SEA-LEVEL RISE

Projections for Maryland

Sea-level Rise Projections for Maryland 2023

SEA-LEVEL RISE EXPERT GROUP

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The members of the Expert Group are deeply saddened by the death of Dr. Christopher Summerfield on December 29, 2019 at the age of only 55. Chris was a member of the Expert Group for Maryland's sea-level rise projections in 2013 and 2018. He was a pioneer in the use of scientifically based sea-level rise projections in coastal planning in Delaware and was sorely missed in the Group's 2023 deliberations.

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This report can be found at umces.edu/sea-level-rise-projections.

Cover photo: High-tide flooding in Cambridge. Photo: Jane Thomas.

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SUMMARY

Sea level has been rising at an increasing rate as a result of global warming. It will almost certainly rise as much in the first half of this century as it did during the entire last century. It could rise three or more times as much by the end of the century. This report provides updated projections of sea-level rise in the State of Maryland, as required at least every five years by the Maryland Commission on Climate Change Act of 2015.

The sea-level rise for which Maryland should plan later this century and beyond depends on the degree to which global society limits its greenhouse gas emissions. In its recently completed Sixth Assessment Report (AR6), the Intergovernmental Panel on Climate Change (IPCC) provided projections of global mean sea-level rise for five scenarios representing different emissions pathways. The projections included here focus on the three most plausible scenarios:

- ***Increasing Emissions*** (SSP3-7.0), in which the rate of emissions doubles by the end of the century.
- ***Current Commitments*** (SSP2-4.5), in which only the present national commitments for emission reductions are met.
- ***Paris Agreement*** (SSP1-2.6), in which emissions reach net-zero during the second half of this century and warming is kept below 2°C.

Use of sea-level rise projections under the *Current Commitments* emissions scenario is recommended as encompassing a realistic representation of the what will be confronted over the 21st century.

The IPCC AR6 produced a database of probabilistic projections of relative sea-level rise for tide-gauge locations around the world that reflect differences caused by thermal expansion, glacier and polar ice sheet melting, winds and currents, and vertical land motion. These are available online for seven locations in Maryland and the District of Columbia. Considered together with extrapolations of tide gauge and satellite observations, these projections indicate that sea level rise will likely be between 0.3 m (1 ft) and 0.5 m (1.6 ft) by 2050 (from a 2005 starting point). Beyond the middle of the century, the pathway of greenhouse gas emissions increasingly matters. Under the *Current Commitments* scenario, the best estimate of sea-level rise in 2100 is 0.8 m (2.7 ft) and sea level will likely rise between 0.6 m (2.0 ft) and 1.1 m (3.5 ft), barring unexpected processes driving rapid ice-sheet melt. Even with exceptionally rapid ice loss, it is very unlikely that it would exceed 1.5 m (4.9 ft). These projections are for mean sea level and do not include the effects of high tides and storm surges which must be factored into flooding risk assessments.

Probability levels associated with this sea-level rise projection should be used as reference points in planning for both the natural and built environment. Median estimates of future sea level are more appropriate for nature-based adaptation such as marsh restoration and living shorelines. Levels at the upper end of the likely range are better reference points for investments in built infrastructure that can be adapted to unforeseen conditions. For infrastructure investments providing essential community services with more than an estimated 50-year lifespan, sea-level projections with a low probability of exceedance with additional ice loss should be considered as a reference point. Such high-end estimates should also be used as exploratory scenarios in the context of flexible adaptation pathways.

INTRODUCTION

The Charge

With its 3,190 miles of shoreline, extensive low-lying coastal land, and productive estuarine habitats, Maryland is particularly vulnerable to multiple consequences of sea-level rise. These include shoreline erosion, inundation, increased storm surge flooding, inhibited drainage, saline intrusion into surface and groundwaters and soils, reduced agricultural yields, wetland loss and migration, ghost forests, and changes in estuarine ecosystems. From 1984 to 2020, 25,600 acres of forests and 3,500 acres of farmland converted to tidal marsh in Maryland.[1] An additional 146,000 acres of land conversion could occur with 0.5 m (1.6 ft) of sea-level rise and 216,000 acres with 1 m (3.3 ft) of sea-level rise.[2] More than 100 communities in Maryland may be at risk of chronic inundation from sea-level rise and storm surges by the end of the century.[3] Almost one-third of those communities are socioeconomically disadvantaged and have fewer resources to mitigate risk, recover from storm damage, or relocate—further exacerbating existing social and economic inequalities.

Recognizing this vulnerability, the *Comprehensive Assessment of Climate Change Impacts in Maryland*,[4] produced in 2008 under the auspices of the then newly created Maryland Commission on Climate Change, included projections of sea-level rise for the region over the 21st century for consideration in adapting to the changing conditions. The Commission continues to take an integrated approach by developing strategies that reduce both the state's greenhouse gas emissions and its vulnerability to climate change.[5] The 2008 assessment recognized that the amount of sea-level rise that would be confronted would depend on whether global emissions continue to grow or are substantially reduced over the course of the century. Thus, it produced projections for two emissions-determined scenarios based on the Fourth Assessment Report (AR4) of the IPCC, published in 2007. Even then, it was noted that sea-level rise would be greater than the IPCC projected if there were more rapid losses from polar ice sheets.

As the number of scientific publications on climate change grew rapidly, the Scientific and Technical Working Group of the Commission on Climate

How will Maryland's extensive shorelines and tidal wetlands—seen here on Mills Island in Worcester County—respond to sea-level rise? Photo: Jane Thomas.

Change produced the report *Updating Maryland's Sea-Level Rise Projections* in 2013.[6] That report relied heavily on a recent assessment of sea-level rise along the U.S. West Coast conducted by the National Research Council.[7] The next year, the Maryland General Assembly passed the Coast Smart Council Act and it was signed into law. The Council was charged with adopting specific siting and design criteria to address impacts of coastal flooding and sea-level rise on future state-funded capital projects.

During its 2015 session, the Maryland General Assembly codified the Maryland Commission on Climate Change, which had initially been created under an Executive Order. The Act officially charged the Commission with advising the Governor and General Assembly "on ways to mitigate the causes of, prepare for, and adapt to the consequences of climate change." It also required each state agency to review its planning, regulatory, and fiscal programs to identify and recommend actions to more fully integrate the consideration of Maryland's greenhouse gas reduction goal and the impacts of climate change, including the consideration of sea-level rise and flooding from storm surges. Another section of the Act specifically requires the University of Maryland Center for Environmental Science (UMCES) to "establish science-based sea-level rise projections for Maryland's coastal areas and update them at least every five years" and make them publicly available.

In response to this mandate, UMCES released *Sea-Level Rise Projections for Maryland* in 2018, five years after the 2013 update.[8] The 2018 projections relied heavily on the IPCC's Fifth Assessment Report (AR5) that was fully completed in December 2014. The AR5 projections had been reconciled with expert elicitation through a structured survey to better estimate ice-sheet contributions. The resulting 2018 projections for Maryland have been widely used in planning within Maryland, and *Guidance for Using Maryland's 2018 Sea Level Projections* was published by Department of Natural Resources (DNR) and Maryland Sea Grant Extension in 2022.[9] The present report provides the mandated update of the 2018 science-based projections. In 2018, the Maryland General Assembly also passed legislation requiring that the Department of Planning develop a plan to adapt to saltwater intrusion into surface water, aquifers, and soils,[10] and that certain local governments develop plans

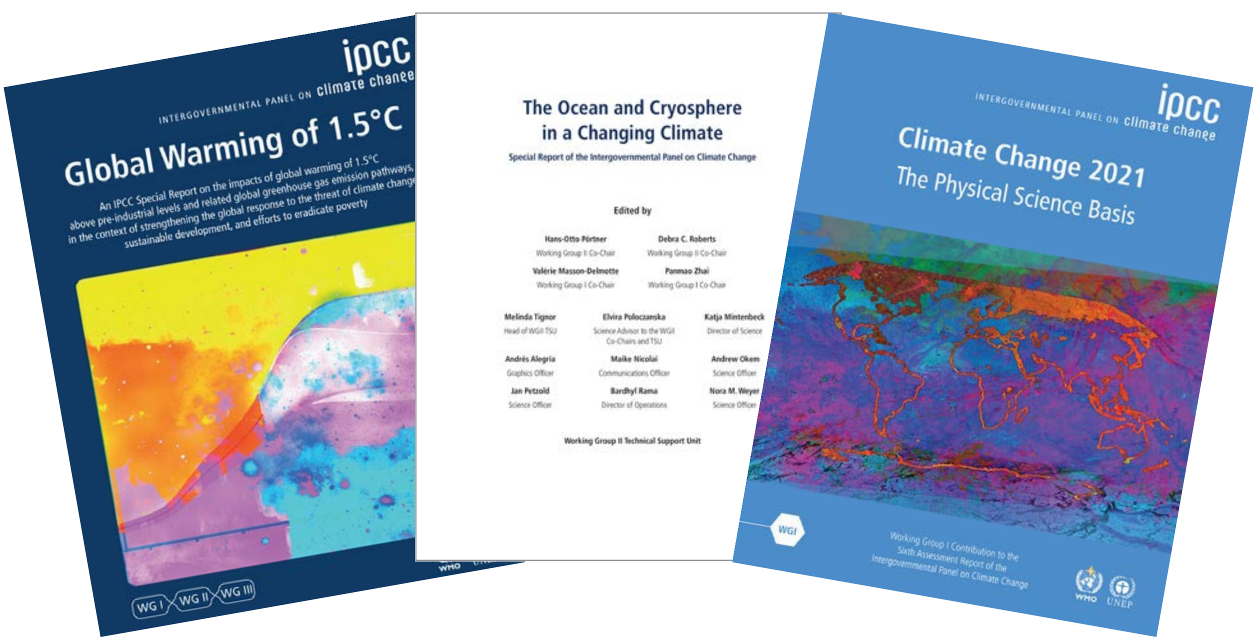
The current document is the fourth in a series of reports including sea-level rise projections for Maryland.

to address nuisance (high-tide) flooding.[11] Both saltwater intrusion and nuisance flooding will be greatly affected by future sea-level rise.

New Developments

Much has transpired since the completion of the IPCC's AR5, on which the 2018 Maryland projections were fundamentally based. The legally binding Paris Climate Agreement came into force in November 2016, with the goal of limiting global warming to well below 2°C, preferably to 1.5°C. In response, in 2018 the IPCC released the *Special Report on Global Warming of 1.5°C*, which described the dangerous consequences of not meeting the Paris Agreement goals, including acceleration of sea-level rise. The Special Report concluded that reducing greenhouse gas emissions to net-zero shortly after 2050 would be required to meet the 1.5°C goal.[12] The next year, the IPCC published a *Special Report on the Ocean and Cryosphere* that more deeply examined the connections between the loss of ice and sea-level rise, and updated the AR5 sea-level rise projections by including new information on the dynamic polar ice sheet contributions.[13] Finally, the concluding Synthesis Report of the IPCC AR6 was published in March 2023, with the physical science component that provides new sea-level rise projections released in August 2021.[14] That 2021 report considers emerging science concerning not only ice sheets but also the importance of regional differences in sea-level rise as influenced by ice melting, ocean processes and vertical land motion along the coast.

On the policy front, the Maryland General Assembly enacted the Climate Solutions Now Act in 2022 that upped the ante on the state's previous commitments to reduce greenhouse gas emissions from our state. This new commitment is for a 60% reduction from a 2005 base by 2030 and net-zero emissions by 2045. Maryland's Governor Wes Moore has committed to taking steps to achieving these emissions reductions and to "take immediate action to mitigate the effects of sea level rise."[15] He pledged to "work with climate scientists, local government officials, and leading organizations to support projects like constructing and replacing sea walls, creating buffers with natural infrastructure, and piloting programs to inject water underground to prevent land subsidence." He also promised to ensure that development is planned with resilience at the forefront and that the state focus on relocation planning as the necessary tool for certain communities facing the greatest risks. With this



Three of the key reports published by the IPCC in the past five years.

report, scientists show their continued commitment to provide scientific understanding that will affect decision-making over the next five years and onward.

Sea Level Continues to Rise Faster

Sea level is continuing to rise at faster rates both globally and in Maryland. Since 1993, satellites have measured rising sea-surface heights across the world's ocean, revealing global mean sea level rising at a rate of over 3.3 mm/yr since then. That rate is accelerating—it increased from 2.3 mm/yr over 1993–2002 to 4.7 mm/yr over 2013–2022.[16] One recent analysis estimated that mean sea level has been increasing by an average of 4.5 mm/yr or more since 1975 at tide gauge locations in Maryland's portion of the Chesapeake Bay (Figure 1).[17] These rates are also accelerating. Greater acceleration over periods of around a decade can result from regional variations in ocean climate, but the longer-term trend in sea-level rise is largely a result of global warming.[18] The challenge for this report is to robustly project the trends into the more distant future as the climate continues to change and global society struggles to limit warming.

Producing this Report

This report was produced through a process similar to that used in 2013 and 2018, as it proved to be very effective and efficient. An Expert Group was formed, consisting of 13 members with particular experience in the Mid-Atlantic region, nine of whom had contributed to the 2018 report. New members were added because of changes in positions and to bring in fresh, relevant perspectives. The Expert Group was provided a preliminary working draft of the report, developed under the direction of its Chair and Co-Chairs in advance of a one-day work session held on April 24, 2023. The draft was discussed and substantially modified during the work session and refined through subsequent discussion and correspondence.

In previous reports, length units were provided in U.S. customary units (i.e., inches and feet). Because of the greater ease moving through scales when discussing rates and lengths, metric units are used here (i.e., millimeters, centimeters, and meters). Where helpful, equivalent feet are provided in the text and appendices.

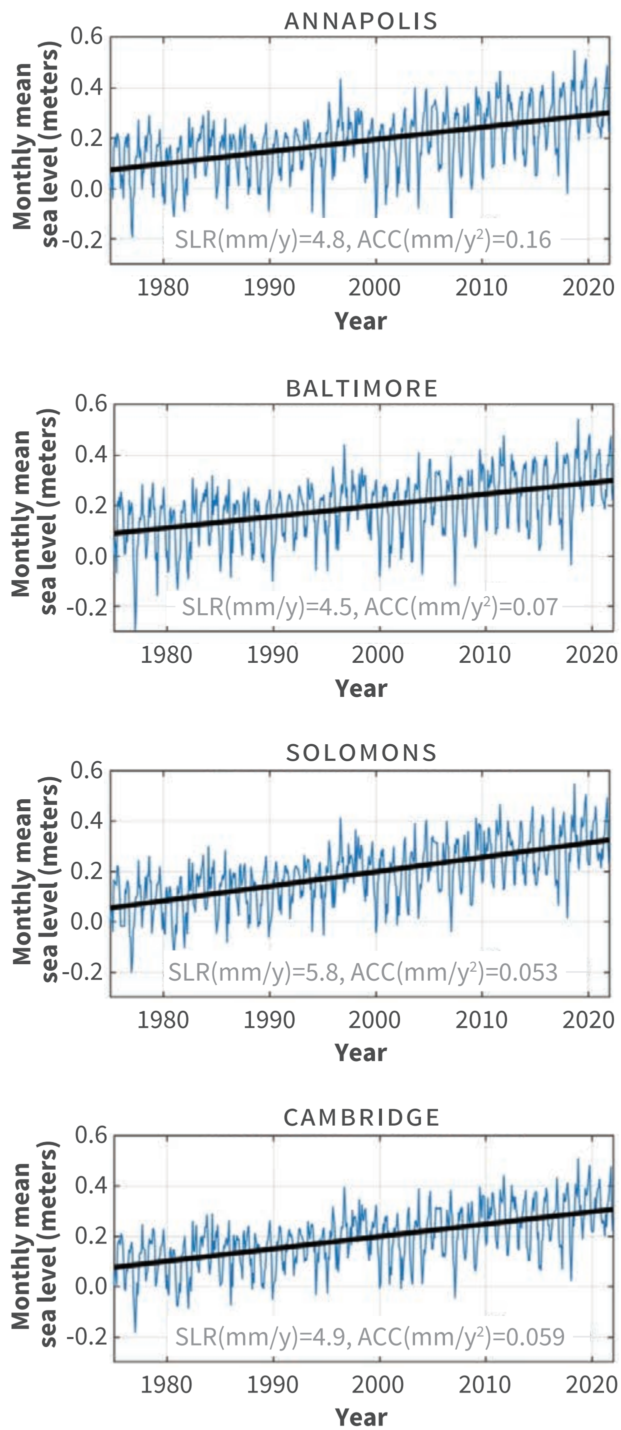


Figure 1. Variations and trends in monthly mean sea level from 1975 through 2021 measured at four Maryland tide gauges, showing the rates of sea level rise (SLR) and its acceleration (ACC).[17]

SEA-LEVEL RISE PROJECTIONS FOR MARYLAND

Why Use Emissions-based Scenarios?

This update continues to rely primarily on projected sea-level rise based on the IPCC scenarios that are derived from future pathways of global emissions of greenhouse gases. The 2023 projections rely on the latest probabilistic projections developed for the IPCC AR6 and published in 2021.[14] The 2018 Update used the "K-14" probabilistic projections[19] that were based on the 2014 AR5 as reconciled with expert elicitation to better determine ice-sheet contributions, some of which have now been incorporated in the AR6 projections.

There are several reasons for relying on the IPCC scenario-specific projections. First, these projections carry the authority of global scientific consensus based on the published literature and the extensive modeling and statistical analyses used in AR6. Second, these projections are driven by the resulting concentrations of greenhouse gases in the atmosphere that we now know with great certainty affect atmospheric and ocean temperatures. Warming temperatures in turn affect the dominant processes affecting sea-level change—the accumulation of heat in the oceans and the melting of land-based ice masses. Third, tying projected changes in climate and sea-level directly to emission pathways allows policy-makers, decision-makers, and the general public to link efforts to limit climate change by reducing emissions to actions needed to adapt to these changes. Another way to put this is that using emission scenarios assists society in avoiding the unmanageable, while managing the unavoidable.[20]

This report responds to the mandate to "establish science-based sea-level rise projections for Maryland's coastal areas." Sea-level projections are quantitative estimates of the likelihood of different amounts of sea-level rise over time, typically conditional upon assumptions about emissions. In contrast, sea-level scenarios are quantitative values or trajectories of sea level intended as reference points for decision-making.[21] The U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force recently updated its Interagency Scenarios that are

Flooding in downtown Annapolis in 2023. Photo posted by a citizen on www.mycoast.org/md.

now linked to the same models as the IPCC AR6 projections.[22] Fundamentally, these scenarios are based on certain levels of global mean sea level in 2100 (i.e., 2.0 m, 1.5 m, 1.0 m, or 0.5 m) rather than driven by warming determined from greenhouse gas emission pathways. The AR6-based projections for Maryland will be compared with the Interagency Scenarios for interoperability.

Five emission-pathway scenarios were used in AR6, as depicted in Figure 2. These scenarios are termed Shared Socioeconomic Pathways (SSP), as opposed to the Representative Concentration Pathways (RCP) used in AR5. Like the RCPs, the SSPs include a suffix that indicates the radiative forcing realized at the end of the century, so SSP5-8.5 can be compared with RCP8.5, although the assumptions and projections are not exactly equivalent.[23]

The Paris Agreement's defining goal is to limit the increase of global mean temperature to well below 2°C above the pre-industrial level, preferably to 1.5°C. Emissions pathways needed to avoid those thresholds are included as the SSP1-2.6 (*low*) and SSP1-1.9 (*very low*) scenarios, respectively (Table 1). Under the *low* scenario, emissions reach

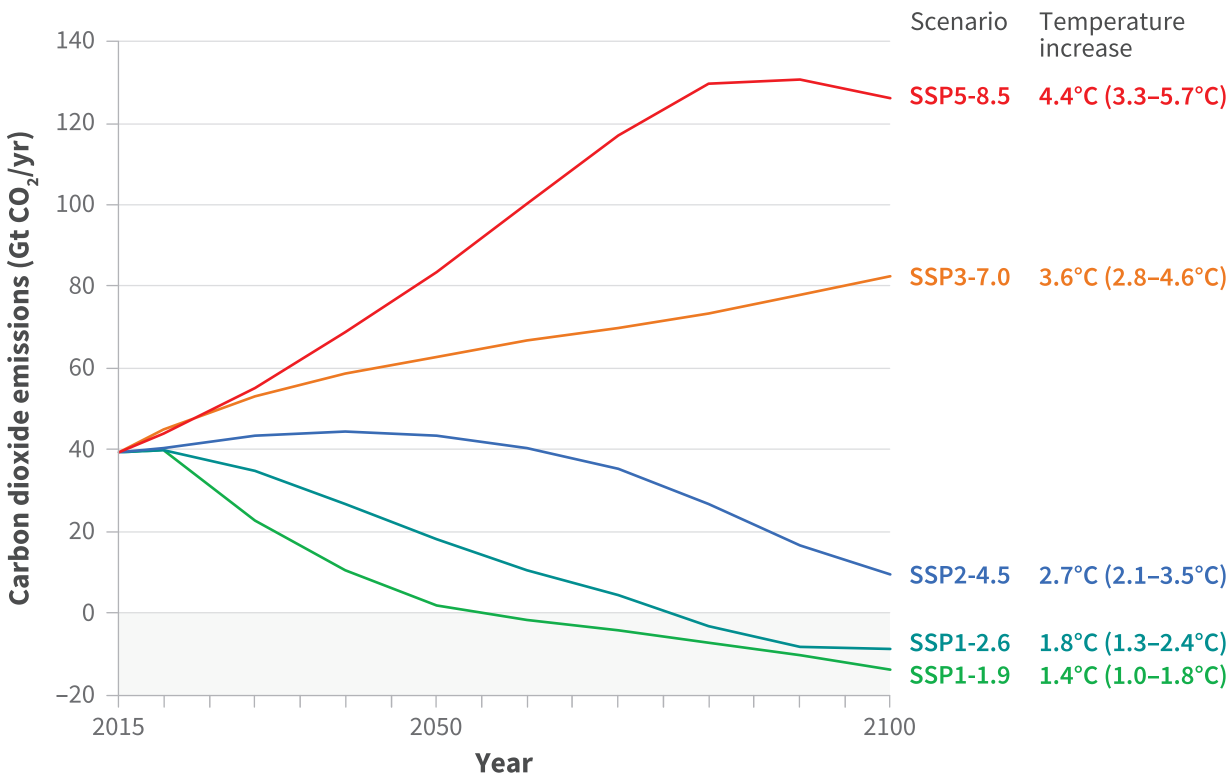


Figure 2. Median pathways of global emissions of carbon dioxide under the five IPCC AR6 scenarios and the best estimates and very likely (90% probable) ranges for increases in global mean temperature over pre-industrial levels that would result from each scenario by 2080–2100.

Table 1. IPCC AR6 emission pathway scenarios with means and very likely ranges of projected global temperature increase above the pre-industrial level in 2100.

Emissions Scenario	IPCC descriptor	Descriptor used in this report	Emissions pathway	Global temperature increase by 2100
SSP5-8.5	very high		double by 2050	4.4°C (3.3–5.7°C)
SSP3-7.0	high	Increasing Emissions	double by 2100	3.6°C (2.8–4.6°C)
SSP2-4.5	intermediate	Current Commitments	decline after 2050	2.7°C (2.1–3.5°C)
SPP1-2.6	low	Paris Agreement (2°C)	net zero about 2080	1.8°C (1.3–2.4°C)
SSP1-1.9	very low		net zero about 2050	1.4°C (1.0–1.8°C)

net-zero abound 2080. In the *very low* scenario, emissions reach net-zero shortly after 2050. Both pathways also assume accelerated carbon dioxide removal to then produce net-negative emissions. AR6 retained the *very high* emissions scenario SSP5-8.5 for continuity with AR5 and to encompass dramatic changes that might result from intensifying feedbacks not included in the climate models. This scenario assumes a rapid growth in fossil fuel combustion through most of the century, with emissions doubling by 2050. This is not very plausible given the level of expansion of fossil fuel resources that would be required, much less the existing national commitments and pledges to reduce emissions. Thus, the IPCC employed a new *high* emissions scenario, SSP3-7.0, with global society doubling its emissions by the end of this century rather than by 2050.

Society and its governments are clearly struggling to meet the Paris Agreement goals. Earth's temperature is on the verge of exceeding 1.5°C of warming within a decade and substantial reductions in greenhouse gas emissions must be achieved in the next few decades to keep warming below 2°C.[24] However, many forecasters of future greenhouse gas emissions conclude that, while current stated national polices and even pledges to reduce emissions are insufficient to limit warming to 2°C, they would result in emissions pathways through 2050 generally similar to the *intermediate* SSP2-4.5.[25] Under such a weak-action pathway, emissions would cease to grow sometime during the next two decades and would then slowly decline but fail to reach net-zero during this century (Figure 2). While policies are not currently in place to achieve this post-2050 decline fully, SSP2-4.5 represents a plausible projection of outcomes of the level of ambition represented in currently adopted policies. According to the IPCC's best estimate, this scenario would result in 2.7°C of warming and there would be many devastating consequences of exceeding the 2°C threshold. Based on this perspective, the *intermediate* SSP2-4.5—termed in this report the *Current Commitments* scenario—is a plausible yet moderately cautious assumption on which to base Maryland's primary sea-level rise projections for the 21st century (Table 1). That outlook should, of course, be revisited in subsequent updates of projections for Maryland in light of both observed global emissions trends and emerging science.

Sea-level projections based on the *high* SSP3-7.0 emissions pathway should also be kept in mind in case nations fail to meet their current commitments to reduce greenhouse gas emissions. In the same vein, projections under the *low* SSP1-2.6 scenario depict the benefits of reducing emissions enough to keep warming under 2°C. For these reasons, this report also provides sea-level rise projections under these two emissions pathways, termed *Increasing Emissions* and *Paris Agreement* scenarios, respectively (Table 1).

Projections for Mean Sea Level

The AR6 used a model synthesis approach that produced probabilistic projections of sea-level changes based on the warming projected under each emissions scenario.[14] The synthesis involved estimation of contributions from individual components of sea-level change, including the contributions of loss of ice mass in glaciers and the Greenland and Antarctic ice sheets, changes in surface and groundwater storage on land, and expansion of ocean volume due to increased heat content and dynamic processes, such as ocean currents and winds that cause variations in sea-surface height within the oceans. The AR6 produced projections for each of the five emissions scenarios that were based on several separate probability distributions of global mean sea level using different ways of estimating losses from Antarctic and Greenland ice sheets about which there was at least *medium confidence*. These distributions were combined in probability boxes, or p-boxes, to produce the reported medians and *likely* (at least 66% probability) ranges. In addition, the AR6 produced projections that considered processes of ice sheet instabilities that are ambiguous in that researchers cannot agree upon the rate and magnitude of their potential contributions.[21] Limited by the availability of published models, the IPCC authors developed these *low confidence* or LC projections only for the *low* SSP1-2.6 and *very high* SSP5-8.5 emissions scenarios. They indicated that sea-level rise at the upper end of the 66% probability range for the *very high* emissions projection “cannot be ruled out under higher emissions.” As described later, the Expert Group used its judgement to estimate what *such a low probability of exceedance with additional ice loss* level would be for Maryland over a century under the intermediate *Current Commitments* scenario.

While the AR6 focused attention on changes in global mean sea level, the ocean models estimated the net effects of these various contributions on regional sea levels throughout the world’s oceans. The National Aeronautics and Space Administration (NASA) provides an online Sea Level Projection Tool[26] that includes site-specific projections of relative sea-level change (including the local effects of vertical land motion) based on the AR6-derived database[27] for tide-gauge sites around the world. The tool provides breakdowns for sterodynamic sea level (expansion of ocean volume due to heat and salinity changes plus the effects of winds and ocean currents) and the contributions of glaciers, the Greenland and Antarctic ice sheets, changes in storage of water on land, and vertical land motion (VLM).

The probabilistic projections presented in this report were obtained directly from the NASA tool and users may directly access it for information for specific tidal-gauge locations.[26] Figure 3 provides median projections of relative sea-level rise at Baltimore for each of the five emissions scenarios, including the two LC projections that incorporate the potential for additional, but more ambiguous, contributions from polar ice-sheet losses. These projections demonstrate the effect on sea level over the next roughly 125 years of the warming associated with these greenhouse gas emissions pathways.

The projected changes are relative to a baseline of the 1995–2014 average (i.e., circa 2005) used in AR6, as opposed to the 2000 baseline previously used in the 2018 Update. There is a 0.02 m (0.8 in)

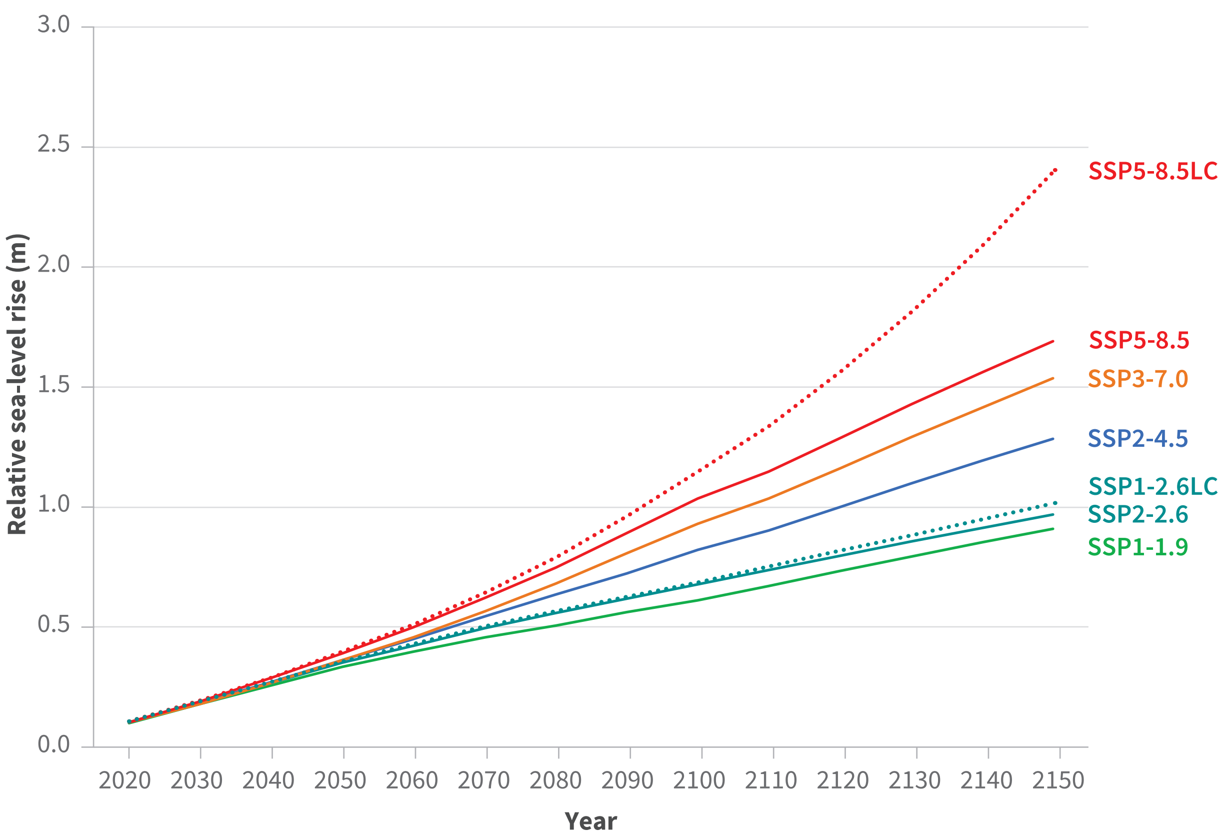


Figure 3. Median projections for sea-level rise at Baltimore under emissions scenarios included in the IPCC AR6. Projections labeled “LC” also include estimates of additional polar ice sheet losses that AR6 regarded with *low confidence*. Source: NASA Sea Level Projection Tool.

difference using the earlier baseline. The projected median sea-level rise from 2005 to 2020 is 0.10 m (0.33 ft) for all of the emissions scenarios if one wishes to consider rise above present sea levels.[28]

As also noted for both the 2018 Maryland projections and the 2022 Interagency Scenarios, there are relatively minor differences in median sea-level projections among the various scenarios of only about 0.05 m (2 in) by 2050, after which the projections diverge markedly because of faster ocean warming and ice mass loss under higher emissions. By 2150, the median sea-level rise under the *very high* emissions scenario is nearly twice that for the *very low* emissions scenario. Not surprisingly, the *intermediate* SSP2.4.5 scenario falls about mid-way between the two scenarios with unabated growth in emissions and the two scenarios in which emissions are reduced to achieve Paris Agreement goals. While global temperature would stabilize and then begin to slowly decline before the end of the 21st century under the two Agreement-compliant scenarios, sea level would continue to rise into the future for centuries to millennia, even if the temperature increase is kept to 1.5°C. This is because of the excess heat that will have been stored deep into the oceans and the continued melting of glaciers and ice sheets underway that respond slowly to atmospheric and oceanic changes. Society must take a long view as we adapt to sea-level rise over many decades into the future while also implementing aggressive steps now to limit warming. The degree to which global society eliminates net greenhouse gas emissions over the next few decades will be the major determinant of the sea levels it will confront toward the end of this century and for centuries into the future.

The AR6-based sea-level change projections provided in the NASA Sea Level Projection Tool include the 5th, 17th, 50th, 83rd, and 95th percentile estimates from the p-box distributions for each of the emissions scenario projections. Quantiles for projected relative sea-level rise at Baltimore in 2100 are depicted in Figure 4 for each of the five

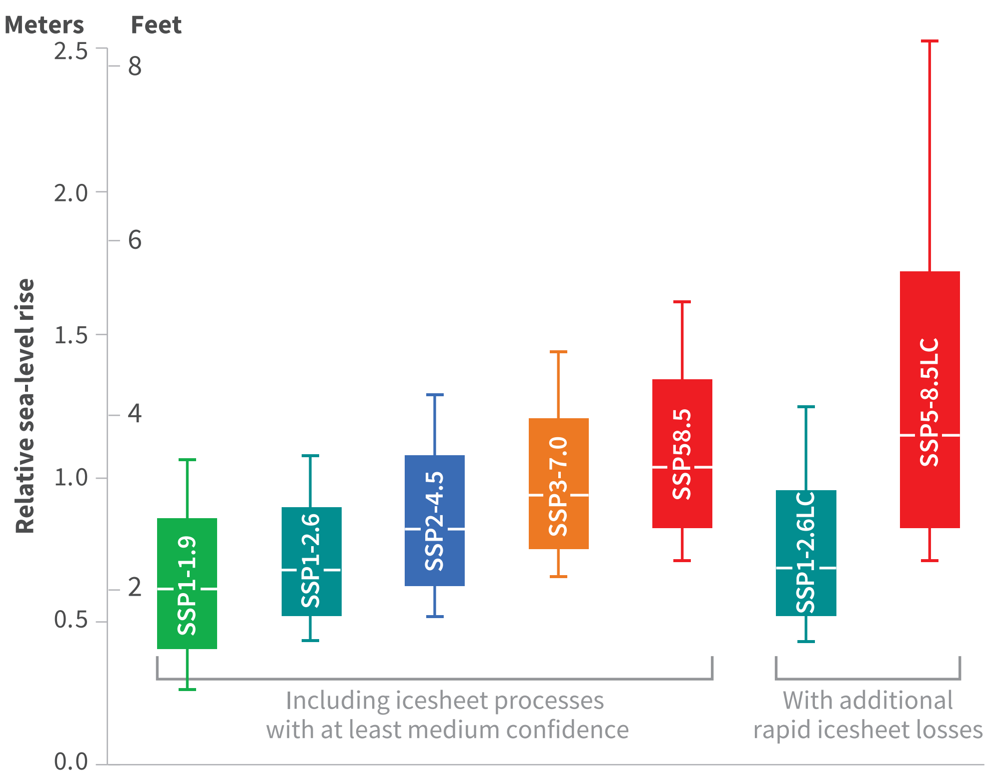


Figure 4. P-box probabilities for projected sea-level rise at Baltimore in 2100 under the IPCC AR6 emissions scenarios. Bars represent *likely* (17th–83rd percentile) ranges, vertical lines the 5th–95th percentile ranges, and white crossbars the medians. Sea-level rise is from a 1995–2015 baseline.

emissions scenarios. Similar estimates can be made for other time intervals up to 2150 using the NASA Sea Level Projection Tool.

In their evaluation of global mean sea-level rise, the AR6 sea-level chapter authors judged the 17th–83rd percentile range to represent the *likely* range of contributions from processes whose projections they viewed to be characterized by at least *medium confidence*. Considering only these processes, they assessed that sea-level rise has at least a 66% chance to be within this range under the given emissions scenario. The authors had less confidence in assessing likelihood of potential contributions outside this range because of the potential for ambiguous rapid ice-sheet losses.[21] Considering the potential additional contribution of these more ambiguous processes in the LC projections for the SSP5-8.5 and SSP2-4.5 scenarios, the p-box distribution is more positively skewed, with its tail extending to higher rates of sea-level rise. This only has a substantial effect after about 2070 under the *very high* emissions scenario, with little influence on the projections under the *low* emissions scenario (Figure 2).

Selecting SSP2-4.5 as the most plausible emissions pathway through this century if only the *Current Commitments* to reduce greenhouse gas emission were achieved, the *best estimate* (median) of relative sea-level rise projected for Baltimore by 2100 is 0.82 m, with a medium-confidence *likely* range of 0.62–1.08 m (Figure 5). By comparing projections among these three scenarios, one can see the consequences for sea level of achieving the *Paris Agreement* < 2°C warming goal or *Increasing Emissions*, in which the emission rate is doubled during the present century. As will be explored later, those differences increase dramatically into the 22nd century. The quantiles for sea-level rise at

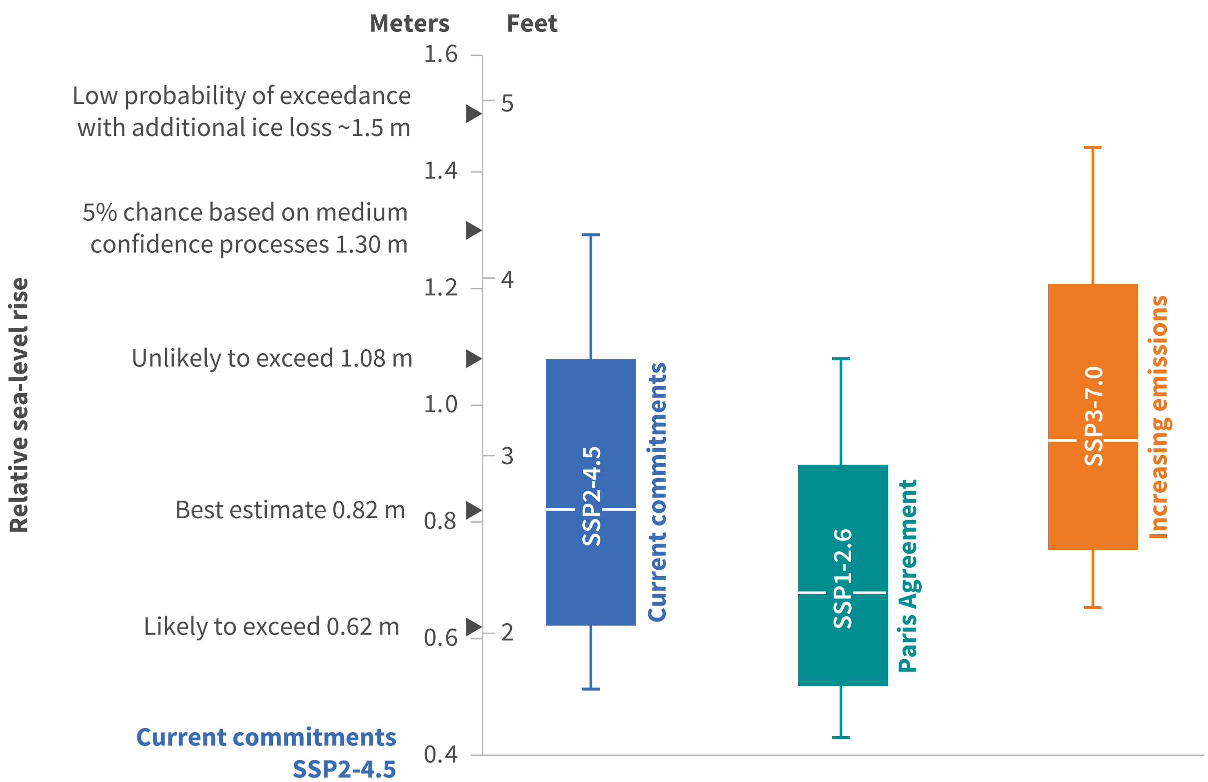
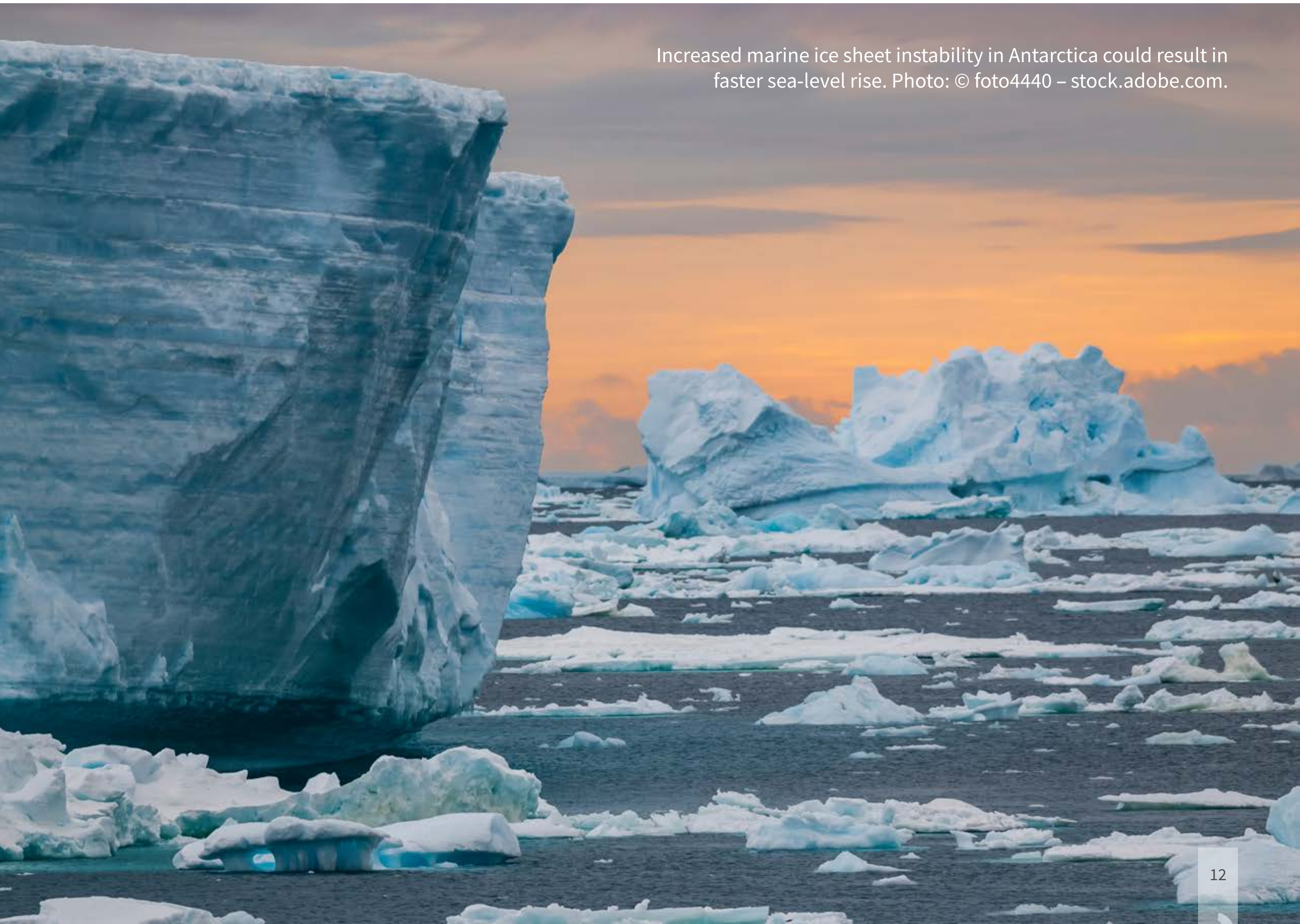


Figure 5. P-box probabilities for projected sea-level rise at Baltimore in 2100 under the three most plausible emissions pathways. Bars represent *likely* (17th–83rd percentile) ranges, vertical lines the 5th–95th percentile ranges, and white crossbars the medians.

Baltimore under all three emissions scenarios are provided in tabular form in Appendix 1 and for the *Current Commitments* emissions scenario at all Maryland tide-gauge sites in Appendix 2.

Quantile estimates have been used in numerous regional assessments as reference points to inform decisions involving varying degrees of risk-tolerance.[21] Where there is higher risk tolerance (e.g., planning for investments that can be adapted to unforeseen conditions), users may prefer to use the *likely* range. For example, if one were managing or restoring an aggrading marsh or creating a living shoreline, one might prefer to plan for sea-level rise encompassing the median projection. On the other hand, where there is lower risk tolerance, levels above the *likely* range using methods characterized by lower confidence would be more appropriate.[13] The sea-level projections for Maryland published in 2018[8] referred to the 95th quantile as a possible reference point for planning critical investments with little risk tolerance. This was included in the subsequent guidance document.[9]

The challenge in using the 95th percentile for relatively risk-intolerant decisions is that the IPCC AR6 authors did not regard it as delimiting the extent of the *very likely* range because the projections do not take into account polar ice sheet processes that are poorly quantified or for which there is low agreement among experts concerning their timing. AR6 notes that "higher amounts of GMSL [global mean sea level] rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of marine ice sheet instability (MISI) and marine ice cliff instability (MICI) around Antarctica, and faster-than-projected changes in the surface mass balance and dynamical ice loss from Greenland."[14] Inclusion of these *low confidence* processes have very minor



Increased marine ice sheet instability in Antarctica could result in faster sea-level rise. Photo: © foto4440 – stock.adobe.com.

effects on projections for the *low* emissions scenario into the next century, but substantially skew the p-box distributions under the *very high* SSP5-8.5 emissions scenario (Figure 4). To manage this dilemma, AR6 authors recommended a communication approach that presents the ambiguity of sea-level projections without overwhelming the projections of those process on which there is a reasonable agreement.[19] This is the approach taken here.

Because comparable LC outputs could not be provided in AR6 for the more plausible RCP2-4.5 and SSP3-7.0 scenarios, the Expert Group used an interpolation approach to estimate plausible projections for these intermediary scenarios. The practice of interpolating between end-member scenarios has been previously used for sea-level rise projections for New Jersey and should be taken as indicative rather than precise.[29] For purposes of interpolation, it is assumed the LC projections scale similarly to the projections based on processes with at least *medium confidence* that do exist for all scenarios. The Expert Group estimated *low probability of exceedance with additional ice loss* levels, falling between the 83rd and 95th percentile for the interpolated LC projections. In the group's expert judgement, sea-level rise is very unlikely to exceed these levels, even considering the potential contribution from rapid ice-sheet loss processes. These levels do not begin to appreciably exceed the 95th percentile for the *Current Commitments* (SSP2-4.5) scenario until after 2070. Table 2 summarizes this estimate and other quantiles that could be used as reference points in applications involving various levels of risk tolerance under this scenario.

Table 2. Relative sea-level rise projections for Baltimore for potential use in guidance for applications and risks, based on *Current Commitments* scenario (SSP2-4.5) from the 2005 (1995–2014 average) baseline. Ranges of extrapolations of observation medians are based on four different sources (see text).

	Sea-level rise probability	2040	2050	2060	2070	2080	2090	2100	2110	2120
METERS	Likely to exceed (17th percentile)	0.19	0.27	0.35	0.43	0.51	0.57	0.62	0.65	0.72
	Best estimate (median)	0.27	0.36	0.45	0.55	0.64	0.72	0.82	0.90	1.00
	Unlikely to exceed (83rd percentile)	0.36	0.46	0.57	0.69	0.81	0.93	1.08	1.23	1.65
	Low probability of exceedance with additional ice loss	0.4	0.5	0.7	0.9	1.1	1.3	1.5	1.8	2.1
	Extrapolations	0.25–0.30	0.34–0.45	—	—	—	—	—	—	—
FEET	Likely to exceed (17th percentile)	0.6	0.9	1.1	1.5	1.7	1.9	2.0	2.1	2.4
	Best estimate (median)	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0	3.3
	Unlikely to exceed (83rd percentile)	1.2	1.5	1.9	2.3	2.7	3.1	3.5	4.0	4.5
	Low probability of exceedance with additional ice loss	1.3	1.6	2.3	3.0	3.6	4.3	4.9	5.9	6.9
	Extrapolations	0.8–1.0	1.1–1.5	—	—	—	—	—	—	—

Extrapolating from Recent Trends

In recent decades, the U.S. Atlantic coast has been experiencing anomalously high rates of sea-level rise as evidenced both in tide-gauge records and in satellite measurements of sea-surface height.[30] This has apparently been caused by climatic variations in the ocean environment in addition to regional patterns of ocean warming.[18] The sea-level rise projections presented by the IPCC represent smooth trajectories into the future upon which episodes of seasonal to decadal variability can occur. Thus, it is particularly pertinent to consider extrapolations from the observational record as well as projections based on emissions-based warming for decisions on shorter time scales, i.e., through 2050. Beyond then, the effects of emissions pathways and associated warming are expected to become more important.

Statistical curvilinear (quadratic) extrapolations from the observed tide-gauge record have been computed for the the National Oceanic and Atmospheric Administration (NOAA) gauges at Baltimore, Annapolis, Solomons, and Cambridge based on data from 1970 to 2022;[31] at Baltimore, Annapolis and Solomons based on 1975 to 2021;[17] and at Baltimore from 1969 to 2022.[32] Similar extrapolations have been made from satellite altimetry observations along the north-east coast from 1993 to 2020.[30] The median tide-gauge extrapolations for Baltimore were somewhat lower than the extrapolated regional sea-level rise (from 2005 to 2050) derived from altimetry. This could be due to heterogeneity within the north-east region or to the longer period over which gauge-based trends were computed. In any case, the medians for all four extrapolations fall within the *likely* range of the emissions-driven projections for 2040 and 2050 (Table 2). It should be kept in mind that there may be periods of a decade or more during which sea level will rise near the upper or lower end of the likely range of the scenario-based projections due to natural variability.[18] This variability can substantially affect the frequency of flooding.

Faster than the Global Average

The world's oceans are not exactly level—sea-surface height varies around the world because of gravitational influences, ocean temperature and salinity differences, and currents and winds. As a result of these factors, sea-level rise in Maryland has been and will continue to be greater than the global average. Beyond the effects of negative vertical land motion (VLM) due to regional geological processes, sea-level rise at Baltimore is projected to be about 17% greater than for global mean sea-level rise in 2100 under the *Current Commitments* emissions pathway (Figure 6). This difference is largely due to ocean dynamic processes associated with circulation in the North Atlantic Ocean and the Gulf Stream off the Mid-Atlantic coast. Also, the loss of mass from the Antarctic ice sheet weakens its gravitational attraction on adjacent ocean waters and affects Earth's rotation and shape, meaning it contributes more to sea-level rise in far-away Maryland than for the oceans as a whole. On the other hand, an equivalent loss from the Greenland ice sheet has disproportionately less of an effect, because it is closer.

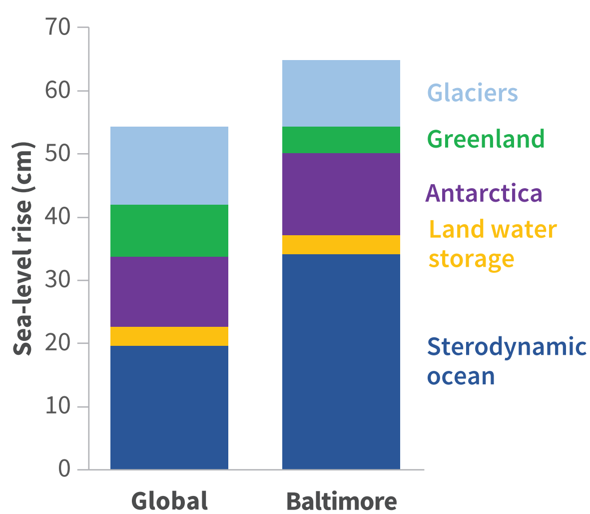


Figure 6. Projected contributions to sea-level rise not attributable to vertical land motion for Baltimore in 2100, compared to global mean sea-level rise for the IPCC SSP2-4.5 scenario (median estimates).

Comparison with the 2018 Projections

The projections provided in 2018 relied on the "K-14" probability distributions under three IPCC AR5 emissions scenarios: RCP8.5, RCP4.5, and RCP2.6. The SSP scenarios used in AR6 differ somewhat in their assumptions and drivers but it is still instructive to compare the sea-level rise projections made in 2018 with those provided here under the equivalent radiative forcing suffixes (i.e., 8.5, 4.5, and 2.6). Recall that the 2018 projections are from a year-2000 baseline and those for 2023 are from 2005, creating about a 0.02 m (1 in) difference. Figure 7 compares the sea-level rise probability distributions in 2100 for the comparable AR6 SSP emissions scenarios with the medians and likely (17^{th}–83^{rd} percentile) and 5^{th}–95^{th} percentile ranges provided in 2018. The medians and likely ranges for the 2023 projections are higher. However, the high-end, 95^{th}-percentile estimates are more comparable. The low-end, 5^{th}-percentile estimates in the 2023 projections are considerably higher than in the 2018 projections.

Tide gauge in Cambridge. Photo: NOAA.

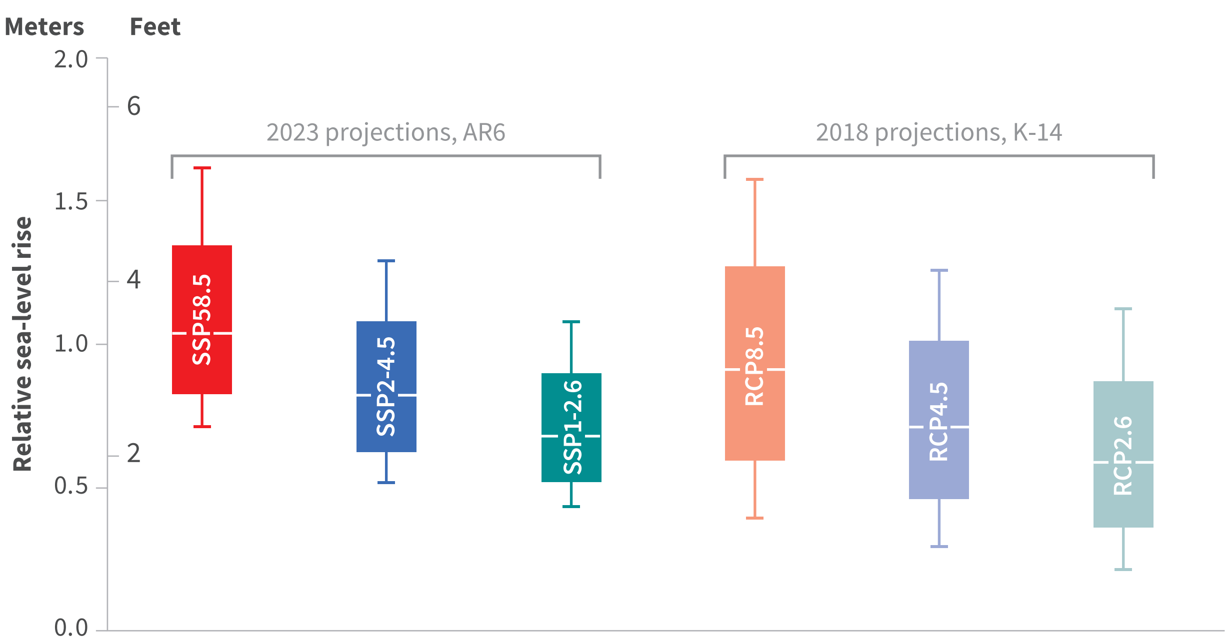


Figure 7. Comparison of 2023 sea-level rise "medium confidence" projections for 2100 at Baltimore with those included in 2018 Update from the 2005 (1995–2014 average) baseline. Bars represent *likely* (17^{th}–83^{rd} percentile) ranges, vertical lines the 5^{th}–95^{th} percentile ranges, and white crossbars the medians.

A small part of the differences in the projections is attributable to slightly higher VLM assumed in the projections for 2023, consistent in both AR6 projections and Interagency scenarios. However, the primary difference is due to higher contributions from melting of Antarctic ice sheets included in the 2023 projection (Figure 8). Improved scientific understanding altered the IPCC's projections and such adjustments—up or down—will certainly be made in future assessments. Going forward, it will be particularly important to take into account assessments informed by emerging science on the loss of ice from polar ice sheets, particularly in Antarctica. New understanding is also emerging on the sterodynamic processes (expansion of ocean volume and the effects of winds and currents) affecting regional patterns of sea-level rise along the coasts. These patterns may be influenced by climatic cycles affecting ocean dynamics and winds, as well as by trends in global warming.

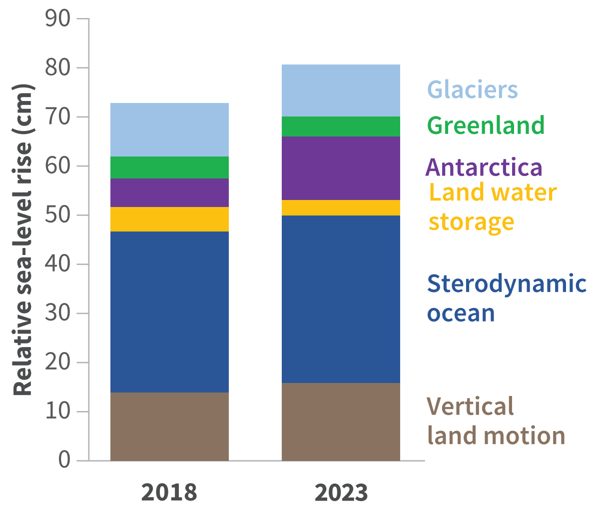


Figure 8. Comparison between the 2018 Update and 2023 Update of the contributions to relative sea-level rise at Baltimore in 2100, under the SSP2-4.5 scenario from the 2005 (1995–2014 average) baseline (median estimates).

A ghost forest of loblolly pine trees on Deal Island. The dead trees are the result of sea-level rise and shoreline erosion. Photo: Carlin Stiehl/ Chesapeake Bay Program CC BY-NC 2.0.

Referencing the Interagency Sea-Level Rise Scenarios

For the reasons discussed earlier, the projections are provided in the context of emissions pathways, consistent with the IPCC AR6. For users who employ the federal Interagency Task Force's sea-level rise scenarios, comparisons between the two approaches for Maryland's coasts are summarized in Figure 9. Using 2100 as a snapshot, sea-level rise at Baltimore as low as under the Interagency Low scenario is only within the *likely* range under an emissions pathway that would achieve the Paris Agreement's 1.5°C goal. Sea-level rise assuming the Intermediate-Low scenario is less than the median for the *Current Commitments* pathway of emissions (SSP2-4.5) and above the median under the *Paris Agreement* pathway (SSP1-2.6). Sea-level rise as high as assumed under the Interagency Intermediate scenario is higher than that *likely* under the *Current Commitments* projection, but less than its 95th quantile. It is within the likely range of projections under *Increasing Emissions* (SSP3-7.0). It approximates the median of the projections including additional rapid ice sheet losses under the *very high* emissions scenario (SSP5-8.5LC). The sea-level rise under the Intermediate-High scenario is substantially less than 5% likely under any of the most plausible, middle three IPCC emissions scenarios, but is comparable to the *low probability of exceedance with additional ice loss* level of 1.5 m (4.9 ft) estimated in Table 2 for the *Current Commitments* emissions scenario.

Variations within the Region

To this point, all projections presented are for Baltimore, the site of the state's longest tide-gauge record and the point of reference used in the 2018 projections. Sea-level rise relative to the adjacent land varies within Maryland, as reflected in the projections at the seven tide-gauge locations included in NASA's IPCC-AR6 Sea Level

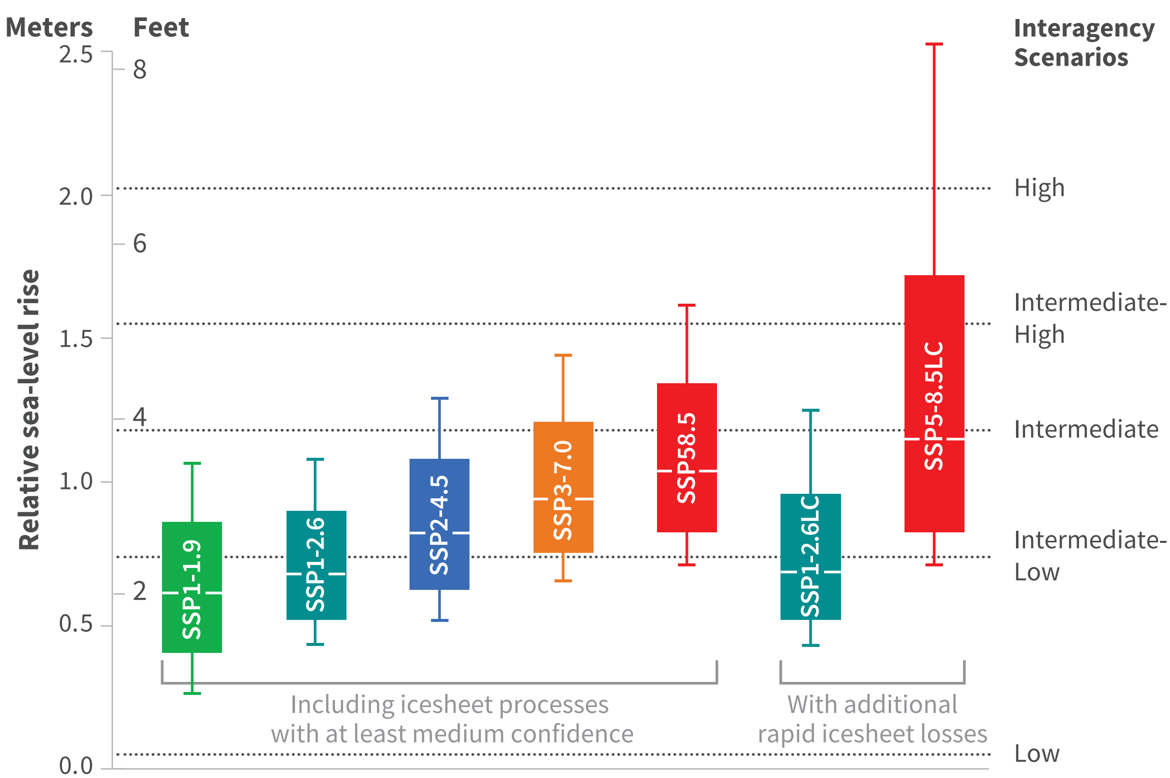


Figure 9. Relative sea-level rise at Baltimore from 2005 to 2100 based on the five Interagency Scenarios compared to the IPCC AR6 projections.

Projection Tool as presented in Appendix 2 for the *Current Commitments* scenario. At least in these projections, the differences between sea-level rise at these locations and Baltimore are due entirely to differences in the rate at which the land is subsiding, resulting in negative VLM. The sterodynamic and ice loss contributions to sea-level rise are estimated by the tool to be essentially the same for all locations within this small part of the world ocean.

Baltimore, Washington, D.C., and Tolchester Beach are undergoing very similar VLM as estimated by NOAA from tide-gauge records (Figure 10).[33] Lower down the Bay, VLM is more negative, with Annapolis (Naval Academy) and Cambridge subsiding faster than Baltimore. Solomons Island (Chesapeake Biological Laboratory) and Ocean City experience slightly more VLM. VLM throughout the Chesapeake Bay region is predominantly the result of glacial isostatic adjustment caused by rebounding

Figure 10. Vertical land motion (mm/yr) estimated by NOAA from tide-gauge records in Chesapeake Bay and adjacent Atlantic coast.

of the land mass to the north that was once burdened by massive ice-age glaciers. Maryland is well south of the glaciated area, so the land is moving downward in compensation for the rebound in the north.[34] More negative VLM could be caused by groundwater withdrawals in Southern Maryland and the Eastern Shore, where aquifer levels have been declining.[35] VLM at Norfolk (Sewells Point) is nearly 70% faster that at Baltimore, largely because of substantial groundwater abstraction in south-eastern Virginia.[36] Over the course of a century, this would result in almost 0.12 m (nearly 5 in) greater relative sea-level rise in Norfolk than in Baltimore.

VLM rates can vary over relatively small scales as a result of groundwater withdrawals and local geotechnical processes. For example, VLM varied from about −1 mm/yr to −5 mm/yr in the Chesapeake Bay region as measured using satellite-borne synthetic aperture radar.[37] Locally higher rates are found in the Hampton Roads area near the mouth of the Bay.[38] Subsidence rates can vary over time, introducing additional uncertainty in projections of VLM over decadal timescales. Where subsidence has been increased as a result of large withdrawals, potential remediation includes reducing the rate of groundwater abstractions or, as is being done in Hampton Roads, the injection of treated wastewater into the underlying aquifer.

Sea Level in the Longer-Term

Sea-level rise into the 22nd century and beyond will greatly depend on the nature, rates, and timing of polar ice losses, particularly those in Antarctica. Through its periodic assessments, the IPCC has been able to incorporate more of the processes involved in its sea-level rise projections and, in AR6, also estimated the ramifications of faster loss of polar ice than scientists are presently able to model with confidence.[39] Nonetheless, there will always remain uncertainties and ambiguities that should not be ignored.

The two AR6 sea-level rise projections that incorporate *low confidence* ice sheet losses help one envision the range of sea-level rise that Maryland may have to confront by the middle of the next century (Figure 11). They represent the *very high* emissions scenario that would likely produce more than 4°C of warming by 2100, and the *low* scenario that would achieve the < 2°C warming goal of the Paris Climate Agreement. Under the *very high* scenario median sea-level rise would grow to 2.4 m (7.9 ft) by 2050 because of the substantially greater contributions from Antarctica, with the 83rd percentile reaching 5.6 m (18.4 ft) because of the considerable uncertainties in the rate of ice loss. Under the *Paris Agreement* scenario, there are only small differences between this projection and the one that considered only *medium confidence* processes, mainly due to modestly greater contributions from Greenland. The projection median would barely reach 1 m (3.3 ft) and the 83rd percentile 1.5 m (4.9 ft) by 2050.

The dramatic divergence under the two scenarios underscores the importance of reducing global greenhouse gas emissions over the next 30–40 years in order to avoid greatly accelerating, potentially multi-meter sea-level rise by the middle of the next century. Scientists are learning more all the time as the climate warms and processes in the cryosphere are observed. However, there is presently a consensus that if the global temperature warms by over 3°C, sea-level rise of multiple meters would result in the coming centuries. Uncertainties and disagreements concern only the timing of this onset and its rate of acceleration. It is more a matter of "when" rather than "if." On the other hand, if the increase in global temperature can be stabilized closer to the < 2°C Paris goal, Antarctic ice loss could continue at a pace similar to today into the next century.[40]

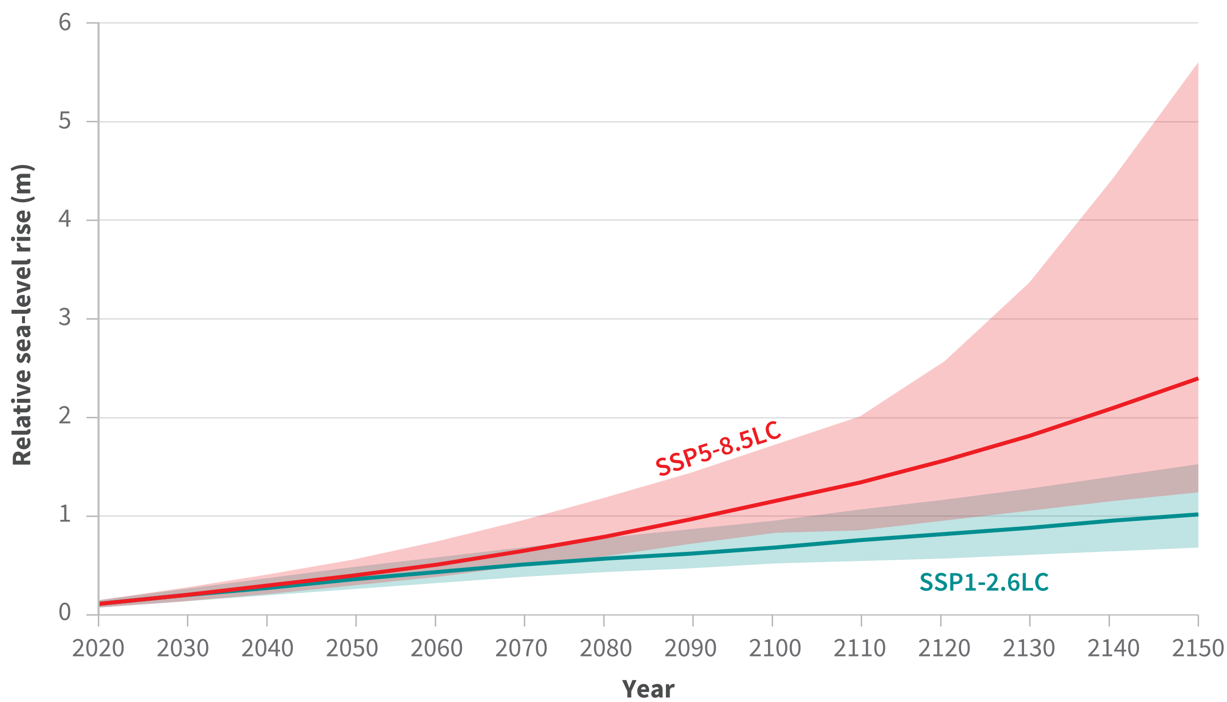


Figure 11. Sea-level rise projections for Baltimore under *very high* and *low* emissions scenarios that incorporate *low confidence* polar ice sheet losses; medians and likely range (17th–83rd percentile) shown.

SEA-LEVEL RISE AND FLOODING

While the primary objective of this report is to provide projections of relative sea-level rise in Maryland decades into the future, tidal waters fluctuate substantially around the mean level over hours to weeks as a result of semi-diurnal tides, lunar cycles that accentuate or minimize the tidal range, freshwater discharges, and winds that drive water into or out of bays and estuaries. Major storms, including hurricanes, tropical storms, and nor'easters, can result in even more substantial storm surges. It is the resulting extreme water levels that define the risks to humans and the built environment rather than the increase in mean sea-level itself. To some extent this also pertains to agricultural and natural systems such as marshes and forests.

Sea-level rise resulting from global warming will affect both high and low tide levels and storm surges by not only increasing the mean sea level but also by altering the characteristics of tidal waves and storm surges. Projections of the extent and frequency of flooding are beyond the scope of this report, but this is a subject of active research and modelling. The general effects of longer-term sea-level rise on flooding are discussed in this section.

Figure 12. Long-term tidal ranges (in meters) at gauging stations.

Tidal Range

Maryland's coasts experience semi-diurnal tides, with high tides and low tides approximately twice a day. The range of the two tides is unequal and changes with the lunar cycle. The tidal range at a specific place is considered to be the difference between the mean lower low water (MLLW) and mean higher high water (MHHW), averaged over many years. The tidal range varies considerably within Maryland and Chesapeake Bay (Figure 12). It exceeds 1 m (3.3 ft) along the Mid-Atlantic coast (1.2 m [3.9 ft] at Ocean City) but is attenuated as tidal waves propagate into Chesapeake Bay. However, the range again increases as tidal waves become constricted by diminishing cross-sectional area and are reflected back from the upper terminus of the estuary. This is evident from Baltimore into the upper Bay and in the upper Potomac River estuary. Consequently, the tidal range at Washington D.C. (1.0 m [3.3 ft]) is nearly twice that at Baltimore (0.5 m [1.6 ft]). The tidal range is also somewhat greater on the eastern side of the Bay as water piles up due to the rotation of the earth.

Tides in estuaries are changing worldwide due to sea-level rise, navigation channel dredging, shoreline hardening, and other anthropogenic actions.[41] The mean tidal range has decreased at Norfolk and Washington, D.C., but increased at upper Bay locations such as Annapolis and Baltimore,[42] as the amplitude of the major semi-diurnal tide has been decreasing in the lower portion of the Bay but increasingly slightly in the upper portion.[43] This is consistent with expectations as water levels and volumes increase within a progressively narrowing estuary.

The responses of tidal amplitude to future sea-level rise will also depend on the degree to which shorelines are protected by bulkheads, rip-rap, and other shoreline armoring. If sea level were to rise by 0.3–0.5 m, between 1,200 and 1,400 km^2 of land could become inundated at high tide, increasing the effective surface area of Chesapeake Bay by over 10%.[44] In that case, the tidal range would actually decline.[45] If, on the other hand, shorelines were extensively armored or flood defenses put in place, the higher tides would be prevented from flooding low-lying areas and the tidal amplitude would increase. This is an additional impact to consider in designing and permitting shoreline management and flood mitigation actions as Maryland adapts to sea-level rise.

Storm Surges

Maryland is vulnerable to storm surges generated by tropical storms and hurricanes. For storms moving north-east just off the coast, such as Hurricanes Irene (2011) and Floyd (1999), north-east to northerly winds can cause dangerous storm surges along the state's ocean coast, while sea level may actually drop in the upper Chesapeake Bay,[46] creating a different kind of hazard for boats docking in harbors. For storms making landfall and moving inland, such as Hurricanes Isabel (2003) and Sandy (2012), however, south-easterly to easterly winds drive water into Chesapeake Bay. Isabel created more than 2 m of flooding in Washington, D.C., Baltimore, and Annapolis.[47] Sandy drove water against the Bay's eastern shore, resulting in more than 1.5 m of flooding at Crisfield. Extratropical cyclones (nor'easters) can also cause storm surge flooding approaching that of hurricanes.[48]

How will storm surges be affected by climate change and sea-level rise? There is scientific consensus that global warming has increased the severity of tropical storms and the amount of associated rainfall.[49] There is also medium-to-high consensus that both of these will increase with 2°C of warming.[50] One recent analysis found that the frequency of Atlantic hurricanes has also increased over time, due mainly to regional rather than global climate change.[51] Aside from the issues of increased storm intensity and severity, sea-level rise will multiply the damages and threats to human life from storm surges that ride above the higher waters. For example, the storm surge from Hurricane Isabel inundated about 2.2 km^2 of Baltimore, causing $29 million in damages. Assuming sea level rose roughly similar to the *Current Commitments* (SSP2-4.5) projections, surge from a storm with a similar track would inundate 5.1 km^2 in 2050 and 9.2 km^2 in 2100, causing damages of $100 million and $150 million, respectively (in 2003 dollars).[52] The combined effects of climate change on sea-level rise and tropical storm intensity will greatly increase flooding frequency along the U.S. Atlantic and Gulf coasts, with a once in 100-year flood level experienced at least once in a decade by the end of this century.[53]

Nuisance Flooding

Long-term tide-gauge records—and, more recently, satellite altimeter measurements—show unequivocally that sea-level is rising at an unprecedented rate. However, daily or weekly variations in tidal water levels make it difficult for the casual observer to perceive this. One change that is apparent to people who live in or frequent low-lying areas is the increased frequency of nuisance flooding sufficient to cause a public inconvenience, such as the closure of roads or water in buildings. In Maryland, these flooding events typically occur when southerly winds drive water up the Chesapeake Bay or when north-east winds raise water levels along the Atlantic coast, particularly if this coincides with high tides. Such nuisance flooding events, sometimes called "high tide" flooding, are increasing in frequency around the United States as sea level rises. As mentioned earlier, Maryland state law requires local governments in its coastal zone to develop plans to address tidal nuisance flooding risks.

Tidal flooding events can be characterized as minor (which are more disruptive than damaging), moderate (damaging), or major (destructive). Threshold elevations for these three categories have been set by the National Weather Service (NWS) for specific coastal locations based on assessments of impacts and by NOAA's National Ocean Service (NOS) based on nationally consistent analysis of tide gauge observations.[54] Many local communities are more familiar with the location-specific NWS thresholds. Communities not near a NOAA tide gauge can establish their own thresholds based on observations of flood impacts. For Maryland, the NOAA NOS thresholds equate to 0.52 m (1.7 ft), 0.82 m (2.7 ft), and 1.19 m (3.9 ft) above current MHHW, respectively. These thresholds, along with NOS's regional frequency analysis, are used by the Federal Emergency Management Agency (FEMA) National Risk Index for coastal flooding.

In 2022, the Interagency Task Force introduced a new set of extreme water-level probabilities to support sea-level rise and flood-exposure assessments and planning.[22] These probabilities are computed from tide gauge records and then can be coupled with sea-level rise projections to assess future changes in the frequency of

High-tide flooding in Cambridge (top) and after the water had receded (bottom). Photos: Jane Thomas.

minor, moderate, and major flooding events under each of the Interagency scenarios. Table 3 illustrates the increased frequency of flooding events in Maryland in 2050 under the Interagency Intermediate scenario, with relative sea-level rise of 0.39 m from 2005.

Table 3. Changes in the frequency of minor, moderate, and major flooding under the Interagency Intermediate sea-level rise scenario (0.39 m above 2005 level); Maryland state average, using National Ocean Service mathematical flood heights.

Flooding threshold	Elevation above MHHW	2020	2050
Minor	0.52 m	2–5 events per year	50 events per year
Moderate	0.82 m	20–30% annual chance	5 events per year
Major	1.19 m	2–5% annual chance	20–30% annual chance

Taking this a step further, NASA and NOAA investigators incorporated the effects of nodal cycle modulations (an 18.6-year lunar cycle that influences tidal amplitude, sometimes called the "moon wobble") into refined estimations of exceedance of flooding event thresholds for the Interagency sea-level rise scenarios.[55,56] These flooding frequency estimates do not fully take into account the extreme water-level probabilities included in the Interagency Task Force report.[22] While flooding probabilities projected by both tools are useful in planning, it should be kept in mind that in Maryland, flooding is predominantly driven by meteorological events that cannot be predicted far in advance. NOAA maintains an online Coastal Inundation Dashboard that provides real-time water levels with forecasts out to 48 hours.[57] MyCoast Maryland, maintained by the Department of Natural Resources, allows citizens to communicate flooding and storm damage in their communities.[58]

Tidal Flood Risk Visualizations

The Maryland Commission on Climate Change Act specifies that these science-based sea-level rise projections include maps that indicate the areas of the State that may be most affected by storm surges, flooding, and extreme weather events. As these probabilistic projections do not rely on one single sea-level rise estimate for one specific date in the future and do not include an analysis on storm surges and other extreme weather events, mapping becomes nearly infinitely complicated and one static map is misleading. There are online mapping tools, such as NOAA's Coastal Flood Exposure Mapper[59] and Climate Central's Coastal Risk Screening Tool,[60] that are useful for geographic plotting of sea-level rise and storm surge on inundation and coastal vulnerability. Both tools are based on reliable elevation data. The NOAA tool allows the selection of sea-level rise above MHHW, storm surge, and high-tide flooding; however, it does not display the combined effects of storm surge or high-tide flooding with sea-level projections or scenarios. It can also display various metrics of societal, infrastructure, and ecosystem exposure. The Climate Central tool allows the selection of water level, which can include projected sea level, combined with specified heights of storm surge superimposed. It also plots particular risks to affordable housing.

The Maryland Department of Natural Resources is starting the process of developing a flood visualization tool for Maryland for use in various planning and management activities. The sea-level rise projections presented in this report will be used in developing that tool. These visualizations should be complete by the end of 2024.

USING SEA-LEVEL PROJECTIONS IN PLANNING

Sea-level rise has already resulted in adverse impacts for Maryland's people and environments, including flooding, erosion, forest and wetland losses, salinization of freshwater supplies and agricultural lands, and impaired drainage. Predominantly as a result of long-term regional land subsidence, relative sea level was rising even during the 19th century, contributing to the loss of historic island settlements in Chesapeake Bay. The rate of rise more than doubled, resulting in about one foot of rise during the 20th century as the world's oceans began to swell in volume with the warming planet.[16] Relative sea level has already risen by more than one-third of a foot during the first 20 years of the present century and appears on a trajectory to rise by as much it did in the last century by the middle of this century, and as much as three times as much by the end of the century as it did during the entire last century. Whether the rise is that much or greater will largely be determined by how much and how soon global society is able to reduce its greenhouse gas emissions. Some scientific uncertainties and ambiguities about the future rate of sea-level rise remain, but the most consequential action that Maryland can take now to address century-scale impacts is to continue to show leadership in an ambitious reduction of greenhouse gas emissions.

The following are important considerations that should be taken into account when utilizing the Maryland sea-level rise projections presented here as reference points.

The last house on Holland Island in Chesapeake Bay as it stood in October 2009. This house fell into the bay in October 2010. Photo: baldeaglebluff CC BY-SA 2.0.

1

The *Current Commitments* sea-level rise projections, based on the *intermediate* (SSP2-4.5) emissions scenario of the IPCC AR6, represent the most plausible basis for anticipating the relative sea-level rise Maryland will experience over the next century. More than other scenarios, the *Current Commitments* scenario encompasses the emissions pathways the world will probably be on as it strives to limit global warming consistent with the goals of the Paris Climate Agreement. The IPCC sea-level rise projections are derived from evidence, rigorous models, and scientific consensus based on the warming that would result. For comparative reference, sea-level rise projections are also provided for the *Paris Agreement* (SSP2-2.6) scenario, assuming that global society succeeds in its quest, and the *Increasing Emissions* (SSP3-7.0) scenario, should emissions instead double by the end of the century. Of course, the scenario and projections used should be re-evaluated in subsequent updates based on developing outlooks on greenhouse gas emissions and concentrations, as well as emerging scientific understanding of the contributions to sea-level rise.

2

The statistical probability estimates for sea-level rise projections (Figure 5, Table 2) are useful reference points in planning and managing risks. Tolerance for flood risk, or the willingness of decision-makers and stakeholders to accept possible consequences of flooding, can help determine which quantile level should be used when selecting a relative sea-level rise estimate. In general, projects with low tolerance for flood risk should consider sea-level rise estimates that have a low likelihood to be exceeded during the project's lifespan, whereas projects with medium or high tolerance for flood risk may consider lower sea-level rise estimates. Guidance on applications with different levels of risk tolerance and timeframes was provided for using the probabilistic estimates from Maryland's 2018 sea-level rise projections and will be updated based on these 2023 projections.[9]

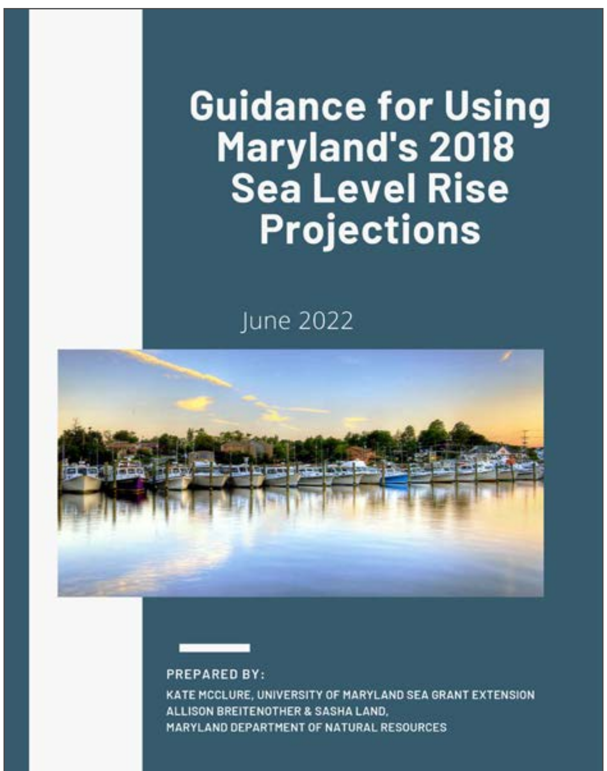
- Best estimates (medians, 50th percentile) are recommended as the sea-level rise estimate for managing or restoring natural infrastructure unless the project scoping determines otherwise.[61] Examples include tidal wetland management and restoration, creating living shorelines, estimation of saltwater intrusion and coastal landscape migration, or protecting estuarine water quality. Particularly when an action has the capacity to be adapted in the future, it is often more important to know how much sea level is most likely to rise rather than how high it could rise.
- Sea-level rise estimates that are unlikely to be exceeded (83rd percentile) are recommended for built infrastructure and community-wide planning with medium tolerance for flood risk.
- Sea-level rise with a *low probability of exceedance with additional ice loss* is recommended as a reference point for projects that have both long expected lifespans (greater than 50 years) and very little tolerance for flood risk because they provide essential services that cannot be disrupted.
- The projections and probabilistic estimates are for mean sea-level averaged over several years. Additional considerations are required to assess flood risks exacerbated by nuisance and storm surge flooding.

3

Flexible adaptation pathways can be a less costly approach to long-term planning for sea-level rise where subsequent adjustments in adaptation are possible.[62] Extreme risk avoidance by using very low-probability levels and scenarios with implausibly high emissions (e.g., SSP5-8.5) or sea-level rise assumptions (e.g., Interagency High) just to be safe comes with costs to society. While sea-level rise cannot be reversed, its rate would be substantially lower later this century and beyond if greenhouse gas emissions are substantially reduced over the next few decades (Figure 11). A flexible adaptation pathway prioritizes low-regret options that make sense under the likely range of sea-level rise, while preparing contingency plans for higher levels of sea-level rise should emission reductions not be realized or polar ice losses more rapid than expected. This requires regular monitoring of emissions reductions, sea-level rise rates, and emerging understanding of ice-sheet contributions to sea-level rise.

4

Maryland Sea Grant Extension and the Department of Natural Resources have developed guidance for incorporating Maryland's sea-level rise estimates into projects.[9] The guidance provides a step-by step approach for selecting relative sea-level rise estimates based on project type, goal, timeframe, and location and on decision-makers' tolerance for flood risks. Updated guidance will be developed during 2023, incorporating the new sea-level rise projections developed in this report, with consideration of flexible adaptation pathways.


Guidance for Using Maryland's 2018 Sea Level Rise Projections

June 2022

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Maryland Sea Grant Extension and Department of Natural Resources will develop updated guidance during 2023.

Sea-level rise projections should be incorporated broadly into planning, regulatory, and site-specific projects, and into community planning. This should consider a wide range of impacts on the communities and seek to incorporate diverse and representative stakeholder perspectives when planning for these impacts.

Appendix 1. Sea-level rise projections with quantile probabilities for Baltimore under the three most plausible emissions scenarios.

	Scenario		Quantile	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140	2150
METERS	Paris Agreement	SSP1-2.6	5	0.04	0.09	0.14	0.20	0.25	0.31	0.35	0.39	0.43	0.44	0.47	0.49	0.52	0.54
			17	0.07	0.13	0.19	0.26	0.32	0.38	0.43	0.47	0.52	0.54	0.58	0.61	0.65	0.68
			50	0.10	0.19	0.27	0.35	0.42	0.50	0.56	0.62	0.68	0.74	0.80	0.86	0.91	0.97
			83	0.14	0.25	0.36	0.46	0.55	0.64	0.73	0.81	0.90	1.00	1.09	1.18	1.27	1.36
			95	0.17	0.30	0.42	0.54	0.65	0.76	0.87	0.98	1.08	1.21	1.32	1.44	1.55	1.66
	Current commitments	SSP2-4.5	5	0.04	0.08	0.14	0.22	0.30	0.37	0.43	0.49	0.51	0.52	0.58	0.63	0.68	0.73
			17	0.07	0.13	0.19	0.27	0.35	0.43	0.51	0.57	0.62	0.65	0.72	0.79	0.85	0.92
			50	0.10	0.19	0.27	0.36	0.45	0.55	0.64	0.72	0.82	0.90	1.00	1.10	1.19	1.29
			83	0.14	0.25	0.36	0.46	0.57	0.69	0.81	0.93	1.08	1.23	1.37	1.50	1.64	1.78
			95	0.18	0.30	0.42	0.54	0.67	0.81	0.96	1.11	1.30	1.48	1.65	1.82	1.99	2.16
	Increasing emissions	SSP3-7.0	5	0.04	0.07	0.14	0.22	0.31	0.40	0.48	0.56	0.65	0.66	0.73	0.81	0.89	0.96
			17	0.06	0.12	0.19	0.28	0.36	0.46	0.56	0.65	0.75	0.78	0.87	0.97	1.06	1.14
			50	0.10	0.18	0.27	0.36	0.46	0.57	0.68	0.81	0.94	1.03	1.16	1.29	1.41	1.54
			83	0.15	0.25	0.35	0.47	0.58	0.71	0.86	1.03	1.21	1.36	1.54	1.72	1.89	2.07
			95	0.18	0.30	0.42	0.55	0.67	0.84	1.02	1.23	1.44	1.64	1.86	2.07	2.29	2.51
FEET	Paris Agreement	SSP1-2.6	5	0.13	0.30	0.46	0.65	0.83	1.02	1.15	1.27	1.41	1.43	1.53	1.61	1.70	1.78
			17	0.22	0.42	0.63	0.85	1.04	1.25	1.40	1.54	1.70	1.77	1.89	2.00	2.12	2.22
			50	0.34	0.61	0.88	1.15	1.38	1.63	1.83	2.03	2.23	2.42	2.62	2.81	3.00	3.18
			83	0.47	0.82	1.16	1.51	1.79	2.11	2.40	2.67	2.95	3.29	3.59	3.88	4.18	4.47
			95	0.57	0.97	1.38	1.78	2.12	2.50	2.86	3.20	3.55	3.95	4.33	4.71	5.08	5.45
	Current commitments	SSP2-4.5	5	0.13	0.27	0.46	0.72	0.97	1.20	1.42	1.60	1.68	1.72	1.90	2.07	2.24	2.40
			17	0.22	0.41	0.63	0.90	1.16	1.42	1.66	1.88	2.04	2.15	2.37	2.59	2.80	3.01
			50	0.34	0.61	0.89	1.18	1.47	1.79	2.09	2.37	2.69	2.97	3.29	3.60	3.91	4.22
			83	0.47	0.82	1.16	1.52	1.86	2.27	2.65	3.06	3.54	4.02	4.48	4.93	5.39	5.84
			95	0.57	0.98	1.37	1.78	2.18	2.66	3.15	3.63	4.25	4.84	5.41	5.97	6.52	7.08
	Increasing emissions	SSP3-7.0	5	0.11	0.24	0.44	0.71	1.01	1.30	1.57	1.83	2.13	2.15	2.41	2.66	2.91	3.15
			17	0.21	0.39	0.62	0.90	1.19	1.51	1.82	2.13	2.47	2.56	2.86	3.17	3.46	3.75
			50	0.34	0.60	0.88	1.19	1.50	1.86	2.24	2.65	3.08	3.39	3.81	4.23	4.64	5.04
			83	0.48	0.82	1.16	1.53	1.89	2.33	2.83	3.39	3.96	4.48	5.06	5.64	6.21	6.78
			95	0.58	0.98	1.38	1.80	2.21	2.74	3.34	4.04	4.74	5.38	6.09	6.80	7.51	8.23

Appendix 2. Sea-level rise projections with quantile probabilities for sites in Maryland and Washington, DC, under the SSP2-4.5 emissions scenario.

	Quantile	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140	2150
BALTIMORE															
METERS	5	0.04	0.08	0.14	0.22	0.30	0.37	0.43	0.49	0.51	0.52	0.58	0.63	0.68	0.73
	17	0.07	0.13	0.19	0.27	0.35	0.43	0.51	0.57	0.62	0.65	0.72	0.79	0.85	0.92
	50	0.10	0.19	0.27	0.36	0.45	0.55	0.64	0.72	0.82	0.90	1.00	1.10	1.19	1.29
	83	0.14	0.25	0.36	0.46	0.57	0.69	0.81	0.93	1.08	1.23	1.37	1.50	1.64	1.78
	95	0.18	0.30	0.42	0.54	0.67	0.81	0.96	1.11	1.30	1.48	1.65	1.82	1.99	2.16
FEET	5	0.13	0.27	0.46	0.72	0.97	1.20	1.42	1.60	1.68	1.72	1.90	2.07	2.24	2.40
	17	0.22	0.41	0.63	0.90	1.16	1.42	1.66	1.88	2.04	2.15	2.37	2.59	2.80	3.01
	50	0.34	0.61	0.89	1.18	1.47	1.79	2.09	2.37	2.69	2.97	3.29	3.60	3.91	4.22
	83	0.47	0.82	1.16	1.52	1.86	2.27	2.65	3.06	3.54	4.02	4.48	4.93	5.39	5.84
	95	0.57	0.98	1.37	1.78	2.18	2.66	3.15	3.63	4.25	4.84	5.41	5.97	6.52	7.08
TOLCHESTER BEACH															
METERS	5	0.04	0.08	0.14	0.22	0.30	0.37	0.44	0.50	0.52	0.54	0.59	0.65	0.70	0.75
	17	0.07	0.13	0.20	0.28	0.36	0.44	0.52	0.58	0.63	0.67	0.74	0.80	0.87	0.93
	50	0.11	0.19	0.27	0.37	0.46	0.55	0.64	0.73	0.83	0.92	1.02	1.11	1.21	1.30
	83	0.15	0.25	0.36	0.47	0.58	0.70	0.82	0.94	1.09	1.24	1.38	1.52	1.66	1.80
	95	0.18	0.30	0.43	0.55	0.67	0.82	0.97	1.12	1.31	1.49	1.66	1.84	2.01	2.18
FEET	5	0.13	0.28	0.47	0.73	0.98	1.22	1.44	1.63	1.72	1.76	1.94	2.12	2.29	2.46
	17	0.22	0.42	0.65	0.92	1.18	1.45	1.69	1.91	2.08	2.19	2.41	2.63	2.85	3.06
	50	0.35	0.62	0.90	1.20	1.50	1.81	2.11	2.40	2.73	3.01	3.33	3.65	3.96	4.28
	83	0.48	0.83	1.18	1.54	1.89	2.29	2.69	3.09	3.58	4.07	4.53	4.99	5.45	5.90
	95	0.58	1.00	1.39	1.80	2.21	2.69	3.18	3.68	4.30	4.89	5.46	6.02	6.59	7.15
ANNAPOLIS															
METERS	5	0.04	0.09	0.15	0.23	0.31	0.39	0.45	0.51	0.54	0.56	0.61	0.67	0.72	0.78
	17	0.07	0.13	0.20	0.29	0.37	0.45	0.53	0.60	0.65	0.69	0.76	0.83	0.89	0.96
	50	0.11	0.19	0.28	0.37	0.46	0.56	0.66	0.75	0.85	0.93	1.04	1.13	1.23	1.33
	83	0.15	0.26	0.37	0.48	0.58	0.71	0.83	0.96	1.11	1.26	1.40	1.54	1.68	1.82
	95	0.18	0.31	0.43	0.56	0.68	0.83	0.98	1.13	1.32	1.51	1.68	1.86	2.03	2.20
FEET	5	0.14	0.29	0.50	0.76	1.02	1.26	1.49	1.68	1.78	1.82	2.00	2.19	2.38	2.55
	17	0.23	0.43	0.67	0.94	1.21	1.49	1.73	1.96	2.13	2.25	2.48	2.71	2.93	3.15
	50	0.36	0.63	0.92	1.23	1.52	1.85	2.16	2.45	2.78	3.06	3.40	3.72	4.04	4.36
	83	0.49	0.85	1.20	1.56	1.92	2.33	2.73	3.14	3.63	4.12	4.59	5.06	5.52	5.97
	95	0.59	1.01	1.41	1.82	2.23	2.72	3.22	3.71	4.34	4.94	5.52	6.09	6.66	7.22
CAMBRIDGE															
METERS	5	0.04	0.09	0.15	0.23	0.31	0.39	0.46	0.51	0.54	0.56	0.61	0.67	0.73	0.78
	17	0.07	0.13	0.20	0.29	0.37	0.45	0.53	0.60	0.65	0.69	0.76	0.83	0.90	0.96
	50	0.11	0.19	0.28	0.38	0.47	0.57	0.66	0.75	0.85	0.94	1.04	1.14	1.24	1.33
	83	0.15	0.26	0.37	0.48	0.59	0.71	0.83	0.96	1.11	1.26	1.40	1.55	1.69	1.83
	95	0.18	0.31	0.43	0.56	0.68	0.83	0.98	1.14	1.33	1.51	1.69	1.86	2.03	2.21
FEET	5	0.13	0.29	0.50	0.76	1.02	1.26	1.49	1.68	1.78	1.82	2.01	2.20	2.38	2.56
	17	0.23	0.43	0.67	0.94	1.21	1.49	1.74	1.96	2.14	2.25	2.49	2.71	2.94	3.16
	50	0.36	0.64	0.92	1.23	1.53	1.85	2.16	2.45	2.79	3.07	3.41	3.73	4.06	4.37
	83	0.50	0.85	1.20	1.57	1.92	2.33	2.74	3.15	3.65	4.13	4.60	5.07	5.54	5.99
	95	0.60	1.02	1.41	1.83	2.24	2.73	3.23	3.73	4.36	4.95	5.53	6.11	6.67	7.25

	Quantile	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140	2150
SOLOMONS															
METERS	5	0.04	0.10	0.16	0.24	0.32	0.40	0.47	0.53	0.56	0.58	0.64	0.70	0.76	0.81
	17	0.07	0.14	0.21	0.30	0.38	0.47	0.55	0.62	0.67	0.71	0.78	0.85	0.93	0.99
	50	0.11	0.20	0.29	0.39	0.48	0.58	0.67	0.77	0.87	0.96	1.06	1.16	1.26	1.36
	83	0.16	0.26	0.37	0.49	0.60	0.73	0.85	0.98	1.13	1.28	1.43	1.57	1.71	1.85
	95	0.19	0.31	0.44	0.57	0.69	0.85	1.00	1.15	1.35	1.53	1.71	1.89	2.06	2.24
FEET	5	0.14	0.31	0.53	0.80	1.06	1.31	1.55	1.74	1.85	1.90	2.10	2.29	2.48	2.66
	17	0.23	0.45	0.70	0.98	1.25	1.53	1.79	2.02	2.20	2.33	2.57	2.80	3.03	3.26
	50	0.37	0.65	0.94	1.26	1.57	1.90	2.21	2.51	2.85	3.14	3.48	3.81	4.14	4.47
	83	0.51	0.87	1.22	1.59	1.96	2.38	2.79	3.20	3.70	4.20	4.68	5.15	5.62	6.08
	95	0.61	1.03	1.43	1.86	2.28	2.78	3.27	3.78	4.41	5.02	5.60	6.18	6.76	7.34
WASHINGTON, D.C.															
METERS	5	0.04	0.08	0.14	0.22	0.30	0.37	0.44	0.49	0.52	0.53	0.58	0.64	0.69	0.74
	17	0.07	0.13	0.20	0.28	0.36	0.44	0.51	0.58	0.63	0.66	0.73	0.79	0.86	0.92
	50	0.11	0.19	0.27	0.36	0.45	0.55	0.64	0.72	0.82	0.91	1.01	1.10	1.20	1.29
	83	0.15	0.25	0.36	0.46	0.57	0.69	0.81	0.93	1.08	1.23	1.37	1.51	1.65	1.78
	95	0.18	0.30	0.42	0.54	0.67	0.81	0.96	1.11	1.30	1.48	1.65	1.82	1.99	2.16
FEET	5	0.12	0.27	0.47	0.72	0.97	1.21	1.43	1.61	1.69	1.73	1.92	2.09	2.26	2.43
	17	0.22	0.41	0.64	0.91	1.16	1.43	1.67	1.89	2.05	2.16	2.38	2.60	2.82	3.03
	50	0.34	0.61	0.89	1.19	1.48	1.80	2.09	2.38	2.70	2.97	3.30	3.61	3.92	4.24
	83	0.48	0.82	1.17	1.52	1.87	2.27	2.66	3.06	3.55	4.03	4.49	4.95	5.40	5.85
	95	0.58	0.98	1.37	1.78	2.19	2.66	3.15	3.64	4.26	4.84	5.41	5.97	6.54	7.09
OCEAN CITY															
METERS	5	0.05	0.10	0.17	0.26	0.34	0.42	0.50	0.56	0.59	0.61	0.67	0.74	0.80	0.86
	17	0.08	0.15	0.22	0.31	0.40	0.49	0.57	0.65	0.71	0.74	0.82	0.89	0.97	1.04
	50	0.12	0.21	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.21	1.31	1.42
	83	0.16	0.27	0.39	0.50	0.62	0.75	0.88	1.01	1.17	1.32	1.47	1.62	1.77	1.91
	95	0.19	0.33	0.45	0.58	0.72	0.87	1.03	1.19	1.39	1.57	1.76	1.94	2.12	2.30
FEET	5	0.16	0.33	0.56	0.84	1.11	1.37	1.62	1.83	1.94	2.01	2.21	2.41	2.61	2.81
	17	0.25	0.48	0.73	1.02	1.31	1.60	1.87	2.12	2.31	2.44	2.69	2.93	3.18	3.42
	50	0.39	0.68	0.98	1.31	1.63	1.97	2.30	2.61	2.97	3.27	3.62	3.96	4.30	4.64
	83	0.52	0.90	1.26	1.65	2.02	2.46	2.88	3.31	3.83	4.34	4.83	5.32	5.80	6.28
	95	0.63	1.07	1.48	1.91	2.35	2.86	3.38	3.90	4.55	5.16	5.77	6.37	6.96	7.55

ENDNOTES

1. Chen, Y., & Kirwan, M. L. (2022). Climate-driven decoupling of wetland and upland biomass on the Mid-Atlantic coast. *Nature Geosciences, 15*, 913–918. https://doi.org/10.1038/s41561-022-01041-x
2. Molino, G. D., Carr, J. A., Ganju, N. K., & Kirwan, M. L. (2022). Variability in marsh migration potential determined by topographic rather than anthropogenic constraints in the Chesapeake Bay region. *Limnology and Oceanography Letters, 7,* 321–331. https://doi.org/10.1002/lol2.10262
3. Dahl, K., Cleetus, R., Spanger-Siegfried, E., Udvardy, S., Caldas, A., & Worth, P. (2018). *Underwater: Rising Seas, Chronic Floods, and the Implications for U.S. Coastal Real Estate*. Union of Concerned Scientists. https://www.ucsusa.org/sites/default/files/attach/2018/06/underwater-analysis-full-report.pdf
4. Boesch, D. F. (Ed.). (2008). *Global Warming and the Free State: Comprehensive Assessment of Climate Change Impacts in Maryland*. Report of the Scientific and Technical Working Group, Maryland Commission on Climate Change. https://mde.maryland.gov/programs/air/climatechange/documents/final-chapt%202%20impacts_web.pdf
5. Maryland Commission on Climate Change. (2008). *Maryland Climate Action Plan*. Maryland Department of the Environment. http://mde.maryland.gov/programs/Air/ClimateChange/MCCC/Publications/2008ClimateActionPlan.pdf
6. Boesch, D. F., Atkinson, L. P., Boicourt, W. C., Boon, J. D., Cahoon, D. R., Dalrymple, R. A., Ezer, T., Horton, B. P., Johnson, Z. P., Kopp, R. E., Li, M., Moss, R. H., Parris, A., & Sommerfield, C. K. (2013). *Updating Maryland's Sea-level Rise Projections*. Special Report of the Scientific and Technical Working Group to the Maryland Climate Change Commission. University of Maryland Center for Environmental Science. https://www.umces.edu/sites/default/files/pdfs/SeaLevelRiseProjections.pdf
7. National Research Council. (2012). *Sea-level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. National Academy Press. https://nap.nationalacademies.org/read/13389
8. Boesch, D. F., Boicourt, W. C., Cullather, R. I., Ezer, T., Galloway Jr, G. E., Johnson, Z. P., Kilbourne, K. H., Kirwan, M. L., Kopp, R. E., Land, S., Li, M., Nardin, W., Sommerfield, C. K., & Sweet, W. V. (2018). *Sea-level Rise Projections for Maryland 2018*. University of Maryland Center for Environmental Science. https://mde.maryland.gov/programs/Air/ClimateChange/MCCC/Documents/Sea-LevelRiseProjectionsMaryland2018.pdf
9. McClure, K., Breitenother, A., & Land, S. (2022). *Guidance for Using Maryland's 2018 Sea Level Rise Projections*. https://dnr.maryland.gov/ccs/Documents/MD_SLRGuidance_June2022.pdf
10. Maryland Department of Planning. (2019). *Maryland's Plan to Adapt to Saltwater Intrusion and Salinization*. Maryland Department of Planning. https://planning.maryland.gov/Documents/OurWork/envr-planning/2019-1212-Marylands-plan-to-adapt-to-saltwater-intrusion-and-salinization.pdf
11. Maryland Department of Natural Resources. (2019). *Nuisance Flood Plan Development Guidance*. Maryland Department of Natural Resources. https://dnr.maryland.gov/ccs/Documents/NuisanceFloodPlan.pdf
12. Masson-Delmotte, V., Zhai, P., Pörtner, H. -O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (Eds.). (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge University Press. https://www.ipcc.ch/sr15/download
13. Oppenheimer, M., Glavovic, B., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., & Sebesvari, Z. (2019). Sea level rise and implications for low lying islands, coasts and communities. In H. -O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (pp. 321–445). Cambridge University Press. https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities
14. Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J. -B., Slangen, A. B. A., & Yu, Y. (2021). Ocean, cryosphere, and sea-level change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1211–1362). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1
15. Moore-Miller for Maryland. (2022). *Maryland's Climate, Our Economic Future: Building a Cleaner, More Prosperous Maryland*. https://wesmoore.com/wp-content/uploads/2022/05/Wes-Moore-For-Maryland-Climate-Plan.pdf

16. Cazenave, A., & Moreira, L. (2022). Contemporary sea-level changes from global to local scales: A review. *Proceedings of the Royal Society A, 478,* 20220049. https://doi.org/10.1098/rspa.2022.0049

17. Ezer, T. (2023). Sea level acceleration and variability in the Chesapeake Bay: Past trends, future projections, and spatial variations within the Bay. *Ocean Dynamics, 73*, 23–34. https://doi.org/10.1007/s10236-022-01536-6

18. Dangendorf, S., Hendricks, N., Sun, Q., Klink, J., Ezer, T., Frederikse, T., Calafat, F. M., Wahl, T., & Törnqvist, T. E. (2023). Acceleration of U.S. Southeast and Gulf coast sea-level rise amplified by internal climate variability. *Nature Communications, 14*, 1935. https://doi.org/10.1038/s41467-023-37649-9

19. Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H., & Tebaldi, C. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future, 2*, 383–406. https://doi.org/10.1002/2014EF000239

20. Scientific Expert Group on Climate Change (2007). *Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable*. Bierbaum, R. M., Holdren, J. P., MacCracken, M. C., Moss, R. H., & Raven, P. H. (Eds.). Sigma Xi and United Nations Foundation. https://www.sigmaxi.org/docs/default-source/Programs-Documents/Critical-Issues-in-Science/download-the-full-report-of-confronting-climate-change-(15mb-164-pages).pdf?sfvrsn=1ae3ad58_0

21. Kopp, R. E., Oppenheimer, M., O'Reilly, J. L., Drijfhout, S. S., Edwards, T. L., Fox-Kemper, B., Garner, G. G., Golledge, N. R., Hermans, T. H. J., Hewitt, H. T., Horton, B. P., Krinner, G., Notz, D., Nowicki, S., Palmer, M. D., Slangen, A. B. A., & Xiao, C. (2023). Communicating future sea-level rise uncertainty and ambiguity to assessment users. *Nature Climate Change*. https://doi.org/10.1038/s41558-023-01691-8

22. Sweet, W. V., Hamlington, B. D., Kopp, R. E., Weaver, C. P., Barnard, P. L., Bekaert, D., Brooks, W., Craghan, M., Dusek, G., Frederikse, T., Garner, G., Genz, A. S., Krasting, J. P., Larour, E., Marcy, D., Marra, J. J., Obeysekera, J., Osler, M., Pendleton, M., Roman, D., Schmied, L., Veatch, W., White, K. D., & Zuzak, C. (2022). *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities along U.S. Coastlines*. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

23. Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., K.C., S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., & Tavoni, M. (2017). The Shared Socio-Economic Pathways and their energy, land use and greenhouse gas emissions implications: an overview. *Global Environmental Change*, *42*, 148–152. https://doi.org/10.1016/j.gloenvcha.2016.05.009

24. Diffenbaugh, N.S., & Barnes, E.A. (2023). Data-driven predictions of the time remaining until critical global warming thresholds are reached. *Proceedings of the National Academy of Sciences, 120*, e2207183120. https://doi.org/10.1073/pnas.2207183120

25. Hausfather, Z., & Peters, G. F. (2020). Emissions—the "business as usual" story is misleading. *Nature*, *577*, 618–620. http://dx.doi.org/10.1038/d41586-020-00177-3

26. NASA. *Sea Level Projection Tool*. https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

27. Garner, G. G., Hermans, T., Kopp, R. E., Slangen, A. B. A., Edwards, T. L., Levermann, A., Nowicki, S., Palmer, M. D., Smith, C., Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Golledge, N. R., Hemer, M., Krinner, G., Mix, A., Notz, D., Nurhati, I. S., Ruiz, L., Sallée, J. -B., Yu, Y., Hua, L., Palmer, T. & Pearson, B. (2021). *IPCC AR6 Sea-level Rise Projections*. Version 20210809. https://doi.org/10.5281/zenodo.5914709. We thank the projection authors for developing and making the sea-level rise projections available, multiple funding agencies for supporting the development of the projections, and the NASA Sea Level Change Team for developing and hosting the IPCC AR6 Sea Level Projection Tool.

28. Because projected values are 19-year averages, the "2020" value is actually a 2011–2029 average and is not fully constrained by the observations to date.

29. Kopp, R. E., Andrews, C., Broccoli, A., Garner, A., Kreeger, D., Leichenko, R., Lin, N., Little, C., Miller, J. A., Miller, J. K., Miller, K. G., Moss, R., Orton, P., Parris, A., Robinson, D., Sweet, W., Walker, J., Weaver, C. P., White, K., Campo, M., Kaplan, M., Herb, J., & Auermuller, L. (2019). *New Jersey's Rising Seas and Changing Coastal Storms: Report of the 2019 Science and Technical Advisory Panel*. The State University of New Jersey. https://climatechange.rutgers.edu/images/STAP_FINAL_FINAL_12-4-19.pdf

30. Hamlington, B. D., Chambers, D. P., Fredrikse, T., Dangendorf, S., Fournier, S., Buzzanga, B., & Nerem, R. S. (2022). Observation-based trajectory of future sea level for the coastal United States tracks near high-end model predictions. *Communications Earth & Environment, 3*, 230 https://doi.org/10.1038/s43247-022-00537-z

31. NASA. *Interagency Sea Level Rise Scenario Tool*. https://sealevel.nasa.gov/task-force-scenario-tool

32. Virginia Institute of Marine Science. *U.S. Sea-level Report Cards*. https://www.vims.edu/research/products/slrc

33. Vertical land motion rates provided in the Interagency Sea Level Rise Scenario Tool except for Ocean City, Gloucester Point, and Richmond, which are provided in the IPCC/NASA Sea Level Projection Tool.

34. Ding, K., Freymueller, J. T., He, P., Wang, Q., & Xy, C. (2019). Glacial isostatic adjustment, intraplate strain, and relative sea level changes in the Eastern United States. *Journal of Geophysical Research: Solid Earth, 124*, 6056–6071. https://doi.org/10.1029/2018JB017060

35. Soeder, D. J., Raffensperger, J. P., & Nardi, M. R. (2007). *Effects of Withdrawals on Ground-water Levels in Southern Maryland and the Adjacent Eastern Shore, 1980–2005*. U.S. Geological Survey, Scientific Investigations Report 2007–5249. https://pubs.usgs.gov/sir/2007/5249/pdf/sir2007-5249.pdf

36. Karegar, M.A., Dixon, T. H., & Engelhart, S. E. (2016). Subsidence along the Atlantic Coast of North America: Insights from GPS and the late Holocene relative sea level data. *Geophysical Research Letters, 43*, 3126–3133. https://doi.org/10.1002/2016GL068015

37. Ohenhen, L. O., Shirzaei, M., Ojha, C., & Kirwan, M.L. (2023). Hidden vulnerability of U.S. Atlantic coast to sea-level rise due to vertical land motion. *Nature Communications, 14*, 2038. https://doi.org/10.1038/s41467-023-37853-7

38. Buzzanga, B., Bekaert, D. P. S., Hamlington, B. D., & Sangha, S. S. (2020). Toward sustained monitoring of subsidence at the coast using InSAR and GPS: An application in Hampton Roads, Virginia. *Geophysical Research Letters, 47*, e2020GL090013. https://doi.org/10.1029/2020GL090013

39. Slagen, A. B. A, Palmer, M. D., Camarge, C. M. L., Church, J. A., Edwards, T. L., Hermans, T. H. J., Hewitt, H. T., Garner, G. G., Gregory, J. M., Kopp, R. E., Santos, V. M., & van de Wal, R. S. W. (2022). The evolution of 21st century sea-level projections from IPCC AR5 to AR6 and beyond. *Cambridge Prisms: Coastal Futures, 1*, E7. https://doi.org/10.1017/cft.2022.8

40. DeConto, R. M., Pollard, D., Alley, R. B., Vellcogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D. M., Ashe, E. L., Kopp, R. E., Li, D., & Dutton, A. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature, 593*, 83–89. https://doi.org/10.1038/s41586-021-03427-0

41. Talke, S. A., & Jay, D.A. (2020). Changing tides: The tole of natural and anthropogenic factors. *Annual Review of Marine Science, 12*, 121-151. https://doi.org/10.1146/annurev-marine-010419-010727

42. Flick, R. E., Murray, J. F., & Asce, L. (2003). Trends in United States tidal datum statistics and tide range. *Journal of Waterway, Port, Coastal, & Ocean Engineering, 129*, 155–164. https://ascelibrary.org/doi/10.1061/%28ASCE%290733-950X%282003%29129%3A4%28155%29

43. Ross, A. C., Najjar, R. G., Li, M., Lee, S. B., Zhang, F., & Liu, W. (2017). Fingerprints of sea-level rise on changing tides in the Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*. https://doi.org/10.1002/2017jc012887

44. Li, M., Zhang, F., Guo, Y., & Wang, X. (2020). Probabilistic projections of high tide flooding for the State of Maryland in the 21st century. In V. Lyubchich, Y. Gel, K. H. Kilbourne, T. J. Miller, N. K. Newlands, & A. B. Smith (Eds.), *Evaluating Climate Change Impacts* (pp. 71–94). Chapman and Hall/CRC. https://doi.org/10.1201/9781351190831

45. Lee, S. N., Li, M., & Zhang, F. (2017). Impact of sea-level rise on tidal ranges in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*. https://doi.org/10.1002/2016JC012597

46. Boicourt, W.C. (2005). Physical response of Chesapeake Bay to hurricanes moving to the wrong side: Refining the forecasts. In K. G. Sellner (Ed.), *Hurricane Isabel in Perspective* (pp. 39–48). CRC Publication 05-160, Chesapeake Research Consortium. https://chesapeake.org/wp-content/uploads/2018/09/CRC0160_05_Hurricane-Isabel-in-Perspective.pdf

47. Li, M., Zhong, L., Boicourt, W. C., Zhang, S., & Zhang, D. L. (2006). Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay. *Geophysical Research Letters*, *33*, L02604. https://doi.org/10.1029/2005GL024992

48. Egan, K., Brown, L., Earwaker, K., Fanelli, C., Grodsky, A., & Zhang, A. (2010). *Effects of the November 2009 Nor'easter on Water Levels*. Technical Report NOS CO-OPS 56, National Oceanic and Atmospheric Administration https://tidesandcurrents.noaa.gov/publications/tech_rpt_56.pdf

49. Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C. -H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2019). Tropical cyclones and climate change assessment. Part I: Detection and attribution. *Bulletin of the American Meteorological Society, 100*, 1987–2007. https://doi.org/10.1175/BAMS-D-18-0189.1

50. Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C. -H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2020). Tropical cyclones and climate change assessment. Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society, 101*, E303–E322. https://doi.org/10.1175/BAMS-D-18-0194.1

51. Emanuel, K. (2021). Atlantic tropical cyclones downscaled from climate reanalyses show increasing activity over past 150 years. *Nature Communications, 12*, 7027 https://doi.org/10.1038/s41467-021-27364-8

52. Li, M., Zhang, F., Barnes, S., & Wang, X. (2020). Assessing storm surge impacts on coastal inundation due to climate change: Case studies on Baltimore and Dorchester County in Maryland. *Natural Hazards, 103*, 2561–2588. https://doi.org/10.1007/s11069-020-04096-4

53. Marsooli, R., Lin, N., Emanuel, K., & Feng, K. (2019). Climate change exacerbates hurricane flood hazards along

U.S. Atlantic and Gulf Coasts in spatially varying patterns. *Nature Communications, 10*, 3785. https://doi.org/10.1038/s41467-019-11755-z

54. Sweet, W. V., Dusek, G., Obeysekera, J., & Marra, J. J. (2018). *Patterns and Projections of High Tide Flooding along the U.S. Coastline Using a Common Impact Threshold*. NOAA Technical Report NOS CO-OPS 086, National Oceanic and Atmospheric Administration. https://www.tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf

55. Thompson, P. R., Widlansky, M. J., Hamlington, B. D., Merrifield, M. A., Marra, J. J., Mitchum, G. T., & Sweet, W. (2021). Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, *11*, 584–590. https://doi.org/10.1038/s41558-021-01077-8

56. National Aeronautics and Space Administration. *Flooding Analysis Tool*. https://sealevel.nasa.gov/data_tools/15

57. National Oceanic and Atmospheric Administration. *Coastal Inundation Dashboard*. https://tidesandcurrents.noaa.gov/inundationdb

58. Maryland Department of Natural Resources. *MyCoast: Maryland*. https://mycoast.org/md

59. National Oceanic and Atmospheric Administration. *Coastal Flood Exposure Mapper*. https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html

60. Climate Central. *Coastal Risk Screening Tool*. https://coastal.climatecentral.org

61. Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy, 51*, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006

62. Haasnoot, M., Kwadijk, J., van Alphen, J., Le Bars, D., van den Hurk, B., Diermanse, F., van der Spek, A., Oude Essink, G., Delsman, J., & Mens, M. (2020). Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environmental Research Letters, 15*, 034007. https://doi.org/10.1088/1748-9326/ab666c

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