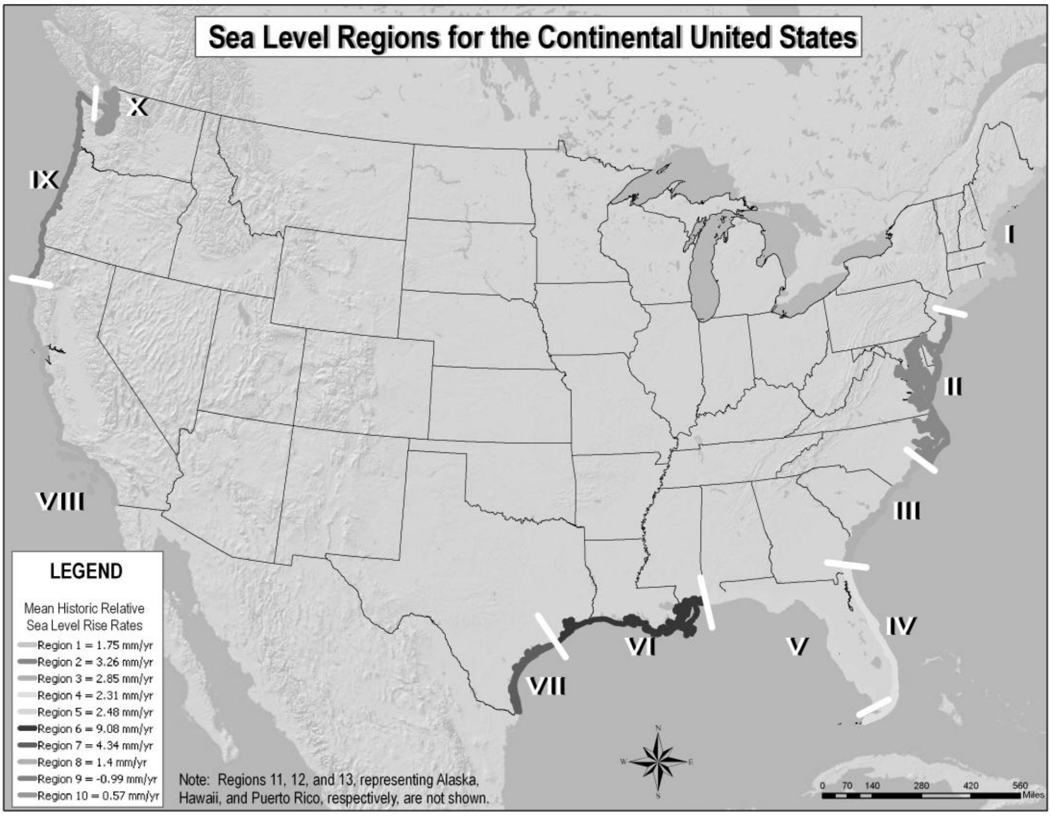

Figure 5-4. Sea level rise regions for the Atlantic, Pacific, and Gulf of Mexico coastlines.

Definition of Coastal Sea Level Rise Regions

As the study was national in scope, it was necessary to adopt a limited number of coastal regions in which local sea level rise could be considered relatively uniform. This was done by reviewing USGS and NOAA sea level rise data, especially the USGS Coastal Vulnerability Index information. Thirteen regions were identified. The 10 mainland regions are shown in Figure 5-4.

Regional, historical, relative SLR rates for each of the 13 SLR regions are shown in Table 5-1. Values were calculated using a regional average approach. Each of the 13 regions is reasonably homogeneous in rate of historical relative SLR. The USGS Coastal Vulnerability Index (CVI) identifies the reach of coastline from the Alabama–Mississippi border west to the southern extent of Brazoria County, Texas (Region 6), as an area where most relative SLR rates exceed 7.0 mm/year. The CVI also identifies the section of coastline from the Mattole River, Humboldt County, California, north to Crescent Bay, Clallam County, Washington (Region 9), as having relative SLR rates less than or equal to 0.0 mm/year (see comment in Table C-1). Uplifting isostatic changes currently exceed eustatic SLR in that area.

Table 5-1. Average Historical Relative SLR Rates for Each of the 13 SLR Regions Identified in this Study with the Range of Relative SLR Rates Extracted From Each Region

Region	Extent of Region	Average Relative SLR Rate (mm/yr)	Range of Relative SLR Rates (mm/yr)
1	New England	1.75	0.9 to 2.75
2	Mid-Atlantic extending from New York, NY, south to Bogue Banks, NC	3.26	2.45 to 4.1
3	Bogue Banks, NC south to the Glynn County/Camden County, SC border	2.85	2.45 to 3.15
4	Glynn County/Camden County, SC border south to the Florida Keys	2.31	2.15 to 2.45
5	Florida Keys to Alabama/Mississippi border	2.48	1.8 to 4.4
6	Alabama/Mississippi border west to the southern extent of Brazoria County, TX	9.08	4.49 to 10.9
7	Southern extent of Brazoria County, TX, to Mexico/U.S.-TX border	4.34	3.7 to 6.89
8	Mexico/U.S.-CA border north to the Mattole River, Humboldt County, CA	1.40	0.1 to 2.75
9	Mattole River, Humboldt County, CA north to Crescent Bay, Clallam County, WA	-0.99 ****	-1.9 to 0
10	Puget Sound east of Crescent Bay, Clallam County, WA to the Canada/ WA, U.S.-	0.57	0.05 to 0.9
11	Alaska	-9.93*	-12.69 to 2.76
12	Hawaii	1.92**	1.12 to 3.36
13	Puerto Rico	1.34***	1.24 to 1.43

*Average of NOAA SLR rates at Juneau and Anchorage.

**Average of NOAA SLR rates from Nawiliwili, Mokuoloe, Honolulu, Kahului, and Hilo.

***Average of NOAA SLR rates from San Juan and Magueyes Island.

****Observed sea level trends available from NOAA tide stations (www.tidesandcurrents.noaa.gov) show that there is substantial variability in historical sea level change rates throughout Region 9; averages do not represent all areas as well as in other regions.

Calculating a Range of Accelerated SLR Rates

The increase in sea level through 2100 is not expected to occur as a linear progression, but rather as a rate that is expected to accelerate through time. The following formula developed by the NRC Marine Board (1987) represents accelerated SLR:

$$E(t) = (0.0012 + (M/1000))t + bt^2 \tag{5-4}$$

where E is the total relative sea level rise (m) compared to 1990 sea level; t is years after 1990; M is vertical land movement (mm/year); and b is a coefficient whose value is chosen to satisfy the requirement that E equals the correct (pre-assigned) eustatic sea level rise value at some time t. Eustatic sea level rise is represented by *(0.0012)t* while isostatic changes (i.e., local vertical land movement) are represented by *(M/1000)t* in the equation. This equation has been used previously by FEMA to establish projections of future sea level rise (FEMA 1991). In that report, FEMA assessed the impact of sea level rise on future flooding assuming 0.30m and 0.91m rise scenarios by the year 2100. Since the1991 report was published, the observed global SLR rate for the period 1900–1999 has been revised to 1.7 mm/year (Bindoff et al. 2007). It might be noted that recent observations have shown the rate of change between 1993 and 2003 to have been 3.1 mm/year (Bindoff et al. 2007) and between 2003 and 2008, 2.5 mm/year (Cazenave et al. 2009). However, it is unclear whether these rates reflect decadal variability or are a long-term trend. Therefore, the equation used in the 1991 FEMA SLR study is revised to

$$E(t) = (0.0017 + (M/1000))t + bt^2 \tag{5-5}$$

to represent recent rates, allowing calculation of total relative sea level rise for each SLR region at any time t using the historical eustatic SLR rate of 1.7 mm/year. Estimated rates of vertical land movement (M) needed for each of the 13 SLR regions are shown in Table 5-2. These rates were determined by subtracting the historical rate of eustatic rise (1.7 mm/year) from the regional relative SLR rates shown in Table 5-1.

To evaluate the constant b in the foregoing equation, an end condition sea level rise magnitude (E) must be chosen for a specified number of years in the future, t. The IPCC AR4 estimates that future changes in global sea level will range between 0.18 and 0.59 m by the year 2100 (Bindoff et al. 2007). Observations indicate that SLR rates may approach the upper bounds of IPCC estimates due to potential increases in ice sheet melting (Vermeer and Rahmstorf 2009). The U.S. Global Change Research Program's Synthesis and Assessment Product 4.1 states that "thoughtful precaution suggests that a global SLR of 1 m to the year 2100 should be considered for future planning and policy decisions" (CCSP 2009). Using temperature increases estimated by the IPCC *Third Assessment Report* (TAR) (Rahmstorf et al. (2007) found that a eustatic rise of 0.5 to 1.4 m by 2100 is possible. Since those publications, Vermeer and Rahmstorf (2009) proposed an extension of the semi-empirical approach developed by

Table 5-2. Summary of Regional Vertical Land Movement Rates (M), mm/yr; Uplift Is Negative

Region	Relative SLR Rate (mm/yr)	Rate of Vertical Land Movement (mm/yr)
1	1.75	0.05
2	3.26	1.56
3	2.85	1.15
4	2.31	0.61
5	2.48	0.78
6	9.08	7.38
7	4.34	2.64
8	1.40	-0.30
9	-0.99	-2.69
10	0.57	-1.13
11	-9.93	-11.63
12	1.92	0.22
13	1.34	-0.36

Rahmstorf et al. (2007) by incorporating “instantaneous” sea level response (e.g., heat uptake of the mixed surface layer of the ocean). This produced a revised projected range in global sea level rise of 0.81 to 1.79 m (0.79 to 1.9 m including one standard deviation) for the period 1990 to 2100 (see Fig. 5-5 to 5-6 and Table 5-3). These most recent projections were used as the basis for the upper bound of eustatic SLR in this study. In addition, note that Pfeffer et al. (2008) found that global sea level rise of 2 m is possible under certain glaciological conditions and that other studies documenting even higher projections have been published.

Response of the SFHA

As the BFE rises or falls in response to climate change, the area subject to inundation by the 1 percent annual chance flood will increase or decrease in a manner determined by local terrain. A simple assumption was adopted in this study, that the overland flood profile approximates a triangular wedge over some mean slope and that the slope does not change substantially for moderate changes of BFE. Then the proportional change of the SFHA will approximately equal the relative change of the BFE, preserving similarity between the pre- and post-change flood wedges. This assumption is not altered by the wave crest component of the BFE because to first order the wave contribution at the coast is a fixed fraction of the available water depth (under the assumption of depth limited breaking) and grows in proportion to changes caused by storm and sea level processes. Figure 5-5 shows a schematic sketch of this assumption.

The Influence of Erosion

A critical limiting assumption was made in the FEMA 1991 sea level rise study. In that study, it was noted that shoreline recession from erosion, expected to

Table 5-3. Summary of Eustatic SLR Projections Above 1990 Levels

Emissions Scenario	IPCC AR4 Projected SLR Ranges at 2100 (m)	Vermeer and Rahmstorf (2009) Projected SLR Ranges at 2100 (m)*	Vermeer and Rahmstorf (2009) Projected SLR Means at 2100 (m)*
B1	0.18 to 0.38	0.81 to 1.31	1.04
A1T	0.2 to 0.45	0.97 to 1.58	1.24
B2	0.2 to 0.43	0.89 to 1.45	1.14
A1B	0.21 to 0.48	0.97 to 1.56	1.24
A2	0.23 to 0.5	0.98 to 1.55	1.24
A1FI	0.26 to 0.59	1.13 to 1.79	1.43

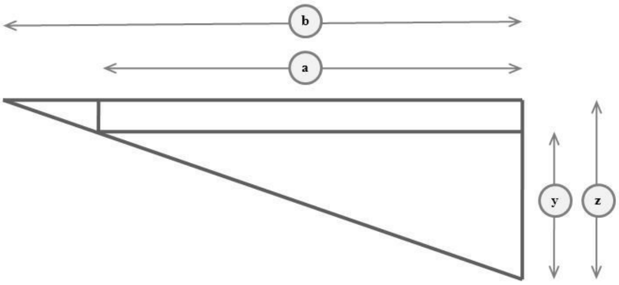

Figure 5-5. The idealized coastal flood plain grows from width a to width *b* as the flood level at the coast rises from *y* to *z* in response to climate change. The relative changes are taken to be equal by similarity.

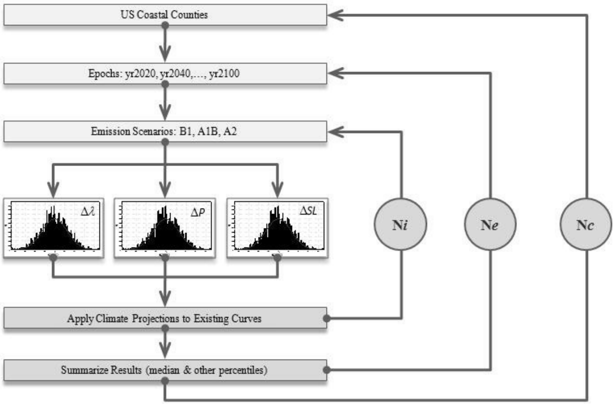

Figure 5-6. Monte Carlo scheme to assess flood response to changes in storm frequency, storm intensity, and sea level rise, represented by draws from the indicated distributions

reduce the size of the SFHA, approximately equaled its landward expansion caused by the increase in sea level. Consequently, while there would be movement in the location of the SFHA, little net change in its size was anticipated. The opposite assumption is that a shoreline would remain fixed through measures such as beach nourishment, shoreline hardening, sandbagging, and such. Both extremes were evaluated as part of this study by simply including or neglecting sea level rise as part of the Monte Carlo simulation discussed in the following section. Without sea level rise, all projected changes in the SFHA are due to storm effects, equivalent to the 1991 assumption that, being offset by erosion, sea level rise has minimal effect on the net change in SFHA. Consequently, skipping SLR within the Monte Carlo loop can similarly be thought of as equivalent to including SLR plus with the offsetting effect of erosion. Additionally, calculations have been made using results from the 2000 Heinz Center study and historic data contained in the USGS CVI to estimate the contributions of direct erosion damage to overall dollar losses to the National Flood Insurance Program through 2100

Monte Carlo Simulations

With the foregoing assumptions for storm frequency, storm intensity, and sea level rise, a Monte Carlo scheme was used to estimate changes in flood response. The procedure is illustrated in Figure 5-6.

It was assumed that the three emissions scenarios are equally likely and, as noted, simulations were performed both with and without SLR as a simple way to estimate the maximum effect of erosion.

Findings and Economic Analysis

Figures 5-7 through 5-12 show percentage estimated changes of the coastal Special Flood Hazard Area at 2100 using median values. These maps include the contribution of sea level rise and so represent an upper bound on the change, with the assumption that present shorelines remain fixed over time. This is a reasonable assumption in many areas and may be more likely in heavily developed areas reluctant to retreat in the face of rising sea level.

It was found that the simulations without sea level rise resulted in significantly lower SFHA increases. The influence of storms is only moderate owing to projections of a slight decrease of overall storm frequency, combined with a slight increase of intensities.

As a final aspect of the work, demographic and economic analyses were performed to assess the impact of these changes on the NFIP. Changes in SFHA, for example, were assumed to imply similar changes in affected population, structures, and policies. Riverine areas were studied in tandem so that the study concluded with an evaluation accounting for all major flood processes.

Acknowledgements

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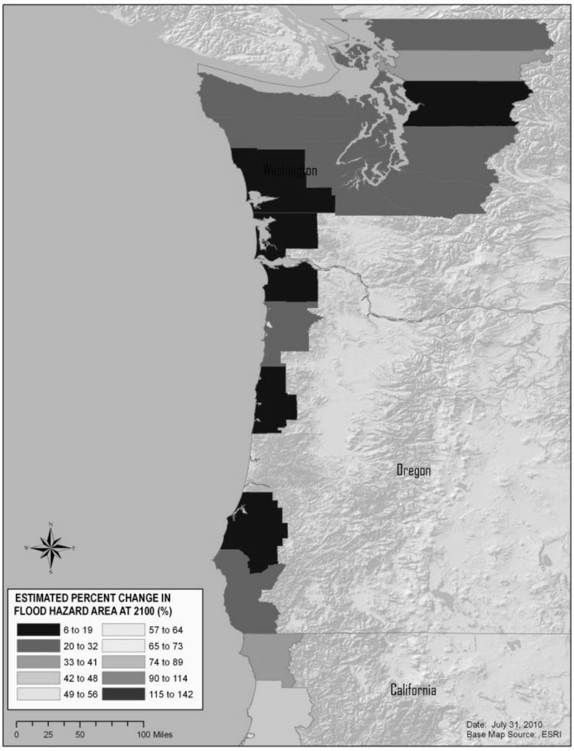

Figure 5-7. Percent change in the coastal SFHA by 2100 for the Pacific Northwest (Base maps courtesy of ESRI)

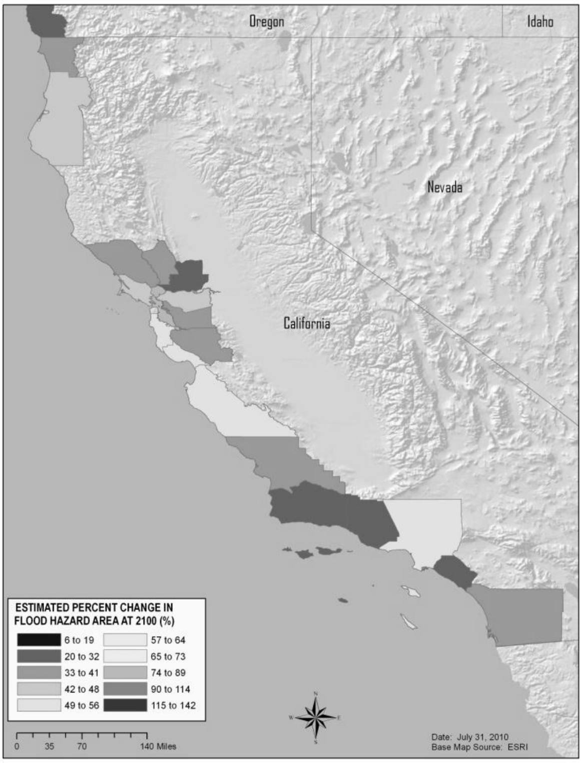

Figure 5-8. Percent change in the coastal SFHA by 2100 for the Pacific Southwest (Base maps courtesy of ESRI)

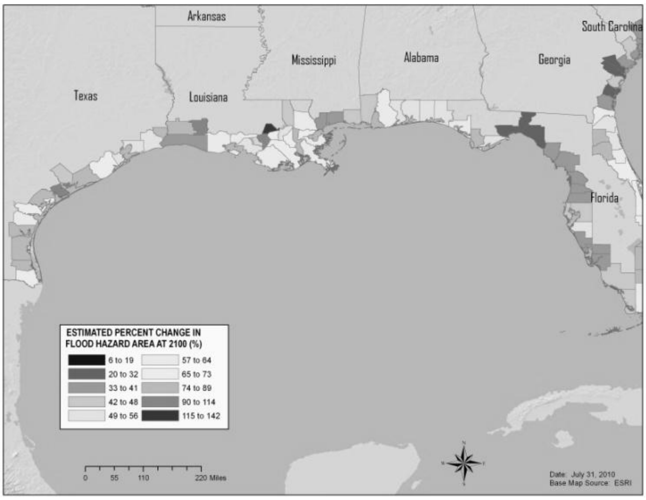

Figure 5-9. Percent change in the coastal SFHA by 2100 for the Gulf of Mexico (Base maps courtesy of ESRI)

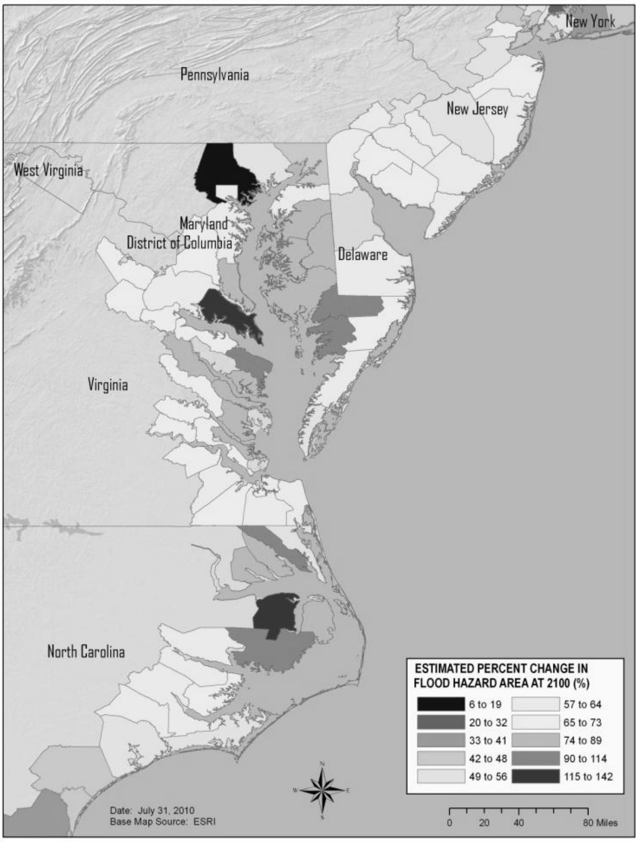

Figure 5-10. Percent change in the coastal SFHA by 2100 for the Southeast (Base maps courtesy of ESRI)

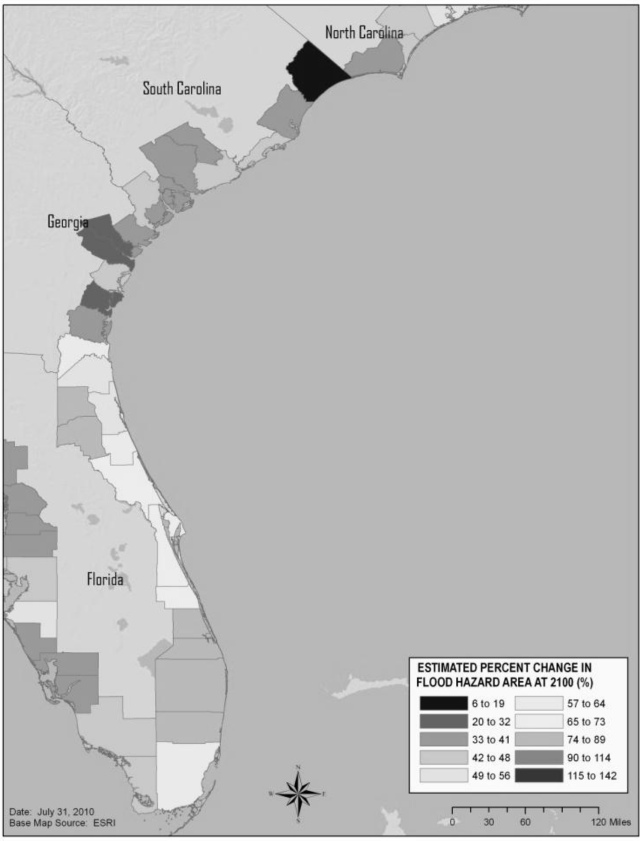

Figure 5-11. Percent change in the coastal SFHA by 2100 for the Mid-Atlantic (Base maps courtesy of ESRI)

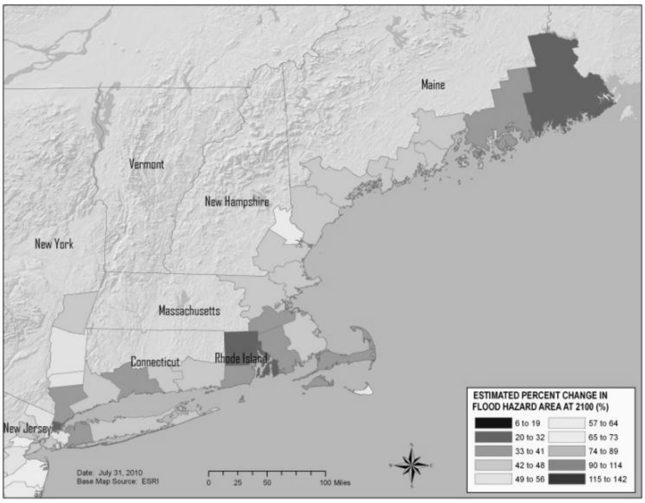

Figure 5-12. Percent change in the coastal SFHA by 2100 for New England (Base maps courtesy of ESRI)

Chapter 6. A "Toolkit" For Sea Level Rise Adaptation in Virginia

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Abstract

Virginia has the highest rates of relative sea level rise recorded on the east coast of the United States. The southeastern region of Virginia has significant economic and strategic activities at risk from current and projected rates of relative sea level rise, increasing the urgency for Virginia to begin sea level rise adaptation planning and implementation. Individual land use decisions will define our tidal shoreline, and influencing and controlling these decisions is central to any sea level rise adaptation strategy. Land use decisions are the domain of local governments, and as awareness of sea level rise and inundation threats grows in Virginia, local governments need a set of tools to develop and implement sea level rise adaptation strategies. A review of currently available planning and regulatory tools shows that localities in Virginia have sufficient authorities to begin adaptation work today, with the potential for more effective approaches in the future if regulatory and legislative changes are made to existing authorities.

Sea Level Rise Impacts in Virginia

Virginia has the highest rate of measured sea level rise over the last 100 years of any state on the East Coast, with the Sewells Point tide gauge in Norfolk recording a centennial rate of .44 m (1.45 ft.) (NOAA Tide Gauges, U.S. Climate Change Program 2009). The rate of sea level rise in the southern Chesapeake Bay is expected to increase in the coming century, increasing from its historic .44 m to a minimum of .7 m (2.3 ft.) per 100 years (Pyke et al. 2008, Virginia Commission 2008, Najjar et al. 2000). Rates could go higher: conservative projections of future rates of sea level rise run from the minimum of .7 m (2.3 ft.) to as much as 1.58 m (5.2 ft.) in the coming century (Pyke et al. 2008, Virginia Commission 2008).

Specific estimates of inundation impacts from projected rates of sea level rise have not been produced, due in part to the lack of high-resolution, comprehensive digital elevation maps for most of Virginia's coastal plain. One study using available elevation data estimates a relative sea level rise of 60 cm/100 years would inundate 1700 km^2 of land in Virginia and Maryland, about half of which is wetlands (Wu et al. 2009). Virginia's ocean shoreline is projected to retreat 1.3 km over this period absent shoreline hardening (Wu et al. 2009). These are simple inundation projections and do not include storm surge inundation nor the regular inundation during spring tides (high tides occurring on the full or new moon).

Impacts on Natural Systems

Increased inundation from higher rates of sea level rise threatens both natural and human systems alike. Higher tidal water levels pose significant potential impacts to the coastal ecosystem, including loss of primary coastal dunes to erosion, loss of existing submerged aquatic vegetation (due to increased water depth, possible decreases in water clarity due to algal blooms and sediments, and increases in water temperature), and inundation of vegetated wetlands in the intertidal zone (Pyke et al. 2008).

Tidal wetlands can accrete vertically and have kept pace with past rates of sea level rise. Changes in sediment budgets, wetlands health, and accelerating rates of sea level rise can overpower the ability of wetlands to accrete vertically, however. Vegetated tidal wetland accretion rates, currently in the range of 3 mm/year in the Chesapeake Bay (Stevenson et al. 1996) will probably not be sufficient to keep pace with the minimum predicted rate of relative sea level rise of around 6 mm/year.

As the intertidal zone moves landward with sea level rise, the coastal ecosystem in that zone will move with it. When this shoreward movement encounters steep slopes, high banks, or hardened shoreline infrastructure, the wetlands will “drown” in place, unable to stay in the intertidal zone as that zone moves (Titus, et al. 1991).

In 2007 Wetlands Watch estimated that Virginia would lose 50 to 80 percent of its tidal wetlands due to the then-expected 60 cm of sea level rise over the next century (Wetlands Watch 2007). The range of those estimates was confirmed by two subsequent studies (National Wildlife Federation 2008, U.S. Climate Change Science Program 2009).

Economic Importance of Natural Systems

The direct economic impact of the loss of these wetlands is hard to evaluate, although some rough values can be placed on the upper bounds of the wetlands dependant fishery in Virginia. The vast majority of finfish and shellfish are dependent on wetlands (Feierabend and Zelazny 1987). Thus a loss of tidal wetlands threatens Virginia’s commercial fishery, valued at $108 million annually (VMRC 2008) and its recreational saltwater fishery valued annually at $820 million in sales and $480 million in services, providing more than 9,000 jobs (Virginia Department of Conservation and Recreation 2007).

Impacts on Built Environment and Regional Economy in Southeast Virginia

High rates of sea level rise in the southern Chesapeake Bay region cause the Virginia Beach-Norfolk-Newport News VA-NC municipal statistical area (MSA) with 1.6 million people to stand out as the largest population center at greatest risk from sea level rise outside of New Orleans (Wetlands Watch 2007). This MSA is ranked 10th in the world for value of assets at risk from sea level rise in the region (Nicholls et al. 2008)

Hampton Roads was ranked eighth in the United States in 2009 for the value of shipping through the port with a $46.5 billion in imports and exports (South Carolina State Ports Authority 2010). The ship construction and repair sector in Hampton Roads provided more than 20,000 jobs and $5.2 billion in output in 2002 (Hampton Roads Planning District Commission 2004). Numerous other shoreline industrial sectors are an important part of the economy of southeastern Virginia and, located only a few feet above mean sea level, all are all at risk from sea level rise and storm surge inundations, as is their contribution to the regional economy.

Sea level rise threatens major government facilities along the tidal shoreline in Virginia. The military services have a number of facilities in southeastern Virginia, including the largest navy base in the world at Naval Station Norfolk. Other facilities such as Langley Air Force Base, Fort Eustis, Dam Neck Annex, and Joint Expeditionary Base Little Creek–Fort Story are also located along the shoreline in low-lying areas vulnerable to inundation. Two National Aeronautics and Space Agency (NASA) facilities, one at Langley and one at Wallops Island, are also along the tidal shoreline in eastern Virginia, and both low-lying facilities are experiencing flooding and erosion problems.

The Department of Defense (DoD) spending in southeastern Virginia was $18.86 billion in 2009, and the direct and indirect economic activity from the military services in the region accounts for roughly 45 percent of the MSA’s gross economic activity (Regional Studies Institute 2009). If sea level rise and inundation threaten the operational readiness of military bases in the region, this economic activity is also threatened.

The DoD has made adaptation to sea level rise a priority as pointed out in the latest Quadrennial Defense Review:

> “Although the United States has significant capacity to adapt to climate change, it will pose challenges for civil society and DoD alike, particularly in light of the nation’s extensive coastal infrastructure. In 2008, the National Intelligence Council judged that more than 30 U.S. military installations were already facing elevated levels of risk from rising sea levels. DoD’s operational readiness hinges on continued access to land, air, and sea training and test space. Consequently, the Department must complete a comprehensive assessment of all installations to assess the potential impacts of climate change on its missions and adapt as required.” (U.S. Department of Defense 2010)

Naval Station Norfolk has 14 World War II-era (and older) piers that experience significant maintenance problems due to the sea level rise that has occurred since they were built. These piers are being replaced at a cost of $35 to $40 million a pier, an indication of the cost of sea level rise adaptation to the military (Navy Facilities Command 2001). This activity is also an indication of the impact on critical infrastructure of the high rates of sea level rise in southeastern Virginia.

The economy of the southeastern region of Virginia benefits from tourism, focused mainly on the oceanfront at Virginia Beach. Economic estimates place the direct value of tourism in Virginia Beach at $864 million in 2008, generating 13,600 jobs (Yochum and Agarwal 2008). Given that with sea level rise, beach recession will accelerate, by some estimates moving the shoreline 1.3 km inland (Wu et.al. 2009), the related beachfront tourism economic sector is at great risk. This recession threatens billions of dollars of oceanfront investments focused on the tourism economy, a major factor in the MSA global ranking for assets at risk from sea level rise, previously mentioned.

Sea level rise is already creating significant flooding problems in older shoreline communities in southeastern Virginia, causing millions of dollars to be spent in adaptation efforts. For example in 2007, Hampton, Virginia, approved a $3 million sand restoration project to protect against storm surges, a project that was recognized by the technical advisors to provide little to no help in the face of sea level rise (Lynch 2007).

Sea Level Rise and Storm Surge Inundation

Sea level rise impacts will not occur gradually like a bathtub filling up. The effects will be felt with each storm surge that runs on top of higher sea levels, pushing water farther and farther inland each time. This effect will be more pronounced in older, established neighborhoods with businesses built in reference to earlier sea levels, flood zones, and shorelines and in areas built upon filled wetlands that are now subsiding. The periodic and more frequent inundation of older neighborhoods built on marsh fill can be observed today in the older cities of southeastern Virginia, such as Norfolk, Portsmouth, Hampton, and Newport News.

It is important to view sea level rise with the addition of storm surge events. Table 6-1 illustrates the effects of storm surge events on top of sea level rise, listing the highest inundations measured since 1927 at the tide gauge at Sewells Point (Norfolk, VA). The table presents historic storm surge data from NOAA records adjusted to current sea level and then measured in reference to today's mean higher high water (MHHW) level. MHHW is the long-term average high tide line from the spring tides that occur twice a lunar cycle.

The intent of these adjustments is to establish a rough storm surge inundation level reference point starting at today's MHHW line. This reference line assumes that anything above that line is not regularly inundated and thus represents dry land normally available for productive use that will be disrupted by storm surges and sea level rise. Given that today's waterfront homes, shoreline businesses, military facilities, and coastal infrastructure will likely remain in their current locations in coming decades and given that most are above today's MHHW, using this reference point is useful in evaluating effects on the current built environment.

This list of major storm surge events includes recent storms that, had they occurred 100 years ago with the sea level some 1.45 ft. lower, would not have inundated as much of today's dry land. The two nor'easters in 2006 illustrate this. Had they come in 1906, they would not be on this list because they would not have flooded as far above today's MHHW line as they did in 2006.

Looking into the future, similar storms in 100 years would reach inundation levels approaching the "storms of record" for the region, assuming the minimum predicted rate of 2.3 ft. of centennial sea level rise. For example, in 100 years the 2009 Veterans Day nor'easter, with the minimum projected 2.3 ft. of sea level rise, would reach to more than 7 ft. above today's MHHW, flooding more of today's dry land than the worst recorded modern storm, the 1933 hurricane.

Over time with sea level rise, storm surge flooding events on today's dry land will become more frequent. Table 6-2 uses a notional scenario to determine the statistical frequency of different flood events with different sea levels. Using this table, a 7-foot storm surge (above mean sea level in this case) could be expected every 26.83 years on average over history, but with the 1.45 ft. of sea level rise at Sewells Point, that storm surge would now occur every 7.32 years on average. With sea level increases at the minimum discussed (~+2.3 ft. over 100 years), this 7-ft. storm surge will occur every 1.71 years on average. For shoreline residents and businesses, the projected increase in inundation event frequency and magnitude is troubling and adds to the urgency to start sea level rise/storm surge inundation planning and adaptation.

Implications for Adaptation Planning and Implementation

The addition of storm surge levels to simple sea level rise inundation in tidal areas presents a number of challenges and opportunities for adaptation planning and implementation.

On one hand, it increases the levels of inundation, which planning needs to address, from a gradual simple centennial rate of 2.3 ft. minimum to a wide range of higher and more frequent storm surge inundation. Adding storm surge inundation on top of sea level rise increases the cost of adaptation measures. Having to address periodic storm surge inundation versus permanent flooding from sea level rise will take different adaptation approaches, further complicating adaptation planning and adding cost.

On the other hand, the inclusion of storm surge inundation in adaptation planning has an ironic beneficial effect by bringing the impacts from inundation closer to the present. As storm surge events are factored into sea level rise estimates, the impacts can be better quantified, as in Tables 6-1 and 6-2, making the case that adaptation planning needs to start sooner. This heightened awareness of future inundation risks can be a significant factor in helping overcome some of the barriers to early adaptation strategies discussed in the next section.

The inclusion of storm surge variability in adaptation planning also helps prepare the local, state, and federal policy process for the uncertainties inherent in planning for sea level rise. Policymakers cannot simply sit and wait for a single inundation number to be produced by the science and engineering community; including storm surge information illustrates the need for flexibility and the need to use adaptive management in the public policy process.

Role of Local Government in Adaptation Planning

With the vast majority of Virginia's shoreline in private ownership,[2] the aggregation of individual land use and shoreline hardening decisions will play a major part in adapting to increased flooding from sea level rise (Titus et.al. 2009). Local governments control land use decisions through zoning ordinances, building codes, and the like, and through placement of public and private infrastructure (roads, schools, hospitals, fire stations, utility services, etc.). Local governments are also responsible for implementing a range of state and federal programs that involve planning, placement of infrastructure, and disposition of federal program funding. Thus, an effective sea level rise adaptation strategy needs to be heavily focused on local governments where these critical decisions are made.

Local land use and infrastructure decisions that ignore or defy climate change realities will complicate and make future adaptation strategies more expensive. They may also expose infrastructure to economic loss and human populations to higher personal risk. Unfortunately, local government shoreline development and infrastructure decisions are made one by one, with little regard for cumulative impact in the present and no regard for future consequences from climate change impacts. These decisions can have long-lived consequences, as the useful life of buildings, transportation segments, shoreline infrastructure, utilities, and the like persist well into the future. In tidal communities experiencing flooding today, we can observe how similar decisions made over past decades compound today's adaptation challenges.

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[2] Many federal and Virginia state documents state that 85 percent of the shoreline of the Chesapeake Bay is privately owned, although no peer-reviewed documentation for that claim can be found. The private ownership percentage of ocean shoreline in Virginia has not been estimated.

Table 6-1. Storm Surge Measured at Sewells Point (Norfolk) Tide Gauge*

Date	Storm	Ft. Above MHHW
August 23, 1933	Hurricane	6.27 ft
September 18, 2003	Hurricane Isabel	5.12 ft
March 7, 1962	Ash Wednesday Storm	5.05 ft
November 12, 2009	Veterans Day nor'easter	4.99 ft
September 18, 1936	Hurricane	4.92 ft
September 16, 1933	Hurricane	4.36 ft
November 22, 2006	Thanksgiving nor'easter	3.96 ft
October 6, 2006	Columbus Day nor'easter	3.76 ft
January 28, 1998	Twin nor'easters (#1)	3.26 ft
September 16, 1999	Hurricane Floyd	3.21 ft
February 5, 1998	Twin nor'easters (#2)	3.12 ft

*The conversion of surge data in reference to today's MHHW was done by Wetlands Watch.

Table 6-2. Notional Frequency of Storm Surges with Sea Level Rise*

Average Number of Years Between Inundation Events					
Event Severity		**Sea Level Rise Change (ft)**			
Flood Stage	**Gauge Level (ft)**	**Historical**	**Present**	**+2'**	**+3'**
Flood	5.00	1.71 yrs	0.33 Yrs	0.10 yrs	0.08 yrs
Moderate	6.00	7.32 yrs	1.71 yrs	0.33 yrs	0.10 yrs
Major	7.00	26.83 yrs	7.32 yrs	1.71 yrs	0.33 yrs
Record	8.02	80.50 yrs	26.83 yrs	7.32 yrs	1.71 yrs

*Table 6-2 is based on unpublished data developed by Northrop Grumman Corporation. "Gauge Level" is measured from mean low water. "Historical" occurrence is average of events from 1927 to 2009. POC: g.featheringham@ngc.com

Many legal and financial disincentives complicate the process of getting individual landowners and local governments to start sea level adaptation work today. Most of these adaptation measures depend on changes to current shoreline land use expectations that limit development and redevelopment options. Local governments are reluctant to place conditions on the development and redevelopment of private shoreline land today and forego the increased property tax revenues that may come from the higher uses of these shoreline properties, frequently the highest value segment of a locality's property tax base. Similarly, private landowners are resistant to restrict their development and redevelopment options to adapt to future sea level rise impacts without fair compensation for the loss of expected return from an unrestricted land use.

The asymmetry of asking localities and individuals to forego present economic gain based upon a potential sea level rise impact coming decades in the future is the main factor hindering adaptation strategy development today. This resistance can even hinder detailed local government planning efforts as these plans begin to identify individual parcels of land that will be at risk from inundation, diminishing their market value. Finding ways to overcome the conflict between current economic incentives and long-range sea level rise adaptation needs is a major challenge to be overcome if we are to start adaptation planning and implementation today.

Focus of Local Government Adaptation Strategy for Sea Level Rise/Storm Surge Protection

Sea level rise adaptation at the local level will have different goals in rural areas than in built-out areas. In rural and undeveloped areas, local government policies should be directed at keeping new development, significant redevelopment, and public facilities and infrastructure out of tidally influenced areas at increasing risk from sea level rise. For built-out areas, with significant infrastructure already placed along the shoreline, policies might involve strategic redirection of redevelopment away from low-lying neighborhoods, elevation and armoring of existing critical infrastructure and neighborhoods, and identification of high-risk neighborhoods for which cessation of public services and disinvestment may become a reality.

In concept, a local government strategy on adaptation to sea level rise and storm surges would first involve collecting data on current inundation and then add modeling future relative sea level rise impacts (including areas of local subsidence where the impacts of sea level rise will be felt more severely). This work should result in identification of zones of high inundation risk where future damage from storm surges can be expected to increase.

Adaptation plans can then be developed to cope with some early risks, and financial incentives, carefully planned infrastructure investment, and even regulatory programs can be focused on zones where risks will become more severe over time to minimize exposure of population and infrastructure to higher inundation risks. In very high-risk zones, the creation of special districts with restrictive tax, investment, and zoning ordinances may be needed to begin orderly disinvestment over time.

Elements of Local Government Adaptation Strategy for Sea Level Rise/Storm Surge Protection

The first requirement for local government involvement in adaptation to sea level rise is public support and awareness. The next steps require localities to acquire the technical, financial, and legal tools to begin climate change adaptation planning and implementation.

Public and political awareness and support for addressing climate change impacts can be generated through outreach, education, and social marketing. In Southeastern

Virginia this work has been made easier following a strong nor'easter that caused extensive flooding during November 12 and 13, 2009, with a peak storm surge nearly 5 ft. above MHHW. With this nor'easter, there have been public calls for a response to what is seen as a pattern of more severe storm surges.

Second, the technical resources need to be sufficient to focus and prioritize local government efforts. These resources include elements like high-resolution digital maps, geographic information system (GIS) data that can place critical infrastructure on those maps, modeling and visualization of zones of increasing risk with sea level rise and storm surges, population and census data overlays to identify high-risk portions populations, downscaled climate change impacts, and so on. This information can be fed into a number of local government processes outlined in the next section.

Third, there must be sufficient financial resources available to meet the adaptation needs identified. Resources will be needed to armor, elevate, and relocate existing infrastructure and property. Direct funding and tax credits will be required to purchase property and secure development rights and easements on private property in inundation zones for which compensation will be required. Based on some early projects to protect the shoreline, adaptation in built-out areas can be a very expensive undertaking (Lynch 2007).

Finally, localities (along with regional, state, and federal government partners) must have programs available to conduct adaptation planning and must have the regulatory authority to place conditions on land use options to avoid a continuation of "business as usual." Local government authorities are critical, but they must involve federal and state government guidance and assistance, without which they are left on their own to struggle with the impacts from sea level rise and to implement adaptation strategies in isolation, if at all (Wetlands Watch Testimony 2009, GAO 2009).

The Virginia Climate Change Commission report proposes a set of actions needed to start adaptation efforts in Virginia. It also outlines a framework for a coordinated state strategy on climate change adaptation that would support local efforts (Wetlands Watch Summary 2009).

Local Government Adaptation Program "Toolkit"

The last element of an adaptation strategy, adequate local government legal and program authorities, is a challenge in Virginia. Virginia localities operate under the Dillon Rule and are only able to exercise specific authority granted to them by the state legislature, a provision in the Virginia Constitution at Article VII, Section 2. This limits the ability of localities in Virginia to address sea level rise without specific authority granted by the Virginia General Assembly. As a result, even if a local government in Virginia has secured the public and political will to develop an adaptation strategy for sea level rise and storm surges and possesses the technical and financial resources, a major remaining hurdle is identifying government and private programs to accomplish this adaptation work.

These programs do exist, and examples of adaptation planning are starting to emerge in Virginia. In three years of work with local governments in Virginia, Wetlands Watch has identified a set of legal authorities, programs, and government directives that may be available today for use by Virginia's local governments to formulate adaptation strategies. This work has also resulted in a list of potential programs that, with new interpretations or some regulatory adjustments, can be used by local governments in adaptation strategies.

This draft set of programs was assembled into a "toolkit" and presented to a group of coastal planners at the May 4, 2010 meeting of the Virginia Chapter of the American Planning Association. The toolkit, which is still being refined, started with an organizational approach that grouped adaptation program needs for local government into three basic functional categories:

- Planning—programs that can create awareness of and prepare for climate change impacts;
- Incentives and Direct Investment/Public Infrastructure—programs that help provide financial incentives to change behavior and programs that build public facilities so that fewer people, buildings, and natural resources are at risk from climate change; and
- Regulatory—programs that decrease the risk from climate change impacts by preventing or redirecting certain land use decisions.

These program initiatives were then placed along a political gradient from lowest political difficulty (planning) to intermediate difficulty (incentives, direct investment) to highest difficulty (regulation). In Virginia today, many localities mention climate change and sea level rise impacts in their planning documents. No Virginia locality has undertaken investment/infrastructure or regulatory measures (land use restrictions, and such) to address adaptation needs. As mentioned earlier, the asymmetric nature of this issue creates political and financial disincentives for action that are strong and difficult to overcome.

Adaptation Program Toolkit Categories

Planning

Local government planning programs, especially longer-range planning programs (planning horizons exceeding 20 years) are useful tools for raising public awareness of sea level rise impacts and for beginning to direct public and private activities away from areas of increasing inundation risk. These government programs encourage rational, comprehensive, long-range planning to help inform future government and private-sector decisions and are processes that should include climate change impacts. In fact, some of this long-range planning work in the tidal regions of

Virginia already includes sea level rise in planning documents, such as state and regional transportation plans, regional economic development plans, regional hazard mitigation and floodplain management plans, and local government comprehensive land use plans. This recent activity demonstrates growing local and regional government awareness and acceptance of the growing threat that sea level rise and storm surge inundation poses.

Incentives/Disincentives

Federal, state, and local government programs along with private-sector programs provide incentives to encourage certain behavior (or disincentives to discourage other behavior) that can include sea level rise adaptation measures. Examples of public incentive programs include tax credits for donation of land development rights (which can include land threatened with inundation), state and local tax incentives for private investments made in a certain way or in certain locations (outside of high-risk inundation zones), and so on.

In addition to encouraging desired behavior through incentives, governments and private-sector efforts can focus on disincentives for increasingly risky investments along the shoreline. Disincentives include federal flood insurance, which increasingly includes sea level rise risk in pricing and availability decisions, and local government special taxing districts, which cover the real, life-cycle costs of servicing high-risk zones (higher taxes in high-risk inundation zones). Private-sector incentive/ disincentive programs include higher private-sector insurance rates and limited availability in high-risk zones[2] as well as financing decisions that include increasing risk of inundation, such as the inundation probabilities outlined in Table 6-2.

Direct Investment and Public Infrastructure

Government programs that directly fund public buildings, bridges, roads, and other public structures should keep that infrastructure out of harm's way, away from coming sea level rise impacts. Once the planning process identifies high-risk inundation zones, public infrastructure should be directed away from those zones. Hospitals, evacuation refuge sites, fire and emergency rescue facilities, key transportation routes and facilities, and other infrastructure need to be outside of projected inundation zones. This demands that as direct investment in public infrastructure is made using state school construction funds, state capital

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[2] Press reports and interviews with private insurers by the author show a withdrawal of at least 50 percent of the private insurance market from writing new policies for wind insurance on primary residences and businesses along Virginia's Chesapeake Bay and Atlantic Ocean shorelines. Wind insurance for second residences is being withdrawn by an even larger percentage of private insurers. Hurricane damage claim deductibles have recently increased on existing policies in Virginia. See for example Fleischman (2006).

transportation project funding, federal housing and economic development programs, and local capital improvement budgets, inundation risks must be taken into account.

Land Use and Regulatory Oversight

Many proposed uses of coastal land require affirmative government action or regulatory permits and certification before the land use changes can be undertaken. As zones of inundation are identified, government regulatory and land use programs affecting activities within those zones should account for sea level rise impacts. Many of these regulatory programs involve natural resource protection and stewardship, although some involve financial regulation. Examples of natural resource regulatory programs include state and local stormwater control programs under the Clean Water Act; federal, state, and local wetlands permitting requirements under the Clean Water Act and Rivers and Harbors Act; land use and zoning approval under local government land use authorities; floodplain management requirements; and the like. An example of a financial regulatory program would be state regulation of the property loss insurance sector in ways that reflect higher risk from sea level rise or placing conditions on economic development funding requiring completion of a long-range vision and plan that addresses sea level rise and inundation risk.

Examples of Local Government Adaptation Tools in Virginia

Existing Planning Authorities in Virginia That Mention Climate Change

Every Virginia locality must by law develop long-range land use plans and review those plans every five years (Code of Virginia [Va. Code] § 15.2-2223). These plans usually have a 20-year planning horizon and are the logical place to start long-range climate change adaptation planning. In areas of the state with tidal waters, localities are also required to include water quality protection measures, including shoreline setbacks, in their long-range planning and zoning (Virginia Code § 10.1-2100). Some tidal area Virginia localities are already incorporating climate change discussions in these plans (Accomack 2008, City of Virginia Beach 2009).

To be eligible for programs under the Federal Emergency Management Agency (FEMA), a community must undertake hazard mitigation planning (Title 44 Code of Federal Regulations [C.F.R.], Chapter 1, Part 201.3).

The community must also have a floodplain management program and appropriate building ordinances in high-risk flood zones to qualify for the National Flood Insurance Program. The Virginia Department of Conservation and Recreation is the lead agency on floodplain management planning (Virginia Code § 10.1-602). Federal regulations permit localities to exceed the stringency of minimum federal standards, allowing for location-specific sea level rise adaptation strategies.

These FEMA-required programs are natural places to start planning for sea level rise impacts. Some hazard mitigation plans in Virginia include sea level rise discussions

(City of Poquoson 2008). Other localities are including sea level rise in their floodplain management plans (Gloucester 2009).

The U.S. Department of Transportation requires states (23 CFR § 450.206) and regions (23 CFR § 450.306) to complete long-range transportation plans before receiving federal transportation funding. In shoreline communities, inundation of transportation segments with sea level rise/storm surges is a long-range risk that should be included in these plans. A section of the current Virginia long-range transportation plan discusses climate change impacts, although there are no recommendations for acting on those projected impacts (Virginia Department of Transportation 2010).

The U.S. Department of Commerce (DOC) requires a regional comprehensive economic development strategy (CEDS) before being eligible for many DOC funding programs (Title 42 United States Code [U.S.C.] § 3162). These regional plans are another opportunity for climate change planning to take place. The Hampton Roads, Virginia CEDS mentions climate change as part of the economic challenge facing the region (Hampton Roads Partnership 2010).

The Coastal Zone Management Act (CZMA) authorizes Virginia's coastal zone program and requires that it prepare a management program for the coastal zone (16 U.S.C. § 1455). This program must include a number of assessments of the natural resources in the zone. In addition, a coastal nonpoint pollution control program must also be developed (16 U.S.C. § 1455b). Grants are provided to eligible coastal states in response. This state planning and reporting process provides opportunities for climate change adaptation planning.

The CZMA language specifically mentions sea level rise as an element of concern at Title 16 U.S.C. § 1451: "Because global warming may result in a substantial sea level rise with serious adverse effects in the coastal zone, coastal states must anticipate and plan for such an occurrence." In response, the Virginia CZM program currently funds three regional planning districts to undertake climate planning, one of which is in the high-risk inundation zone in southeastern Virginia.

The U.S. Fish and Wildlife Service requires each state and territory to prepare a wildlife action plan in order to receive funding under the Wildlife Conservation and Restoration Program and the State Wildlife Grants Program (16 U.S.C. § 669e). The wildlife action plans present a strategy for meeting critical wildlife conservation needs in a state. The plans are periodically updated, providing an ongoing opportunity for involvement. There is voluntary guidance for states to include climate change in their plans and Virginia's wildlife action plan update underway currently includes climate change impacts.

Virginia requires localities to submit water supply plans (Virginia Code § 62.1-44.38:1). Given the potential threats to water supplies from climate change impacts, these plans can be used in adaptation planning. Virginia's Water Supply Planning

Program is looking at climate change impacts, working jointly with the U.S. Geologic Survey (personal communication with author).

Planning Authorities in Virginia That Could Include Climate Change

The Clean Water Act requires municipalities to have a stormwater management plan (42 CFR § 122.26). Given projections of increased sea level rise and increased storm intensity, this planning process should be a place where local governments start sea level rise adaptation planning. The Municipal Separate Storm Sewer System Management Program (MS4) requires regional or watershed plans developed with public input and provides an opportunity for including climate change impacts (33 U.S.C. 1251 §402) (4 Virginia Administrative Code [V.A.C.] 50-60-90).

The U.S. Department of Defense is authorized to make community planning assistance grants to undertake joint land use studies where use conflicts emerge between a military facility and the surrounding community (10 U.S.C. § 2391). These grants have been primarily used to study use conflicts between military aircraft operations and incompatible land use surrounding a facility that compromise operations, usually buildings in potential accident and high aircraft noise zones. However, with sea level rise and inundation, the surrounding community's response (or lack of response) will affect military base operations and could be eligible for inclusion in this planning program. The U.S. Navy is looking at these planning funds as applicable to sea level rise/inundation planning (personal communication with author).

The U.S. Department of Housing and Urban Development requires a consolidated plan prior to a locality receiving HUD housing funding (24 CFR Part 91). This planning process is another tool for sea level rise adaptation planning, especially when using federal funds to place housing along tidal shorelines.

The U.S. Forest Service requires long-range plans for national forests (16 U.S.C. § 1604), and Virginia has the George Washington and Jefferson National Forest system within its boundaries. The national forest plans are updated on a 10- to 15-year cycle and provide an opportunity to address climate change impacts. The George Washington–Jefferson National Forest plan revision is currently underway in Virginia, and a background document in the revision mentions climate change as a management issue there.

Local governments in Virginia are authorized by Code of Virginia § 15.2-2230.1 to study the cost of public facilities (roads, sewer, water, etc.) needed to implement a comprehensive plan. This authority would allow life-cycle cost planning at the local level. If the life-cycle cost or total ownership cost of land use decisions along the shoreline were included, it changes the calculations for local governments in the face of sea level rise and higher storm surges. This long-term evaluation of infrastructure costs could be another way to overcome resistance to early adaptation planning outlined in Section 3 because future costs of repairing roads, sewer and stormwater lines, and other utilities in the face of sea level rise would become apparent.

Financial Incentives That Could Include Climate Change

Shoreline lands need to be kept open wherever possible in a sea level rise adaptation strategy. Virginia offers generous tax treatment for land preservation tax credits generated under these programs at Code of Virginia § 58.1-512—a tax credit equal to 50 percent of the value of any conservation easement donated by a Virginia taxpayer over land in Virginia (providing that the easement qualifies as a charitable contribution under IRC § 170[h]) up to $600,000. In addition, the Code of Virginia at § 58.1-3666 allows local governments to exempt from taxation wetlands and shoreline buffers under permanent easements allowing inundation. Buffers must be at least 35 ft. wide.

Keeping development and redevelopment out of areas at high risk of inundation is essential. Transfer of development rights is a process whereby the rights to develop a parcel (in an area where a locality wants to discourage development and redevelopment) are transferred to another parcel (where this development is preferred). This tool is used to preserve open space or protect natural resources and could be a way of keeping development out of inundation zones while allowing property owners to recoup some of their investment. Virginia allows localities to authorize the transfer of development rights at Code of Virginia § 15.2-2316.2.

Owners of developed land in areas of high risk of inundation have vested rights in the current land use, a land use that may be increasingly at risk with sea level rise. Amortizing those vested rights over time—in a phase out period—allows the landowner to recoup investment but moves those nonconforming land uses out of high-risk inundation zones over time. Courts have recognized a reasonable amortization period as preventing a "takings" claim wherein the property owner seeks full compensation for the loss of the higher use of their land. Vested rights are discussed at Code of Virginia § 15.2-2307.

The National Flood Insurance Program (NFIP) is a significant economic force in shoreline areas at risk from inundation, with flood insurance required in high flood-risk zones. Eligibility for the NFIP is already conditioned on a locality undertaking a number of adaptation measures for existing flooding risks. If properly focused on sea level rise inundation, this program could create additional incentives directed at adaptation to sea level rise risk. A federal study is underway to determine the impacts of climate change on the NFIP.

Virginia, like all states, regulates the private insurance industry. Insurance cost and availability sends a strong market signal to areas with high risk of inundation, and as insurance companies set rates and determine availability, these decisions will affect adaptation responses. With more expensive insurance and limited availability, property and business owners in high-risk zones will seek other, safer areas to live and operate businesses. At present, private-sector providers of wind insurance have begun to limit coverage in coastal areas in Virginia or have withdrawn completely from some areas (Fleishman 2006). If these actions continue, they will begin to shape investment patterns along the tidal shoreline in Virginia.

In areas of high risk from inundation, public services to maintain current land uses and landowner expectations will become more expensive. Those expenses can be offset in a special taxing district wherein residents in high-risk zones are assessed a higher tax to pay for those services, sending a clear financial signal as well to those areas. Virginia Code at § 15.2-2400 allows the creation of local government special districts to accomplish certain necessary tasks; these could be used in high-risk inundation zones to create disincentives for land uses at odds with higher risk from sea level rise.

Direct Investment and Infrastructure Decisions That Could Include Climate Change

Each Virginia locality is authorized at Virginia Code §15.2-2239 to prepare a capital improvement plan (CIP) for needed capital investments. The preparation of the CIP usually occurs with comprehensive land use planning updates and offers a chance to incorporate climate change impacts in local government infrastructure investment decisions. Placement of roads, schools, firehouses, police stations, and other public facilities are governed by the CIP, and all these facilities need to account for sea level rise in coastal communities.

At the federal level, projects built under the authority of the U.S. Army Corps of Engineers' civil works program are required to take sea level rise into account (U.S. Army Corps of Engineers [USACE] 2009). This regulatory guidance begins to outline the steps needed for all infrastructure investments along the coastline. I am unaware of any civil works project that has explicitly taken sea level rise into account, although given the long lead time on these projects, some civil works projects currently being developed may be undergoing this review.

Regulatory Authorities in Virginia that Could Include Climate Change

Programs exist at the local, state, and federal level to regulate development activities along the tidal shoreline in Virginia, areas that are increasingly at risk from sea level rise inundation. Some of these authorities reside with local government zoning and building ordinances. Other authorities place restrictions on development along these shorelines to protect the natural ecosystem. These authorities can be used to keep the shoreline open and resilient and better able to adapt to sea level rise. They can also be used to keep infrastructure and housing out of shoreline areas at increasing risk from sea level rise.

The strongest potential climate change adaptation regulatory tools are local zoning and building code authorities, as these govern the use of land and the placement of infrastructure along the shoreline and set minimum building safety and performance standards. Counties in Virginia are given broad powers to protect the public health and welfare at Virginia Code § 15.2-1200 and specific zoning authority at Virginia Code § 15.2-2280. These local government zoning authorities have great potential for controlling development and redevelopment in high-risk inundation zones. To date, however, there is no evidence of a locality using this authority specifically to address sea level rise.

Localities have zoning and building code authorities granted to them by state and federal statutes as well that can be used in sea level rise adaptation strategies. The Chesapeake Bay Preservation Act (Virginia Code §10.1-2100/9VAC10-20) provides local governments with tidal shorelines a number of land use authorities including overlay districts along the shoreline within which development and redevelopment is restricted to protect water quality. FEMA authorizes local government floodplain zoning and building code requirements (42 U.S.C. § 4001/ 44 CFR § 60.1) as a mandatory requirement prior to any locality receiving federal flood insurance. This authority is overseen in Virginia by the Department of Conservation and Recreation's floodplain management program (Virginia Code § 10.1-602).

Virginia, like most coastal states, has regulatory programs to protect its coastal and tidal estuarine ecosystem. Much river and tidal estuarine bottomland is state owned and disturbance requires a permit from the Virginia Marine Resources Commission. Development and redevelopment affecting mudflats, nonvegetated wetlands, and vegetated intertidal wetlands require a permit from federal regulators and state regulatory bodies. State authority for wetlands protection is found at 9 VAC 25-210 /Virginia Code §§ 62.1-44.15 and 62.1-44.15:20. For tidal wetlands, the primary state authority is given to the Virginia Marine Resources Commission at Code of Virginia § 28.2-1300, which has delegated that authority to most of the local governments in tidal areas of Virginia. The federal government also regulates wetlands through the Clean Water Act (33 U.S.C. § 1344) and the Rivers and Harbors Act (33 U.S.C § 403). The coordination of state and federal wetlands regulatory programs occurs during a joint permit application process.

Virginia has not moved to include sea level rise into its state regulatory programs, despite clear historical evidence that significant rates of sea level rise exist in the state and that those rates can affect the quality and quantity of coastal and tidal estuarine natural resources. The Virginia Department of Environmental Quality (DEQ) rejected a recent challenge to a wetlands permit made by Wetlands Watch, which objected to sea level rise not being taken into account. The DEQ stated, "The DEQ VWPP (Virginia Water Protection Permit) Program does not have the regulatory authority to speculate on how sea level rise may affect the distribution and type of wetlands present in the project watershed" (Virginia Department of Environmental Quality 2008).

Wetlands Watch is challenging a federal wetlands permit application with the USACE Norfolk District based on the applicant not including sea level rise impacts in the permit application (Wetlands Watch 2010). No decision has been made at this time.

Disturbance of primary coastal dunes requires a permit to ensure that development does not encroach upon these dunes (Virginia Code § 28.2-1408/4VAC20-440-10). Development is allowed only within a zone 20 times the average shoreline recession rate over the last 100 years, a rate that does not accommodate future projections for accelerated rates of sea level rise and which can be expected to increase rates of shoreline recession (Wu et al. 2009).

In addition to the zoning authorities previously mentioned, the Chesapeake Bay Preservation Act (CBPA) (Virginia Code §10.1-2100/9VAC10-20), which is administered by local governments, requires regulatory approval for development and redevelopment activities in buffer zones along the shoreline. These buffers are the land behind the wetlands in tidal areas, generally set as the land shoreward at least 100 ft. from the high-tide line. The CBPA could be a very effective tool for regulating development in zones of future inundation along the shoreline; however, to date no locality has included current or projected sea level rise into its regulatory deliberations.

Erosion and sediment control programs (Virginia Code §10.1-560/4VAC30-50) and municipal stormwater control programs (Virginia Code § 10.1-603.3) regulate development and developed areas along the shoreline and are designed to control shoreline runoff pollution. To the extent that these authorities affect shoreline development, they have the potential to be used in sea level rise adaptation. They will also need to accommodate other predicted climate change endpoints beyond sea level rise, such as increased storm intensity, as those impacts can limit the efficacy of stormwater and erosion control practices.

The Virginia Department of Historic Resources (DHR) has a role to play in climate change adaptation, as their approval must be granted before any disturbance/ development can occur near a historic site (Virginia Code § 10.1-2200/17VAC10). With sea level rise threatening many shoreline historic sites in Virginia, these DHR decisions have a role to play in sea level rise adaptation strategies.

Next Step: Improving Adaptation Authorities

All of the programs listed above have shortcomings in their statutory and regulatory authorities because they have a retrospective focus, using historic data in making current program decisions. Few of these programs have included historic rates of sea level rise in their operations, the exception being the FEMA, which recently updated mean sea level in its flood hazard map modernization effort. (In southeastern Virginia, the FEMA map modernization updated mean sea level from 1923, adding nearly 1 ft. to the base flood zones in the maps.) One other exception, as mentioned above, is the USACE issuance of guidance including historic rates of sea level rise in its civil works construction projects, although I could not find examples of this guidance being applied (USACE 2009).

The inclusion of climate change and sea level rise impacts in some local government planning documents in Virginia is an indication of the seriousness of the sea level rise problem and the willingness of some local governments to address it. To become useful in developing sea level rise adaptation strategies, government authorities and regulations will need to switch from a retrospective focus to one that explicitly includes both historic and projected rates of sea level rise in program decisions. In Virginia, moving beyond planning to develop incentives and make regulatory decisions that include future sea level rise will be difficult for local governments. Progress beyond planning will require specific mandates from federal agencies for federal programs implemented at the regional or local level and legislative authority from the Virginia General Assembly for those state and local programs necessary to implement a sea level rise adaptation strategy.

Conclusions

Significant rates of sea level rise are occurring in Virginia and indicate the need for the development of sea level rise adaptation strategies in coastal regions. Local governments are critical to the development and implementation of these strategies, given their role in implementing federal programs and in regulating land use. Many regional and local governmental entities in Virginia have included discussions of climate change and sea level rise impacts in their planning documents, indicating growing awareness of the problem. The next steps, focusing incentive and investment programs on the problem and developing a regulatory component to sea level rise adaptation strategies, will be more difficult politically, although the outlines of a local government toolkit for developing these strategies is emerging.

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Chapter 7. Response to Sea Level Rise in Coastal Communities: A Virginia Case Study

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Abstract

Sea level rise will cause a broad range of impacts on coastal communities in the mid-Atlantic region of the United States. It is critically important that state and local governments use an integrated approach to planning for adaptation to sea level rise to ensure that to the extent possible societal and environmental concerns are balanced with protection of infrastructure and the built environment. The Hampton Roads region in southeastern Virginia is used as a case study in discussing this set of challenges.

Hampton Roads and Sea Level Rise

The Hampton Roads region in southeastern Virginia is among the most vulnerable metropolitan areas in the United States for population and infrastructure at risk to sea level rise. The region is home to an extensive military presence, the Port of Virginia, and an extensive tourism industry. The majority of the population of approximately 1.6 million people lives in areas that will be extensively impacted by rising sea levels and the corresponding increase in storm surge.

The staff of the Hampton Roads Planning District Commission (HRPDC) is currently involved in a multi-year effort to plan for the impacts of climate change and sea level rise in the region. This effort is funded in part by the Virginia Coastal Zone Management Program. The HRPDC is one of three Virginia coastal planning district commissions (PDC) involved in multi-year planning efforts. The Middle Peninsula Planning District Commission and the Northern Virginia Regional Commission are involved in similar projects.

Hampton Roads experienced sea level rise of 4.44 mm per year (+/- 0.27 mm/yr) for the period from 1927 to 2006 (Figure 7-1). This translates to 1.46 ft. of sea level rise over the last 100 years (NOAA 2008). This measure is based on the Sewells Point tide gauge at the mouth of the Elizabeth River. This change has made the region more vulnerable to storm surge flooding over time. Accurate prediction of future sea level rise rates is problematic, a fact that is openly acknowledged within the scientific community. Several factors contribute to this difficulty including unknown future greenhouse gas emission rates, an incomplete understanding of ice melt dynamics, and possible future changes in ocean circulation patterns. To deal with this uncertainty most predictions of future sea level rise are given as ranges. As an example, the 2009 report titled *Global Climate Change Impacts in the United States* references sea level rise ranges associated with three different Intergovernmental Panel on Climate Change (IPCC) emission scenarios and more recent estimates of global sea level rise that substantially exceed the IPCC estimates (Karl et al. 2009). At the low end of the scale, the IPCC lower emission scenario predicts between 0.6 and 1.3 ft. of global sea level rise by 2100. At the high end of the scale are more recent estimates that suggest between 3 and 4 ft. of global sea level rise by 2100. Regardless of which projected trend is most accurate, for Hampton Roads the effects of global sea level rise will be exacerbated by local land subsidence.

Land subsidence is a significant factor in the rate of sea level rise in Hampton Roads (CCSP 2009). Several factors contribute to land subsidence within the region. First, Hampton Roads is affected by glacial isostatic adjustment related to the demise of the Laurentide Ice Sheet (Engelhart 2009). A second factor is the removal of groundwater from aquifers under the region. As the water is removed for drinking and other uses, the aquifers compress slightly, further contributing to subsidence. The rate of subsidence varies across the Hampton Roads region. In general, land subsidence accounts for between one-third and one-half of the observed sea level rise in the region for the period 1927 to 2006. The remaining component in sea level rise in the region is the result of a combination of the global phenomena of thermal expansion of seawater and polar ice melt associated with climate change.

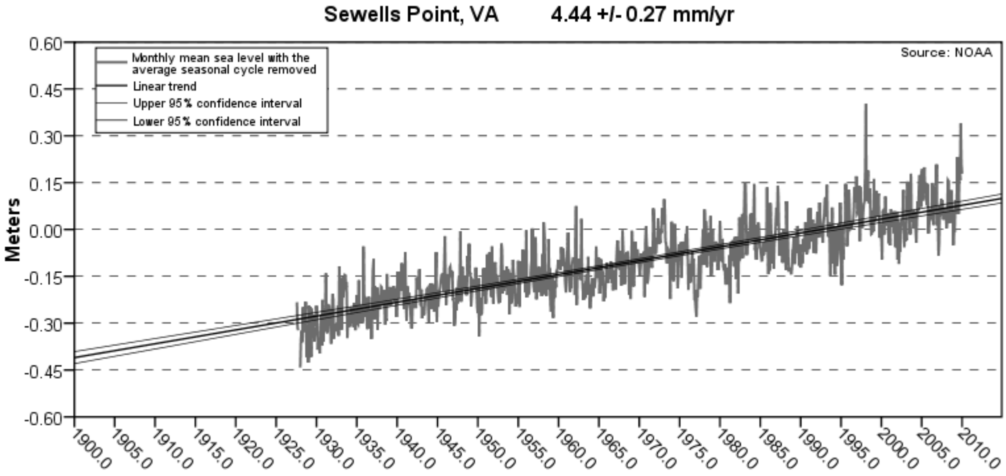

Figure 7-1. Historic Sea Level Rise at Sewells Point, Virginia, 1927-2006. Prepared by the Hampton Roads Planning District Commission. Source: NOAA (2008)

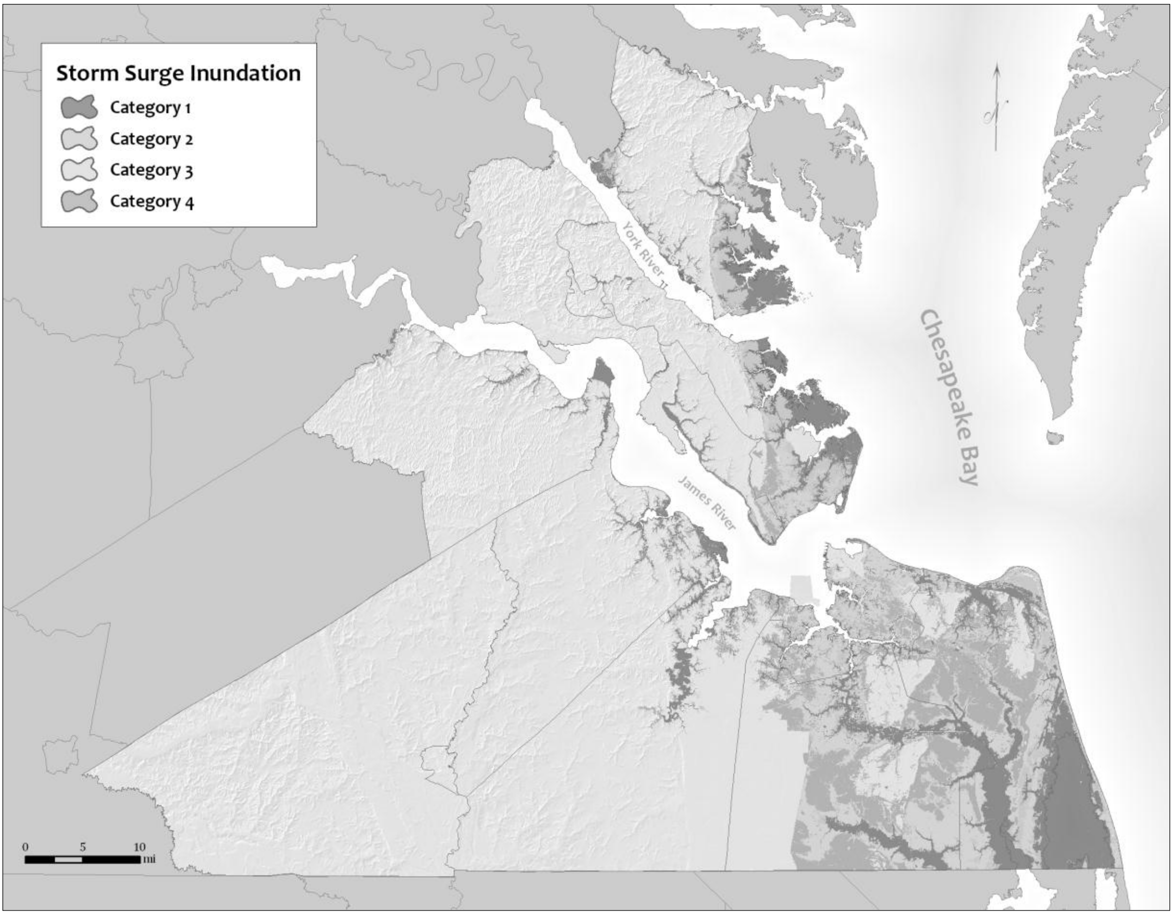

Figure 7-2. Storm Surge Inundation for Hampton Roads,
(Based on data from Virginia Department of Emergency Management)

Changing Storm Surge Threat

Climate change and associated sea level rise will have significant effects on the built environment in the Hampton Roads region. Storm surge flooding has been exacerbated during the last century by rising sea levels. This trend is projected to accelerate with potentially dire consequences. Coastal storms already pose significant risks to Hampton Roads and recent storm events confirm how vulnerable the region is to flooding. Hurricane Isabel, for example, caused a level of flooding similar to the unnamed August 1933 hurricane, despite the fact that the 1933 hurricane was the stronger of the two storms. The increase in sea level between 1933 and 2003 was sufficient to cause the flooding from Isabel nearly equal to the 1933 storm (Boon 2005). The risk of storm surge flooding will continue to increase both in consequence and in frequency.

Climate Change and Sea Level Rise Impacts by Sector

Infrastructure Impacts

The Hampton Roads region is particularly vulnerable because of its highly dense population near the shore (CCSP 2009). The Virginia Beach-Norfolk Metropolitan Statistical Area is one of the most vulnerable areas in the world; it is the 10th largest coastal metropolitan area in terms of assets exposed to sea level rise (Governor's Commission on Climate Change 2008). Specific areas of the region at risk due to sea level rise or flooding from storms include the eastern part of the peninsula and the Elizabeth River and North Landing River watersheds. The number of nationally, regionally, and locally important structures, facilities, and systems at risk is large. Critical infrastructure such as roadways, railways, and utilities are located in vulnerable areas. A study by the U.S. Department of Transportation analyzed the impacts of sea level rise on transportation infrastructure due to inundation and storm surge flooding (Wright and Hogan 2008). Important transportation infrastructure in Hampton Roads that is vulnerable to sea level rise includes the Interstate 64 Hampton Roads Bridge Tunnel. A number of military installations, including Naval Station Norfolk, Joint Expeditionary Base Little Creek–Fort Story, Joint Base Langley-Eustis, Fort Monroe, Naval Weapons Station Yorktown, Naval Shipyard Norfolk, and others are also in vulnerable areas (Governor's Commission on Climate Change 2008).

Economic Impacts

The Hampton Roads regional economy is heavily dependent on several industries associated with its coastal location. These include tourism, the military, and the Port of Virginia. Tourism along the oceanfront is a large factor in the Virginia Beach economy, and it affects the rest of the region. The military has several installations that will be more vulnerable to sea level rise and are already vulnerable to storm surge flooding. Loss of these installations and the transfer of their personnel to other areas of the country would result in the loss of many jobs and supporting area industries. The Port of Virginia and related industries will also be affected by climate change. Port and shipbuilding infrastructure may be inundated or periodically flooded, resulting in work stoppages or the removal of these facilities entirely. Replacement costs for any of these facilities would be very high. Additionally, increases in storm occurrences may result in higher insurance costs for infrastructure, homes, and businesses, potentially leading to lower rates of economic development and growth.

While climate change will pose many serious challenges for the region, mitigation and adaptation to climate change will offer Hampton Roads several opportunities for economic development. Hampton Roads is well suited for two such opportunities in particular. The development of wind energy will be important to reducing greenhouse gases, and offshore wind will be a significant resource to develop. An area with Category 5 and 6 (high potential for wind energy) winds lies offshore of Virginia

Beach. In addition to being an ideal location for wind energy generation, Hampton Roads has assets that could serve to make the region a hub of logistical support, including a deep-water port and developed industrial capacity, which could help the region take advantage of offshore wind energy development elsewhere along the Atlantic Coast. Hampton Roads also has a developing modeling and simulation industry with institutions such as the Virginia Modeling, Analysis and Simulation Center (VMASC) in Suffolk (associated with Old Dominion University in Norfolk) and the Virginia Institute of Marine Science (VIMS) in Gloucester. VIMS is already working on modeling the impacts of climate change, and VMASC could utilize some of its capabilities.

Ecological Impacts

Natural resources provide a wealth of benefits, including ecological services such as water quality enhancement and wildlife habitat as well as recreational value. Protecting, preserving, and enhancing the natural resources of Hampton Roads are vital to sustaining its natural environment and its quality of life. To this end, several regional efforts have aimed to identify those areas that should be protected and to develop policies that achieve that goal. These efforts include the Southern Watershed Area Management Program and the Hampton Roads Conservation Corridor Study (HRPDC 2007). Through these projects a regional green infrastructure network was identified. The network consists of areas that are valuable natural habitat and areas that contribute to water quality protection. The most recent version of the regional green infrastructure network includes more than 500,000 acres of high value lands.

However, the ecological services provided by the high-value natural resources in the regional green infrastructure network are increasingly coming under threat from climate change. Temperature increases, sea level rise, and more frequent and intense storms all negatively affect valuable natural resources. In addition, climate change will exacerbate other stressors such as land development, fertilizer use, and increases in human population (Jasinski and Claggett 2009). In addition, the Chesapeake Bay region is more vulnerable to sea level rise than most places because of its flat topography and extensive development (Glick et al. 2008). In the Chesapeake Bay, including Hampton Roads, land subsidence further increases vulnerability to sea level rise. Since much of Hampton Roads' green infrastructure lies along the coast, sea level rise and the accompanying increases in storm surge will have a profound effect on the region's natural resources and its ability to maintain and preserve those resources into the future.

Research by organizations such as the U.S. Global Change Research Program and the National Wildlife Federation (NWF) has described the potential effects of climate change on natural resources. Expected changes include reduced populations of plants and animals, shifts in species' ranges, conversion of habitat types, inundation of low-lying areas, increased turbidity and nutrient content of water bodies, and erosion of coastal and riparian areas (CCSP 2009). Inundation of wetlands increases the salinity of the ecosystem and can also infiltrate groundwater aquifers, which can reduce species diversity (Glick et al. 2008).

In some cases wetland migration inland will occur as a natural response to sea level rise, but often development of hard flood protection systems present barriers to this process. Protecting upland buffers from development can reduce wetlands loss further down the road (Glick et al. 2008). Other cases new wetlands may also be created as sea level rises and inundates low-lying coastal areas, converting the hydrology, soils, and vegetation. The overall result, however, will be a large loss of wetland acreage.

The National Wildlife Federation performed a sea level rise impact analysis of the Chesapeake Bay region and Delaware Bay in 2008 using the Sea Level Affecting Marshes Model (SLAMM) and simulating five processes caused by sea level rise—inundation, erosion, overwash, saturation, and salinity (Glick et al. 2008). The sea level rise scenarios used were taken from or based on those designed by IPCC. Additional scenarios were run based on sea level rises of 1 m, 1.5 m, and 2 m by 2100. In this case, sea level rise refers to eustatic global sea level rise. Two scenarios are of particular use here. The Governor's Commission on Climate Change referenced the A1B scenario (0.39 m of sea level rise) in its description of climate change impacts on the commonwealth. The model showed significant impacts across the entire study area. In the A1B-Maximum scenario (0.69 m of sea level rise), tidal marsh area declines by 36 percent, and 57 percent of the Chesapeake Bay region's tidal swamps also disappear by 2100. In addition 4 percent, or more than 400,000 acres, of coastal land is also lost through inundation or erosion. These losses and more predicted effects of climate change have the potential to form a "completely different Chesapeake Bay region" with different landforms, flora, and fauna (Glick et al. 2008).

NWF also ran the model for several Chesapeake Bay region subareas, including two in Hampton Roads—Mobjack Bay between Gloucester County and the peninsula and South Hampton Roads. The model predicts different impacts for these areas. In the Mobjack Bay area, undeveloped dry land declines by 13 percent under the A1B-mean scenario and by 19 percent under 1 m of sea level rise, with much of this occurring in Eastern Hampton and Gloucester (Glick et al. 2008). Other impacts predicted for the area include soil saturation, conversion of brackish or high marsh (with its associated vegetation) to salt marsh, and conversion of dry land to transitional marsh. The study assumed that developed lands would be protected from sea level rise for this scenario. The scenario does not predict or account for any increase in developed land.

The South Hampton Roads coastal area is similarly affected. In both cases a significant part of the area is already developed. (The assumptions for developed land are maintained for this analysis as well.) Undeveloped dry lands are predicted to decrease by 16 percent under the A1B-mean scenario and by 22 percent under a 1-m rise in sea level. Tidal flats and tidal swamps are also predicted to lose significant area. Some environments, such as salt marshes, are expected to experience significant increases. Ocean beach is expected to decline significantly, though the analysis does not allow for artificial beach renourishment (Glick et al. 2008). A significant inland area of Virginia Beach will be threatened because of the reach of the North Landing River, which will be subject to increased tidal flooding.

To assess the potential impact of sea level rise on ecologically important areas of the region, a GIS analysis was performed on the regional green infrastructure network. This network consists of areas in the region that are ecologically valuable for water quality purposes, habitat, or both (HRPDC 2010). The plan provides an inventory of existing natural resources and valuable areas as well as a guide for preservation and protection efforts. Incorporating sea level rise projections helps prioritize areas that should be preserved to allow for inland migration of salt and brackish marshes in coastal and riparian areas. The latest update to the regional plan identified more than 500,000 acres of high value areas, including more than 12,000 acres of land of high value for water quality, more than 96,000 acres of land of high value for habitat, and more than 400,000 acres of high value for both.

Long-term viability of the green infrastructure network will be in part affected by sea level rise as areas are inundated or subject to more frequent flooding. Climate change may result in the permanent loss of green infrastructure or significant change in some areas. Accurately modeling the impacts of sea level rise on green infrastructure requires consistent high-resolution elevation data.

Because these data were not yet available, an analysis was done using Category 1 storm surge (approximately 4 to 5 ft. above normal sea level) as a proxy for projected impacts from the combination of sea level rise and increased storm surge. However, better elevation data are needed for more reliable impact analysis. Using storm surge data reveals areas at risk both due to inundation and to increased flooding from storms. To analyze the impacts of sea level rise on the regional green infrastructure network, storm surge data were overlaid on the network using GIS (Figure 7-3). The analysis showed that more than 84,000 acres, or 16.5 percent of the region’s green infrastructure network, will be at risk of inundation or more frequent flooding due to climate change. This includes approximately 3900 acres of area valuable for water quality, 1500 acres of area valuable for habitat, and nearly 79,000 acres valuable for both. In addition, this analysis does not account for how climate change will exacerbate many of the other stressors already affecting the region’s green infrastructure, such as non-surge riverine flooding, nutrient pollution from development and agriculture, and increased salinity in waterways and aquifers.

Planning For Climate Change and Sea Level Rise

Modeling Storm Surge Changes Associated with Sea Level Rise

Modeling future changes to storm surge associated with sea level rise is among the most important steps in planning for climate change impacts in Hampton Roads. An analysis conducted by staff at the Virginia Institute of Marine Science, the Chesapeake Bay Observing System, and Noblis provides insight into the value of this type of modeling. This analysis used high-resolution elevation data and hydrodynamic modeling to analyze the impact of a major storm event that is modified by sea level rise (Stamey et al. 2010). The researchers used Hurricane Isabel as the test case for their analysis and modified it using set intervals of sea level rise between 0.5 m and 2.0 m (Fig. 7-4 through 7-10). One of the focal areas of the analysis was centered on Lynnhaven Bay in Virginia Beach (Figure 7-4). This area is among the most densely populated in the City of Virginia Beach with extensive multi-family and commercial structures. The Hampton Roads Conservation Corridor (HRPDC 2006) system is overlaid to show the vulnerability of natural systems to a large storm event modified by sea level rise. The analysis shows that because of sea level rise, the study area will be greatly affected by storms and that the conservation corridor system is extremely vulnerable to flooding. Additionally, vulnerability will increase over time as sea level continues to rise. Hurricane Isabel showed that parts of the region and the conservation corridor system are already vulnerable, but a similar storm 50 to 100 years from now could devastate the area. A catastrophic storm event, represented by the Hurricane Isabel +2 m scenario (Figure 7-10), has the potential for extensive damage to both the built and natural environments.

It is recognized that hurricanes produce significant impacts due to storm surge flooding, but their relatively infrequent rate of occurrence along the Atlantic Coast causes many to believe that adaptation or other protection actions can be postponed because the likelihood of a hurricane occurrence is a relatively low risk. However, nor'easter storms, which impact the region much more frequently than hurricanes, are now having effects similar to contemporary hurricanes. The Veteran's Day Nor'easter of November 11-13, 2009 had a nearly identical peak water level rise as observed during Hurricane Isabel, and this storm damaged the coastal communities for several days with continuous high winds and increased storm surge. Thus, the damaging effects of the combination of sea level rise and storms will occur more frequently, perhaps several times per year. Because of this increased risk, adaptation must not be allowed to be postponed.

Mitigation and Adaptation to Climate Change

An effective response to climate change impacts will require both mitigation and adaptation. Mitigation actions are intended to reduce the extent and rate of acceleration of climate change by reducing greenhouse gas emissions. Adaptation actions are intended to minimize the adverse impacts of climate change on built and natural systems. Given current atmospheric greenhouse gas levels, global temperatures will continue to rise over the next century, making adaptation a necessity regardless of mitigation strategies. The reverse is also true: without mitigation, climate change will at some point exceed cost-effective adaptive capacity. The long-term rate of climate change will be determined by our global ability to limit the growth of greenhouse gas emissions and eventually reduce them during the next

20 to 40 years. The extent and type of adaptation measures needed in Hampton Roads will largely be determined by global greenhouse gas emissions during the 20 to 40 year window. If global greenhouse gas emissions are held flat or reduced during that time period, sea level rise rates are projected to be problematic but manageable. If greenhouse gas emissions continue to rise significantly during that period, massive melting of polar ice will result, and sea level rise will have a catastrophic impact on the eastern portion of Hampton Roads.

Mitigation

Most of the mitigation options for limiting climate change involve reducing emissions. Mitigation focuses on reducing the impacts of climate change before they occur; it is proactive rather than reactive (Godschalk 2003). Lowering emissions rates sooner will lessen the overall magnitude of climate change and its effects. However, no single technology can provide all the mitigation potential in any sector, so adaptation will still be required (IPCC 2007). Emissions reductions can be achieved through greater energy efficiency or switching to lower- or non-emissions sources of energy. Reforestation is another potential mitigation strategy because of carbon storage. Strengthening natural systems by removing development stressors can also help mitigate some climate change impacts. Most mitigation strategies, however, require behavioral change. Among the policies that can be implemented to drive this change and lower emissions are taxes on emissions, land use regulations that promote more mass transit and reduce driving, and other taxes and incentives that offset energy efficiency or alternative energy (IPCC 2007).

Adaptation

Adaptation to climate change will involve both changing development patterns and protecting existing development with flood control measures. Many adaptation options are available. In general, these can be broken down into three categories: protection, accommodation, and retreat (Karl et al. 2009). Protection refers to structural solutions to shield against flooding, storm surge, or inundation. Possible measures include seawalls, bulkheads, dikes, and storm surge barriers (CCSP 2009). Accommodation refers to retrofitting or enhancing existing structures or environments. This could include elevating buildings, nourishing beaches, or enhancing wetlands (Karl et al. 2009). Retreat refers to a broad range of options that allow or encourage people and ecosystems to move away from vulnerable areas. These can include setbacks, rolling easements, and development restrictions (CCSP 2009). Effective adaptation to sea level rise or flooding should focus on reducing growth in areas forecasted to be affected during the next century (Jasinski and Claggett 2009). Using growth management to adapt to sea level rise has multiple benefits. It can protect existing ecosystems near the shore and provide public value by preserving them for recreation or public access. This ability to meet other needs such as stormwater management and habitat provision is a general hallmark of many adaptation options. They do not just help localities adapt to climate change; they can also enhance quality of life and the natural environment.

Research by the Chesapeake Bay Program describes another method of adapting to climate change. The program's work differentiates between adaptation and increasing resilience. Adaptation focuses on specific targets to plan for, while resilience planning focuses on increasing the robustness of built or natural infrastructure to deal with a wide range of possible conditions (Pyke et al. 2008). Resilient systems bend under stress but do not break, so they are able to weather storms more effectively and recover more quickly. Adaptive systems are characterized by redundancy, diversity, efficiency, strength, interdependence, adaptability, and collaborativeness (Godschalk 2003). They are designed so that the failure of one part does not cause the whole system to collapse. For cities, resilience implies distributed infrastructures that reinforce each other, while also being able to operate independently during crises (Morrish 2008). Adaptive responses are more appropriate when future conditions are predictable, while resiliency allows for uncertainty (Pyke et al. 2008).

Adaptation of natural systems to climate change will look significantly different from adaptation in the built environment. Some possible adaptation approaches for natural systems include protecting key resources, reducing anthropogenic stress, increasing representation, and using the practices of replication, restoration, refugia, and relocation (CCSP 2008). Protection focuses on identifying ecosystems or species that provide a foundation for the region's natural environment. Reducing anthropogenic stress focuses on reducing or eliminating pollution or other stressors that result from development. Adapting through representation requires identifying and protecting a diversity of species so that the ecosystem can survive and recover. Replication focuses on protecting several distinct populations of important species to replicate ecosystems or similar habitats in separate locations so that they are not all lost during a stochastic event. Restoration focuses on bringing back damaged ecosystems that are either more resilient to climate change than others or are in locations more protected from the effects of climate change. Refugia refers to identifying less sensitive areas within their present or future ranges of refuge for species threatened by climate. Relocation describes artificially moving species to areas they might naturally migrate to because of climate change but are prevented from reaching by the lack of migration corridors or the presence of barriers created by development. Species may also be relocated to areas that are more resilient to climate change and other stressors (CCSP 2008). Unlike options designed for the built environment, these adaptation options for natural systems mostly focus on reducing impediments to these systems adapting themselves.

Related Planning Efforts

Hampton Roads localities are currently working on several climate change adaptation and mitigation initiatives. A committee has been meeting for several months to discuss coordination of Energy Efficiency and Conservation Block Grant funds spending. Localities worked together to submit regional applications for climate change mitigation projects. Non-entitlement localities worked together to submit a regional application for lighting upgrades, and three entitlement communities allocated funds to a regional greenhouse gas emissions inventory. The HRPDC Elizabeth River Restoration Program Steering Committee is investigating coastal resilience planning areas around the river, and planning is underway for a project to account for industrial and contaminated sites that may be inundated or flooded due to sea level rise. Regional emergency management personnel are engaged in two projects relating to climate change adaptation. The first is updating the region's hazard mitigation plans, including most of the peninsula and southside communities. For the first time, the plans will account for sea level rise. Additionally, HRPDC is in the process of developing a regional critical infrastructure/key resources plan, which will include sector plans focusing on resiliency.

Development of a Framework for Climate Change Adaptation in Hampton Roads

One of the goals for the next two years is to develop a regional framework for mitigating and adapting to climate change in Hampton Roads. The framework is intended to capture the results of the stakeholder involvement and policy formulation process and to serve as a regional guidance document for meeting the challenges of climate change. The framework will serve as a living document to be updated over time as knowledge about climate change improves and conditions in Hampton Roads change. Several significant difficulties exist in developing the framework. These include the unknown future rate of global greenhouse gas emissions, technical difficulties in downscaling global climate models to predict regional impacts, and an extremely long planning horizon. Given these challenges, the framework must be flexible and modular so that its structure can be revised and sections can be updated easily as circumstances and scientific knowledge change.

Establishment of a specific set of goals for the framework will be accomplished through an extensive stakeholder involvement process. The following broad goals will be used as a starting point for that process:

- Identify and implement regional and local measures that contribute to state and national efforts to mitigate climate change;
- Structure mitigation and adaptation efforts to ensure the continued economic vitality and ecological integrity of Hampton Roads; and
- Keep safety and high quality of life for citizens of Hampton Roads paramount in the mitigation and adaptation process.

In addition to the goals for the process, the framework's structure will also be revised and improved through stakeholder involvement and subsequent research and modeling. The following structure will be used as a starting point.

Mitigation efforts will focus on completing the regional greenhouse gas emissions inventory and developing an implementable action plan. This plan will include establishing regional and local emissions targets as well as the identifying and implementing greenhouse gas emission control measures.

Adaptation efforts will focus on data and information acquisition, vulnerability assessments, and the development of strategies for both the natural and built environments. General data and information needs include consistent, high-resolution elevation data for Virginia's coastal plain, an improved understanding of sea level rise rates, enhanced modeling tools for storm surge changes associated with sea level rise, and improved models for regional changes in precipitation patterns.

Information needed for natural systems adaptation includes a vulnerability assessment for at-risk ecosystems and priorities for adaptation options. Once these are acquired, several climate change stressors will need to be evaluated. These include sea level rise and storm surge, atmospheric temperature increase, changes in precipitation patterns, and increasing temperature, acidity, and salinity of waters. Specific environments will need to be evaluated, and adaptation plans will need to be developed for each—the Chesapeake Bay and its tributaries, tributaries to the Albemarle/Pamlico Estuary, tidal wetlands, non-tidal wetlands, uplands, and barrier islands.

Information needs for built environment adaptation include a vulnerability assessment for at-risk areas and infrastructure as well as further research into adaptation options and their feasibility. Adaptation plans will be needed many sectors, including

- Transportation infrastructure (roads, bridges, tunnels, and rails)
- Residential structures
- Commercial structures
- Stormwater systems
- Wastewater systems (including public sewers and private septic systems)
- Drinking water supply infrastructure
- Communication and mass media infrastructure
- Military facilities
- Port facilities
- Hospital and medical facilities
- Government and emergency management infrastructure and facilities

Two additional elements to be included in the framework are a climate change educational program for Hampton Roads citizens and the establishment of monitoring and evaluation goals so that the regional impacts of climate change and the results of the mitigation and adaptation efforts can be measured and documented.

The Importance of Integrated Planning Efforts: A Cautionary Tale

Two recent projects in Hampton Roads underscore the need for an integrated approach to infrastructure planning in light of sea level rise. The first is the new light rail line under construction in the City of Norfolk, which is scheduled to open in 2011. Hampton Roads Transit (HRT), the agency responsible for the project, announced on May 26, 2010, that an at-grade crossing at Brambleton Avenue and 2nd Street must be rebuilt after flooding caused the underpinnings to settle. The area surrounding the intersection is subject to tidal flooding during storm events. An HRT spokesman stated that when the light rail system opens, it could be shut down periodically due to high water. Given the projections for accelerated rates of sea level rise, the wisdom of locating a new rail line in an area that is currently subject to tidal flooding must be called into question.

The second project involved rebuilding a sand spit at the mouth of Back River in the City of Hampton. The sand spit, known as Factory Point, was breached by a pair of coastal storms several years ago. Many homes in the Back River watershed are vulnerable to tidal flooding and were severely impacted by Hurricane Isabel. A group of citizens became convinced that the breaching of the sand spit played an important role in increasing the vulnerability of the area to flooding. Despite expert analysis from engineers and coastal scientists that the reconstruction of Factory Point would do nothing to alleviate tidal and storm surge flooding in the Back River watershed, the Hampton City Council, under pressure from citizens, moved forward with the reconstruction project (Figure 7-11).

Given the limited funding available for infrastructure projects and the changing flood threat associated with sea level rise, it is imperative that flood control measures and infrastructure protection projects in areas vulnerable to flooding be included in local and regional long-range plans. In addition, these planning efforts must be multidisciplinary to ensure that climate change and sea level rise are fully considered and that decisions are informed by these emerging capabilities to model and visualize impacts from the combined effects of sea level rise and storms. Finally, the time has come for the coastal communities subject to increased flooding associated with sea level rise to ask difficult questions about the wisdom of continued development in the most vulnerable areas.

The following series of maps (Fig. 7-3 through 7-11) is a demonstration of the capability of running high-resolution inundation models using hypothetical scenario conditions developed by VIMS as part of the Chesapeake Bay Inundation Prediction System (CIPS). The sea level rise increments depicted are not a prediction of future sea level rise.

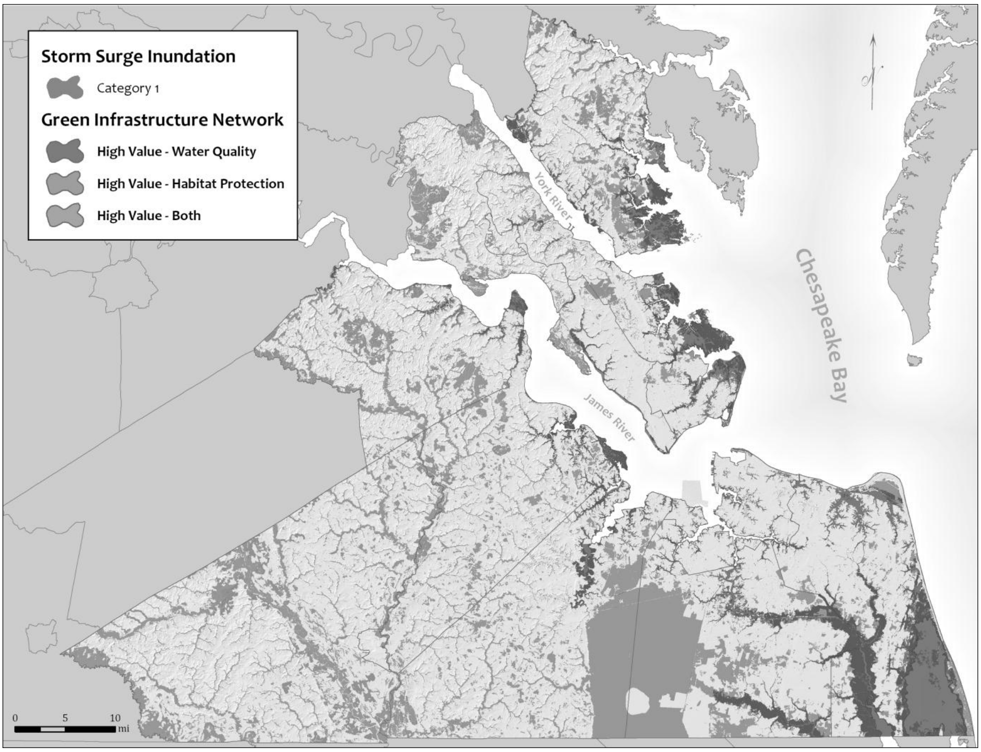

Figure 7-3. Hampton Roads Green Infrastructure Network and Category 1 Storm Surge (Source: HRPDC)

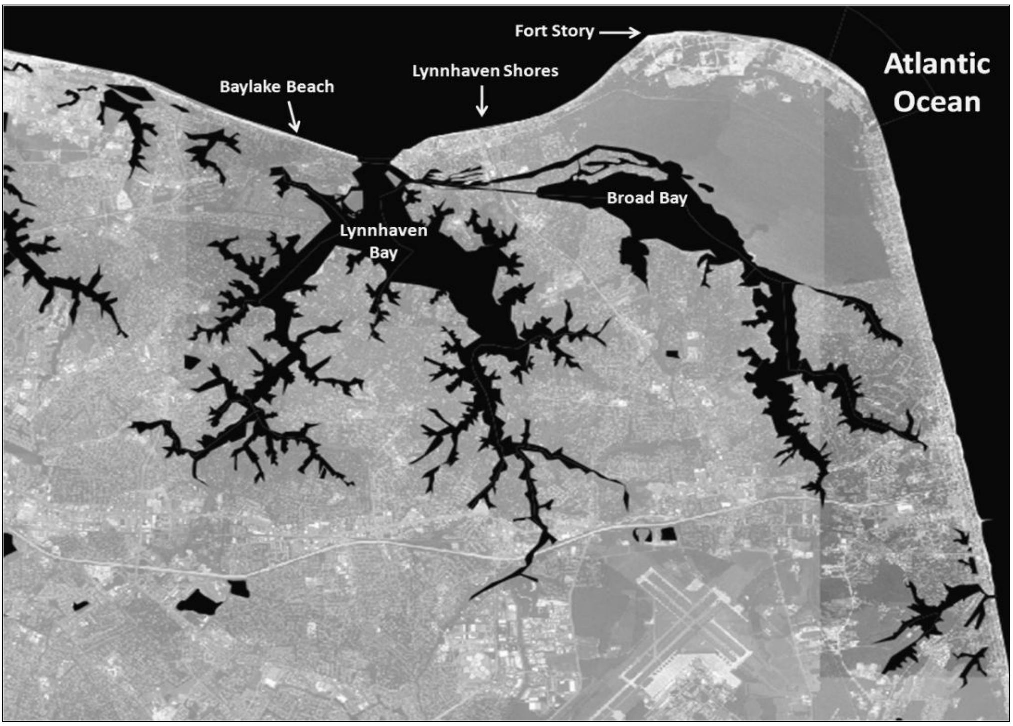

Figure 7-4. Lynnhaven River Watershed, Virginia Beach, VA (Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

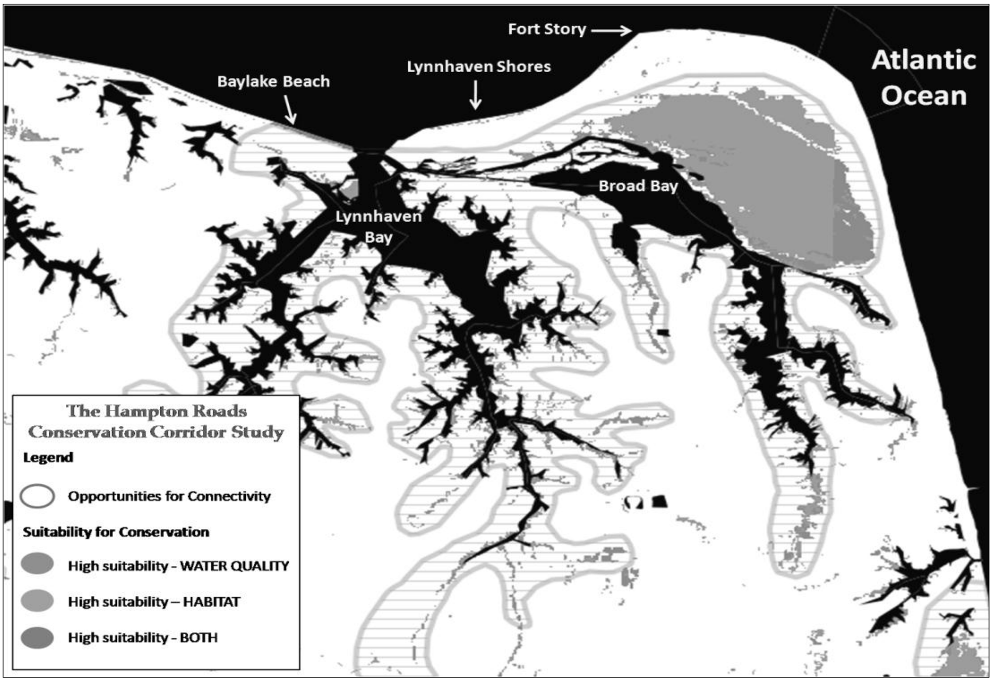

Figure 7-5. Lynnhaven River Watershed with green infrastructure overlay (Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

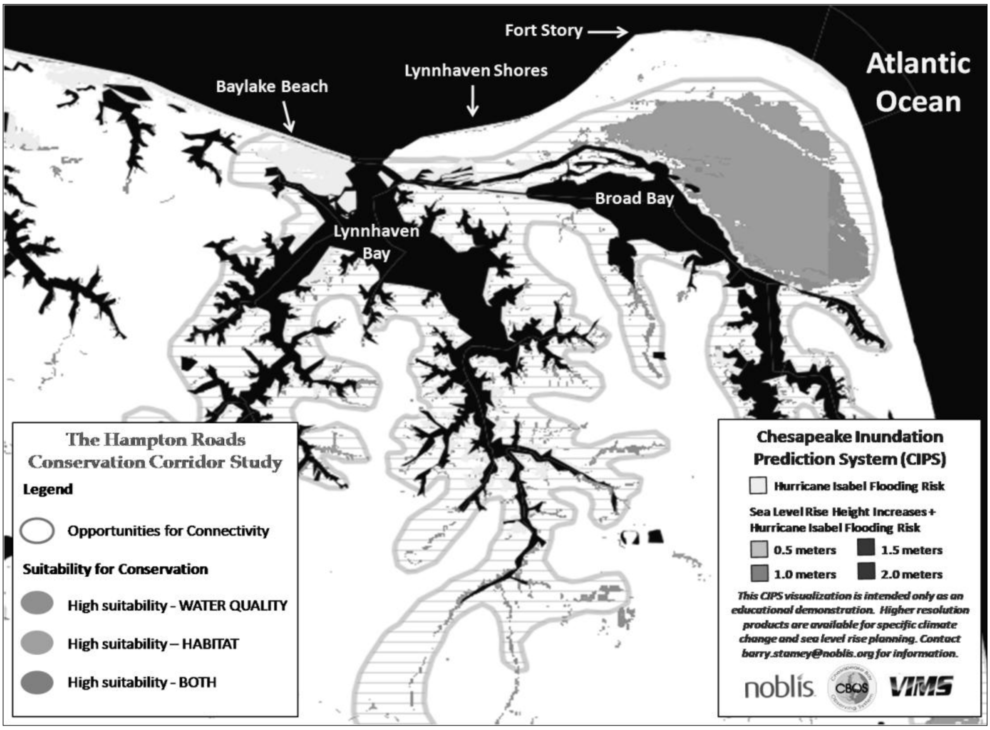

Figure 7-6. Hurricane Isabel Flood Risk (Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

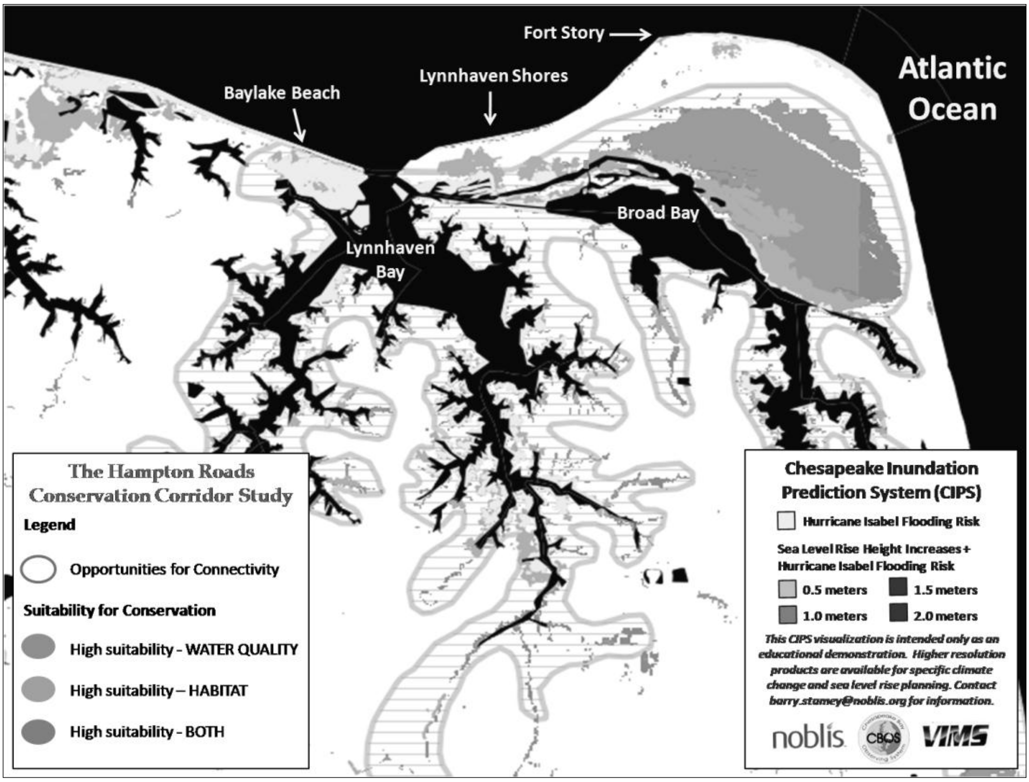

Figure 7-7. Hurricane Isabel Flood Risk plus 0.5-m sea level rise
(Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

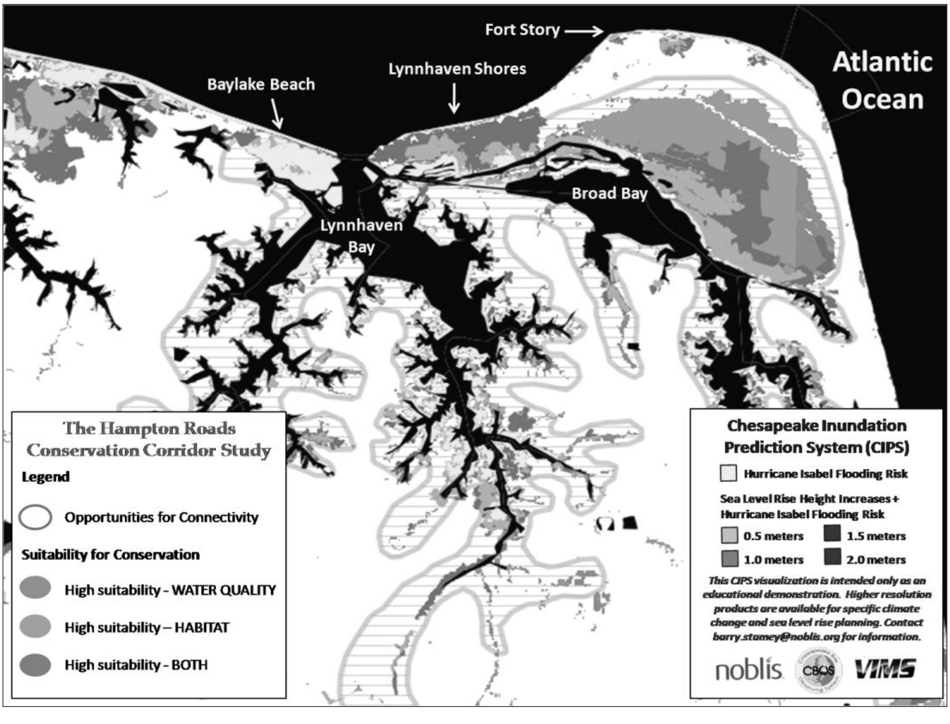

Figure 7-8. Hurricane Isabel Flood Risk plus 1.0-m sea level rise
(Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

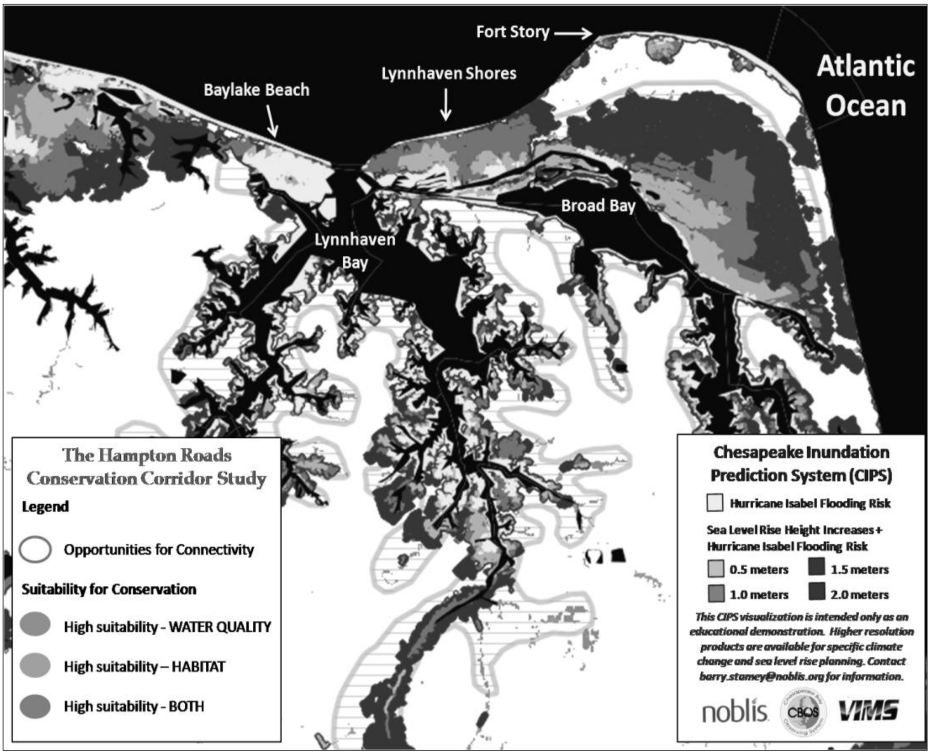

Figure 7-9. Hurricane Isabel Flood Risk plus 1.5-m sea level rise
(Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

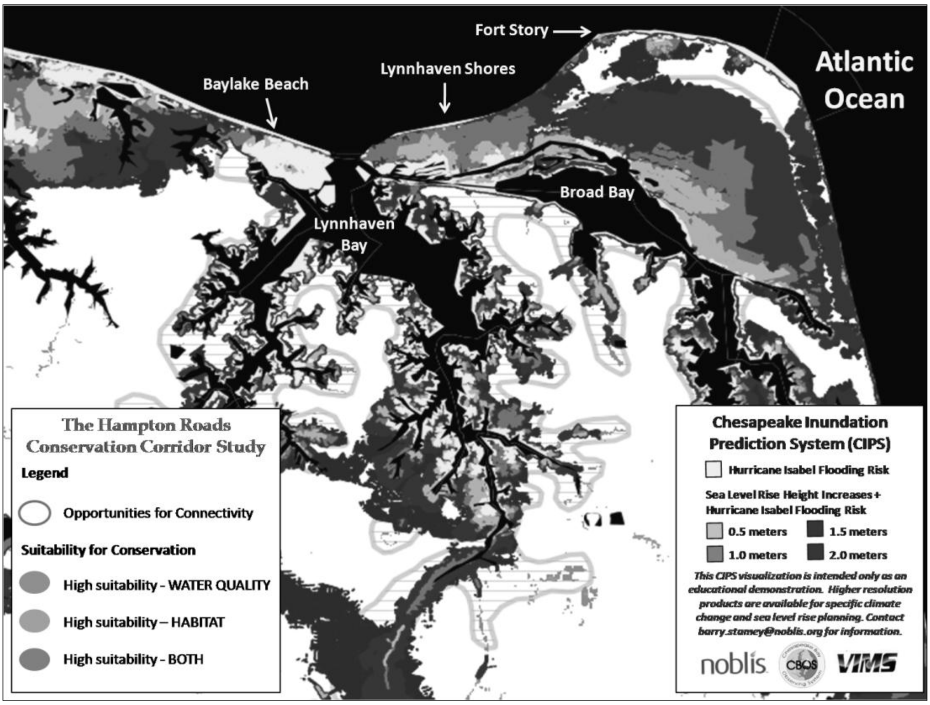

Figure 7-10. Hurricane Isabel Flood Risk plus 2-m sea level rise
(Courtesy of Henry Wang and Barry Stamey, Virginia Institute of Maritime Science)

Resources

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Acknowledgments

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Chapter 8. Sea Level Rise and the Impact of Lesser Storms

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Abstract

Much attention has focused on the impact of major storms on coastal communities and infrastructure along the U.S. coastline. Named hurricanes such as Isabel, Katrina, and Ike have caused enormous damage and pose a considerable threat to coastal regions from the Gulf of Mexico to the Mid-Atlantic states. While lesser unnamed storms, principally extratropical storms (winter storms or nor'easters), lack the destructive power of a major hurricane, they occur more often and produce storm tides that inundate low-lying areas with greater frequency if not greater height. However, one of the consequences of sea level rise is that extratropical storms, which have not caused significant flooding in the past, will begin to do so in the future. The lower Chesapeake Bay region, with land subsidence rates among the highest on the U.S. East Coast, now has relative sea level rise rates in the 4 to 6 mm/year range, making it particularly sensitive to increased flooding with time. Real time data and improved metrics are needed to enable community planners and emergency managers to respond effectively to this threat.

Sea Level: Static or Dynamic?

The issue of sea level rise, like other aspects of climate change, has encountered an attitude of doubt—a reluctance by many among the general public as well as some public figures to accept a disturbing view of the future based on unfamiliar evidence. Even among scientists and engineers who regularly deal with such evidence, there is a tendency to set the issue aside. The well-known concept of the 100-year flood, for example, specifies a water level extreme that has a 1-in-100 chance of occurring in any given year. The question is, will this same statistic hold true 100 years later—or even 10 years later in coastal areas? Almost certainly not in either case. Sea level is in fact dynamic and continually changing in relation to whatever vertical datum is chosen as a reference. The vertical datum can be thought of as sea level made static for a time, either by averaging local measurements over a specific period of years (tidal datum) or by selecting an equipotential gravitational surface that approximates mean sea level at one or more control points (orthometric datum).

In regions where sea level is rising relative to the land, the risk of inundation during tropical storms and hurricanes also increases but at a rate very small in comparison to the water level change due solely to the effects of the storm—the storm surge. A Category 4 hurricane on the Saffir-Simpson Hurricane Wind Scale is capable of producing a storm surge of about 4.0 to 5.5 m (13 to 18 ft.). Not only do these numbers overwhelm relative sea level rise in the short term, they also tend to obscure other forms of water level change including the astronomic tide. Storm tide is the proper term for the observed water level maximum during a storm. It is the sum of storm surge, astronomic tide, and local sea level anomaly. The anomaly in turn consists of subtidal, seasonal, and decadal cycles in water level in combination with relative sea level rise observed at local tide stations.

Global Sea Level Rise

At very long time scales, global (absolute or volumetric) sea level change results from two fundamental processes—change in the total heat content and salinity of the oceans (density or steric change) and water mass exchange between the land and the ocean (e.g., melting of ice sheets grounded on land). Both have received added scrutiny in recent years in the context of a sea level budget. See, for example, Eq. 8-1 (Leuliette and Miller 2009).

$$SL_{total} = SL_{steric} + SL_{mass} \qquad (8\text{-}1)$$

The first term in Eq. 8-1 has been determined directly by satellite altimeter radar measurements that provide both global and regional estimates of sea level rise rate (sea level trend) as shown in Figure 8-1 from the NOAA Laboratory for Satellite Altimetry (http://ibis.grdl.noaa.gov/SAT/slr).

Leuliette and Miller (2009) present data for terms two and three in Eq. 8-1 that produce budget closure in roughly equal amounts, while Cazenave et al. (2009) do so with a larger contribution from term three due to high rates of land ice shrinkage in recent years. While much depends on water mass addition for accelerations in future, globally averaged sea level rise rates, satellite altimetry also reveals that global change is far from uniform as shown in Figure 8-2.

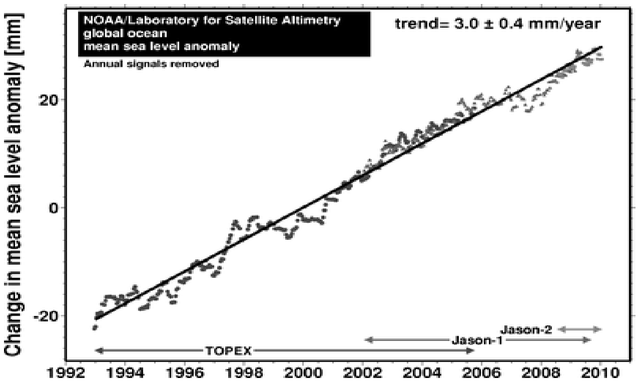

Figure 8-1. Global ocean mean sea level trend from TOPEX, Jason 1 and Jason 2 satellite altimetry. Source: Altimetry data are provided by the NOAA Laboratory for Satellite Altimerty

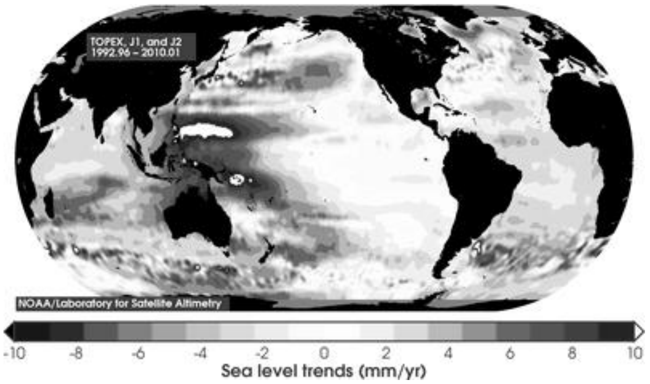

Figure 8-2. Global variation in mean sea level trend from TOPEX, Jason 1 and Jason 2 satellite altimetry. Source: Altimetry data are provided by the NOAA Laboratory for Satellite Altimerty

The variations in mean sea level trend shown in Figure 8-2 in part represent spatial variations in the rate of heat transfer from the atmosphere to the ocean consistent with the empirical relationship between global sea level rise and global mean surface temperature proposed by Rahmstorf (2007). Other studies further suggest non-uniform sea level rise rates due to redistributions of mass locally from glacial ice and ice sheet reductions in Greenland and Antarctica (Mitrovica et al. 2001, Douglas 2008).

Sea Level Change on the Mid-Atlantic Coast

In addition to relative sea level rise, the Mid-Atlantic region of the U.S. East Coast experiences other forms of low-frequency sea level change that contribute to storm tides locally. Although the mean sea level trend value provided by satellite altimetry in this region (2.9 ± 0.4 mm/year) is not significantly different from the global value given in Figure 8-1, there are clear differences in rates of land subsidence along with sea level variance at tidal, sub-tidal, seasonal, interannual, and decadal time scales.

Tidal and Subtidal Change

Astronomic tides exist in response to the gravitational interaction between the earth-moon-sun system and the oceans of the earth. Tides along the U.S. Mid-Atlantic coast are mainly semidiurnal and are an example of a *microtidal* marine environment where the average tidal range is less than 2 m. This stands in sharp contrast to the Bay of Fundy in Nova Scotia where the tidal range may exceed 12 m (40 ft.). Residents there have acclimated to this *macrotidal* regime and built their infrastructure accordingly. Moreover, astronomic dominance makes water levels there very predictable. In the Chesapeake Bay region, they are less so; the astronomic tide usually accounts for less than 70 percent of the total variance in water level in any given month compared to more than 99 percent in the Bay of Fundy. In short, daily water levels in the Chesapeake Bay are not always predictable, no matter how good the astronomic tide model. The reason for this is illustrated in Figure 8-3 where the residual between the observed water level and the astronomic tide consists of quasi-periodic oscillations

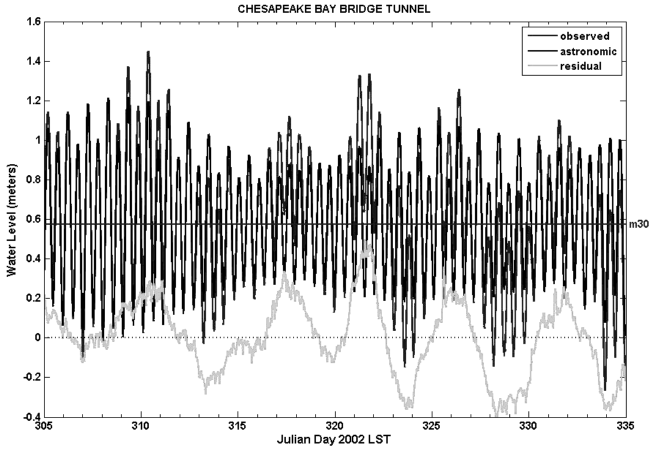

Figure 8-3. Observed, astronomic, and subtidal water level at the Chesapeake Bay Bridge Tunnel, VA.

with amplitudes often approaching those of the astronomic tide itself. The residual or *subtidal oscillation* typically has a variable period of 4 to 6 days and derives from atmospheric forcing associated with the regular passage of weather fronts (Wang 1979). While subtidal oscillations in water level are not predictable, they are easily observed when present—usually during fall, winter, and early spring. Storm surge, which is also induced by weather, appears as part of the subtidal change.

The Seasonal Cycle

Although represented in prediction formulas by a pair of tidal harmonic constituents with periods of 1 and 1.5 years, this cycle represents a steric effect caused by seasonal heating and cooling of the ocean water column. Thermal inertia causes a lag between maximal summer heating and maximal expansion (rise) in water level during fall months with the reverse in winter and spring, which accounts for the annual constituent. From the lower Chesapeake Bay to eastern Florida, there is a semiannual forcing, which appears to be related to variations in the strength of the Florida Current (Sweet et al. 2009). An example of the seasonal cycle is shown in Figure 8-4.

Interannual, Decadal Change

Numerous papers have been published describing sea level variability at decadal time scales on the U.S. East Coast in response to low-frequency forcing by deep ocean wind stress curl (Hong et al. 2000, DiNezio et al. 2009). These are oscillations at variable periods longer than 4 years with amplitudes of 10 to 15 cm (4 to 6 in.). Interannual and decadal change can make a substantial contribution to raised sea level anomalies seen as elevated water level spanning almost the entire East Coast for a month or so as happened in June 2009 (Sweet et al. 2009). Some decadal highs appear to be associated with El Niño events while others do not. Decadal cycles are not predictable but can be observed in monthly mean sea level (MMSL) records (e.g., see Figures 8-4 and 8-5).

Figure 8-4 shows observed MMSL and the seasonal cycle for the past 7 years at Sewells Point in Hampton Roads, VA. The seasonal cycle is represented by the solar annual (Sa) and solar semiannual (Ssa) constituents determined by least squares harmonic fit to MMSL data from 1928 through 2009.

As the Figure 8-4 demonstrates, the seasonal cycle represents an average behavior from which observed MMSL values in any given year can and do deviate substantially. Monthly averaging removes tidal/subtidal change, but low-frequency interannual variability, very low-frequency (decadal), and ultra-low-frequency change (linear trend) remain.

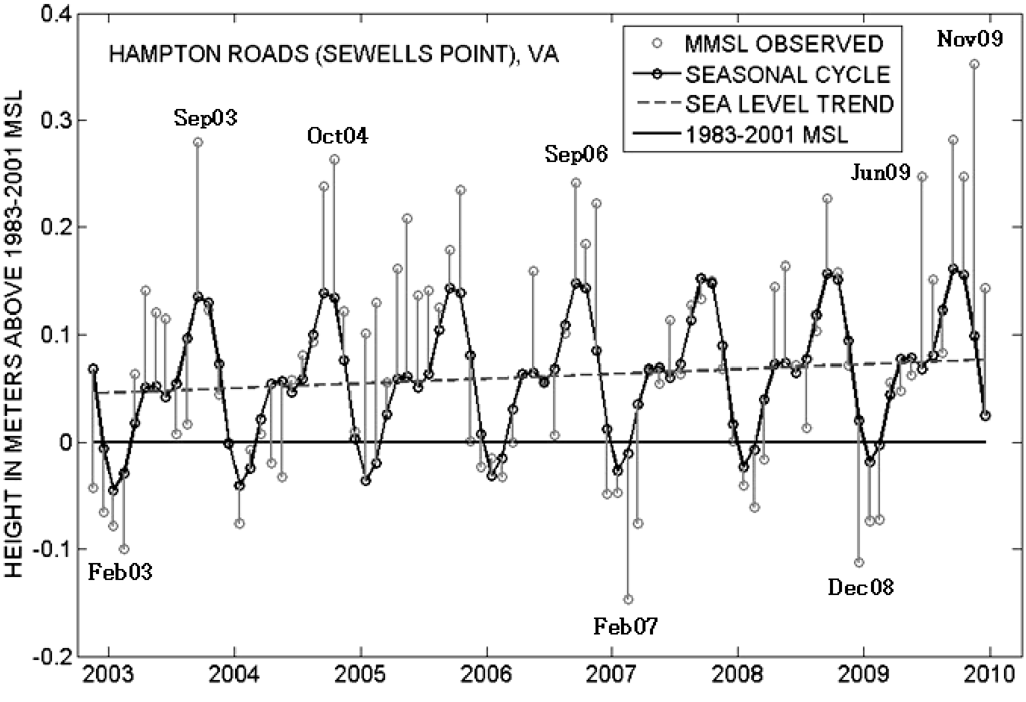

Figure 8-4. Monthly mean sea level, seasonal cycle and sea level trend, 2003-2009 at Hampton Roads, Sewells Point, VA

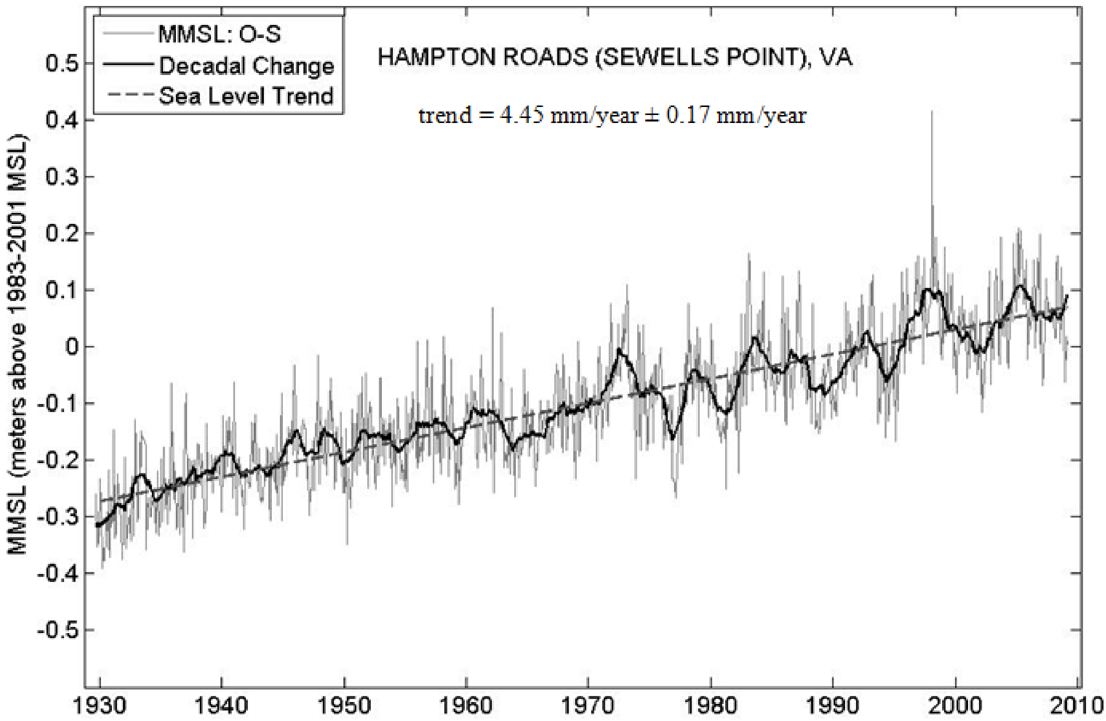

Figure 8-5. Monthly mean sea level (seasonal cycle removed), decadal change and sea level trend from 1928 through 2009 at Hampton Roads, Sewells Point, VA

Relative Sea Level Trend

The sea level trend shown in Figure 8-4 was obtained by least squares fit to the 1928-2009 MMSL series at Sewells Point. Both trend and the decadal change can be seen more clearly in Figure 8-5. Decadal change was obtained here by applying a 19-month moving average to the Sewells Point series with seasonal cycle and trend removed. Trend plus decadal change were added back to the original observations minus the seasonal cycle (O-S) to obtain the display in Figure 8-5.

The trend for Sewells Point, shown in Figures 8-5 and 8-6, is the relative trend based on the longest record now available, which indicates 4.45 mm/year of sea level rise relative to the land. Relative trends at other nearby locations are somewhat less (Zervas 2009) but are still greater than the 20th century global estimate (1.7 mm/year), suggesting a land subsidence rate of up to 2.7 mm/year or about 61 percent of the relative rise at Sewells Point.

Defining an Anomaly for Sea Level

An anomaly can be defined in different ways, but it is basically a deviation from what is considered normal. Over the course of geologic time sea levels have been much lower than today, but they have also been higher, which complicates our concept of normal sea level. At present time, we have chosen to be guided by celestial cycles of the moon and sun; the mean solar day for standard time and the lunar month repeating phases of the moon are two examples. With astronomic tides being dominated by lunar attractive forces, it is not surprising that they vary over the lunar month as well as over much longer cycles including the 18.6-year regression of the lunar nodes. To avoid fractional sampling of the seasonal cycle, the National Ocean Service (NOS) has chosen to average tides over a 19-year interval known as the National Tidal Datum Epoch (NTDE). The NTDE names a specific 19-year series, which is used to officially define the tidal datum of mean sea level (MSL) among other datums, such as mean higher high water (MHHW) and mean lower low water (MLLW). Because sea level continues to change at most locations, the NTDE is updated as needed roughly every 20 years but more often in regions undergoing rapid subsidence. The present NTDE includes the years 1983 to 2001. As both a definition and ongoing measure of normal sea level, MSL is a readily available and very convenient candidate in U.S. waters.

An Anomaly Based on the Lunar Month

When setting out to separate normal from abnormal sea level, the lunar month makes a good choice because it separates most of the predictable components from most of the unpredictable components of sea level change.

A lunar month marking the recurrence of lunar phases is 29.53 mean solar days in length, which is quite close to 30, the average number of days in the calendar month. Selecting 30 days as an averaging period for water levels effectively removes the astronomic tide including both its diurnal and semidiurnal components as well as the main solar-lunar conjunctive cycle (spring-neap cycle) and lunar declination and distance cycles (tropic-equatorial, apogean-perigean tides)—all of which are very predictable. Not so predictable are the subtidal oscillations (and storm surge) described previously, but a 30-day window depicts them quite clearly through the zero-mean residual appearing in graphs such as Figure 8-3. The 30-day average in turn tracks the seasonal cycle, the interannual and decadal change, and the relative sea level trend.

New Metrics for Sea Level Change in Near-Real Time

With the exception of the seasonal cycle, the sea level components listed above are unpredictable. However, each one represents a distinct geophysical process simultaneously combining with others to produce an anomaly that changes slowly with time in keeping with the processes involved. Well before a forecast tropical or extratropical storm reaches an area, it is useful to know whether local water levels are already elevated, and by how much, as the storm arrives.

m30-MSL

With my colleagues John Brubaker and David Forrest at the Virginia Institute of Marine Science (VIMS), I have proposed the use of a 30-day running mean at active stations that display unverified water levels logged at 6-minute intervals in near-real time. Designating this mean by the symbol *m30*, our sea level anomaly is defined as *m30-MSL*, simply the deviation of monthly mean sea level from long-term mean sea level as defined by NOAA for the current NTDE. We presently display this metric in near-real time at eight active water level stations in lower Chesapeake Bay (six NOAA stations and two active VIMS stations) at www.vims.edu/tidewatch. While this metric is intended specifically for near-real time applications, its equivalent can easily be found using MMSL for the calendar month in place of m30 for any past month and year. NOAA maintains an extensive inventory of MMSL data that can be referenced to MSL directly at www.tidesandcurrents.noaa.gov.

Extratidal Water Level: HAT and LAT

The MLLW tidal datum is also known as the chart datum below which soundings are given on nautical charts for U.S. waters. In other countries, notably the United Kingdom, the datum of lowest astronomical tide (LAT)—the lowest *predicted* water level at a given location—is used as the chart datum. Both are a practical means of ensuring navigators that they have the sounding depth indicated even at lowest tide levels. This advantage would be quickly lost, however, if the high water counterpart—MHHW or highest astronomical tide (HAT)—were used as the chart datum. A navigator in that case would have to pay strict attention to changes in tidal stage and tidal range when underway in regions with shallow depths. In the reverse situation where flood risk is paramount, it makes sense to use a higher datum, such as MHHW or preferably HAT, as the metric for referencing storm tides. For example, a storm tide forecast of 6 m (20 ft.) above MLLW will mean quite different things to a waterfront property owner in Gulfport, Mississippi, than an owner in Eastport, Maine, given the 11-fold difference in diurnal range (MHHW-MLLW) at these locations. By specifying storm tide heights in meters (feet) above HAT, the difference in tidal range is taken into account.

Tide table predictions published months in advance must of necessity be generated relative to a fixed tidal datum. Whether MLLW, LAT, or any other offset from MSL is used as a reference, predicted hourly heights will appear to oscillate about the MSL datum. Once an accepted set of tidal harmonic constants have been obtained through harmonic analysis at a given tide station, then a unique HAT and LAT emerge as offsets from MSL at that station after generating predictions over the 19-year period of the current NTDE. Water levels that exceed these datums in either direction are by definition *extratidal* as opposed to intertidal.

Problems of flooding do not really begin until water levels exceed HAT and become extratidal. They can do so in three ways due to three processes that occur in combination with the astronomic tide:

1. Storm surge
2. Subtidal change
3. Sea level anomaly

Figure 8-6, a computer graphic from www.vims.edu/tidewatch (the Virginia Institute of Marine Science uses English units) shows the behavior of all three processes in a moving 30-day window. Figure 8-6 covers the month of June 2009 at Sewells Point, VA, during which an elevated sea level anomaly warning was issued by NOAA National Ocean Service for the U.S. East Coast (Sweet et al. 2009). The m30-MSL anomaly shown in Figure 8-6 for this period is 0.82 feet (=2.17-1.35) or 25 cm. The extratidal maximum noted on June 22 (XHW=0.78 feet or 24 cm) is almost entirely due to the anomaly in combination with a perigean-spring tide since there was no storm during June 2009, and the subtidal oscillation was muted.

Real Time Astronomic Tide (referenced to m30)

Note that the astronomic tide shown in Figure 8-6 also rises above the HAT level at times. This may seem contradictory; however, HAT is a fixed tidal datum, an offset from the MSL tidal datum. Unless local tidal characteristics undergo a significant change, HAT will not change until MSL itself is revised upward under a new NTDE prompted by sea level rise. Actual astronomic tides, unlike predicted ones, need not be constrained to oscillate about MSL when processing water levels in near-real time (e.g., half-hourly updates). Moreover, when MSL is used as the reference level, the residual (observed minus predicted) is often labeled as storm surge when, in fact, that residual contains all three processes undifferentiated. If m30 is taken as the reference, then short-term change on a time scale of hours and days (storm surge, subtidal change) can be effectively separated from long-term change on a scale of months and years (interannual, decadal change; sea level trend). An example of long-term change in Hampton Roads occurred over the 70 years between the August 1933 "storm of the century" and hurricane Isabel in September 2003; relative sea level rise was the major contributor to a 43 cm (1.4 ft.) difference in sea level anomaly based on the m30 values compared to MSL for the 1983-2001 NTDE (Boon 2005).

Astronomic tides referenced to m30 can be derived in two ways: (1) time local harmonic analysis of continually updated 30-day water level time series or (2) harmonic predictions with tidal harmonic constants obtained from a single analysis of a longer (e.g., 369-day) series. In the latter case, the solar annual (Sa) and solar semiannual (Ssa) tidal constituents representing the seasonal cycle (see Figure 8-4) are not included in the predictions since the running 30-day mean (m30) captures the actual variability at those periods.

Storm Surge in Perspective

While sea level anomalies and the subtidal change have important roles to play, there is little doubt that storm surge is the major process driving the threat of inundation in most coastal regions. However, the threat is quite different for tropical versus extratropical storms. Tropical storms and hurricanes produce the highest storm surge but do so typically over a smaller region and a shorter time interval compared to extratropical storms, which may affect extended areas within a 100-mile radius for more than 1 day.

The most recent extratropical storm to visit the Chesapeake Bay area occurred over a 3-day period, November 11-13, 2009. Figure 8-7 shows a 30-day window for Money Point, Virginia, on the Southern Branch of the Elizabeth River, including 30-day (7a) and 3-day plots (7b). The storm began shortly after 8:00 p.m. LST on November 10 with the subtidal variation near a low of -40 cm (-1.3 ft.), offset almost exactly by a positive sea level anomaly of the same amount. From that time onward the residual rose uninterrupted approximately 2 m (6.5 ft.) before reaching its peak on the night of November 12. Should this be called a 2-m storm surge, or is a part of that rise simply a continuation of the ongoing subtidal oscillation? These questions arise because there is no clear distinction or cutoff point between the two weather-induced, transient oscillations in either the time domain or the frequency domain. To put the storm tide in perspective, three of the four highest high water heights recorded at Money Point occurred during the November 2009 nor'easter; the highest occurred during the night of November 12, 2009, and the second highest was recorded during hurricane Isabel on September 18, 2003.

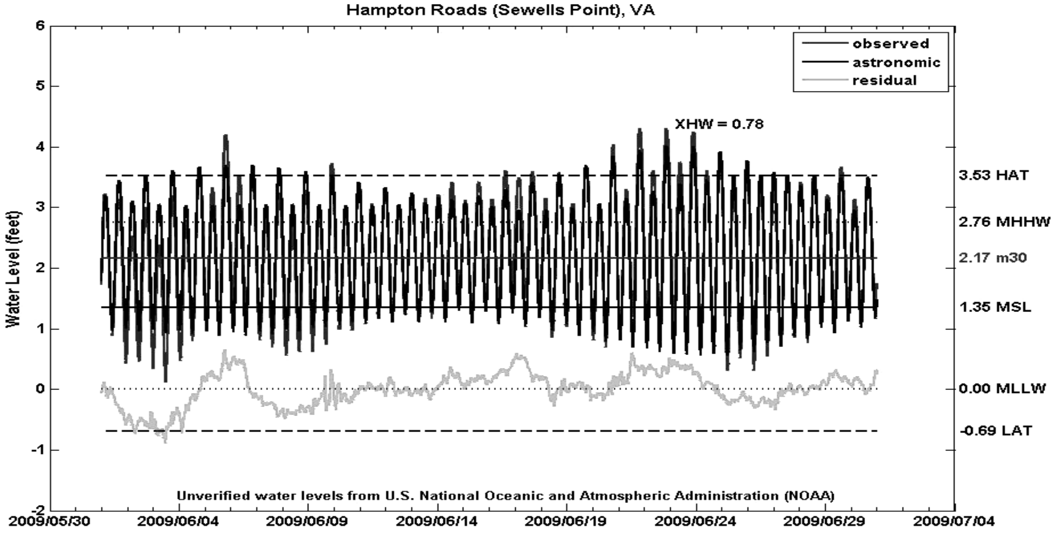

Figure 8-6. Thirty-day plot of water levels at Sewells Point, VA, June 2009

Storm Tide Rankings, Hampton Roads

The water level station at Sewells Point in Hampton Roads is one of the primary stations in the NOAA National Water Level Observation Network (NWLON). It has been carefully maintained since 1927and has one of the longest continuous records in the East Coast region. Table 8-1 presents the 10 highest water levels recorded there between 1928 and 2009, ranked according to height in feet above HAT[1]. Although the extratidal water levels ranked 1 and 2 in this table were produced by hurricanes, they were closely followed by three more ranked 3, 4, and 5 from the same extratropical storm in November 2009. Of the 10 highest extratidal water levels, seven were produced by extratropical events.

At Money Point, the maximum extratidal storm tide height during the November extratropical storm (4.69 ft., Figure 8-7b.) actually exceeded the extratidal height of 4.43 ft. observed there during hurricane Isabel.

Water-Level Stations Still Needed

Years of continuous water level observations at NWLON stations have provided crucial information about storm tide risk, including not just a tabulation of the highest extremes experienced in the past but the underlying processes that caused them—processes like those discussed in this paper ranging from local tidal characteristics and land subsidence to ocean-atmosphere interactions and global sea level rise.

It is tempting going forward to label these measurements old technology superseded by satellite observations and computer models. Were it not for navigational needs, many tide stations might not have been established or maintained over a century or more.

What are often labeled storm surge models are actually total water level models forced by the astronomic tide at the open boundary, bundled with additional forcing derived from forecast surface winds and atmospheric pressure over the model domain, plus forecast river inflow in some regions. However, hydrodynamic models in coastal areas are particularly sensitive to changes in wind speed and direction—changes that can easily occur during the 6-hour interval that most models require before updating their forecast. Under these circumstances, local water level observations are needed to verify model predictions in near-real time—in addition to the usual verification after the event. Post-storm analysis, however, should do more than facilitate model verification. It should provide an improved understanding of the reasons why a given storm tide presented in the way that it did. Coastal planners and emergency managers should be aware of this information and take advantage of it during future storm events.

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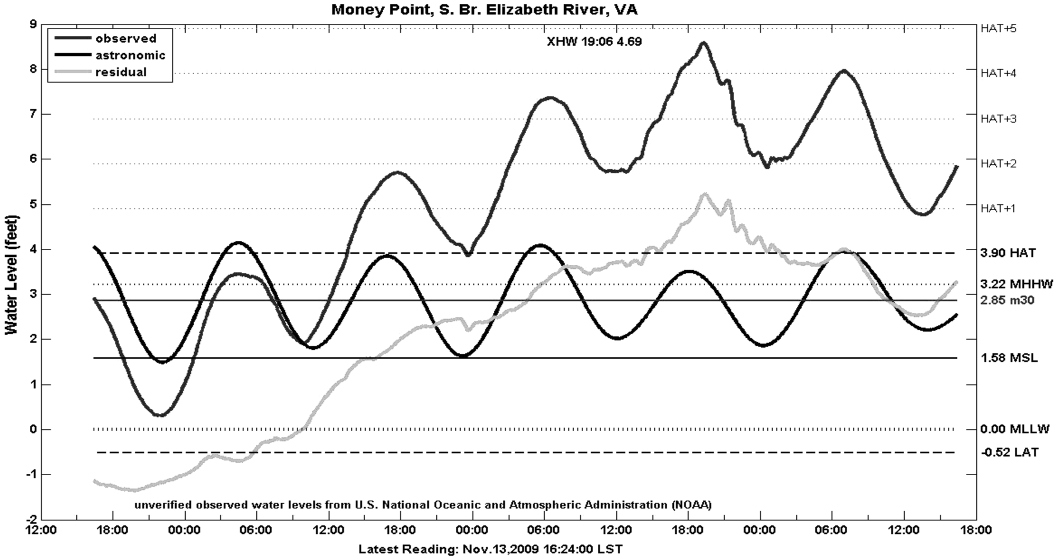
[1] The HAT-MSL offset at Sewells Point was determined from a VIMS analysis, not analysis by OAA/NOS.

Table 8-1. Extratidal Water Levels at Sewells Point

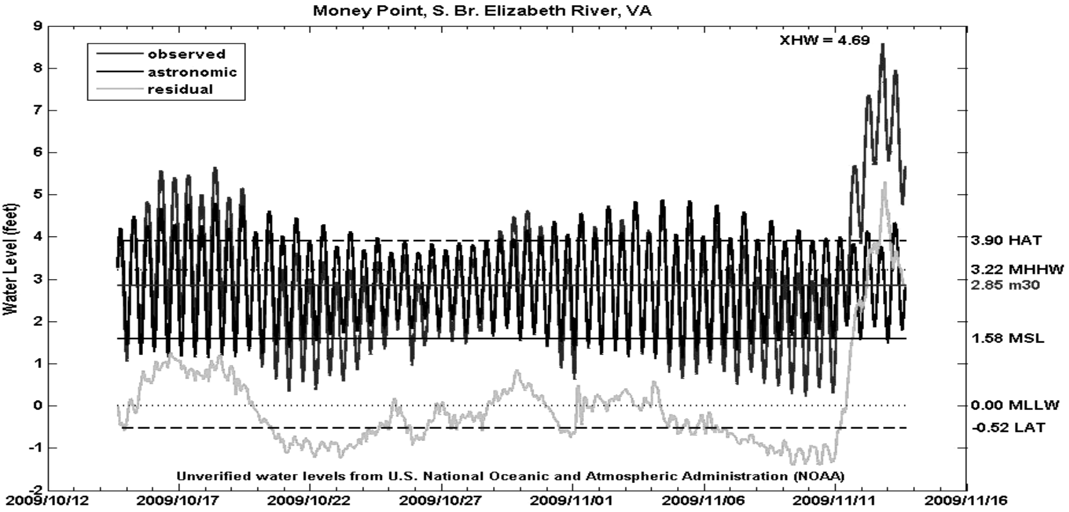
Rank	High[2]	Date	Time	Storm
1	4.49	19330823	09:18 LST	hurricane
2	4.36	20030918	16:00 LST	hurricane
3	4.20	20091112	18:18 LST	extratropical
4	3.79	20091113	06:12 LST	extratropical
5	3.69	19620307	10:00 LST	extratropical
6	3.20	20091112	06:00 LST	hurricane
7	3.19	19360918	10:00 LST	extratropical
8	3.10	20061122	10:06 LST	extratropical
9	3.05	19980205	04:00 LST	extratropical
10	2.99	20061007	08:42 LST	extratropical

[2] Height in feet above HAT

Water level observing stations today are by no means lacking in new technology. New microwave radar sensors that have no physical contact with the water will shortly replace older, contact-type sensors that are more costly to install and maintain. In addition, NOAA/NOS have developed a new single-pile instrumentation platform (SPIP) to ensure survival and obtain water level and meteorological measurements under the most extreme conditions. An example is the 7.6-m (25-ft.) NOAA Sentinel installed in Bay Waveland, Mississippi. The system, shown in Figure 8-8, replaces an NWLON station destroyed during hurricane Katrina in 2005. This particular SPIP is designed to withstand a Category 4 hurricane, but others could be designed at a different scale for lesser storms likely to be encountered in other regions.



(a) Three day



(b) Water level records

Figure 8-7. Thirty-day (**a**) and 3-day (**b**) water level records ending November 13, 2009, Money Point, VA

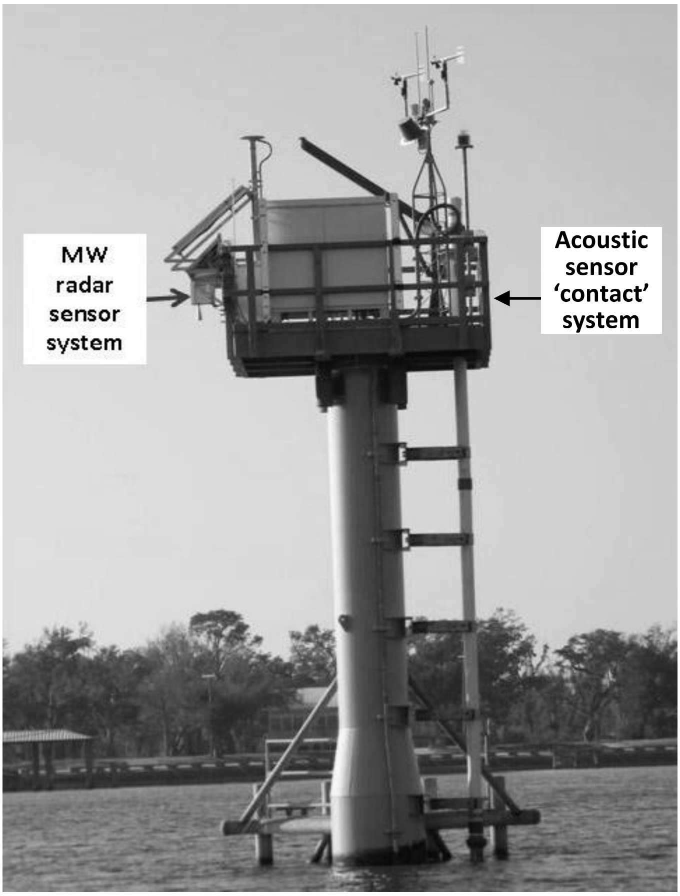


Figure 8-8. NOAA/NOS Sentinel with microwave radar and acoustic water level sensor systems, Bay Waveland, MS. (Used with permission from NOAA.)

Conclusions

Category 3 to 5 hurricanes on the Saffir-Simpson scale are capable of inflicting unimaginable damage in the locales most at risk of encountering them, most prominently the Gulf of Mexico and the east coast of Florida. Elsewhere on the U.S. East Coast, lesser storms are predominant, including Category 1 to 3 hurricanes and extratropical storms or nor’easters. In the Chesapeake Bay within the Mid-Atlantic coastal region, only three hurricanes have made the “top 10” list of extreme water levels experienced at Hampton Roads since 1928; the remainder were extratropical storms. Hurricane Isabel in September 2003 and an unnamed hurricane in August 1933 are most frequently cited not only for the high water levels they produced but also for the extreme wind- and wave-induced damage that accompanied them. With some exceptions, extratropical storms are more often remembered as nuisance events because, while they are not as physically destructive and life threatening as hurricanes, they are fully capable of flooding infrastructure (parked cars, homes, businesses) by a few inches to a few feet of water in low-lying areas. Timely warnings allow cars to be moved and homes and businesses to be prepared for high water.

Amid the present climate change debate, some aspects of future risk, for example, an increase in storm frequency, may remain unclear. Sea level, however, is clearly dynamic. There can be little doubt that sea level trends along the Mid-Atlantic coast will continue upward at 3 to 6 mm/year relative to the land with higher rates not at all unlikely in the decades ahead. Given this scenario, coastal inundation caused by ordinary winter storms as well as major storms will take on greater importance. A more complete understanding of risk in this instance must proceed with the recognition that storm tides consist of more than storm surge alone. We must recognize that an added, probabilistic element exists in every extratropical storm and given the unfolding combination of astronomic tide, storm surge, and sea level anomaly the resulting storm tide may surprise us in some sub-regions much more than others. For this reason it will pay to have an operational water level station near those communities most at risk and advise emergency managers on how best to use the information obtained from it in near-real time.

Acknowledgments

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Chapter 9. Vulnerability and Governance for Adapting to Sea Level Rise

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Abstract

This paper summarizes the roles of the federal and state governments in promoting adaptation to sea level rise. It identifies a number of areas in which states require federal support to promote adaptation to sea level rise and potential support mechanisms. Given that federal climate change legislation is stalled for the near future, this paper suggests that the scientific and engineering communities can play a role in reducing coastal vulnerability. Ultimately, this paper concludes that the primary challenge in adapting to rising sea levels will be promoting the adoption of governance structures that can adapt to handle changing social and environmental conditions as sea level rise is experienced. To achieve that goal, the federal government's efforts should be focused on providing an overarching adaptation strategy along with appropriate information and incentives to foster state capacity building.

Introduction

According to Intergovernmental Panel on Climate Change (IPCC) estimates, sea levels will rise between 0.18 and 0.6 m by 2100 (IPCC 2007). More recent studies suggest that actual sea level rise by the end of the century is likely to be closer to 1 m (Vermeer & Rhamstorf 2009). This rise in sea level will result in the loss of substantial amounts of coastal land and associated ecosystems and infrastructure (Adger et al. 2007). While the impacts of rising sea levels will certainly be significant, the fact that large-scale inundations will not happen for many years makes it difficult for governments to generate sufficient political will to engage in climate change adaptation today that will reduce vulnerability to sea level rise impacts in the future. This paper introduces the concept of socio-economic vulnerability as a decision-making tool for sea level rise planning and examines the roles of the states and the federal government in reducing vulnerability to sea level rise. It also highlights the governance challenges associated with promoting adaptation to sea level rise and considers the appropriate role of the federal government in facilitating sea level rise adaptation.

Fundamentally, there are two broad approaches that policy-makers can take in adapting to sea level rise. They can choose to hold the line through a combination of engineering measures, or they can pursue realignment. Holding the line through coastal engineering often involves employing a variety of hard structures to protect particular sections of the coastline. In addition, holding the line can be achieved through the use of soft engineering, such as continued beach nourishment to replenish eroding shorelines. In contrast, managed realignment is a term that refers to a broad variety of approaches used to pull populations away from the coastline and make space for rising seas.

This paper assumes that different responses to sea level rise will be appropriate along different sections of the coast. Over time, we simply cannot afford the types of massive protection structures and significant investments in nourishment that would be required to maintain the entire coastline in its present position. However, there are sections of the coast that have particular strategic, commercial, or cultural significance that we may simply be unwilling to cede to rising seas. Consequently, the fundamental governance challenge in adapting to rising sea levels lies in crafting institutions that can critically examine our coastal assets and employ the best combination of defense and retreat to protect strategic, cultural, and natural resources from the threat of rising sea levels.

I propose a vulnerability approach to decision-making that enables local governments to comprehensively assess the risks posed by climate change and weigh adaptation options. As described below, this approach calls on the federal government to provide leadership and facilitate state and local actions to adapt to sea level rise.

Defining Vulnerability

Adaptation is broadly defined as any activity that seeks to decrease a system's vulnerability to climate change. Vulnerability, in turn, is a measure of society's inability to cope with shifts in climate patterns and the resulting changes in environmental conditions and resource availability (Adger et al. 2007). This definition, employed by the IPCC, recognizes that vulnerability to climate change is the result of a combination of factors related to exposure to natural hazards and the societal mechanisms to deal with the hazard exposure (adaptation). It recognizes that both natural and social factors contribute to vulnerability.

To illustrate the two prongs of vulnerability, consider the case of a low-lying coastal plain. From a natural hazards perspective, the low-lying coastal plain is vulnerable to climate change because there is a risk that it will become inundated as sea levels rise. This risk of inundation is a vulnerability that exists as a baseline environmental condition resulting from exposure to external physical forces. Under a natural hazards conception, vulnerability is defined as the exposure of a system to exogenous destabilizing forces, particularly severe weather events and long-term climatic shifts (Brooks et al. 2005).

This baseline vulnerability to sea level rise resulting from natural hazard exposure may be further exacerbated by increased building in the coastal zone, raising the number of lives and value of properties at risk. While natural hazard exposure is thus increased, the impact on social vulnerability will depend on the mechanisms of coastal governance that are available to respond to the impacts of climate change. That is, coastal communities may create an array of social and economic institutions that lower their exposure to climate change risks even where physical exposure to natural hazards is increased.

Attempting to encapsulate these social and environmental factors, the wider vulnerability literature tends to recognize three key elements of vulnerability: (1) exposure to natural hazards; (2) resilience; and (3) adaptive capacity (Adger 2006, McFadden et al. 2007). Even if all greenhouse gas emissions had been halted in 2000, the committed warming we have yet to experience is projected to result in an additional 12 to 13 cm of sea level rise (Meehl et al 2005). Given that global greenhouse gas emissions have increased over the last decade, natural hazard exposure due to sea level rise will only increase for the foreseeable future. Consequently, near-term vulnerability reduction efforts must focus on improving the resilience and adaptive capacity of coastal communities or seek to reduce natural hazard exposure by physically moving people out of the coastal zone.

Adaptive capacity is a term that defines the ability of a society to choose among various adaptation options (Klein et al. 2003). Adaptive capacity is increased by equipping societies with the tools they need to understand the ultimate effects of climate change, the adaptation options available, and the costs and benefits of each option. Thus, building adaptive capacity is a combined scientific and social process through which observations about climate change impacts are noted and studies on potential policy and engineering solutions are conducted and shared with the coastal community. Adaptive capacity is then built when policy-makers and community members engage these options and begin the process of determining how they will respond to particular climate change outcomes.

In the context of rising sea levels, adaptive capacity may be developed by gaining a better understanding of the range of engineering and retreat options available to coastal communities. Over time as these options are more thoroughly studied, coastal communities and policy-makers will be better able to evaluate the relative merits of coastal defense structures and retreat. This evaluation is an inherently social/political process in which policy-makers and their constituents will be forced to define which elements of the coastal zone—whether ecosystems or the built environment—are worthy of protection and to determine how these valued elements will be protected. Therefore, the development of adaptive capacity is the creation of governance structures that can generate and communicate scientific information about climate change in a way that it can be used to make policy decisions reflecting the collective social values of coastal constituents.

Resilience, a concept borrowed from ecology, is the measure of a system's ability to withstand disturbance and remain stable (Gunderson 2000). Ecologists have broadly used resilience as a management concept that aims to preserve the robustness of natural systems so they can recover from stresses and retain their productivity. For example, natural resources managers often aim for redundancy of functional ecological groups so that a decline in a single species will not cause the whole system to collapse (Levin and Lubchenco 2008).

Similarly, in social systems, resilience is a measure of the ability of communities to withstand disturbances. Because it is defined at the community level, social resilience is a measure of the social capital of societies and communities (Adger 2000). Social resilience looks to the broadly defined institutions of a society and examines their ability to withstand disturbance. Social resilience can thus be characterized by a variety of factors including inclusivity of a governance system, the willingness of citizens to trust their leaders, and the ability of institutions to respond and adapt to disturbances (Adger 2000).

In some cases, promoting ecological and social resilience may result in the same vulnerability reduction strategies. For example, communities concerned about protection from flooding and storm surge may choose to address these concerns by promoting the ecological resilience of fringing wetlands or mangrove systems. Properly conserving these barrier ecosystems enhances ecological resilience by promoting ecosystem health, thereby increasing the ability of the system to recover from a later environmental disturbance. At the same time, wetland and mangrove systems can constitute an important natural flood barrier, which can increase the ability of the built environment to withstand storm surge events.

However, it is important to note that there are alternative institutions for promoting social resilience that do not necessarily lead to positive outcomes for ecological communities. For example, a community concerned about coastal flooding could choose to build seawalls and insure all properties against flood risk. While the community with seawalls may have greater exposure to natural hazards because it has eliminated its natural source of flood protection, it may be equally resilient if it has sufficient insurance to cover the costs of rebuilding in the event of catastrophic flood losses. This community would be equally resilient from a social perspective because it has created a series of social and economic institutions that enable it to rebuild and recover from the impacts of flood damage. However, this community has clearly increased its exposure to natural hazards and, depending on the ability of its social and financial systems to sustain repetitive economic and property losses, it may become less resilient over time.

This example reveals that to preserve both natural and built environments, policymakers should adopt a socio-ecological vulnerability framework to guide their decisions. Such a framework requires an explicit valuation of both human and natural resources and an understanding of how to build mutually robust systems. In the coastal wetlands example, a socio-ecological vulnerability approach would counsel that the most robust systems are those that seek to preserve the ecosystem services of wetlands and use them as a tool to reduce societal exposure to natural hazards resulting from inundation.

When considering climate change governance frameworks to adapt to sea level rise, remember that even the best coastal engineering solutions cannot protect the entire coastline. Over time, it simply becomes too costly to armor the whole coast or engage in the type of large-scale, systematic nourishment necessary to hold the line. Consequently regardless of the near-term approach coastal governments choose to protect eroding shores, the fundamentally different threat of gradual inundation from sea level rise will eventually require some amount of coastal retreat. The question then becomes whether policy-makers will choose to sacrifice coastal ecosystems near term to prolong the useable life of all developed coastal environments or if they will choose to engage in substantive planning to create a matrix of solutions that are appropriate for different areas of the coast. This latter approach is precisely what the socio-ecological model of vulnerability calls for. Under this model, policy-makers would consider the threats to both ecosystems and societal systems from disruptions due to climate change. In assessing the threats to both systems, policy-makers should identify key vulnerabilities ranging from loss of critical ecosystems to the gradual inundation of places of cultural or economic significance. They should then engage in a public process to determine which areas are particularly important to protect and define the engineering and policy solutions needed to protect them.

An example of this approach is the California Bay Conservation and Development Commission's (BCDC) efforts to start a dialogue about the impacts of sea level rise in the San Francisco Bay. According to BCDC's projections, sea level rise in the area will subject land currently in the 100-year flood plain to an extreme high tide by 2050 (BCDC 2009). If these projections are correct, both the San Francisco and Oakland Airports would be completely underwater by the end of the century, and valuable bay wetlands could be lost to coastal squeeze. Recognizing that these outcomes are undesirable for a variety of economic, social, and ecological reasons, BCDC is beginning a discussion with other state and local officials to determine which parts of the bay's shoreline and critical infrastructure must be protected and which areas may be appropriate for the implementation of retreat policies.

Limitations on the Ability of Governments to Reduce Vulnerability to Sea Level Rise

Using the process outlined above, coastal governments employing a socio-economic vulnerability approach can take steps to reduce their exposure to the hazards of sea level rise. Using the socio-economic vulnerability approach, a key aspect of structuring the societal response is a comprehensive social dialogue about the potential responses to coastal inundation. In this dialogue, two of the most important factors shaping government responses to sea level rise are the underlying legal mandates that structure government authority and political pressures, particularly from littoral property owners who may lose their homes.

The most important limitations on governments' ability to reduce vulnerability to sea level rise stem from legal and political limitations on telling private landowners what they can do with their property. As discussed above, one of the clearest and most comprehensive methods of reducing natural hazard exposure to sea level rise is simply to move people out of the coastal zone. However, the takings protection of the Fifth Amendment imposes a significant limitation on government's ability to force people to move out of areas with high natural hazard exposure.

The Fifth Amendment provides that the government may not take private property without providing just compensation. Historically, the Fifth Amendment was understood to apply to permanent physical occupations of land. This means that if the government wants to physically move people off private property at risk of inundation, it must pay them the fair market value for that property (United States v. 50 Acres of Land). Clearly, the costs associated with physical takings limit government's ability to require people to move out of areas that are vulnerable to the impacts of sea level rise.

Perhaps more troubling to coastal policy-makers, the takings doctrine also imposes limitations on the ability of the state to regulate coastal development. While the Supreme Court has recognized that states and localities may constitutionally impose zoning restrictions that are, on net, mutually beneficial to their constituents (Schwartz 2003), the Court was also quick to recognize that some regulations, while stopping short of physically appropriating land, will "go too far" and must also be recognized as takings (Pennsylvania Coal v. Mahon). These regulatory takings were most famously recognized in the coastal context in the case of *Lucas v. South Carolina Coastal Council*.

In *Lucas*, a coastal property owner claimed that the State of South Carolina had taken his property by regulation. The property owner had purchased several parcels of land on the South Carolina coast for future development. Between the time of his purchase and his initial permit application for construction on one of the lots, South Carolina passed its Beachfront Management Act, which imposed coastal erosion setbacks on all new development. When the erosion setback was applied to the Lucas property, the resulting lot was too small to build on, so the Coastal Council denied his application for a construction permit. Appealing this denial all the way to the Supreme Court, Lucas claimed that the Beachfront Management Act was a taking of his property. The Supreme Court ruled for Lucas, finding that the setback requirement deprived him of all "reasonable and beneficial use" of his property and therefore amounted to a compensable taking.

The takings doctrine thus sets important limits on the requirements that state and local governments may impose to increase the resilience of the built environment. While in general coastal governments are free to impose setbacks or freeboard elevation requirements to accommodate sea level rise, *Lucas* instructs that the same principles cannot be used to prevent new development in the flood hazard zone. What's more, case studies of permitting activities by state and local governments reveal that takings concerns are often central to the dialogue surrounding coastal permitting and are frequently used to allow expanded development in areas that are vulnerable to the impacts of erosion and sea level rise (Peloso 2010, Moser 2005).

States are not completely without tools to accommodate the rising sea, however, because *Lucas* recognizes that those regulations that merely codify background principles of common law will not be takings. This means that states can rely upon the common law doctrines of public trust and erosion to take title to land that becomes submerged as sea levels rise (Peloso & Caldwell 2011, Caldwell & Segall 2007). Employing these background principles, all states have to do is prevent the armoring of the shoreline and ensure adequate space for habitat migration, and ultimately they will take title to submerged land under a rolling easement (Titus 1998).

While the rolling easement is thus, in theory, an important tool to permit states to accommodate coastal habitat and move people out of the coastal hazards zone, it does not have any teeth until the property is submerged or a purchased conservation easement over fringing wetlands moves landward. Consequently, the rolling easement does not permit states to prevent development in the coastal zone today on land that will be subjected to inundation due to sea level rise in the future. This results in two major challenges for coastal managers. First, they must make decisions about whether to install or repair infrastructure to support new or redeveloping communities that will be subjected to inundation in the near future. Second, the continued development of the coast results in increasingly entrenched property owner interests that may make it difficult, if not impossible, to actually implement the rolling easement as sea levels rise.

Nowhere is this latter struggle more apparent than along the Texas coast, the birthplace of the rolling easement. The Texas Open Beaches Act codifies the rolling easement by declaring all beach seaward of the first line of vegetation to be public beach, forbidding the construction of coastal defense structures and granting the state the right to condemn any properties that come to lie on the public beach (Tex. Nat. Res. Code Ch. 61). In theory, this should mean that as the beaches retreat, the state will take title to the beaches and private homes lying on the beach will be removed. However, in practice the politics of property law and disaster response have combined to create a situation in which enforcement of the Open Beaches Act has become nearly impossible. In fact, after the 2005 hurricane season, the state promulgated new rules permitting reconstruction of homes on the public beach because removing them all was too difficult politically (31 Tex. Admin. Code § 15).

A similar outcome can be seen along the ocean coastline of North Carolina. North Carolina has a no coastal hardening policy, which prohibits the construction of seawalls along the state's ocean coastline (15 N.C.A.C. § 07M.0202). However, property owners whose homes are threatened by erosion are able to obtain permits for the placement of sandbags as "temporary erosion control structures" (15 N.C.A.C. § 07H.1705(a)). The intent of this program is to buy time for property owners to come up with a more permanent solution to deal with the erosion threat, and the sandbags are supposed to be removed at the end of the permitting period. However, much like the case in Texas, local authorities have found that once sandbags have been permitted, it is nearly impossible to compel their removal, resulting in a de facto hardening of the coast.

What the these experiences reveal is that one of the most pressing policy challenges in addressing sea level rise is finding ways to promote resilient coastal development that is capable of adapting to sea level rise. While the threat of takings claims certainly poses a concern, it is often political pressures that most strongly shape development at the coast. Because of this dynamic, a failure to engage in comprehensive planning for sea level rise and the promotion of structural measures and retreat options to accommodate the sea will lead to an ad hoc armoring of the coast as individual properties become threatened by rising seas.

Furthermore, if states pursue rolling easements and other policies of retreat, they will need institutional support to develop and understand the contours of their coastal governance regimes and the extent to which background principles in the state's common law can be used to accommodate rising sea levels. In the context of climate change governance, it is important to remember that the common law has never before seen anything like the changes we are about to experience, and therefore, there is some uncertainty as to how common law judges may interpret states' initiatives to reduce vulnerability to sea level rise.

Common law is judge-made law that takes legal principles from prior decisions and applies them to the new facts and circumstances in a case. Over time, this accumulation of judge-made law results in legal principles that can be used to guide actions. Because common law evolves over time, it can and does vary from state to state, meaning that an adaptation approach found to be consistent with the common law in one state will not necessarily be valid under the common law of other states.

The greatest challenge in applying common law to sea level rise stems from the fact that the common law applies the rules of dynamic river boundaries and customary uses of land in English law to the coastal zone. This approach generally assumes that while a property boundary determined by the water line is ambulatory, it is equally likely to move in either direction. Further, it encapsulates a number of peculiarities about the nature of shoreline uses and crown title in England. Consequently, the common law has developed a series of rules applied to coastal property, which assume that over time, a coastal property owner may gain or lose land due to shifts in environmental conditions that modify shoreline boundaries (Sax 2010). Such rules may not be appropriate when applied to the large, unidirectional shift caused by sea level rise, which will result in coastal property owners gradually but steadily losing title as their land is submerged and becomes part of the public trust.

Further complicating the legal picture, not all states have a robust body of common law fully defining the legal rules applicable to their particular shorelines. When there is no precedent in a state's common law, policy-makers are left to speculate as to how a court may rule. In this context of undefined law, policy-makers may be discouraged from making particular adaptation decisions because they cannot be certain whether the adaptation policies they adopt will withstand takings claims or other legal challenges that result.

The uncertainty of the common law demonstrates the importance that information sharing and learning by example will play in helping states develop approaches to adapt to sea level rise. In addition, it is clear that state and local governments will need additional resources to help them define and understand the contours of their common law. Furthermore, additional research into the use of alternative land use tools, such as conservation easements, and time-limited development rights would increase the adaptive capacity of states by helping them to better understand the tools that are legally available to them to promote adaptation to sea level rise.

The Role of State Land Use Policies in Reducing Coastal Vulnerability

Because of the highly context-dependent nature of vulnerability, adaptation decisions must be made on the local level. This is particularly true when it comes to adaptation to sea level rise because many vulnerability reduction measures are fundamentally questions of land use, which is legally controlled by state and local governments. Because of their ability to make zoning, land use, and building code decisions, state and local governments will be central to programs to adapt to rising sea levels.

Under the Tenth Amendment of the United States Constitution, all powers not expressly granted to the federal government are reserved for the states. It is through these reserved powers that states are granted the authority to control land use decision-making. In many states, the power to control land use is further delegated to local governments, which enforce zoning and building codes. Because local governments control what is built, where it is built, and how building occurs, they have a critical role to play in promoting adaptation to sea level rise.

Through zoning, setbacks, and building code measures, including elevation requirements, state and local governments have the ability to reduce coastal vulnerability by limiting the number of people building in hazard prone areas, making space for coastal habitats to move landward, and ensuring that coastal infrastructure is resilient to the threats of rising sea levels. Consequently, the engagement of local governments and city planners in discussions about the impacts of sea level rise will be essential to any adaptation strategy.

As mentioned in the previous section, political constraints and fear of takings claims are two of the principle reasons that state and local governments may not be able to act to promote coastal retreat as a response to sea level rise. Other significant barriers to promoting adaptation to sea level rise and resilient community design are constraints on funding, the availability of information, and coordination concerns. While many local governments are concerned about the impacts of sea level rise, the lack of detailed information on the extent and timing of these impacts tends to make it difficult to incorporate them into planning decisions. In addition, with limited time and funding, it is often difficult for states and local governments to prioritize substantive discussions about and responses to sea level rise (Moser 2005).

Furthermore, while many local governments are aware of and concerned about the impacts of sea level rise, they are often at a loss for what to do. That is, while states are increasingly successful in disseminating information about the impacts of climate change, there are still large information gaps on available adaptation options. In addition, many of these adaptation options require coordination to succeed. For example, local jurisdictions in North Carolina and California report considering retreat as an adaptation strategy but state that they would not attempt it if they thought that neighboring jurisdictions were likely to defend the coast. All of this suggests that there is an important role for both the federal government and state governments in promoting the dissemination of information about sea level rise and adaptation options, fostering dialogue about various adaptation strategies, and helping local governments to implement both policy and structural measures that decrease their vulnerability to climate change.

The Role of the Federal Government in Reducing Coastal Vulnerability

While the federal government cannot directly control coastal land use, there are several important roles that it can play in promoting adaptation to sea level rise. Numerous studies point to three primary roles that the federal government should play in facilitating climate change adaptation. These roles are (1) providing information on climate change impacts, (2) coordinating responses to climate change, and (3) providing resources for states to pursue adaptation activities (Pew 2010, GAO 2009).

Another significant role for the federal government that is often overlooked is its ability to provide political cover and uniformity. Case studies of local jurisdictions reveal that while many coastal policymakers are concerned about the impacts of climate change in their jurisdictions, they are politically unable to institute the necessary changes to decrease vulnerability to sea level rise (Peloso 2010). Furthermore, in some coastal areas, the only form of land use planning to reduce vulnerability is base flood elevations and other minimum requirements of federal flood insurance and disaster relief programs (Peloso 2010). Because of the political difficulties associated with promoting adaptation to sea level rise, coastal policymakers report that they would benefit from top-down planning mandates that provide political cover while permitting them to proceed with needed vulnerability reducing activities (Peloso 2010).

Current Federal Programs That Can Be Used to Reduce Coastal Vulnerability

One of the most important actions that the federal government can take immediately is to ensure that the programs it already has in place do not conflict with the adaptation goals of states. In the context of adaptation to sea level rise, this means that federal programs should avoid supporting actions that increase vulnerability by creating a false sense of security among coastal residents and those programs that encourage increased vulnerability to natural hazards through development and redevelopment in the coastal zone. In addition, the federal government has the ability to encourage states to engage in comprehensive flood zone planning and management and to adopt community designs that are resilient to rising sea levels.

The Coastal Zone Management Act offers federal funding to states for the implementation of federally approved coastal zone management plans. Under current federal regulations, coastal zone management plans already require a number of land management measures, including the implementation of land use policies to minimize the risks of flood loss in the coastal zone (15 C.F.R. § 923.3(c)). The act also calls for planning measures to address the adverse effects of sea level rise on the coastal zone. Congress is due to consider the reauthorization of the Coastal Zone Management Act, which may provide important opportunities to incorporate additional sea level rise planning into state coastal zone management plans.

The other major federal programs that directly affect vulnerability to sea level rise are the federal disaster relief programs administered through the National Flood Insurance Program and Stafford Disaster Relief. The National Flood Insurance Program has been widely criticized for historic failures to charge actuarially sound rates, particularly for repetitive loss properties that are located in flood hazard zones (GAO 2008). When combined with grants for rebuilding under the Stafford Disaster relief program, the National Flood Insurance Program has the potential to increase vulnerability to sea level rise by facilitating post-disaster rebuilding in coastal hazard zones. To the extent that existing federal disaster relief programs permit coastal property owners to externalize the natural hazard risks associated with living in the coastal zone, they will encourage increased coastal development and, thereby, may actually increase vulnerability to sea level rise.

However, there are several important aspects of the National Flood Insurance Program that also deserve attention for their importance in reducing vulnerability to sea level rise. One of the most significant of these programs is the establishment of base flood elevation in flood prone communities. The base flood elevation, which is set by FEMA based on historic flood data, becomes the minimum elevation to which a home must be built to be eligible for federal flood insurance (44 C.F.R. § 59.2). Particularly in communities where zoning and land use planning are not employed, the FEMA base flood elevation serves as the most important, and perhaps only, mandatory measure to reduce vulnerability to sea level rise and storm surge.

The effectiveness of the FEMA base flood elevation requirement in decreasing the vulnerability of the built environment to storm surge impacts is clearly seen in Galveston, Texas. In 2008 Hurricane Ike resulted in significant storm surges washing over Galveston Island and the Bolivar Peninsula. The result was near-total devastation of the Bolivar Peninsula, where older homes were not elevated. In contrast, the elevated newer development on West Galveston Island was largely undamaged. According to local officials, these disparate outcomes occurred because FEMA base flood elevation requirements were applied to all of West Galveston Island, while much of the Bolivar Peninsula was developed before base flood elevation requirements existed.

The other FEMA program that can play a significant role in reducing vulnerability to sea level rise is the Hazard Mitigation Grant Program. This program provides state and local governments with federal funding in the wake of disaster declarations to implement programs to reduce the loss of life and property in future natural disasters (Stafford Act). With respect to sea level rise adaptation, the two most significant measures supported under the Hazard Mitigation Grant Program are the elevation of flood prone structures and the acquisition of property for conversion to open space. While the Hazard Mitigation Grant Program may be a significant tool to promote adaptation in the wake of disasters, it is subject to obvious financial constraints, and the limited size of the program constrains its utility as a broad-based adaptation tool.

Through existing programs under FEMA disaster relief and the Coastal Zone Management Act, the federal government has the ability to encourage both planning for sea level rise and specific measures to reduce hazard exposure. What these programs lack is a systematic means of generating and disseminating information about the impacts of sea level rise and adaptation options to policy-makers. In addition, neither of these programs on its own provides overarching federal direction for adaptation policy.

Although many federal agencies are currently engaged in some degree of climate change adaptation planning, no agency has been granted the authority to direct and coordinate the development of a larger federal climate change adaptation plan (Pew 2010). President Obama has established a Climate Change Adaptation Task Force, which is charged with developing federal recommendations for adapting to climate change impacts. However, until the task force issues its final report, it is difficult to predict how its recommendations will be implemented to create an overarching federal adaptation policy.

Proposed Federal Legislation to Promote Adaptation to Climate Change

The potential for legislation creating authority to establish a broad federal adaptation policy and formal coordination of agency efforts was seen in climate change legislation before Congress between 2009 and 2010. Both the American Clean Energy and Security Act, passed by the House in 2009, and the American Power Act, released by Senators Kerry and Lieberman in May 2010, create comprehensive legal regimes to address climate change. While the focus of these bills is on controlling carbon pollution by establishing a cap and trade system for large emitters of greenhouse gases, each has provisions that would create a federal program for climate change. Both of these programs call for increased research and adaptation planning and rely on the allocation of emissions allowances from the cap and trade program to fund select adaptation activities. These programs create an overarching federal structure to plan for climate change adaptation, but they generally do not address the infrastructure challenges associated with sea level rise. Although it is highly unlikely that either of these bills will ultimately become law, their provisions reveal what Congress envisions to be the appropriate role for the federal government in facilitating adaptation.

The House bill, the American Clean Energy and Security Act, has four major adaptation provisions. The act would establish (1) the U.S. Global Change Research Program, (2) a national climate change service, (3) regulations calling for state adaptation plans, and (4) a national resources adaptation strategy. It would also establish the U.S. Global Change Research Program and require the president to develop a national global change research and assessment plan. The program would require the president to designate an interagency committee to facilitate cooperation and coordination of all federal research activities related to global change. To promote understanding of the impacts of climate change, the act would require the president to perform a national vulnerability assessment within one year of the act's passage and every five years thereafter. In an effort to facilitate information exchange, the act would call upon the National Academies of Science and Public Administration to conduct a quadrennial study to document federal and state policies for climate change adaptation and mitigation and evaluate their realized and potential effectiveness. Finally, the president is to establish a global change resource information exchange to make useful information on adaptation and mitigation available to policy-makers.

The act calls for the establishment of a national climate service within NOAA to advance the understanding of climate variability and global change. The National Climate Service is to be built upon the existing structure of the National Weather Service and would also establish a network of six regional centers to work with state climate change offices to provide information on climate change that local policy-makers need to make adaptation decisions.

The American Clean Energy and Security Act would require the EPA administrator to establish regulations governing state climate change adaptation plans. Under the act, states would be required to submit climate change adaptation plans to the administrator for approval, and approval of a state's plan would be required to receive emissions allowances to fund adaptation activities. At minimum, the act specifies that state climate change adaptation plans must:

- assess and prioritize vulnerabilities to climate change impacts based on the best available science;
- assess the potential for reductions in carbon emissions through changes in land use;
- identify and prioritize specific cost-effective programs to increase resilience to climate change; and
- undertake, to the maximum extent practicable, measures to protect and enhance ecosystem functions.

To maintain eligibility for allowance allocations, states would be required to update their adaptation plans at least once every five years. According to the EPA's estimates of allowance values, states with approved adaptation plans would be eligible to receive a share of allowances that together would be valued between $1.4 billion and $7.2 billion to sponsor adaptation activities (House Committee on Energy and Commerce 2009).

The final adaptation section of the American Clean Energy and Security Act addresses the creation of a national strategy for natural resources adaptation. The act would require the Council on Environmental Quality to advise the president on the development and implementation of a national natural resources climate change adaptation strategy. The act specifies that the minimum elements of this strategy are to be as follows:

1. a national vulnerability assessment of natural resources;
2. a description of current resources;
3. identification of natural resources with the greatest need for protection;
4. specific protocols to integrate adaptation into conservation and management of resources by the federal government;
5. specific actions that the federal government should take to increase the resilience of natural systems;
6. specific mechanisms to promote communication and coordination between federal agencies;
7. specific actions to develop and implement a national resources inventory; and
8. a process to guide the development of agency and department specific adaptation plans.

The act calls for the coordination of information of natural resources adaptation through the establishment of a national climate change and wildlife science center. The act also requires that each federal agency or department create an adaptation plan to be approved by the president and submitted to Congress.

In addition, the act provides for additional allowances to be allocated to states that prepare natural resource adaptation plans detailing current and projected efforts to address the projected impacts of climate change. To be eligible for allowances for natural resources adaptation, state plans must be approved by the secretary of the interior and the secretary of commerce if appropriate.

The American Power Act, the bill proposed by Senators Kerry and Lieberman, contains a far less comprehensive climate change adaptation program. The bill largely adopts the natural resources adaptation provisions and the National Climate Service of the American Clean Energy and Security Act as passed by the House. However, the bill does little to promote adaptation beyond the natural resources adaptation program.

The American Power Act does permit the EPA administrator to establish additional adaptation programs in the following important areas:
1. water system adaptation;
2. flood control, protection, prevention, and response;
3. education about wildfire protection practices; and
4. coastal state economic protection.

However, the bill specifies neither the contents of these programs nor how they would be funded.

Overall, both federal bills would increase adaptive capacity of coastal states through increased generation and coordination of information about the impacts of climate change. The information generated by the National Climate Service is likely to be particularly significant in facilitating adaptation to sea level rise by providing local officials with more precise information about the localized impacts of sea level rise. This information will increase adaptive capacity because it will increase the ability of policy-makers to evaluate the tradeoffs associated with particular adaptation options. The allocation of allowances through the bills will also increase the ability of states to adapt because it will provided necessary resources to implement key vulnerability-reducing measures.

The state adaptation plans called for under the American Clean Energy and Security Act, if included in the final climate change law, could fulfill several important roles in facilitating adaptation to sea level rise. First, the plans provide critical funding for state adaptation activities. Second, the act provides political cover for states that wish to pursue adaptation planning because the available funding allows state and local decision-makers to politically justify making adaptation planning a priority. Finally, federally approved state adaptation plans help provide a level of uniformity and certainty, which eliminates the risk that some states and localities will undertake adaptation measures in isolation and be ineffective.

The Role of the Scientific and Engineering Communities in Reducing Coastal Vulnerability

With efforts to pass a comprehensive climate change bill currently stalled in the Senate, the focus of climate change adaptation efforts will remain at the state and local government levels. While states lack the overarching support framework and mandate of a federal legislative scheme, they can still take important steps to reduce coastal vulnerability. Because of the broad informational needs of states and political pressures to maintain and possibly expand coastal communities, the role of the scientific and engineering communities in promoting resilient community design becomes even more critical.

There are two primary roles the scientific and engineering communities can play in reducing vulnerability to sea level rise. First, they can increase adaptive capacity by engaging policy-makers and communicating research findings on the impacts of sea level rise, the importance of coastal habitat preservation, and engineering solutions that can accommodate rising sea levels. Second, the engineering community in particular can enhance coastal resilience by developing and insisting upon infrastructure designs that are mindful of sea level rise and are prepared to accommodate it.

Because of the takings doctrine and political factors previously highlighted, it is unrealistic to expect that stopping coastal development or requiring coastal retreat will be a first order adaption strategy in many coastal communities. Instead, coastal governments are likely to attempt to protect as much property as possible from the encroachment of rising seas until it becomes financially or technically impossible to do so. Such efforts will likely require major engineering projects to continue to provide basic infrastructure, such as roads and water lines, to coastal communities. In addition to the extent that coastal governments choose to defend the shoreline or permit property owners to hold back rising seas, substantial engineering projects may be required for coastal defense structures.

Engineers can enhance resilience of basic infrastructure to sea level rise by collaborating with coastal systems scientists and urban planners to create systems that are robust to the impacts of sea level rise. In some cases, this may involve steps as straightforward as elevating the roads likely to be inundated. In other cases, it may require sophisticated new designs that permit major infrastructure to be picked up and moved to accommodate the advance of rising seas.

The engineering community can make another major contribution to coastal resilience by developing and adhering to voluntary building codes designed to accommodate the potential for rising sea levels. This could permit the continued development or redevelopment of coastal property that is adaptation ready. For example, a coastal resilience building code might emphasize systems to accommodate rising sea levels, such as freeboard elevation requirements and home designs that can easily be relocated to avoid sea level rise inundation. The development of voluntary environmental building codes, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) code, have been influential in other areas of domestic energy and environmental policy. For example, the Department of Energy, through the Energy Policy Act of 2005, is authorized to require the adoption of building energy efficiency codes created by voluntary organizations, such as ASHRAE and the International Green Construction Code (IGCC). Thus, the development of a voluntary coastal resilience building code today could be an important initial step to promoting adaptation to sea level rise.

Scientists and engineers also have a significant role to play in enhancing the adaptive capacity of coastal governments. As highlighted above, many coastal governments have significant informational needs in understanding both the localized impacts of climate change and the available adaptation options. Thus, the scientific and engineering communities should engage other elements of civil society to ensure that policy-makers are adequately informed about the threat of sea level rise, the consequences of a failure to adapt, and available adaptation options. To ensure that the specific informational needs of local governments are met, scientists should aim to collaborate directly with policy-makers and focus their efforts on targeted questions that are responsive to the policy communities immediate needs. A strong example of such collaboration can been seen in North Carolina, where the Division of Coastal Management convened a sea level rise science forum to provide scientists and policy-makers an opportunity to communicate and explore the potential impacts of sea level rise in the state.

Conclusions

From a governance perspective, the most critical steps to promoting adaptation to sea level rise are empowering and enabling state and local governments to take proactive measures to reduce their vulnerability. These measures can focus either on increasing adaptive capacity by providing states with more information about risks, impacts, and adaptation options or focus on increasing socio-ecological resilience by promoting solutions that enhance the ability of both built and natural environments to withstand the impacts of climate change.

There are three primary areas in which state and local governments require support to facilitate adaptation to sea level rise. First, state and local governments require information on the impacts of sea level rise and options to adapt. Second, localities require the time, support, and resources to more fully develop the contours of their own legal regimes to deal with rising sea levels. In many cases, state and local governments would benefit from a federal mandate providing political cover for increased adaptation planning. Finally, all levels of government must engage in a dialogue about what resources we wish to protect and how we want to protect them. To this end, states require support to facilitate public processes in which they can discuss the projected impacts of sea level rise, the vulnerability of places, and possible adaptation measures.

A fundamental challenge for policy-makers confronting sea level rise is that our current legal and regulatory system was created in a period of relative environmental stability. As a result, it is designed to manage a stable system, not one with the large-scale unidirectional changes that we expect as a result of climate change. This means that governance structures themselves will need to adapt to confront the new social, political, and legal challenges posed by climate change. To this end, governments will benefit from comparative policy studies and evaluations where they can learn from the example of others. This suggests that the principal roles for the federal government should be (1) disseminating information about climate change impacts and adaptation strategies, (2) providing resources and institutional support to promote the adaptability of governance structures, and (3) providing an overall national adaptation strategy and a framework for coordination across different levels of government to decrease socio-ecological vulnerability.

Finally, there are a number of important roles that the scientific and engineering communities can play today to enhance coastal resilience to climate change. Most important among these are (1) engaging the public and policy making communities to enhance adaptive capacity through the communication of research findings and (2) promoting community and infrastructure design that can accommodate rising sea levels.

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Chapter 10. Defining Coastal Science Needs of the Engineering Community for Meeting the Challenge of Sea Level Rise

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Abstract

Forecasts suggest that within little more than a generation the already historically high rate of sea level rise could begin an accelerating trend that would carry on well into the end of the century. The overall effects of this rise have been widely reported, from increased flooding of low-lying coasts and dramatic losses of coastal wetlands to the disappearance of small island nations like the Maldives. The sea level threat is unique among the many major problems posed by global warming as it is both global in reach and local in outcome, with a capacity to change some of the greatest densities of population, commerce, and essential infrastructure on the planet. Addressing many of the aspects of the challenge, especially coastal infrastructure, will require interaction between science and engineering, with science providing the framework of physical processes from which engineers can determine risk, stresses, and loads. This paper discusses basic physical inputs that can underpin viable engineering solutions for sustaining coastal infrastructure in era of rapidly rising sea level.

Background

In August 2008 Hurricane Ike, a Category 5 storm, hit the East Texas coast in one of the most populated and commercially important metropolitan areas along the Gulf of Mexico—the Galveston Bay/Galveston/Houston metropolitan region. Among the many concerns about the storm's hazards for people and structures was the fate of Galveston Island and the city of Galveston. The catastrophe of the 1900 hurricane still resonates in the area today, and the book, *Isaac's Storm*, published in 1999, about the horrors faced by the residents of Galveston on the fateful day in September of 1900 has never been a best seller in the area. As has happened many times after the construction of the seawall in 1903, damage to Galveston was largely confined to wind and flood damage; the horrendous destruction wrought by huge storm waves in the 1900 hurricane was largely avoided, with only fairly local damage by wave overtopping of the sea wall.

It is difficult to imagine that the engineers who designed the Galveston sea wall in 1903 had any idea that it would still be serving its purpose more than a century later, despite the limited wave overtopping during Ike, which suggests that the freeboard of the structure is no longer sufficient. The state of coastal science and engineering about wave generation and dynamics, the loads that waves could impose on coastal structures, and the relations of shore processes to sea level rise (even they realized sea levels were rising) was primitive back then. The progress of coastal science and engineering since has been impressive. Nevertheless, there still much left to be done, particularly in maintaining present and future infrastructure in an era where sea levels could rise faster than at any time since the advent of instrumental records (hence, no detailed analogues). Even knowing where the future shoreline might be in many cases, in lieu of simple submergence, remains problematical, and it is here that we will start.

Shore Erosion and Retreat

The most crucial information in assessing risk and the sustainability of developed coasts from sea level rise is where the shoreline will be. Flooding and wave damage from storms, risks to life and limb, and even assurance that structures or development constructed today will meet their designed amortization schedules all either increase (in the case of the first two) or decrease (in the case of the last) with proximity to the shoreline. For the last 30 years, immense effort has been devoted to deriving estimates of shore erosion or retreat rates. Because obtaining rates from *in situ* shore profiles is time consuming and likely to be flawed by too short a record and not being site specific, historical maps and aerial photography have been the principal means of obtaining long-term and synoptic erosion and/or retreat rates. This has been both good and bad: Good because the data are probably reliable up to the date compiled (and probably for the immediate future); however, bad because there is no way beyond linear extrapolation to forecast future trends from such information. There is gathering evidence that the late 20th century sea level record documents considerable, even increasing, inter-decadal variability (see Chapter 3). The 1990s and early 2000s are the best example of this, with an acceleration (in the U.S. Mid-Atlantic Coast, exceeding 1 cm yr^{-1}) that was the largest of the last half century, followed by a deceleration with dramatic intra-annual low stands in sea level (Kearney and Riter, in review). If even a reasonable correlation between sea level rise and shore erosion/retreat could be determined by regression—and then probably only on sandy beaches as discussed later—it would be credulous to believe that such a relationship might be meaningfully extrapolated for predicting future trends decades away (Fig. 10-1).

Bruun (1961) proposed a now a famous relationship between the amount of sea level erosion and sea level rise. This two dimensional model (Fig. 10-2) indicates that the *R,* the amount of shoreline retreat, is a function of the rise in sea level, *S;* the cross-shore width of the active profile, *L*; the depth of closure, *h;* and *B,* the elevation of the dune crest or cliff (i.e., the landward limit of sediment transport). In simple algebraic form, the model is as follows:

Figure 10-1. Illustration of the problems using historical maps and aerial photographs.

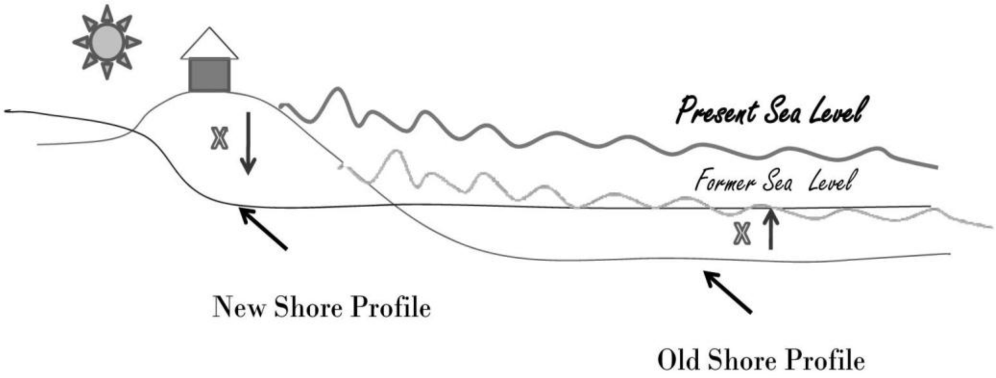

Figure 10-2. Diagram showing general relation of the amount of shoreline retreat for a particular rise in sea level. This relationship only holds for sandy beaches. After Titus (1991).

$$R = SL/(h + B) \tag{10-1}$$

The chief difficulty in applying the model is determining the depth of closure or the depth of the seaward limit of the active beach profile.

A principal recurring theoretical objection to Bruun's Rule is that it is predicated on an equilibrated beach profile. Bruun's original postulate for the existence of equilibrium profile was based on analyses of beach profiles in Monterey, California, and in Denmark (Bruun 1954). Bruun found that a power function provided the best mathematical description of profile plan form, viz:

$$h(y) = Ay^{2/3} \tag{10-2}$$

where y is the distance in meters in the shore normal direction, y is the depth in meters, and A is a profile scaling factor (related to sediment size, Dean 2002). Bruun assumed that the profile was in equilibrium, an assumption later validated by Dean (1977). In the decades since Dean's validation, there have been variations offered to improve Bruun's original model for specific conditions, particularly for gravity forcing in the upper profile (Komar 1998), but the basic power relationship holds. Only in the instance of severe coastal storms tracking close to shore, which can produce high, short-period waves of great erosive power moving sediment so far offshore that it may takes decades for the summer-long period swell to return it (Zhang et al. 2004), is the assumption of an equilibrium profile tacitly inviolate and thus excludes a necessary theoretical underpinning of the model. It also is open to question whether the Bruun Rule would still apply if global sea level rise were to accelerate toward the top of IPCC's estimates. With such a rapid rise—far beyond the global sea level trends current when Bruun and others made their observations—the likelihood of an equilibrium existing in beach profiles may be moot, if for no more fundamental reason than shoreline retreat would shift largely to coastal submergence rather erosion.

In summary, the usefulness of the Bruun Rule lies so not much in its ability to predict shoreline retreat during a period of perturbation (i.e., during sea level rise) but rather as a scenario-building tool for predicting how in relaxation beaches adopt a new equilibrium profile, during which the shoreline assumes a new landward position. It is limited to sandy beaches—not mud beaches, marsh shorelines, and the like—comprising geometrically simple coasts. Bruun never argued for universality of his model, and hence objections like those voiced by Cooper and Pilkey (2004) inasmuch as they implicitly attack the model rather than its improper use are specious. Recent work (Zhang et al. 2004) refining the multiplier effect of the shoreline retreat vis-à-vis sea level rise of the Brunn Rule for U.S. Atlantic Coast barrier beaches can provide a reasonable forecast of where shorelines might be with a certain rise in sea level.

For non-sandy beaches and shorelines, especially along irregular coasts, the modeling of future shoreline position with sea level rise currently lacks any physical foundation. Rosen (1980) tried to adapt the Bruun Rule for the Chesapeake Bay, an estuarine system of over 9,600 km of shoreline, and predictably had very limited success. Apart from there being few sandy beaches in the Chesapeake, with mud or marsh shorelines predominating, the absence of ocean swell waves means that the efficiency of the comparatively small storm waves is heightened because sediment eroded during winter stays offshore, unlike the open coast where long period swell out of the southeast moves much of it back on shore in summer.

There is no question that shore erosion is major process of shoreline retreat in the Chesapeake Bay (and probably other estuaries); we need only compare the dramatic shoreline retreat on island shorelines facing the main bay stem to those facing the mainland (Fig. 10-3). Numerical models linking rate of shoreline retreat to sea level

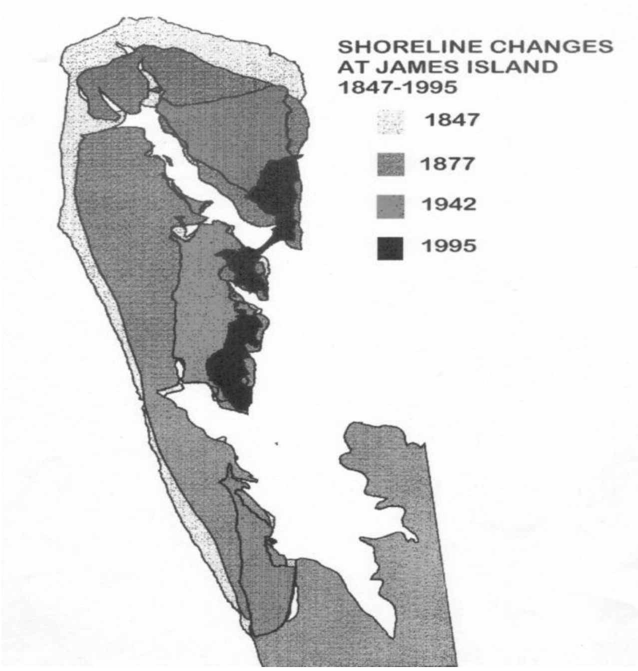

Figure 10-3. Shorelines at James Island, Maryland, showing the large land loss since the middle 19th century. Courtesy of J.C. Stevenson.

rise are not available for protected, complex coasts, and it is unlikely that statistical models could be developed to encompass more than a small reach of shoreline. Perhaps the best that can be done for the near future is to employ a submergence model. Although they are naïve, by assuming little, such models do not lead to theoretical cul-de-sacs.

Waves: The Force of Coastal Change

Rising sea levels will not only erode shorelines and cause coastal submergence, exposing infrastructure to inundation, but it will also bring the power of waves closer to structures not previously within the zone of potential wave attack and impose greater static and dynamic loads on existing marine facilities. Long shore transport rates also are a function of incident waves and their height.

The actual influence of sea level rise on wave dynamics as they might affect coasts may be most pronounced in protected shallow coasts like bays and estuaries. Assuming that open coast shore profiles will equilibrate as sea levels rise, then the nearshore depth parameter should effectively remain unchanged. Open coasts will not be immune from the general effects of global change, however. There already is evidence that significant wave heights (H_{sig}) from intense coastal storms are increasing in both the North Pacific and North Atlantic (Ruggiero et al. 2010). Nevertheless, because the mud or marsh shores of estuarine coasts probably do not maintain a nominal equilibrium profile, at least as documented by Bruun and others, then a deeper shore profile in a shallow bay could lead to potentially larger waves from the same wind field. In the Chesapeake Bay, with an average depth of 4.5 to 6.1 m (15 to 20 ft.), a rise in sea level by 2100 at the upper envelope of the IPCC AR4 predictions (~60 cm) would be a proportionately significant increase water depth (~13%), with the potential for proportionately much larger waves.

Because wave power varies by the square of the wave height, the implications of deeper water in shallow protected coasts becomes clear. As an example, consider the equation for drag force exerted by waves on cylindrical object like a piling:

$$(F_D)_{max} = \tfrac{1}{2}\rho C_D H^2 K_D \qquad (10\text{-}3)$$

where the principal parameters are C, the diameter of the cylinder; C_D, the wave drag exerted on it; H, the wave height; and K, a coefficient. This formula is predicated for shallow water situations using solitary wave theory and does not assume oscillatory conditions of the Airy wave theory (Goda 2007).

For vertical structures like sea walls, bulkheads, or breakwaters, accurate wave height predictions not only are necessary for estimating hydrodynamic loads but also for designing freeboard limits with acceptably low probabilities of wave exceedance (e.g., 0.001 for a critical facility or buildings with high occupancy rates) (Fig. 10-4, FEMA 2007). Moreover, the breaking wave force exerted against vertical structure is again related to the square of the stillwater depth (d_2):

$$F_{brkw} = 1.1\ C_p\gamma d_s^2 + 1.91 d_s^2 \qquad (10\text{-}4)$$

where the other parameters are C_p, the dynamic pressure coefficient, and γ, the specific weight of water.

Even wave runup, an important consideration in the design inclined sea walls, is a function of the significant wave height (H_s), though the relationship is also dependent on wave incidence, the surf-similarity parameter (ξ, or Ibarren Number; Batjes 1974),

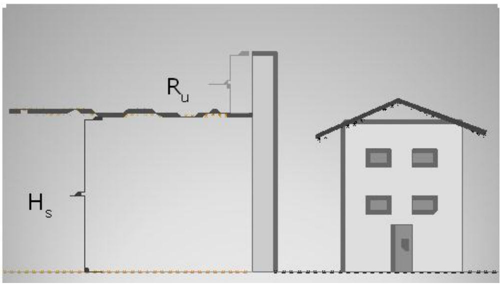

Figure 10-4. Relationship of significant wave height (H_s) to wave runup (R_u) maximum for calculation of freeboard for vertical structure like a sea wall.

slope angle, and material permeability. However, because runup is critical to the determination of sea wall overtopping and the vulnerability of landward structures to flooding and even wave damage, again the influence of sea level on significant wave height cannot be discounted.

Sea Level Rise and the Tidal Frame

The literature on the effects of global warming and accelerated rates of sea level rise is replete with descriptions of increased flooding risk and loss of life, damage to coastal structures, and overall for potential social disruption. The threat of even more powerful waves, as this paper has argued, is also considerable. However, often missing in such hazard forecasts is any mention of tides, other than their capacity to facilitate the damage done by storm surge and waves to communities if a storm hits the coast at high tide (especially a perigean spring tide). This is not wholly surprising as tides for many coasts, except those at the upper end of the mesotidal range or higher, are often secondary to waves in coastal evolution. For example, in a microtidal coast like the Chesapeake Bay where mean tidal range in the middle and upper part of the estuary is 0.3 m or less, tidal velocities are low. In Baltimore Harbor, mean tidal velocities average about 0.8 kts (~1.5 km hr^{-1}, NOAA 1999). Such low velocities have very little erosive potential, especially for the estuarine muds, which characterize much of the bay, as the Shields function makes clear. This could change, however, if the tidal frame is increased as a result of sea level rise.

Definitive studies of tidal amplification with rising sea levels are few, and where they have been investigated, it is not clear whether human activities (e.g., port construction changing harbor hydrography) contemporary with sea level rise were more a factor than changing water levels. A recent study (Jay 2009) along the U.S. Pacific Coast down into Mexico showed that tides have been increasing at a rate of 2.2 percent per century. In Astoria, Oregon, tides were increasing at the highest rate found for the study area, about 25 cm per century. The study concluded that the effects of sea level rise on tidal amplification would result in greater rates of shore erosion. It is likely the impact on shore erosion will be most pronounced for mesotidal (2- to 4-m mean tidal range) and macrotidal (> 4-m mean tidal range) coasts, where coarser sediment entrainment and transport by the tides already occurs.

What could be expected of the impact of a higher tidal range on coastal structures? First, an amplified tide could magnify ambient loads (hydrostatic and hydrodynamic) on structures at high tide, particularly during spring periods of the lunar cycle. However, the most probable outcome would be an increase in tidal velocities, and existing coastal structures could exacerbate the problem—even in areas where maximum velocities, whether at flood or ebb, were previously well below the shear velocities required for entrainment of the prevalent particle size.

Even the Port of Baltimore might be susceptible to this phenomenon considering that bulkheads and seawalls throughout the harbor constrain the ability of floodwaters to spread laterally (Fig. 10-5). If a greater volume of water has to pass through a constriction to the flow, velocities will increase. Higher tidal velocities could scour pilings where no scouring existed (Fig. 10-5).

Increased tidal velocities can cause greater scour of bridge and pier pilings. Most studies of scour around pilings have focused on unidirectional flow conditions typical of rivers (cf. *HEC 18*, Richardson and Davis 2001) rather than the bidirectional flow that occurs in tidal conditions. Some recent studies (e.g., Escarameia 1998, Vasquez and Walsh 2009), however, have examined scour under tidal conditions with respect to flood duration, the effect of reversal on flow direction, and such. These papers, though, have a basic conceptual problem with their use of sinusoidal or square tidal cycles. A growing body of literature (cf. Stevenson et al. 1988) has documented that sinusoidal tides seldom characterize coastal areas, and more commonly tidal cycles display strong differences between time and peak velocities with respect to flood and ebb tides (termed time velocity asymmetry, Postma 1961). This phenomenon, where peak velocities typify one part of the tidal cycle, certainly can affect the nature of scour on the pilings. In many areas, especially estuarine channels, there is evidence that ebb domination eventually emerges over the cycle of channel development (Stevenson et al 1988). How sea level rise will affect such channels, particularly as modified by shore protection features, has yet to receive close examination.

Ultimately, the major limitation in forecasting whether rising sea levels will amplify the tidal frame and increase tidal velocities and, additionally, whether existing or future shore protection features could contribute to this trend is a lack of specific information about the relations of sea level rise to tidal dynamics for many developed coasts. This information includes temporal trends in sea level rise vis-à-vis changes in tidal amplitude and adequate baseline data on port hydrography (beyond current velocities) where dredging and new construction may be enlarging or contracting the area flooded. The approaches to the Port of Baltimore, for example, are dredged often enough that the hydrographic characteristics could vary substantially from one year to the next. Such changes also affect wave characteristics as well.

Natural or “Soft” Engineering Solutions to Sea Level Rise

The use of natural systems (a.k.a., alternative) for mitigation of coastal erosion, flooding hazards, and the overall coastal vulnerability to accelerate sea level rise is gaining in popularity. The most often cited “natural” solutions to moderating the extent and power of storm surges during hurricanes are coastal wetlands, particularly marshes. The general rule of thumb is that surge height is decreased for each linear 2.5 km of marshes. Unfortunately, this lacks rigorously testing. It was hoped during Hurricane Katrina, which transversed a considerable distance of coastal marshes along the Louisiana coast, that the storm surge would have been appreciably diminished. However, there have been no concrete data produced to date that definitively determined the degree of surge dampening that could be attributed to the

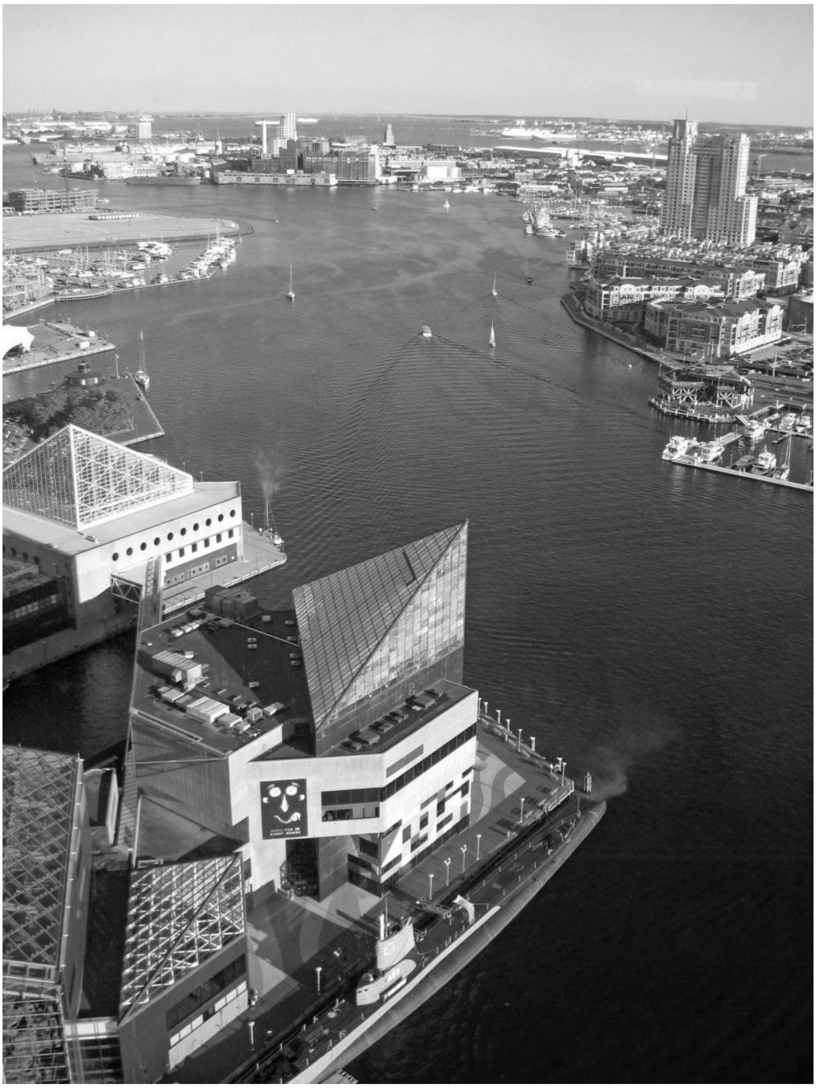

Figure 10-5. Entrance to the Baltimore Inner Harbor. The flow of tidal waters at flood and ebb are constricted as they flow into the Inner Harbor by a sea wall at Fort McHenry on the left and docks and bulkheads of Lazaretto Point on the right.

marshes. Whatever dampening of surge elevations the marshes provided, the storm track flooded New Orleans after it moved northwest of the city.

Several problems make it difficult to assess the possible degree of coastal flood protection afforded by marshes and other coastal wetlands, such as swamps. Marsh canopies differ in height, structure, and biomass, and the extent of coverage of intact marshes can vary widely, especially in an area of active marsh loss, such as Louisiana. An additional complication occurs when wind fields from a hurricane affect coasts long before the arrival of the storm surge. Resio and Westerink (2008) theorize that in these circumstances sustained winds from exceptionally strong hurricanes can blow down grasses and other marsh plants (known as lodging), effectively negating the ability of marshes to dampen surge levels. Some evidence suggests this occurred during Hurricane Katrina (Resio and Westerink 2008).

Some recent findings link excess anthropogenic nutrient inputs in marshes along the U.S. Atlantic and Gulf coasts to organic matter decomposition and root degradation (Swarzenski et al. 2008). Thus, poor and shallow rooting as well as a lack of structural strength of the root mat can greatly increase the likelihood of plant lodging in marshes with even low-intensity hurricanes (Category 1 or 2). In fact, the general appearance of such marshes can be deceptive with regard to their potential for storm surge and wave dampening. Root:shoot analyses (Turner 2004) show a strong bias to lush above-ground biomass while the rooting is poorly developed with low shear strength.

It should not be construed, however, that natural solutions have no real contribution to make in planning for coastal protection in an era of rapid sea level rise. Wetlands clearly enhance coastal sustainability especially by providing ecosystem services; nevertheless, their role in coastal protection is likely to be secondary to more traditional structural measures. Moreover, with rates of loss of coastal marshes likely to increase dramatically with accelerated sea level rise, marsh survival is its own unique problem.

Conclusions

Models for global sea level rise in the Fourth Assessment of IPCC indicate that a dramatic rise in the sea level trend is only a few decades away. The threat this rise poses to the world’s coastal infrastructure is probably without historical parallel; meeting the challenge will require that science and engineering provide the necessary information on future coastal dynamics and risk to structures and the social—economic and life—sustaining services they provide. Fulfilling this mandate will not be easy, as the science for predicting future sea level change is still in development and the requisite data for creating engineering solutions—even for specific localities—are incomplete or absent. The engineering community, however, will still be called on to provide a “fix” regardless of the lack of precedent or inadequate understanding.

One emerging consensus about future sea level rise is that, whatever its eventual magnitude (ignoring the calamity of an extensive polar melt down), rapid change (acceleration) is only decades away (IPCC 2007). Mobilizing the resources to address the vulnerability of existing coastal infrastructure and what may be done to lessen it (retrofitting, replacement, or even redevelopment) is timely. To assess the structural capability of essential infrastructure for even the overall risk to port operations from sea level rise, the following basic coastal science and engineering information would seem a minimal requirement:

- future shoreline position;
- storm wave height from evaluation of freeboard;

- wave power; and
- changes in tidal hydrography.

As discussed earlier, determinations of all these essential factors in considering future sea level rise present problems. However, it is possible to develop scenarios, if not robust estimates, so that planning can occur.

Future Shoreline Position

The pitfalls of deriving rates of shoreline change from often incomplete or equivocal data—particularly in attempting to identify a link with sea level variation—were noted previously. Nonetheless, for general scenario building along low-lying, irregular coasts, simple submergence models provide a useful prediction level for FEMA flood hazard zones. This essentially baseline approach ignores the contribution to shoreline retreat from shore erosion, though the possibility of obtaining reasonable erosion rates for most of these coasts is, as discussed, doubtful. It may be some time for any real understanding becomes available for complex coasts. Fractal geometry, for example, is still more promising as a descriptive rather than as predictive tool as the process linkages remain intriguing if not amenable in any real engineering application (cf. Tebbens et al. 2002).

An additional problem even with such a simple scenario is obtaining accurate elevation data for upland areas. For very low-lying areas with 1: 2000 or lower gradient, where even a decimeter of error might be critical, accommodating this constraint is often problematical despite the growing use of Lidar for nearshore topographical mapping. Real-time kinematic (RTK) GPS has potential and can be implemented to obtain vertical accuracies of ≤1 cm. Moreover, employing this procedure locally can open up the possibilities of "shrink wrapping" older, coarse elevation data if they are internally consistent.

For sandy beaches, especially barrier islands beaches, the Bruun Rule remains a viable option regardless of the generally unfounded criticisms levied against it (e.g., Cooper and Pilkey 2004). Zhang et al. (2000) has produced refined estimates of retreat rates for substantial areas of the U.S. Atlantic Coast, which can be used for scalars for future sea level rise. Lingering theoretical concerns about the concept of an equilibrium profile, which is implicit in the Brunn Rule, can be overlooked by employing Goda's (2007) precept that what appears to work is the criterion by which coastal engineers should be guided, and not whether all details have been worked out.

Wave Height and Power

Determining how sea level rise will affect wave characteristics in shallow protected coasts such as estuaries and bays is clearly a consideration for predicting changes in freeboard exceedance and damage from coastal storms. The *Coastal Engineering Manual* and the older *Shore Protection Manual* contain basic calculations and nomograms defining depth of water and wave height and wave power relationships.

Of course, a genuine analysis of such relationships requires more than these calculations and nomograms can provide (e.g., shore profile characteristics such as offshore bars and channels and bottom and shoreline refraction), but they are clearly useful during an initial planning exercise as a first approximation of the magnitude changes that might occur.

More sophisticated analyses can be developed for areas of particular importance for existing or future coastal infrastructure. The recent *Mid-Bay Island Feasibility Study* engineering component of James and Barren Islands is a good example. Fortunately, much of the software used in developing the data is available online from the U.S. Army of Corps, Vicksburg (e.g., STWAVE, which helps compute wave transformations from shoaling and refraction in shallow water). Models of effective wave height and power can be created using archetypical storms for storm surge and wind stress inputs. Combined with methods described in the FEMA *Coastal Construction Manual* for determining likely storm surge and wave impacts on both shore protection features and buildings, forecasts can be made for retrofitting existing structures or the types of structures and materials that may be required to limit future risks.

Changes in Tidal Hydrography

Information is readily available on how to estimate changes in the tidal frame from sea level rise. However, there is little discussion in the *Coastal Engineering Manual* devoted tidal impacts on coastal structures. The apparent gap is readily understandable because tidal energies are comparatively low for most of the U.S. Atlantic and Gulf Coasts. The Gulf Coast is largely microtidal (0-2 m mean tidal range), and the Atlantic Coast is similarly characterized for the most part as low to moderate tidal energies. The Georgia coast is notably mesotidal (2-4 m mean tidal range), but even here tidal power is a very much secondary to waves as a coastal hazard, and then largely as a facilitator of greater coastal flooding if storms make landfall at high tide.

Nonetheless, there is the potential, as noted, that the constrictions in tidal flow created by coastal structures such bridge pilings and seawalls and bulkhead at harbor entrances, could be enhanced sufficiently to cause undercutting. In this regard, the extensive engineering literature (see HEC 18, 4th Edition) on the effects of extreme river discharges bride piling failure due to scour by very high flow velocities produced by the restriction from the pilings themselves. The basic equations presented in this literature might be used to good effect to predict scour of bridge and wharf pilings.

As described earlier, the essential relations of the tidal prism (area flooded and the rise in the flood tide above mean tide level) can be used to derive velocities. In addition, the literature on tidal inlets (cf. Bruun and Metha 1978) describe how to derive of the effects of double jetty structures or large seawalls at harbor entrances.

Acknowledgments

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Chapter 11. Summary of Breakout Session Discussion: Potential Solution Tracks, Research Needs, and Directions

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Abstract

The objective of the Sea Level Rise and Coastal Infrastructure Workshop, held on June 9-10, 2010, was to bring together scientists, engineers, and policy-makers to define requirements and next steps for developing timely and socioeconomically acceptable solutions for accommodating the challenges posed by rising sea level. In addition to presentations on recent research findings in the subject area, the breakout sessions provided a forum for discussion among experts from a variety of disciplines to collaborate on these issues. Discussion during these sessions covered a wide range of topics, specifically including future sea level rise prediction methods, anticipated impacts on society, proposed engineering solutions, and future steps to ensure actions are taken to address the threat of sea level rise. The results of each discussion topic are provided in this summary.

Introduction

The Sea Level Rise and Coastal Infrastructure Workshop was held on June 9-10, 2010, at the ASCE Bechtel Center. The participants represented several academic, governmental, public, and private organizations including National Oceanic and Atmospheric Administration, Environmental Protection Agency, U.S. Geological Survey, U.S. Army Corp of Engineers, U.S. Navy, City of Baltimore, City of Richmond, Northrop Grumman, Virginia Institute of Marine Science, AECOM, Michael Baker Jr. Inc., Federal Emergency Management Administration, University of Florida, University of Maryland, National Oceanographic Data Center, Wetlands Watch, Manomet Center for Conservation Sciences, Hampton Roads Planning District Commission, Fugro Atlantic, and Vinson & Elkins, LLP. The agenda of the workshop is shown in Table 11-1.

The afternoon of the first day and the second half-day were devoted to breakout sessions. A range of topics were covered in these sessions, many based on the series of presentations that comprised the first morning session. Other topics evolved out of more general discussions of sea level rise and coastal infrastructures issues, especially those on political and social aspects. The most important points raised in discussions, reflecting a wide range of interests from planning to coastal engineering, are summarized in the following pages.

Predicting Future Sea Level Rise and Its Physical Impacts

The morning presentations on sea level rise focused on discussion of its causes, decadal variability, and relations to global climate change. In the breakout sessions following, discussions centered on the improvement of future global sea level forecasts and their relevance on regional and local scales, as well as how it may affect coastal inhabitants.

Allied to the concerns about the uncertainties in forecasts of future global sea level rise, comments were made about the lack of sufficient data to make use of predictions of sea level rise. Chief among the gaps in data identified were detailed information on land elevation in many areas sufficient enough to model future inundation levels due to sea level rise effects. While some areas of the coastal regions are surveyed in detail for land elevation data, it was pointed out that many potential land areas in danger of being affected by a combination of sea level rise and resulting changes in storm surge lack this through coverage. Particularly with older data, data surveys used for past sea level heights may be infrequent and/or irregular in time and location, making it difficult to assume the sea level height in between data points. The location of measurement was also suggested to have a significant effect on the data, as sea level height can vary by region.

High-resolution elevation data in all coastal regions was suggested as a tool that could be useful step to help more accurately predict sea level rise rates on a local scale. A participant did point out that the United States Geological Survey (USGS) had published a national shoreline change assessment in 2007, and that there were also considerable information available on shore erosion rates for the California coast and the barrier islands of the U.S. Atlantic Coast. However, it was also noted that the extensive and highly irregular shorelines of many Atlantic Coast estuaries were often poorly inventoried with respect to shoreline erosion data. Moreover, it was commented that the relations of such erosion rates to rates of sea level rise were often not clear, and that a linear relationship between a certain rate of sea level rise and shoreline rate cannot be assumed to always coincide.

Another frequently mentioned information gap was the absence of reliable data on rates of shore erosion/shoreline retreat that can be expected with different rates of sea level rise. Considerable concern was voiced about the stability of the land and how the lack of adequate data on phenomena such as subsidence, or settlement of the land, make translating sea level rise scenarios down to local scales for planning purposes highly uncertain. Some regions could see larger than predicted rises in sea level, while others may experience little effects at all.

In response to the discussion of problems in determining future trends in sea level rise, many comments were made regarding the scarcity of information on how and where people would be affected by rising sea levels. The degree of impact of sea level rise can vary depending on the location of interest, the size of the area considered, and the number of people within that area. Variations in the methodology measurement of the number of people in coastal regions was stressed as a point of diverging opinions. The chapter by Crowell et al. is a major step in this direction, since as it was pointed out several times, the desire to address sea level rise (as is true of other environmental issues) is more likely to be stronger and become translated into policy where the numbers of people affected are greater.

Participants in the breakout sessions were in general agreement that the information ranging from global forecasts of future sea level rise to regional and local data shore erosion rates and how they related to rates of sea level rise were either lacking or fraught with uncertainty. It was commented, however, that the presenters had made a convincing argument that the probability of a dramatic rise in global sea level was high, whatever its ultimate rate, and in terms of timing was only a few decades away. With this realization, discussions in the remainder of the breakout sessions turned to considering what can be done, especially within the context of engineering solutions.

Engineering Solutions

The discussions about engineering solutions to anticipated sea level rise touched on a number of issues, including the role of the engineering community—in particular, the American Society of Civil Engineers (ASCE)—in informing the public with the necessary information and tools to begin addressing the potential risks of sea level rise to coastal infrastructure. Among the important information suggested were questions of both feasibility and cost of addressing the issue.

Discussions also turned to possible groups that could create a “toolbox” that would enable decision makers, planners, and others to frame such questions for better communication with engineers. Potential partnerships or collaborative efforts among several organizations to begin to addressing this issue were also discussed. Participates understood the need for room in public and private budgets to include sea level rise adaptive measures, as well as the need to seek additional funds from grants or other sources to offset costs.

Comments were also made about the role of scientists and engineers in particular taking on the role of framing the hard decisions that likely will have to be made in ways the wider community can understand. It was remarked that, given the probable short lead time before the onset of global acceleration in sea level rise, that scientists should educate the public on the realities of what can be done as opposed to what many believe might be done.

In later sessions general discussions shifted from the contribution the engineering community can make in educating the public of the sea level threat and the options available for ameliorating the risk, to topics concerning actual measures to be taken. Suggested steps to be taken for adaption to sea level rise were discussed on both a national and local scale.

On a national scale, three main steps were suggested—first being to jointly research and assess the known information on the subject of sea level rise. This includes defining costal infrastructure and categorizing it based on its threat in the event of rising sea levels. Ultimately, the goal of this step would be to figure out, given what is known, what actions need to be taken to receive the attention and funding needed to address this issue.

The second step discuss was the need to establish groups of people and/or regulatory groups to work on addressing sea level rise concern. This would include the involvement of stakeholders and raised awareness of the public. It was suggested that appropriately chosen federal agencies could provide funding requirements to localities affected by the threat of sea level rise.

The third and final step discussed was the creations of a framework in which all gathered information is concentrated, to allow for more standardized and simplified assessments of infrastructure and environmental impact. Products of this framework that were suggested included steps for coastal localities to select appropriate actions based on circumstances, unit costs incurred by governments or other agencies, and possible legislative actions needed to help coastal communities adapt.

On a local rather than national scale, a wide range of topics were considered, from zoning and wise planning solutions, to easements and setbacks. It was emphasized that local efforts should focus on stopping the exacerbation of the problem by allowing vulnerable infrastructure to continue to be built in potential inundation zones, and instead focus efforts on the development of long-range plans with solutions that have both mitigative and adaptive value. Whatever the chosen action of local agencies, making the decision on long-term plans is better done now than later; otherwise, it is harder to make preparations.

For infrastructure in danger of sea level rise effects, it was suggested that a “triage” be instituted to ensure coastal areas receive the most immediate attention for mitigative measures, whether it be new better-adapted construction, or the retrofitting of existing structures. Three options were discussed, each with its own advantages and disadvantages. First, protect what exists by building “armor” around it, or elevating it to higher heights. Solutions suggested were the use of vegetation with strong root systems, living shorelines, and storm surge barriers, among many others.

The second option is to accommodate what is in place through infrastructure modification. Various methods of were discussed that are already in used such as raising the street level as Sacramento has done. The third option is retreat, or the moving back of the infrastructure into less potentially risky zones. This third option was cited as a possibility because in the event of a natural disaster(s), it will at some point become cheaper to retreat rather than rebuilding and repairing every time something happens. This is the most sustainable option of the three, but also the most drastic and costly in the short-term. This approach was proposed in recognition that, with the looming sea level acceleration and limited resources (financial and technical), "we cannot save everything." Whatever its theoretical merits, it was noted that such a policy would be politically unacceptable and difficult to implement. Clearly, adaptive governance represents a possible avenue, but it is more within the realm of a policy framework in which engineering will have to work.

To enforce efforts to adapt coastal environments for sea level rise on a local scale, various possible methods were suggested. With the support of law-making agencies, using the law to enforce required building heights and threaten property rights if law are not followed was one possibility. From a more engineering-based approach, a professional engineering standard was also suggested that would provide a checklist for professional engineers (PEs) to sign off on before a structure is built or modified. In order for engineers to be amenable to this change, it was suggested that a tool be developed to provide PEs with the knowledge to be able to confidently sign off on this checklist. Other suggestions included Environmental Impact Statements, and FEMA risk advisory letters, as well as variations on agreements with landowners about what happens when their property is affected by sea level rise.

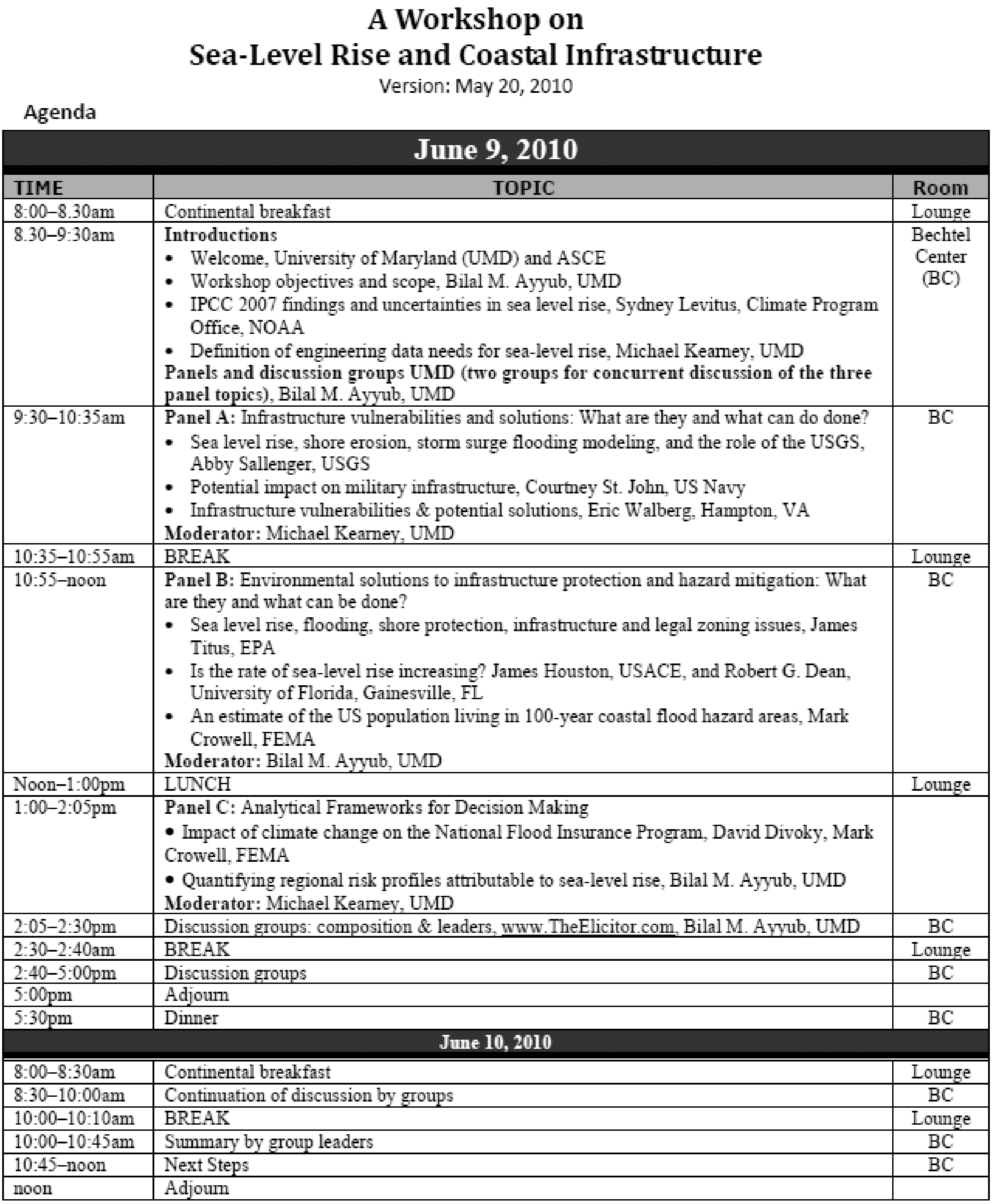
Later discussions turned back to areas in which engineering can make its unique contribution to the problems and potential solutions discussed throughout the workshop. The civil engineering community is best qualified for the role of evaluating existing coastal infrastructure vulnerability to future sea level rise and its estimated costs of upgrades or replacements, and also providing an informed prospective on what feasible solutions may be available in the near future. Numerous points were made, however, that there are no readily available databases for existing coastal infrastructure, in terms of type of structure, location, age, or condition.

It was suggested that the ASCE standard for construction in seismically active areas might serve as a guide for developing a protocol for coastal infrastructure; and the ASCE could initiate a program as an organizational goal. Interactions with the U.S. Department of Housing and Urban Development (HUD), Federal Highway Administration (FHWA), American Planning Association, state and regional regulatory groups, as well as the U.S. Climate Change Science Program (www.climatescience.gov) could help develop a framework for targeting the appropriate information needs and disseminating the information to relevant groups and agencies. One result could take the form of a manual similar in its intended audience to the Federal Emergency Management Administration (FEMA) *Coastal Construction Manual*.

The Way Forward

A final series of discussions focused on how to move forward with an agenda for broadening the audience for engaging in conversations about the risk that future sea level rise poses for coastal infrastructure. A range of possibilities were mentioned, from initiatives for national and regional programs for educating coastal states, communities, and individual stakeholders, to working with elected officials to develop mechanisms for funding both research and outreach. The importance of educating others—civilians, policy makers, and landowner alike, about this issue of sea level rise. The creation of an easy-to-read brochure for specific audiences that provides the basics of the issue was a popular suggestion. In addition making documentation and pertinent information widely available for coastal regions to use for planning purposes was also suggested. Providing classes or information sessions on how to use this material was also suggested – allowing an easy way for interested parties to learn about the issue and what actions are appropriate to take. A critical point raised by several participants is that no one agency at the federal level has a defined an area of interest in the specific issue of sea level rise, although the National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), United States Army Corps of Engineers (USCOE), FEMA, and USGS most notably have staked claims to the general topic in various ways.

As was noted, the subject of the workshop, sea level rise and coastal infrastructure, is one that has science, engineering, policy and, potentially, regulatory aspects. It thus overlaps the mandate of several federal agencies, but it presently has no defined home in any. The next step forward may indeed be indentifying a source of federal stewardship.



A Workshop on Sea-Level Rise and Coastal Infrastructure

Version: May 20, 2010

Agenda

June 9, 2010

TIME	TOPIC	Room
8:00–8.30am	Continental breakfast	Lounge
8.30–9:30am	**Introductions** • Welcome, University of Maryland (UMD) and ASCE • Workshop objectives and scope, Bilal M. Ayyub, UMD • IPCC 2007 findings and uncertainties in sea level rise, Sydney Levitus, Climate Program Office, NOAA • Definition of engineering data needs for sea-level rise, Michael Kearney, UMD **Panels and discussion groups UMD (two groups for concurrent discussion of the three panel topics)**, Bilal M. Ayyub, UMD	Bechtel Center (BC)
9:30–10:35am	**Panel A:** Infrastructure vulnerabilities and solutions: What are they and what can do done? • Sea level rise, shore erosion, storm surge flooding modeling, and the role of the USGS, Abby Sallenger, USGS • Potential impact on military infrastructure, Courtney St. John, US Navy • Infrastructure vulnerabilities & potential solutions, Eric Walberg, Hampton, VA **Moderator:** Michael Kearney, UMD	BC
10:35–10:55am	BREAK	Lounge
10:55–noon	**Panel B:** Environmental solutions to infrastructure protection and hazard mitigation: What are they and what can be done? • Sea level rise, flooding, shore protection, infrastructure and legal zoning issues, James Titus, EPA • Is the rate of sea-level rise increasing? James Houston, USACE, and Robert G. Dean, University of Florida, Gainesville, FL • An estimate of the US population living in 100-year coastal flood hazard areas, Mark Crowell, FEMA **Moderator:** Bilal M. Ayyub, UMD	BC
Noon–1:00pm	LUNCH	Lounge
1:00–2:05pm	**Panel C:** Analytical Frameworks for Decision Making • Impact of climate change on the National Flood Insurance Program, David Divoky, Mark Crowell, FEMA • Quantifying regional risk profiles attributable to sea-level rise, Bilal M. Ayyub, UMD **Moderator:** Michael Kearney, UMD	
2:05–2:30pm	Discussion groups: composition & leaders, www.TheElicitor.com, Bilal M. Ayyub, UMD	BC
2:30–2:40am	BREAK	Lounge
2:40–5:00pm	Discussion groups	BC
5:00pm	Adjourn	
5:30pm	Dinner	BC

June 10, 2010

8:00–8:30am	Continental breakfast	Lounge
8:30–10:00am	Continuation of discussion by groups	BC
10:00–10:10am	BREAK	Lounge
10:00–10:45am	Summary by group leaders	BC
10:45–noon	Next Steps	BC
noon	Adjourn	

Table 11-1. Agenda for Sea Level Rise and Coastal Infrastructure Workshop

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