Updating Maryland's **Sea-level Rise Projections**

Scientific and Technical Working Group
Maryland Climate Change Commission

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Introduction

Sea-level Rise and the Free State

With its 3,100 miles of tidal shoreline and low-lying rural and urban lands, "The Free State" is one of the most vulnerable to sea-level rise. Historically, Marylanders have long had to contend with rising water levels along its Chesapeake Bay and Atlantic Ocean and coastal bay shores. Shorelines eroded and low-relief lands and islands, some previously inhabited, were inundated. Prior to the 20th century, this was largely due to the slow sinking of the land since Earth's crust is still adjusting to the melting of large masses of ice following the last glacial period. Over the 20th century, however, the rate of rise of the average level of tidal waters with respect to land, or relative sea-level rise, has increased, at least partially as a result of global warming. Moreover, the scientific evidence is compelling that Earth's climate will continue to warm and its oceans will rise even more rapidly.

"As storms such as Hurricane Sandy have shown, it is vital that we commit our resources and expertise to create a ready and resilient Maryland, by taking the necessary steps to adapt to the rising sea..."

—Governor O'Malley

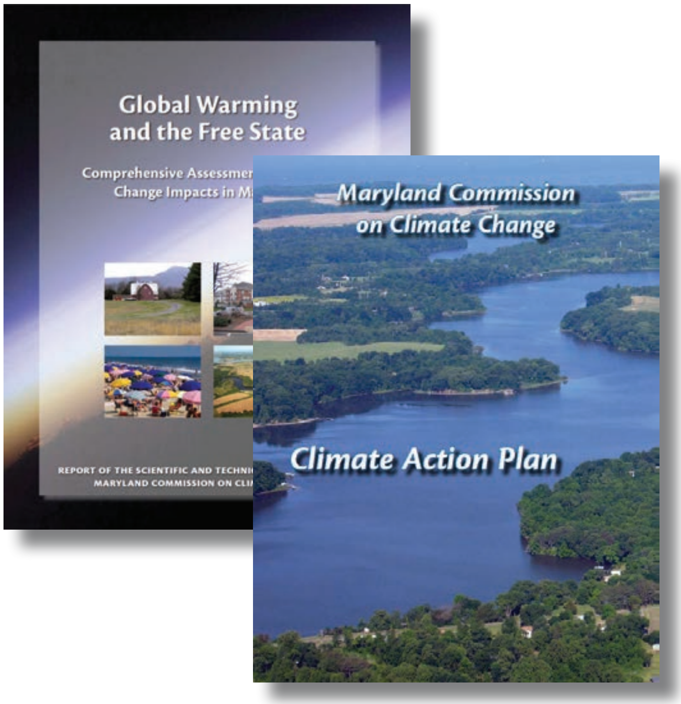
Recognizing the scientific consensus around global climate change, the contribution of human activities to it, and the vulnerability of Maryland's people, property, public investments, and natural resources, Governor Martin O'Malley established the Maryland Commission on Climate Change on April 20, 2007. The Commission produced a *Plan of Action*[1] that included a comprehensive climate change impact assessment, a greenhouse gas reduction strategy, and strategies for reducing Maryland's vulnerability to climate change. The *Plan* has led to landmark legislation to reduce the state's greenhouse gas emissions and a variety of state policies designed to reduce energy consumption and promote adaptation to climate change.[2]

Downtown Annapolis was flooded during Hurricane Isabel in 2003. Higher sea levels will increase the extent and frequency of flooding from such storms.

Don Boesch

Sea-level Rise Projections in the Maryland Climate Action Plan

Previous projections[3] of sea-level rise specific to Maryland and extending throughout the 21st century were developed by the Climate Change Commission's Scientific and Technical Working Group (STWG) and presented in its 2008 report, *Comprehensive Assessment of Climate Change Impacts in Maryland*[4]. These projections were used in Phase I[5] of a *Comprehensive Strategy to Reduce Maryland's Vulnerability to Climate Change* that specifically addressed vulnerability due to sea-level rise and coastal storms. Phase II[6] included broader strategies to build societal, economic, and ecological resilience.



Left: Global Warming and the Free State, a Comprehensive Assessment of Climate Change Impacts in Maryland.

Right: Climate Action Plan, Maryland Commission on Climate Change.

These projections indicated that Maryland might experience a relative sea-level rise of 0.82 m (2.7 ft) during this century under a scenario of lower greenhouse gas emissions[7] and as much as 1.04 m (3.4 ft) under a scenario of higher greenhouse gas emissions. These, and the other climate change projections used in the STWG assessment, were developed in early 2008 following the release of the Fourth Assessment of the Intergovernmental Panel of Climate Change (IPCC).[8] The IPCC took a conservative approach to projecting sea-level rise that included modeling of the specific processes that would contribute to sea-level rise, such as expansion of the volume of the ocean as it warmed and the melting of glaciers. It indicated that the rise in global mean sea level (GMSL) would not likely exceed 0.52 m (1.7 ft) by the end of the century. However, the IPCC explicitly excluded future changes in flows from polar ice sheets that, at that time, could not be confidently modeled based on the peer-reviewed literature. It noted that, if flows from polar ice sheets would grow linearly with global mean temperature, the projection might increase by as much as an additional 0.2 m (0.7 ft).

With emerging evidence of a more rapid acceleration of polar ice sheet melting[9], the IPCC projections were criticized as being too conservative even as they were published. Around the same time of the release of the IPCC report an alternative method for projecting sea-level rise, called the semi-empirical approach, was published.[10] It is a statistical, rather than a process-based, approach that mathematically fits a relationship between the observed sea-level rise and temperature increase over the past century. Future sea-level rise is then estimated based on projections of future global mean temperature, using the same emissions scenarios and climate models used by the IPCC. This resulted in significantly greater best projections for global sea-level rise of 0.87 m (2.9 ft) and 0.72 m (2.3 ft) for the same higher and lower emissions scenarios used in the 2008 Maryland Assessment. The projections of relative sea-level rise used in the Maryland assessment were based on projections of GMSL rise derived from the 2007 version of the semi-empirical model. These projections were also adjusted by the rate of vertical land movement (VLM) of -1.7 mm yr^{-1} derived from 20th century estimates of relative sea-level rise for coastal Maryland as a whole. There was no explicit attempt to include a range of estimates, as only the mean projections were used.

Rapidly Developing Science

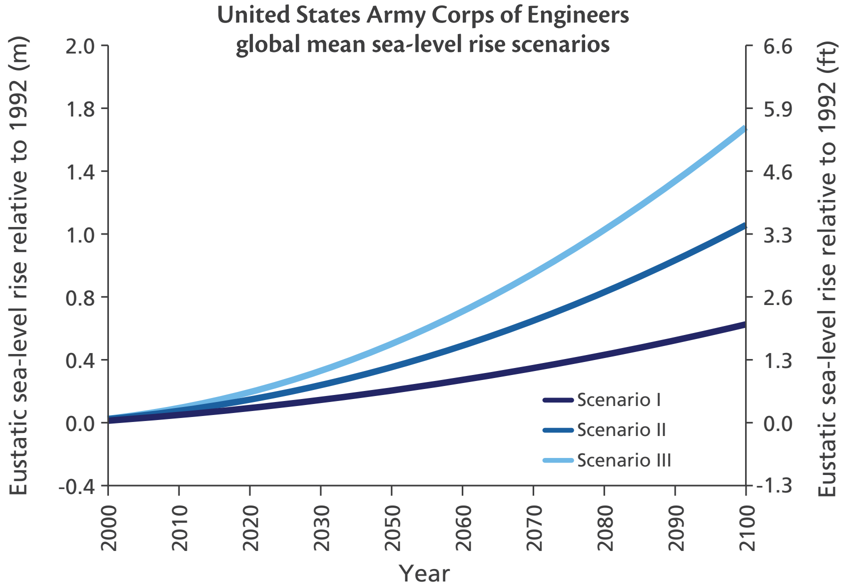
Since 2008, there has been a virtual explosion of the scientific literature related to past and future sea-level rise that can better inform projections of sea-level rise for Maryland. These publications include a refinement of the semi-empirical approach[11]; criticisms of this approach[12]; more definitive estimation of present and future rates of melting of polar ice sheets and glaciers; detailed assessments of sea-level rise indicators from tide gauges, satellite altimeter measurements, and coastal sediment deposits; studies of historical sea-level rise based on tide gauges within the region; and investigations of the causes of regional differences in sea-level rise. In general, these scientific results have demonstrated: (1) the 20th century experienced the highest rate of sea-level rise in the last 2,000 years[13]; (2) global mean sea level (GMSL) rose at an average rate of 1.7 mm yr^{-1} during the 20th century based on tide gauge records[14] and an average of 3.2 mm yr^{-1} from 1993 to the present based on satellite measurements[15]; (3) rates of melting of the Greenland and West Antarctic ice sheets accelerated[9]; and (4) sea level is likely to rise more than estimated by the IPCC 2007 assessment.

Key Message

The 20th century experienced the highest rate of sea-level rise in the last 2,000 years.

Recent Federal Guidance

In 2011, the U.S. Army Corps of Engineers (USACE) issued guidance[16] for incorporating the direct and indirect physical effects of projected future sea-level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects. Insofar as it affects federal projects in the State of Maryland, as stated in Executive Order 01.01.2012.29, this guidance should also be considered in developing Maryland-specific sea-level projections. Rather than requiring a specific range of sea-level rise to be used in planning, the Corps guidance specifies that alternatives be evaluated under three scenarios of a curvilinear increase in sea level during the 21st century: low, resulting in 0.5 m (1.6 ft) of GMSL rise by 2100; medium, resulting in 1.0 m (3.3 ft); and high, resulting in 1.5 m (4.9 ft). The guidance indicated that GMSL rise should be adjusted by the local rate of vertical land movement (VLM) for planning specific projects.



Sea-level rise scenarios included in the Corps guidance for coastal project planning.[16]

A large piece of ice calving off the Margerie Glacier in Glacier Bay, Alaska. Photo by Larry D. Moore, 2011. From http://commons.wikimedia.org/wiki/File:Margerie_calving.jpg

The Charge

On December 28, 2012, Governor Martin O'Malley issued an executive order on Climate Change and "Coast Smart" Construction that requires State agencies consider the risk of coastal flooding and sea-level rise to capital projects and to site and design such projects to avoid or minimize associated impacts. In addition, Section 7 of the order directs: "The Scientific and Technical Working Group shall review the sea-level rise projections in the Maryland Climate Action Plan (2008) and shall provide within 180 day of the effective date of this Executive Order, updated projections based on an assessment of the latest climate change science and federal guidance." This present report responds to the directive through interpretation of recent scientific results to produce projections useful for sea-level rise adaptation in Maryland.

Jane Hawkey

Coastal erosion during Tropical Storm Hanna (2008) on Taylors Island, in Dorchester County. The effects of coastal storms become worse when paired with sea-level rise.

The Approach

This revision of sea-level rise projections for Maryland was developed through consultation with a group of experts from Maryland and the Mid-Atlantic region. These experts included several who led or participated in the national assessments of sea-level rise published within the past year that are discussed below, as well as authors of recently published papers on sea-level rise in Chesapeake Bay and the Mid-Atlantic region. Three members of the Scientific and Technical Working Group (STWG) that produced the 2008 Maryland Assessment, who are familiar with sea-level rise issues, were included in the expert group to ensure continuity and context. The group of experts was convened on March 8, 2013 for a focused workshop to review and revise a draft framework document that drew heavily from recent national assessments. Drafts were subsequently reviewed and revised by the group of experts to produce this consensus report.

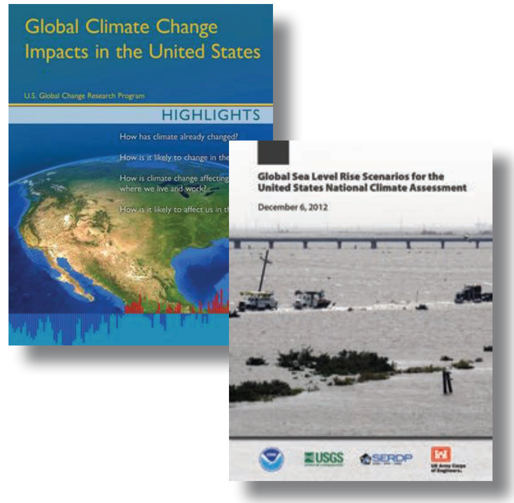
Experts participate in a workshop on March 8, 2013 to start the process of updating sea-level rise projections in Maryland.

Maryland Sea Grant

Building Blocks

Recent Assessments

During 2012, two important assessments of projected sea-level rise were published: a report by the National Research Council (NRC) on sea-level rise along the California, Oregon, and Washington coasts[17] and the development of sea-level rise scenarios[18] used in the National Climate Assessment[19] that is scheduled to be released in 2013. The NRC assessment examined in detail the latest science concerning the processes contributing to sea-level rise, including thermal expansion of ocean volume; melting of glaciers, ice caps, and ice sheets; terrestrial water storage; and factors that would affect sea-level rise along the U.S. West Coast, including changes in ocean circulation and vertical land movement. From these, processed-based projections were made through the 21st century and contrasted with projections made using the revised (2009) semi-empirical approach.[11]

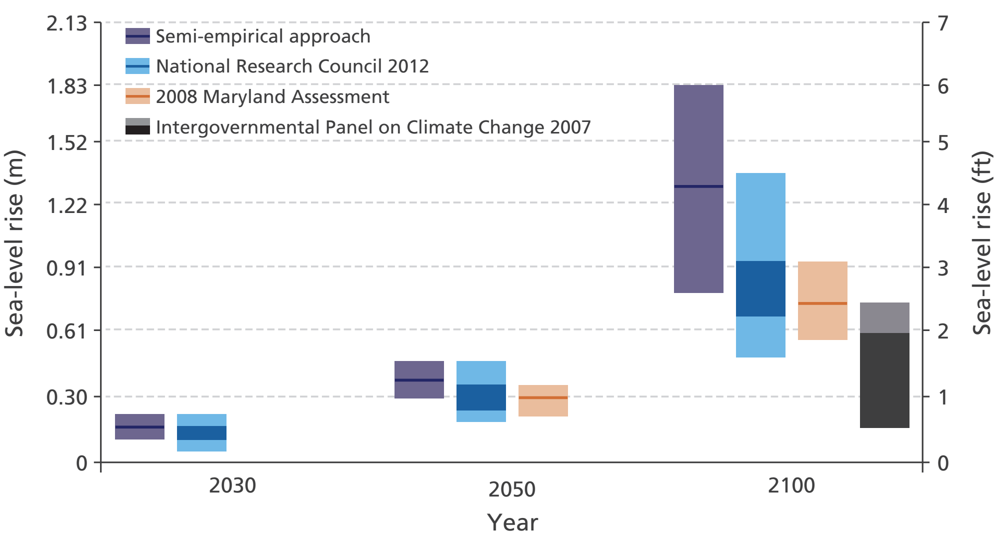


Left: Global Climate Change Impacts in the United States published by the National Climate Assessment in 2009. The updated report is scheduled to be released in 2013.

Right: Global Sea Level Rise Scenarios for the United States National Climate Assessment published by the National Research Council.

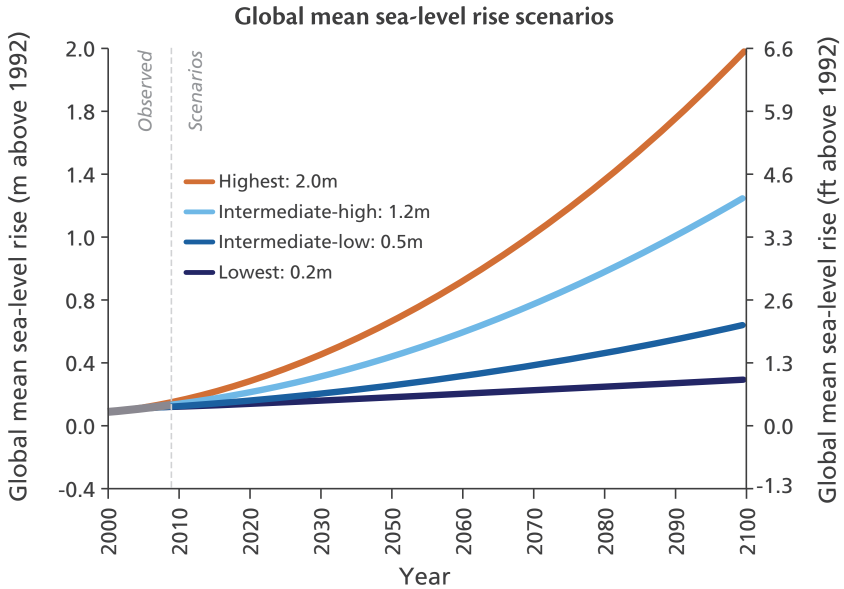
The figure below compares these projections with those that served as the basis for the 2008 Maryland Assessment. For the NRC projections, the dark portion of the bars represent the confidence limits of the mean and the full bars represent the 5 to 95% probabilities. Also depicted are the Intergovernmental Panel on Climate Change (IPCC) projections plus the scaled-up ice sheet component (lighter shade) that was mentioned earlier. As presented here, ranges of projections do not differentiate among the emissions scenarios on which they are based. The much higher range for projections based on the semi-empirical approach is caused, in part, by inclusion of a scenario with greater emissions[20] than the "higher emissions" scenario that has been used in the 2008 Maryland Assessment. Even so, the semi-empirical projections produce greater sea-level rise for a given emissions scenario than process-based models used by the NRC and IPCC.

Comparison of global mean sea-level rise projections



Comparisons of global mean sea-level (GMSL) rise projections developed by the National Research Council[17] with those generated by the semi-empirical approach[11] as presented in the NRC report. The GMSL rise component projections used in the 2008 Maryland Assessment[4] are included for comparison as are projections for 2100 by the IPCC Fourth Assessment,[8] including the scaled-up ice-sheet component.

The expert panel that developed sea-level rise scenarios for the National Climate Assessment (NCA) used a different approach. After synthesizing prior assessments, the panel recommended four discrete scenarios for the purposes of risk assessment, building on the scenario approach in the U.S. Army Corps of Engineers guidance discussed above. The Corps used multiple scenarios to deal with key uncertainties for which no reliable or credible probabilities can be obtained. The NCA report[18] notes that how much weight decision makers would put on different parts of the distribution would depend on the time frame being considered, costs, consequences of disruption or damage, and the level of risk aversion. Thus, the highest scenario might be used for long-term projects where there is low tolerance of risk, and the lowest scenario might be used for decisions in which the tolerance of risk is high. The report also stresses that the need to take into account regional differences from the global mean, but does not specifically estimate them for the diverse coastlines of the United States.



Sea-level rise scenarios developed for the National Climate Assessment.[18]

The approach taken in this current assessment for Maryland follows the approach used in the recent National Research Council (NRC) report for the West Coast. This probabilistic approach is similar to that undertaken in Intergovernmental Panel on Climate Change (IPCC) assessments for projections of global temperature, sea-level rise, etc., and provides the relative advantage of understanding the likelihood of a specific sea-level rise trajectory. This allows some narrowing of possible and probable outcomes. In addition, specific regional factors such as vertical land movement (VLM) and ocean dynamics are incorporated to provide Maryland-specific projections.

Key Message

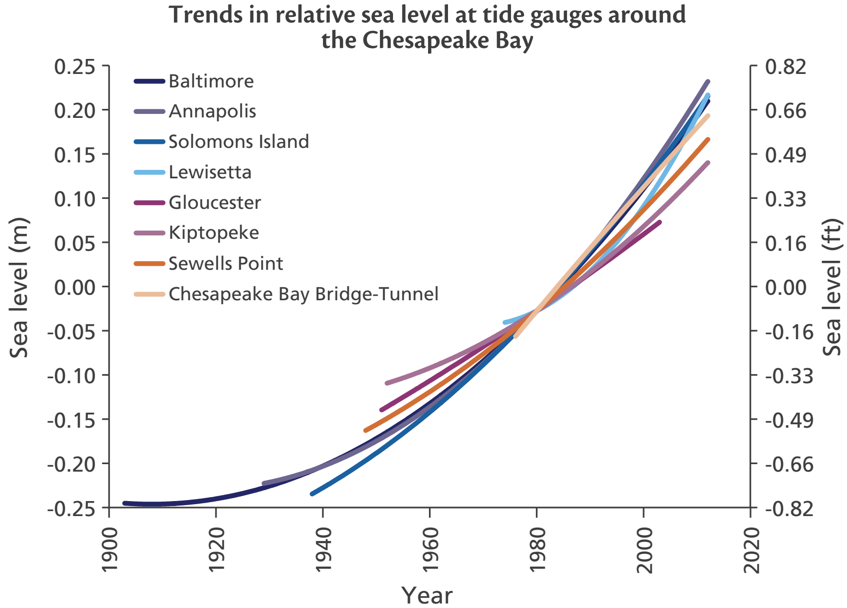
This reassessment narrows the probable range of relative sea-level rise based on the latest science, including regional vertical land movement and ocean dynamics.

The first report on the Fifth Assessment of Intergovernmental Panel on Climate Change, dealing with the Physical Science Basis, is scheduled to be released in September 2013. These projections are based on a new set of greenhouse gas concentration scenarios called Representative Concentration Pathways (RCPs) that better reflect greenhouse gas emission reduction possibilities and climate change stabilization goals.[21] These RCP scenarios span the greenhouse-gas radiative forcing values found in the literature, ranging from RPC 2.6, with greenhouse-forcing peaking in 2020, to RCP 8.5, with greenhouse-gas forcing continuing to rise into the 22nd century.

Recent Sea-level Rise in Maryland and the Mid-Atlantic Region

Several papers published within the last year provide detailed analysis of sea-level rise trends as measured by tide gauges along the Mid-Atlantic coast. These papers consistently show that sea level has been rising faster in that region than elsewhere along the Atlantic coast.[22-24] The rate of sea-level rise began to increase in the late 1980s. Sea level along this coast is influenced by the flow of the Gulf Stream, rising as the flow declines.[25] The more rapid sea-level rise in the southern portion of the Mid-Atlantic Bight, including the Chesapeake Bay, has been attributed to the continuous weakening of the Gulf Stream since about 2004.[26]

While relative sea-level rise of 7-8 mm yr^{-1} has been measured at Maryland tide gauges between 2002 and 2011, this time period is too short to interpret this higher rate as a trend, much less attributed to one factor. The Climate Change and "Coast Smart" Construction Executive Order takes explicit note of these recent scientific results, stating: "In July 2012, the U.S. Geological Survey published research in the journal *Nature Climate Change* documenting that over the last 20 years, sea levels along the 1,000 kilometer stretch of coast running north from Cape Hatteras to north of Boston, which includes the State of Maryland, have risen at an annual rate three times to four times faster than the global average."



Relative sea-level rise over the past century from analysis of tide gauge records from the Chesapeake Bay; sea level is relative to 1980.[23] The mathematical analysis applied removes oscillating modes to depict the underlying trends.

A tide gage at Bishop's Head, Maryland, in Dorchester County.

National Weather Service

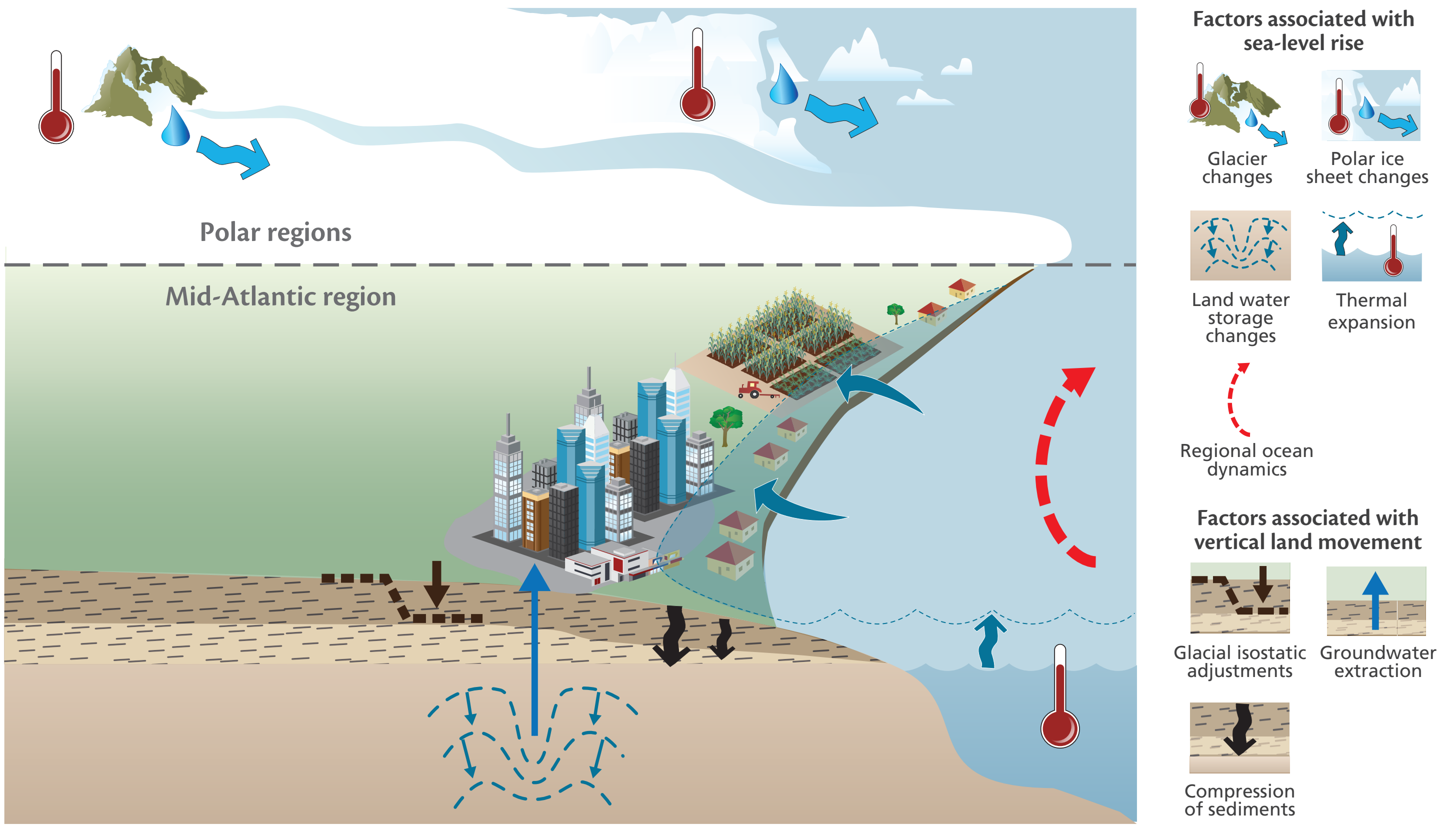
Projecting Future Sea-level Rise for Maryland

Factors That Will Determine Sea-level Rise in Maryland

Developing projections for relative sea-level rise along Maryland's coasts requires consideration of the many factors that will affect: (1) the rise in global mean sea level (GMSL); (2) regional differences in sea level with regard to the global mean; (3) vertical land movement (VLM); and (4) changes in tidal range and storm surges due to inundation.

Process-based projections of GMSL, such as those undertaken in the Intergovernmental Panel on Climate Change (IPCC), National Research Council (NRC) and National Climate Assessment (NCA) assessments, include the contributions of thermal expansion, melting glaciers, the net loss of ice from Greenland and Antarctic ice sheets, and land water storage. The effects on GMSL of longer-term geological processes such as ocean ridge spreading, tectonic plate movement, and depression of continental margins by the weight of sediment and sea water are thought to be negligible over this century. Beyond the dynamics of glaciers, the amount of water stored on the continents is being affected by human activities through depletion of ground water and storage of water in artificial reservoirs. While the addition of water storage behind dams was significant during the 20th century, groundwater depletion is expected to exceed expanded surface-water storage during the present century, thus change in land-water storage is expected to make a small, positive contribution to sea-level rise.

The surface of the world's oceans is not, in fact, level, but varies regionally due to spatial variations in temperature, gravity, and the dynamic motions of ocean currents, among other effects. As the world warms and more water is added to the oceans the rise in sea level will also not be uniform. For example, since 1993, when satellite altimeter measurements have been able to repeatedly measure the sea-surface height over the world's oceans, the rate of sea level has increased by as much as 10 mm yr^{-1} in parts of the western Pacific Ocean while actually declining in parts of the eastern Pacific. Melting of polar ice sheets will reduce the polar land mass and thus the gravitational attraction of ocean water, counter-intuitively resulting in sea-level decline in nearby polar regions and sea-level increase in tropical regions. The effects of these dynamic ocean processes on sea levels along the U.S. northeast coast are considered in a subsequent section.



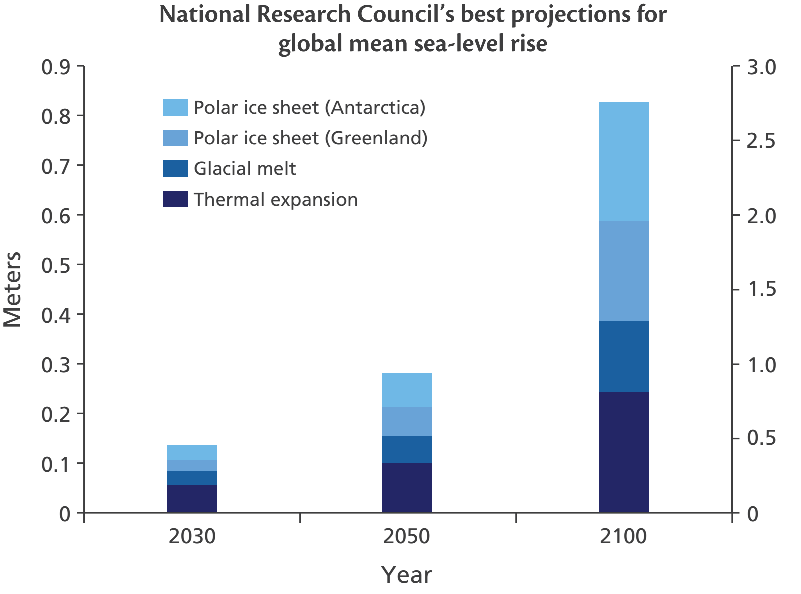
Water levels along Maryland's coasts are actually observed with respect to the land elevation, which in turn is affected by vertical land movement (VLM). VLM is influenced by several subsurface geological processes. In coastal Maryland, the most important of these processes is glacial isostatic adjustment (GIA). The melting of glaciers that existed during the last ice age that ended about 12,000 years ago resulted in a readjustment of Earth's crust. The crust is rising up where it was depressed by this massive load and adjusting downward where a forebulge was created south of where the great glaciers stood, including Maryland. As the melting proceeded, the inundation of the present continental shelf caused further flexing of the crust. GIA is still going on, thousands of years after the disappearance of the glaciers. In addition, VLM may result from compression of unconsolidated sediment lying atop the crust or as a result of extraction of ground water, causing slumping of overlying formations. These effects can be more geographically limited than GIA and may account for differences in VLM within coastal Maryland. The compression processes are often referred to as subsidence, but subsidence is sometimes also used to describe the net effect, including GIA. To avoid confusion, VLM is used here to describe the aggregate effects. More detailed consideration of the rates of GIA and VLM is given in a subsequent section, as is consideration of changing tidal ranges and storm surges on coastal inundation.

As land subsidence occurs in Maryland, more areas in the state are at risk of flooding due to sea-level rise. Photo from Guy W. Willey Sr.

Global Mean Sea Level

The most recent and thorough assessment of the likely rise in global mean sea level (GMSL) that developed process-based projections was that of the National Research Council (NRC).[17] It was developed by prominent U.S. experts and reviewed by the rigorous NRC process for a similar purpose, advising adaptation planning along the states of California, Oregon, and Washington. Future sea-level projections will always produce differences as new data are produced and methods are refined. However, until the release of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment, the NRC projections provide the best scientific consensus projections of GMSL rise for use in adaptation planning.

The NRC projections for GMSL rise demonstrate that, while thermal expansion of the ocean volume is expected to make up the largest component throughout the century, as time goes on, the proportional contribution by the loss of mass of the Greenland and Antarctic ice sheets is expected to increase. Furthermore, the probability distributions for the polar ice sheet contributions are very broad. This is a major factor in extending the high end of the range of projections. Put another way: whether GMSL rises faster than the best projection of 0.83 m (2.72 ft) by 2100 depends largely on the rate of loss in the mass of the polar ice sheets.



Contributions to the component sources of global mean sea-level rise for the National Research Council's best estimates.[17]

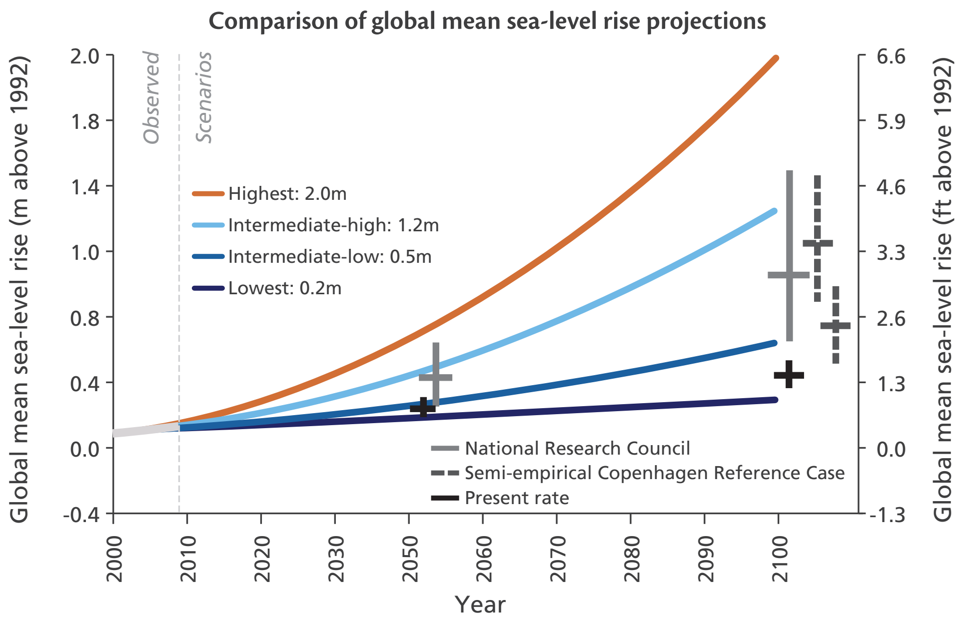
Comparison of global mean sea-level rise projections

	2050		2100	
	Projection or central estimate (m)	Uncertainty range (m)	Projection or central estimate (m)	Uncertainty range (m)
National Research Council 2012[14]	0.28	0.18–0.48	0.83	0.50–1.40
Semi-empirical approach				
A1FI scenario (highest emissions)[11]	0.40	0.36–0.48	1.42	1.11–1.74
A2 scenario (higher emissions)[11]	0.38	0.34–0.46	1.24	0.97–1.50
B1 scenario (lower emissions)[11]	0.36	0.31–0.44	1.03	0.80–1.27
Zero 2016 scenario[25] (human emissions cease in 2016)	0.28	0.23–0.38	0.59	0.40–0.80
RCP 4.5 scenario[25] (used in the IPCC Fifth Assessment)	0.32	0.24–0.40	0.90	0.64–1.21
CPH reference scenario[25]	0.32	0.24–0.40	1.02	0.72–1.39
National Climate Assessment scenarios[15]				
Highest	0.63		2.00	
Intermediate-High	0.40		1.20	
Intermediate-Low	0.22		0.50	
Lowest	0.10		0.20	

Projections based on the semi-empirical approach assume that sea-level change in the future will have the same relationship to the radiative forcing of greenhouse gases and global air temperature change as it has in the past. The projections are sensitive to different data sets for temperature and sea level as well as different statistical techniques.[27] Largely because of these limitations, semi-empirical projections have not attracted a consensus of acceptance by sea-level rise experts. Still, they are useful to compare with projections derived from process-based models to bound likely outcomes and to compare the consequences of different emissions scenarios.

The Antarctic ice sheet might have lost enough mass to cause the worlds' oceans to rise about .05 inches, on average, between 2002 and 2005. Photo from NASA.

Comparing the National Research Council (NRC) projections for global mean sea level (GMSL) rise by the end of the century with the scenarios used in the National Climate Assessment shows that the NRC projections encompass the Intermediate-Low to Intermediate-High scenarios, or 0.5 to 1.2 m (metric measurements will be used throughout this analysis and converted to feet at the end). Projection of the rate of "present" GMSL rise measured by satellite altimeters since 1993 (3.2 mm yr^{-1}), with no acceleration due to global warming, yields a rise greater than the Lowest scenario. Projections from the semi-empirical approach assuming that greenhouse gas emissions fall abruptly to zero after the year 2016 likely exceed the Intermediate-Low level of 0.5 m.[28] The NRC projections also suggest that GMSL rise will very likely exceed the Intermediate-Low level. Consequently, there is little justification based on current scientific understanding for anticipating anything less than a 0.5 m rise in GMSL by the end of the century.



Comparison of the National Research Council's projections of global mean sea-level (GMSL) rise for 2050 and 2100[17] with the scenarios used in the National Climate Assessment.[18] Also compared are sea-level rise projections based on extrapolation of present rates (based on satellite measurements since 1993) and based on the semi-empirical approach for two emissions scenarios: Copenhagen Reference Case without emissions reductions imposed (higher range) and a case where human greenhouse gas emissions ceased in 2016 (lower range).[28]

There is only a very small probability that global mean sea level (GMSL) rise will be more than 1.4 m by the end of the century according to the National Research Council (NRC) projections; this level is comparable to the upper-most range for semi-empirical projections in the Copenhagen reference case for greenhouse gas emissions. Therefore, this might be practically considered the upper limit that would occur this century.

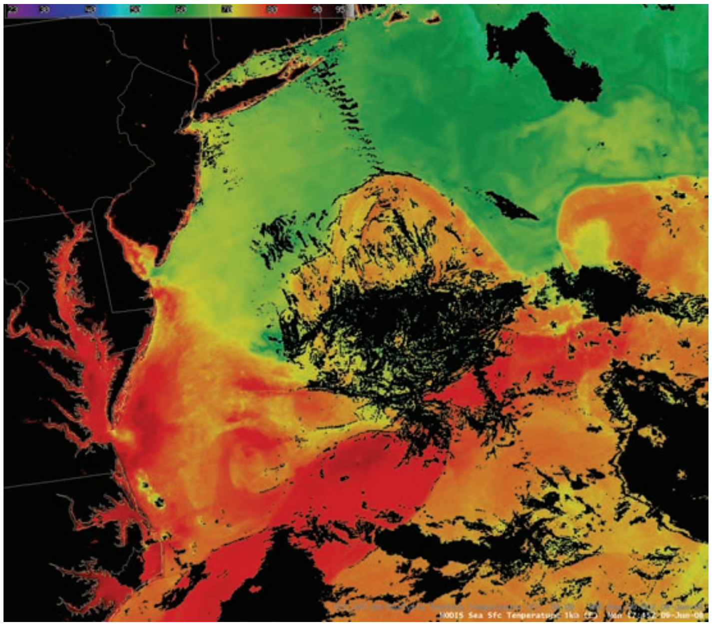
The two semi-empirical projections included in the figure above were among several undertaken in order to explore the continued sea-level rise beyond the end of this century that is implied under mitigation efforts taken to avoid a 2°C increase in global mean temperature. It is important to note that sea level continues to rise through 2300 under all scenarios, but with widening differences depending on when emissions are reduced during the 21st century.[29] Furthermore, this continued sea-level rise is practically irreversible through emissions reductions made later.

Several observations can be made based on these comparisons. First, both the lowest and highest scenarios used in the National Climate Assessment appear to be highly unlikely based on current understanding, with most projections falling within the Intermediate-Low and Intermediate-High scenarios. A reasonable conclusion might be that GMSL rise of less than 0.50 m by the end of this century is very unlikely and that a rise of more than 1 m, while certainly possible, is not likely. Second, projections of sea-level rise by 2050 are more tightly constrained between 0.20 and 0.40 m, with, as one would expect, emissions scenarios making relatively little difference. Third, differences in 21st century emissions trajectories begin to have significant consequences for the rate of sea-level rise toward the end of this century and result in even greater differences during the next. In other words, steps taken over the next 30 years to control greenhouse gas emissions and stabilize global temperatures during this century will largely determine how great the sea-level rise challenge is for coastal residents in subsequent centuries. There is not much they could do then to slow sea-level rise because of the inertia of ocean warming and polar ice sheet loss.

Key Message

There is no justification based on current scientific understanding for anticipating anything less than a 0.5 m rise in global mean sea level by the end of the century.

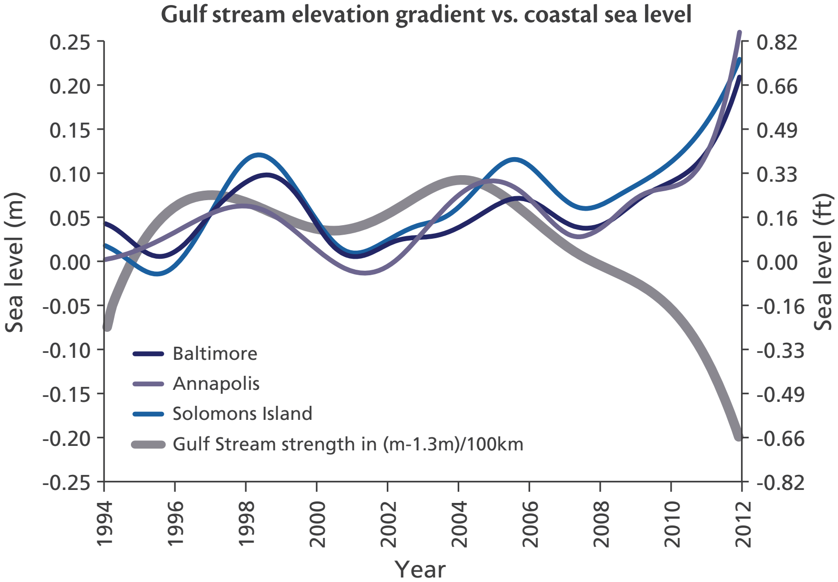
Regional Ocean Dynamics



The trajectory of the Gulf Stream is apparent in the warmer temperatures (red) to the northeast off of Cape Hatteras. The force of the Gulf Stream flow affects sea level in the Chesapeake Bay (MODIS-NASA).

Recent research suggests higher rates of sea-level rise along the Mid-Atlantic coast during the past decade or two[21-23] and links this trend with the decline in strength of the Gulf Stream.[26] Sea-level projections for Maryland should take such regional ocean dynamics into consideration. As the Gulf Stream flows from the coast at Cape Hatteras and turns north-eastward, the Coriolis force, resulting from the rotation of the earth, acts to force water offshore. To balance this effect, ocean water is drawn off the shelf in the Middle Atlantic Bight and the sea surface along the coast is typically about one meter lower than in the open ocean on the far side of the Gulf Stream. If the flow of this massive current declines, the height gradient is diminished, with the sea surface falling in the open ocean, but rising along the coast. As the figure below shows, sea level at Chesapeake Bay tidal gauges varied over several years in relation to variations in Gulf Stream flow. Beginning around 2004, however, the flow of the Gulf Stream went into steady decline and, by 2007, sea level at the tide gauges in the Middle Atlantic Bight was showing a steady increase. It is important to keep in mind, however, that this analysis has just recently been published and understanding is likely to evolve as more scientists investigate the phenomenon.

Factoring in changes in ocean dynamics into sea-level rise projections for the rest of the 21st century is not a straightforward matter. It is uncertain whether the recently observed trend will continue. Other ocean dynamic processes may also play a role. For the purpose of these projections of relative sea-level rise for Maryland, model projections of the ocean dynamic contribution to sea-level rise for Washington, DC are used: best projection of 0.17 m by 2100, with a low of 0.13 m and high of 0.19 m.[25]



At Maryland tide gauge stations (colored lines) low frequency modes of relative sea level, including decadal oscillations and sea-level rise, closely mirror changes in the Gulf Stream strength derived from satellite altimeter data (gray line).[26]

Vertical Land Movement

Determination of the rate of vertical land movement (VLM) is not a simple matter, but has been estimated using several techniques. A rate of VLM of -1.7 mm yr^{-1} was assumed for coastal Maryland in the 2008 Maryland Assessment. This was based on published interpretations of tide gauge data and re-leveling surveys that suggested VLM of -1.7 to -2.4 mm yr^{-1} for coastal Maryland.[30] More recently, VLM rates estimated for Maryland tide gauge stations located within the Chesapeake Bay ranged from -1.3 at Baltimore to -1.9 mm yr^{-1} at Cambridge[31, 32], where subsidence due to groundwater withdrawals may have played a role. A higher rate of -2.73 mm yr^{-1} was estimated for Ocean City, on the Atlantic coast of Maryland, but this is based on a much shorter gauge record, beginning only in 1975.

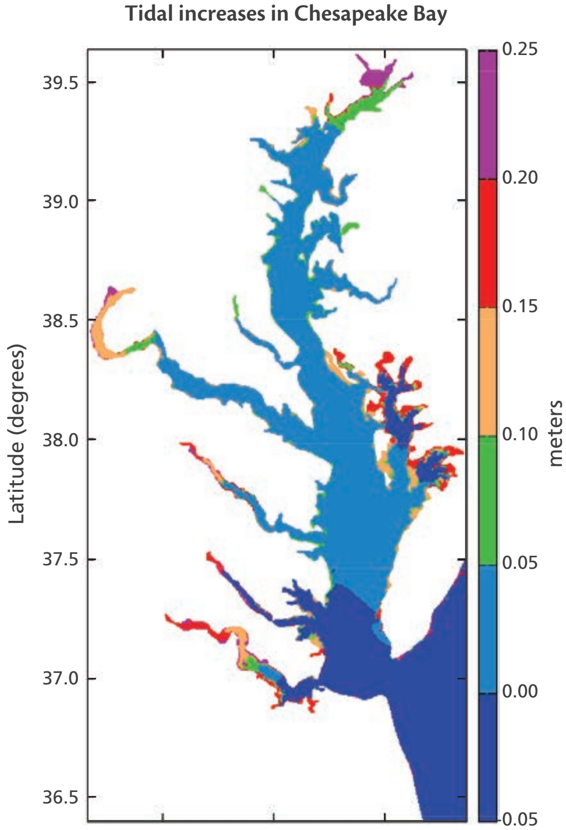
Estimates of VLM determined from tide gauge measurements are derived by difference from estimates of sea-level rise that are complicated and uncertain. VLM can also be estimated from geological sea-level indicators, such as microfossils in salt-marsh deposits and isotope dating; through repeated measurements of elevation by a geographic positioning system (GPS); or computer models of glacial isostatic adjustment (GIA). However, these estimates may not agree, in part because of the different time periods for which they can be applied.[33] Models of GIA, corrected for associated changes in sea surface height resulting with changes in gravity as the crust adjusts, can indicate what the expected effect on tide gauge measurements should be.[34] Estimates from one model are available for tide gauge sites around the world and indicate the net GIA effect on relative sea level to range from 0.76 to 1.02 mm yr^{-1} for Maryland tide gauge sites.[35] Finally, using geological methods, VLM over the last 4,000 years was estimated to have been -1.3 mm yr^{-1} for a site within the inner Chesapeake Bay.[36] For the purpose of this projection of relative sea-level rise in Maryland, a best-estimate VLM adjustment of 1.5 mm yr^{-1} continuing throughout the 21st century was used, with 1.3 mm yr^{-1} as a low estimate and 1.7 mm yr^{-1} as a high estimate. It should be kept in mind, however, that VLM may be greater locally due to sediment compaction and groundwater withdrawal effects.

Multiple Ways to Estimate Vertical Land Movement

- **Releveling of land surveys**
- **Models of glacial isostatic adjustment and other crust movements**
- **Repeated elevation measurements using Global Positioning System**
- **Subtraction of assumed sea-level rise from tide gauge records**
- **Geological interpretation of sediment record using microfossils and dating techniques**

Changes in Tides and Storm Surges

In terms of human infrastructure, it is not only mean sea level that is of concern, but the height of tides and storm surges. Tidal range in a semi-enclosed bay or estuary is influenced by the depth of the water body. It can be reduced farther away from its connection with the sea due to frictional resistance, or it can be magnified if the morphology of water body creates resonance at the same frequency of tidal oscillation, for example in the Bay of Fundy. If sea level rises substantially this will increase the volume of the estuary and thus reduce frictional resistance along the bottom and change its resonance properties. Increasing tidal range over time has, in fact, been observed at a number of East Coast tide gauges.[37]



A one-meter rise in sea level will shift the resonance response of the Chesapeake Bay toward 24 hours, thus increasing tidal range in the upper Bay.[38]

The tidal range in the Chesapeake Bay is greatest at the mouth and decreases up the Bay due to friction along the bottom acting to slow tidal currents as the tide progresses from the mouth to the head of the estuary. A one-meter rise in sea level will allow more efficient propagation of the tidal wave in the bay and shift the resonant period closer to the tidal frequency. As it does, it could increase the tidal amplitude resulting in an approximate 0.05 m (0.16 ft) increase in tidal range over much of the Maryland portion of the bay, but a much greater increase of up to 0.2 m (0.66 ft) in the upper bay and the heads of some of its tidal rivers.[38]

Modern record storm surges of more than 2 m (7 ft) were experienced in portions of the Chesapeake Bay during Hurricane Isabel in 2003; storm surge levels were highest in the uppermost Bay and tidal Potomac River near Washington, DC.[39] While the frequency of tropical storms is not projected to increase as a result of global warming during the 21st century, highly intense storms are projected to become more common.[40] Moreover, because of warming of sea surface temperatures, tropical storms should maintain more of their intensity as they progress to the higher latitudes along the Mid-Atlantic coast.

Leaving aside assessment of the consequences of changing tropical storm intensity that are beyond the scope of this assessment, the height of storm surges experienced in the Chesapeake Bay would increase for any given storm strictly as a function of the deepening of the bay due to sea-level rise. If mean relative sea level, and thus the average depth of the bay, would increase by one meter, storm surge heights would be expected to increase even more. The amount of increase has not yet been modeled for the Chesapeake Bay and deserves further study, however one study indicated that storm surges could increase 20-50% more than the relative sea-level rise for wetland-fronted, shallow bays in coastal Louisiana.[41] Furthermore, as tidal range would be expected to increase in the upper reaches of the bay and its tributaries, high water events driven by southern winds or storm surges coinciding with astronomic high tides would be further exaggerated.

Putting It All Together

Using the National Research Council's (NRC) projections of global mean sea-level rise as a starting point, projections of relative sea-level rise in Maryland are made here through adjustment for the "fingerprint" effects of the land-ice contributions, as well as inclusion of the dynamic ocean contributions and the effects of vertical land movement.[42] Fingerprint adjustments for reductions in land ice are appropriate because the effects of loss of ice mass in Greenland on sea levels along the U.S. East Coast are not the same as the loss of an equivalent mass in Antarctica.[34] Sea level will increase less close to the ice mass because the gravitational attraction of ocean water is diminished and will increase more farther away from the site of the declining mass. Fingerprint adjustments were used by the NRC in estimating the effects on relative sea level along the U.S. West Coast. Similarly, land-ice change scale factors appropriate to Maryland's location were applied to the contributions of glaciers (0.9), Greenland (0.5)[43], and Antarctica (1.25)[44] to the relative components of global mean sea level (GMSL) rise projected by the NRC.

The adjusted contributions can thus be summed for thermal expansion, land-ice loss, dynamic ocean effects, and vertical land movement (VLM). These are presented as Best, Low, and High projections of relative sea-level rise for Maryland for 2050 and 2100. As points of reference, our Low projection for 2100 is approximately equal to the National Climate Assessment's (NCA) Intermediate-Low Scenario after adjustment for VLM; our Best projection is about 0.3 m (1 ft) lower than the NCA Intermediate-High Scenario; and our High Scenario is nearly 0.45 m (1.5 ft) lower than the NCA Highest Scenario. With regard to the Army Corps of Engineers planning scenarios, our Best projection is slightly lower than Scenario II and our High projection is equivalent to Scenario III after adjustment for VLM. Neither the NCA's Lowest Scenario or the Corps' Scenario I appear to be realistic considerations based on the recent NRC projections.

Global Mean Sea-level Rise (National Research Council 2012)	Thermal (m)	Glaciers (m)	Greenland (m)	Antarctica (m)	GMSL Rise	
					meters	feet
2050 best	0.10	0.06	0.06	0.07	0.3	0.9
2050 low	0.04	0.05	0.04	0.03	0.2	0.6
2050 high	0.19	0.07	0.10	0.13	0.5	1.6
2100 best	0.24	0.14	0.20	0.24	0.8	2.7
2100 low	0.10	0.13	0.15	0.08	0.5	1.7
2100 high	0.46	0.19	0.34	0.48	1.4	4.6

Maryland Relative Sea-level Rise	Thermal (m)	Glaciers (m)	Greenland (m)	Antarctica (m)	Dynamic (m)	VLM (m)	Relative SLR	
							meters	feet
2050 best	0.10	0.05	0.03	0.09	0.09	0.075	0.4	1.4
2050 low	0.04	0.05	0.02	0.04	0.07	0.065	0.3	0.9
2050 high	0.19	0.06	0.05	0.16	0.10	0.085	0.7	2.1
2100 best	0.24	0.13	0.10	0.30	0.17	0.15	1.1	3.7
2100 low	0.10	0.12	0.08	0.10	0.13	0.13	0.7	2.1
2100 high	0.46	0.17	0.17	0.58	0.19	0.17	1.7	5.7
Land ice change fingerprint scale factors		0.9	0.5	1.25				

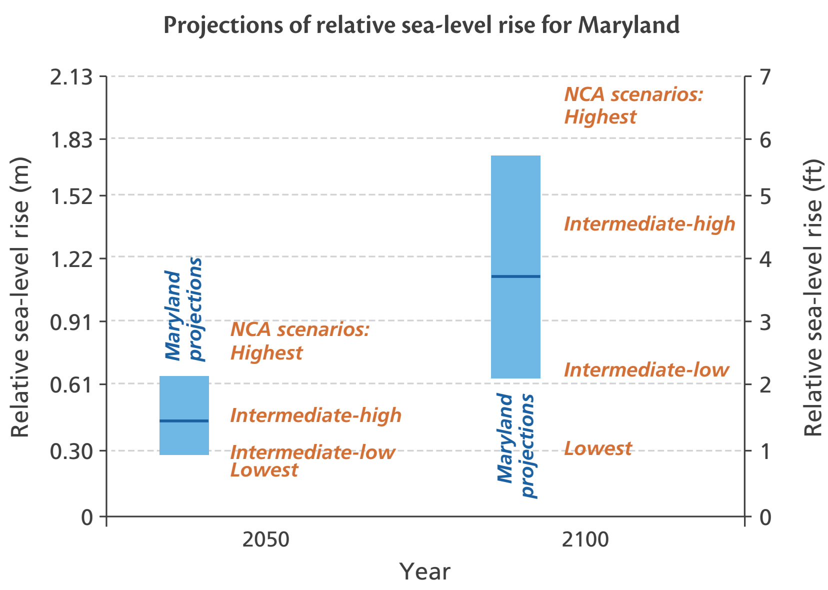
Practical Advice for Adaptive Planning

The challenge in responding to Governor O'Malley's directive is to provide sound and actionable advice based on current scientific understanding. This must be done mindful of, but despite, the uncertainties. Based on the synthesis provided here, the following recommendations are provided:

1. It is prudent to plan for relative sea-level rise of 2.1 feet by 2050 in order to accommodate the high end of the National Research Council (NRC) projections as adjusted for regional factors particular to Maryland. Based on the various methodologies available today, it is very unlikely to rise more than that within that timeframe. This would essentially constitute an increase in mean sea level, on top of which storm surge would have to be factored in, to judge the risks to land-based facilities.

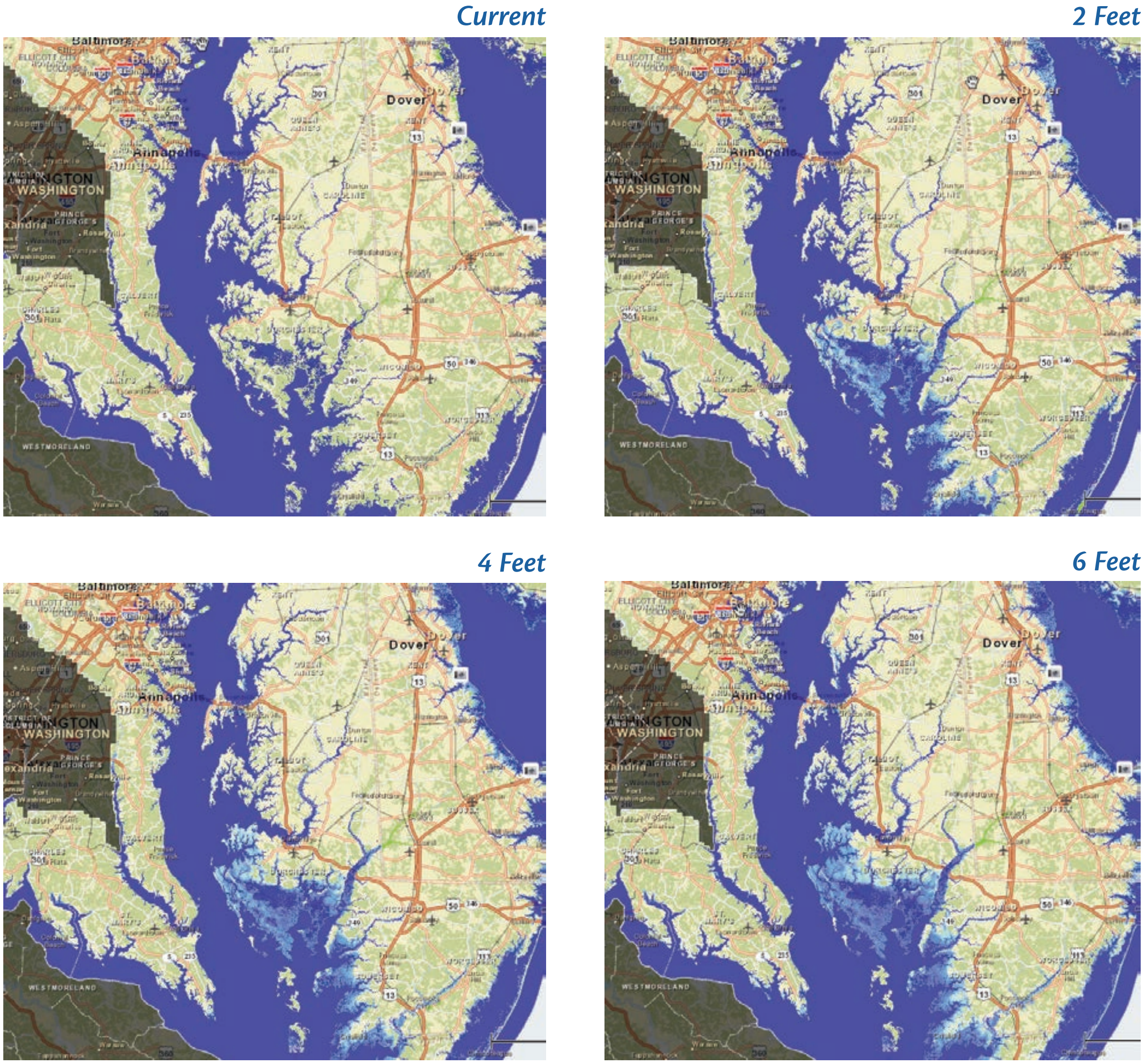
2. Providing planning advice for the end of the century is more challenging, both because the actual greenhouse gas emissions trajectory is unknown and because of greater uncertainties in the models of sea-level response, particularly regarding the rate of loss of the mass of polar ice sheets. How one should use the guidance provided by our projections depends both on the longevity of investments at risk and the acceptance of risk. For example, if one were concerned about an investment in facilities or public infrastructure the useful life of which is not intended to extend beyond this century or which could tolerate very occasional inundation, one might find it acceptable to use our Best projection of sea-level rise of 3.7 feet for adaptation planning. [Note that the projection derived by the 2008 Maryland Assessment for the higher emissions scenario was 3.4 feet.] If, on the other hand, one is concerned about facilities and infrastructure intended to be useful well into the next century or for which any risk of inundation is unacceptable, it might be prudent to use our High projection of relative sea-level rise of 5.7 feet. Such considerations are beyond the scope of this report. Furthermore, planners and engineers should also take into consideration anticipated changes in storm surge heights and tidal flood levels as a result of future sea-level rise, a subject deserving further research.

3. The projections presented here are improvements on those used in the 2008 Maryland Assessment because they are based on the recent process-based projections by the National Research Council and include a range of possibilities that reflect uncertainties about greenhouse gas emissions and the responses of climate and land ice. In contrast with the scenario-based approaches used in the U.S. Army Corps of Engineers guidance, the National Climate Assessment, and adaptation planning in the neighboring states of Delaware[45] and Virginia,[46] these new projections also narrow the range of possibilities and define probabilities based on current scientific evidence. Because our scientific understanding will continue to improve and the trajectories of greenhouse gas emissions will become clearer over time, periodic updating of these sea-level rise projections should be undertaken. Certainly, the new sea-level rise projections in the forthcoming Intergovernmental Panel on Climate Change (IPCC) should be considered.



Newly developed projections of relative sea-level rise for Maryland compared with the National Climate Assessment scenarios,[18] adjusted in the same manner for Vertical Land Movement. Ranges for the Maryland projections span High to Low projections, with the Best projection indicated by thick lines.

4. Maryland's Climate Action Plan addresses both actions taken to limit the magnitude of climate change (commonly referred to as mitigation) and those taken to adapt to climate change. This is appropriate as they are two sides of the same coin: adaptation is required even if aggressive mitigation is undertaken, but without mitigation adaptation becomes increasingly daunting.[47] This is particularly evident with regard to sea-level rise, which will continue to occur through this century and into the next as a result of the global warming that has already occurred. Furthermore, global warming will be substantially greater in subsequent centuries, unless greenhouse gas emissions are substantially reduced during this one.



Sea-level rise map showing land inundation under current conditions (top left), under 2 feet of sea-level rise (top right), under 4 feet of sea-level rise (bottom left), and under 6 feet of sea-level rise (bottom right). Maps are derived from high resolution LIDAR imaging and are taken from NOAA Sea Level Rise and Coastal Flooding Impacts Viewer (http://www.csc.noaa.gov/digitalcoast/tools/slrviewer).

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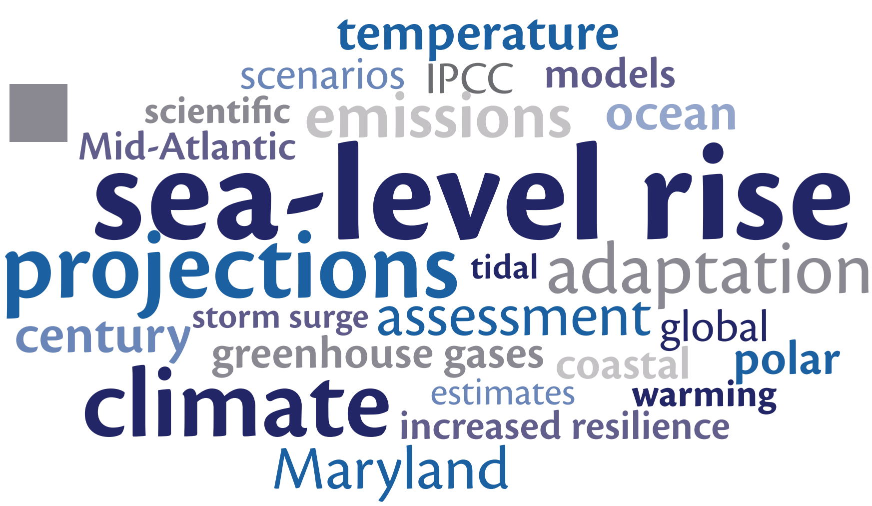
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