

Sea-level

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*Projections for
Maryland 2018*



DEAD END
NO
TURN AROUND

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SEA-LEVEL RISE EXPERT GROUP

Donald F. Boesch*, University of Maryland Center for Environmental Science, Chair

William C. Boicourt*, University of Maryland Center for Environmental Science

Richard I. Cullather, University of Maryland, College Park

Tal Ezer*, Old Dominion University

Gerald E. Galloway, Jr., University of Maryland, College Park

Zoë P. Johnson**, Naval Facilities Engineering Command

K. Halimeda Kilbourne, University of Maryland Center for Environmental Science

Matthew L. Kirwan, Virginia Institute of Marine Science

Robert E. Kopp*, Rutgers University

Sasha Land, Maryland Department of Natural Resources

Ming Li*, University of Maryland Center for Environmental Science

William Nardin, University of Maryland Center for Environmental Science

Christopher K. Sommerfield*, University of Delaware

William V. Sweet, National Oceanic and Atmospheric Administration

* Contributor to *2013 Updating Maryland's Sea-level Rise Projections*.

* The views expressed in this article do not necessarily represent the views of the agency or the United States.

UMCES STAFF CONTRIBUTORS

Dr. Donald F. Boesch
Dr. Ming Li
Jane Hawkey

COVER PHOTO CREDITS

Front Cover: Flooded road during Hurricane Florence in Neavitt MD, August 2018. © Jane Hawkey

Back Cover: Dead trees in Blackwater National Wildlife Refuge 2017. David Harp/ChesapeakePhotos.Com

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Summary

In fulfillment of requirements of the Maryland Commission on Climate Change Act of 2015, this report provides updated projections of the amount of sea-level rise relative to Maryland coastal lands that is expected into the next century. These projections represent the consensus of an Expert Group drawn from the Mid-Atlantic region.

The framework for these projections is explicitly tied to the projections of global sea-level rise included in the Intergovernmental Panel on Climate Change Fifth Assessment (2014) and incorporates regional factors such as subsidence, distance from melting glaciers and polar ice sheets, and ocean currents. The probability distribution of estimates of relative sea-level rise from the baseline year of 2000 are provided over time and, after 2050, for three different greenhouse gas emissions pathways: Growing Emissions (RCP8.5), Stabilized Emissions (RCP4.5), and meeting the Paris Agreement (RCP2.6). This framework has been recently used in developing relative sea-level rise projections for California, Oregon, Washington, New Jersey, and Delaware as well as several metropolitan areas.

The Likely range (66% probability) of the relative rise of mean sea level expected in Maryland between 2000 and 2050 is 0.8 to 1.6 feet, with about a one-in-twenty chance it could exceed 2.0 feet and about a one-in-one hundred chance it could exceed 2.3 feet. Later this century, rates of sea-level rise increasingly depend on the future pathway of global emissions of greenhouse gases during the next sixty years. If emissions continue to grow well into the second half of the 21st century, the Likely range of sea-level rise experienced in Maryland is 2.0 to 4.2 feet over this century, two to four times the sea-level rise experienced during the 20th century. Moreover, there is a one-in-twenty chance that it could exceed 5.2 feet. If, on the other hand, global society were able to bring net greenhouse gas emissions to zero in time to meet the goals of the Paris Climate Agreement and reduce emissions sufficient to limit the increase in global mean temperature to less than 2°Celsius over pre-industrial levels, the Likely range for 2100 is 1.2 to 3.0 feet, with a one-in-twenty chance that it would exceed 3.7 feet.

The difference in sea-level rise between these contrasting scenarios would diverge even more during the next century, with the failure to reduce emissions in the near term resulting in much greater sea-level rise 100 years from now. Moreover, recent research suggests that, without imminent and substantial reductions in greenhouse gas emissions, the loss of polar ice sheets—and thus the rate of sea-level rise—may be more rapid than assumed in these projections, particularly under the Growing Emissions scenario.

These probabilistic sea-level rise projections can and should be used in planning and regulation, infrastructure siting and design, estimation of changes in tidal range and storm surge, developing inundation mapping tools, and adaptation strategies for high-tide flooding and saltwater intrusion.



A road on Hoopers Island that floods regularly during extreme tidal events, Dorchester County MD, 2009. David Harp/ChesapeakePhotos.Com.

Dorchester County is “the rural Ground Zero” of sea-level rise in the Chesapeake, where climate change is leaving a mark—not in 25 or 50 years, but now, says Tom Horton, Bay Journal.

Tom Horton
High Tide in Dorchester, 2017

Introduction

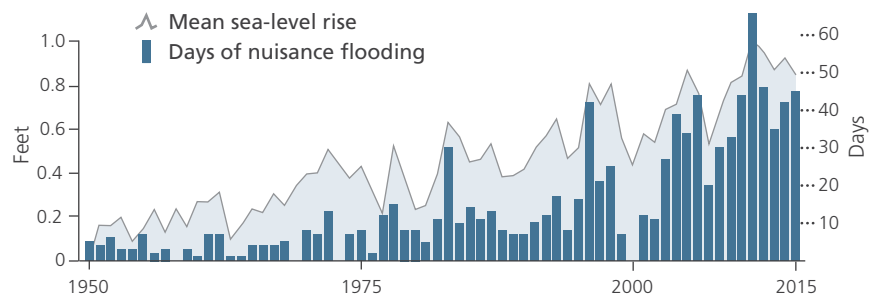
SEA-LEVEL RISE ALREADY THREATENS MARYLAND

Maryland, with its 3,100 miles of tidal shoreline along both the Chesapeake Bay and its tributaries and the state's Atlantic Ocean shoreline and coastal bays, is highly vulnerable to sea-level rise. When the ocean slowed its rapid rise following the Last Ice Age, filling the Chesapeake Bay about 7,000 years ago, water levels continued to rise slowly, not because the ocean was rising so much as the land was sinking. Some once-inhabited islands were lost or all but obliterated. While varying by less than 4 inches over 2,000 years, during the 20th century the ocean began to rise steadily again as Earth's climate has warmed due to human activities, causing the warming ocean to expand its volume and glaciers to lose melt waters to the sea. The level of Chesapeake Bay water with respect to the land is now rising about three times as fast as it was during Colonial times, threatening more densely built communities and infrastructure that developed over the interim.

“Once [coastal inundation] impacts become noticeable, they’re going to be upon you quickly. It’s not a hundred years off — it’s now.”

Dr. William V. Sweet, NOAA Silver Spring, MD, 2016.

Effects of accelerated sea-level rise are already apparent, including shoreline erosion, deterioration of tidal wetlands, and saline contamination of low-lying farm fields. “Nuisance” tidal flooding (also referred to as high tide flooding) that occurred just a very few days per year in Annapolis in the 1950s now occurs 40 or more days per year (Figure 1).¹ Surges resulting from tropical storms or Nor’easters also spread farther and



higher, superimposed on the higher sea level. Earlier in 2018, the documentary film *High Tide in Dorchester* depicted the already apparent effects of sea-level rise on that low-lying Eastern Shore county.

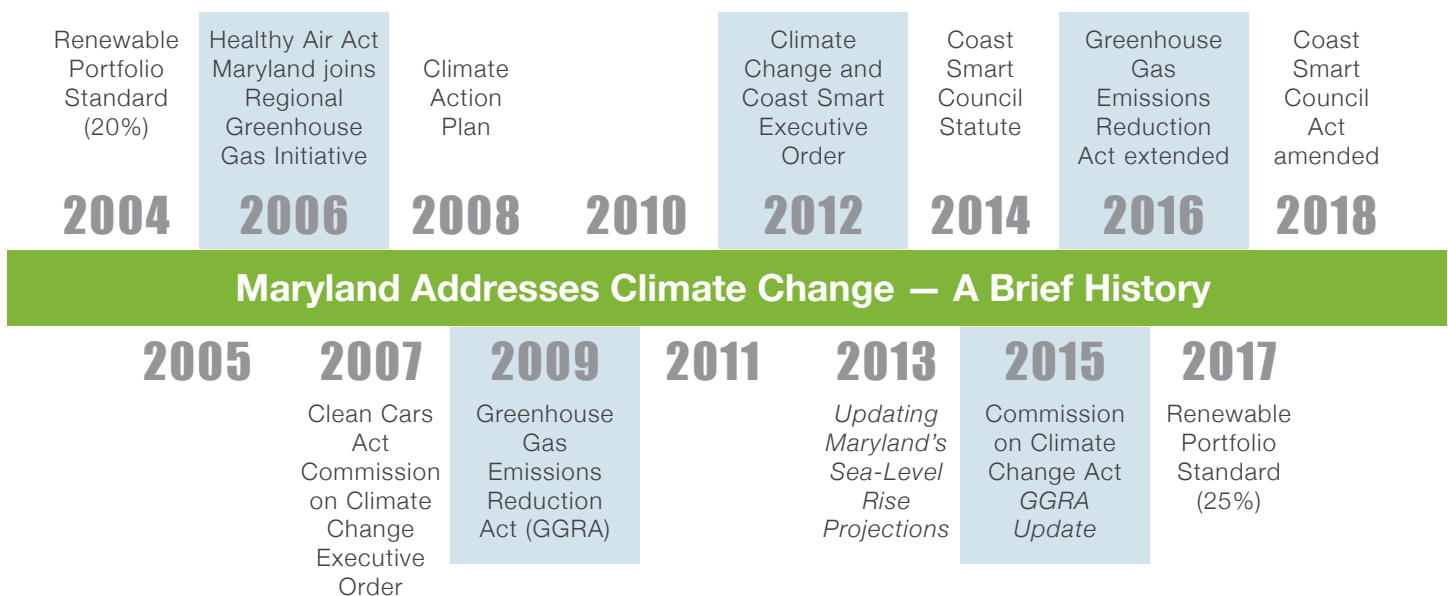
Figure 1. Sea-level rise has increased the frequency of nuisance flooding in Annapolis, based on the NOAA threshold for minor flooding of 1 foot above mean high-higher water.

Our scientific understanding indicates that the rate of sea-level rise will continue to accelerate into the foreseeable future, even if global society is able to limit global warming to the levels committed to under the Paris Climate Agreement. Reliable projections of future sea level along Maryland's coasts are, therefore, critical for planning the state's future and insuring its resilience to the changes ahead.

MARYLAND ADDRESSES CLIMATE CHANGE

The State of Maryland has taken the threats of climate change seriously for well over a decade. The Healthy Air Act of 2006 and the Clean Cars Act of 2007 require the regulation of carbon dioxide emissions. As authorized by the former act, Maryland joined the Regional Greenhouse Gas Initiative (RGGI), a cooperative effort among nine northeastern states to reduce carbon dioxide emissions from fossil fuel-fired power plants. In 2007 the Maryland Commission on Climate Change was created to develop a Climate Action Plan with the goal not only to limit climate change by reducing greenhouse-gas emissions, but also to guide the state's efforts to adapt to the changing climate. The Plan contributed to the enactment in 2009 of the Greenhouse Gas Emissions Reduction Act that established the commitment to reduce emissions by 25% by 2020. Supported by subsequent Commission reports, this act was extended in 2016 to achieve the goal of reducing emissions by 40% by 2030.

Under the aegis of the Commission on Climate Change, comprehensive strategies were developed to reduce Maryland's vulnerability to sea-level rise and coastal storms,² as well to protect human health, agriculture, forests, Bay and aquatic ecosystems, water resources and population growth and infrastructure.³ Maryland instituted Coast Smart to develop and apply siting and design criteria to avoid or minimize impacts associated with sea-level rise and coastal flooding on state-funded capital projects. Coast Smart was given statutory authority in 2015, which was broadened in 2018.



PREVIOUS PROJECTIONS OF SEA-LEVEL RISE

A component of the 2008 Climate Action Plan was a *Comprehensive Assessment of Climate Change Impacts in Maryland* that included projections of sea-level rise as part of a broader assessment.⁴ Those projections were derived from semi-empirical models that had been recently published. They served as a basis for the strategy to reduce vulnerability to sea-level rise and coastal storms mentioned above, and also informed the Coast Smart Construction Program strategy.

With the emergence of many new scientific reports and the issuance of federal government guidance based on multiple sea-level rise scenarios, the Maryland Commission on Climate Change decided in 2013 that the sea-level rise projections merited more in-depth expert examination and updating. An Expert Group was convened that produced the report *Updating Maryland's Sea-level Rise Projections*.⁵ While the 2008 projections were based on semi-empirical models that relate global sea-level changes to changes in global temperature and aggregate the various contributions to sea level, the 2013 projections used a disaggregated approach following a 2012 National Research Council (NRC) report on sea-level rise along the U.S. West Coast.⁶ In this approach, the contributions of thermal expansion, melting of glaciers and Greenland and Antarctic ice sheets, and dynamical changes in ocean currents were individually assessed and then placed in the context of their regional expression and of vertical land motion. The range and central tendency of the contributions to sea-level rise were based on judgments of the NRC committee drawn from a literature review. In the taxonomy of a recent comprehensive review of sea-level rise projections, this was a “bottom-up central ranges” approach.⁷

CURRENT APPROACH

The current 2018 sea-level rise projections for Maryland are mandated by the Maryland Commission on Climate Change Act of 2015 that codified the membership and responsibilities of the Commission.⁸ The Act also specifically requires that “the University of Maryland Center for Environmental Science [UMCES] shall establish science-based sea-level rise projections for Maryland’s coastal areas and update them at least every 5 years.” The Act further specifies that these projections shall include maps that indicate the areas of the state that may be most affected by storm surges, flooding, and extreme weather events, and shall be made publically available on the Internet.

This report is in response to that mandate and was developed through a process very similar to that used in 2013, as it proved to be highly efficient. An Expert Group was formed, consisting of 13 members from the Mid-Atlantic region, seven of whom had contributed to the 2013 report. New members were added because of changes in positions or to bring in some fresh and relevant perspectives. The Expert Group was provided a preliminary working draft of the report, developed under the direction of its Chair in advance of a one-day work session held on October 11, 2018. The draft was discussed and substantially modified during the work session and refined by subsequent correspondence.

Rapidly Developing Science

Publication of new research on the recent and future rise of sea level and other germane topics has virtually exploded in recent years. A very recent review of mapping sea-level change in time, space and probability found 16 sets of global mean sea-level rise projections published in or since 2013.⁷ Interested readers should consult that review for an in-depth synthesis. Here we merely touch on recent developments for issues relevant to our projections.

ACCELERATION OF SEA-LEVEL RISE

Historically, estimation of the recent rates of global sea-level rise was hindered by reliance on a limited number of tide-gauge records, which are affected both by vertical land motions due to ongoing isostatic adjustments following the last glaciation and other factors, and by weather-related variations. Estimates of global sea-level rise ranged from 1 to 2 mm/yr, but the degree and timing of acceleration were debated. Satellite altimeters have been measuring the elevation of most of the ocean surface only since 1993. After several years of these measurements, it became apparent that the rate of rise in the global mean sea level (GMSL) deduced from satellite measurements averaging more than 3 mm/yr was greater than that estimated for the 20th century based on tide gauges (about 1.4 mm/yr), indicating that sea level was rising at a faster rate toward and after the end of the 20th century. Eventually, the accumulation of 25 years of precision satellite data allowed the estimation of a statistically significant acceleration in the rate of global mean sea level during this period of 0.084 mm/yr/yr. This is the acceleration driven by climate change, after correction for the effects of volcanic eruptions and the El Niño-Southern Oscillation (ENSO), a globally influential climate cycle. If this rate of acceleration in the rise were to continue to 2100, GMSL would be 2.2 feet higher than it was in 2000.⁹

Scientists at the Virginia Institute of Marine Science have assessed the rate of relative sea-level rise reflected in records from 45 tide gauges in the United States and one in Canada for the period 1969 through 2014.¹⁰ These relative sea level measurements reflect the level of the water with respect to the adjacent land and are not equivalent to the satellite-derived estimates of mean global sea level. The scientists found median acceleration rates for Maryland gauge stations in the range of 0.15 to 0.18 mm/yr², except at Solomons Island where the rate was 0.22 mm/yr². Based on these calculations, the Institute provides on its website an interactive Sea-Level Report Card for selected

stations that depict the mean sea level projected by the quadratic trend through 2050, as depicted in Figure 2 for Baltimore.¹¹

The demonstration of sea-level rise acceleration based on both global and local scales underscores that simply linear projection of past observations of sea-level changes almost certainly underestimates future sea level.

Projections of future sea level based on observed acceleration of both global and local rise provide important context for the theoretically derived projections.

CONTRIBUTIONS TO SEA-LEVEL RISE

Recent publications have also clarified the contributions to observed sea-level rise attributable to the expansion of the ocean due to its warming and the melting of glaciers and polar ice sheets. In the past this has been a matter of considerable scientific debate, with an unexplained gap between the observed global mean sea-level rise and the sum of the estimated contributions. With the aid of gravity measurements made from satellites, that gap has largely closed and we now have a better estimation of the contributions to changing ocean volume and how those contributions are changing over time. While thermal expansion was responsible for most global sea-level rise during the 20th century, the melting of ice sitting on land—either mountain glaciers or polar ice sheets—has contributed more than half of global sea-level rise during the period of the satellite altimeter record beginning in 1993.¹² Loss of ice mass contributed proportionally more during the more recent part of that period (2005-2015), with the increasing contributions of Greenland and Antarctica particularly notable (Table 1).¹²

There are two important implications for these trends for projecting future sea level for Maryland. First, while the contributions from thermal expansion will likely continue at a similar rate because of the more or less steady rate of warming, the contributions of polar ice sheets will very likely continue to grow, but at rates that cannot be narrowly predicted because of the complex process of ice sheet loss. The range of possible outcomes will widen beyond

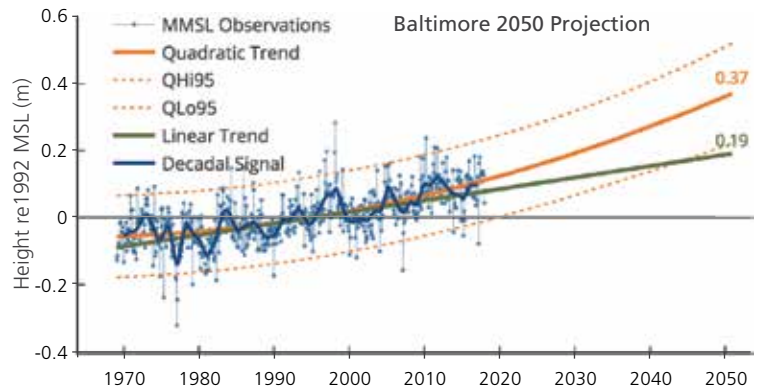


Figure 2. Sea-level change at the Baltimore tide-gauge station from 1969 through 2014 fit with a quadratic trend curve with an acceleration rate of 0.15 mm/yr². The dashed lines encompass 95% of the sea-level observations recorded projected forward around the solid-line median.

Table 1. Individual contributions to global mean sea-level rise in mm/yr.

	1993-2015	2005-2015
Thermal expansion	1.30	1.30
Glaciers	0.65	0.74
Greenland	0.48	0.76
Antarctic	0.25	0.42
Residual	0.37	0.28
Total	3.05	3.50

the extrapolation of present trends during the second half of the present century. Second, the Antarctic contribution, although small in the 20th century, is growing the most rapidly. Because of the gravitational effects of declining ice mass on ocean levels, loss of a given mass of ice on Antarctica will raise sea level in Maryland more than twice as much as the loss of an equivalent mass on Greenland.¹³

POLAR ICE SHEETS

New knowledge has also rapidly developed on the processes and rates at which the Greenland and Antarctic ice sheets are losing mass as the planet has warmed. Greenland is losing ice mass at an accelerating rate because of the deficit between surface ice accumulation and melting, and the discharge of solid ice from glaciers to the ocean.¹⁴ In Antarctica, where portions of the ice sheet rest on a seabed that slopes downward toward the continent, the major threat is not so much a deficit in ice accumulation as a rapid loss of ice from the glaciers along their ocean margins due to warming waters of the Southern Ocean. The weakening of ice shelves results in collapse of ice cliffs. This risks destabilizing the massive glaciers that partially rest on the seabed. Such destabilization could result in dramatically increased contributions to sea-level rise later this century if global warming follows a pathway of largely unabated greenhouse gas emissions.¹⁵ Under such scenarios, global sea-level rise could exceed 6.5 feet by the end of this century and 20 feet by the end of the next century.

OCEAN DYNAMICS

The report presenting 2013 updated projections of sea-level rise for Maryland discussed the then relatively new findings that the Mid-Atlantic coast was a “hot spot” of higher sea level and that this might be a result of a slowing down of the flow of the Gulf Stream.¹⁶ Other recent results suggest that the dynamic ocean variability affecting relative sea level along the East Coast has been driven more by local winds than a decline in “conveyor-belt” circulation (formally the Atlantic Meridional Overturning Circulation) that includes the Gulf Stream.^{17,18} There is also the suggestion that the “hot spot” of accelerated sea-level rise may have shifted in recent years to the South Atlantic Bight south of Cape Hatteras.¹⁸ In any case, dynamic ocean variability over periods of days to decades can affect coastal sea level and exacerbate tidal flooding in low-lying areas.^{19,20} Offshore tropical storms can also disrupt Gulf Stream flow, elevating coastal sea level for a week or two following the storm’s passage.²¹

PROJECTION METHODS

Scientific projections of future sea-level rise have particularly advanced since 2013,⁷ requiring reconsideration of the method used in the 2013 update for Maryland. An Interagency Task Force updated its scenarios of global mean sea-level rise for use in the Fourth National Climate Assessment (NCA).²² These six scenarios are widely divergent and not explicitly based on greenhouse gas emissions pathways, although the NCA discusses the likelihood of the different scenarios under different pathways. The Task Force's guidance on how to employ these scenarios in planning decisions and adjust the global projections for regional differences, including vertical land movement, was considered in this report.

A number of new projection methods are probabilistic in that they include not only estimates of a central trend (such as a median) and range, but also of the probability of outcomes beyond those central tendencies. Furthermore, these projections are explicitly tied to the greenhouse emissions pathways that are used in Intergovernmental Panel on Climate Change (IPCC) assessments. Several of these probabilistic projections of global mean sea level were compared to each other and to semi-empirical and central-range projections in the aforementioned recent review.⁷

The probabilistic framework for projecting sea-level rise developed by Dr. Robert Kopp and his colleagues in 2014²³ has already been widely used for coastal planning.²⁴ The probabilistic projections have provided the basis for sea-level rise projections for the States of California,²⁵ Oregon,²⁶ Washington,²⁷ and Delaware.²⁸ These probabilistic projections were also compared with the six Federal Interagency Task Force scenarios discussed above and the projection framework was used to translate the Interagency Task Force's global scenario into local scenarios.²²

2018 Projections

METHODS

Probabilistic projections based on IPCC Representative Concentration Pathways (RCPs) developed by Kopp et al.²³ are here used to establish science-based sea-level rise projections for Maryland's coastal areas. There are several compelling reasons for choosing this framework:

- Probabilistic projections include central estimates, such as the median or Likely range, and lower probability outcomes in a consistent manner, allowing the consideration of risk tolerance to plausibly greater sea-level rise.
- Separate projections tied to specific greenhouse gas emissions pathways make clear how reductions of emissions affect the risks of sea-level rise.
- Its central projections of global mean sea-level rise are by design in good agreement with those of the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) and compare well with other published probabilistic models.⁷
- Projections based using this framework have been used in a growing number of state and regional projections in the U.S.
- Projections of relative sea-level rise are available—already incorporating the contributions of vertical land motion, fingerprints of land-ice melting, and regional ocean dynamics—for tide gauges around the world, including several in Maryland.

Dr. Kopp, a member of this Sea-Level Rise Expert Group, facilitated the use and interpretation of the outputs from the statistical models. These outputs are available for four tide-gauge stations along Maryland's Chesapeake Bay (Baltimore, Annapolis, Cambridge, and Solomons Island) and for Washington, DC, near the head of the Potomac River estuary.

Dr. Kopp, with additional collaborators, complemented these projections in a subsequent publication in which they developed additional projections that incorporate more rapid discharge from marine-based ice sheets in Antarctica that potentially could occur.²⁹ The open source code is available and supporting information published with that paper and available online from the journal website includes files detailing the probability distributions from 2000 to 2300 for the two sets of projections at specific tide-gauge locations around the world: (1) based on IPCC Fifth Assessment projections reconciled with

an expert elicitation study to determine ice-sheet contributions (here referred to as K14 projections); and (2) additionally incorporating a physical model of the processes of Antarctic ice-shelf hydrofracturing (resulting from meltwater flowing down crevasses) and collapse of ice cliffs (here referred to as DP16).

Available projections for three different IPCC greenhouse gas emissions pathways (RCPs) are labeled in this report as:

- Paris Agreement (RCP2.6), under which emissions begin to decline now and become net zero later in the century, thus offering a reasonably good probability of keeping the increase in global mean temperature to less than 2°C above pre-industrial levels in line with the Paris Climate Agreement;
- Stabilized Emissions (RCP4.5), under which emissions stabilize around their current levels slowly and then begin to decline after 2050; and
- Growing Emissions (RCP8.5), in which emissions continue to grow until the end of the century.

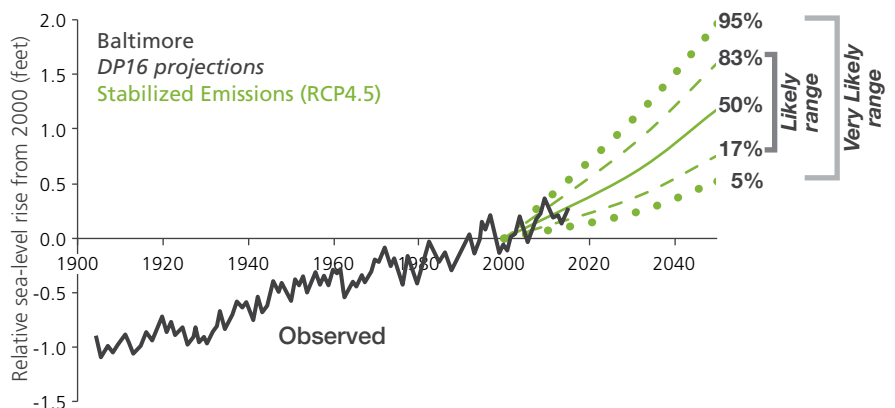
Here, we examine three emissions pathways, for convenience referred to as Paris Agreement (RCP2.6), Stabilized Emissions (RCP4.5), and Growing Emissions (RCP8.5).

RELATIVE SEA-LEVEL RISE OVER THE CENTURY

The projections and probabilities for relative sea-level rise in Maryland through 2050 are based on the DP16 projection for the Stabilized Emissions pathway. These were chosen because the DP16 projection includes realistic short-term, high-end projections, and there is very little difference among the three emissions pathways over the next 30 years. Although the growth in emissions in recent years has followed the Growing Emissions pathway, it is hoped that emissions will begin to stabilize

within that time frame. Figure 3 shows the probabilities of the projections around the median, with the 17 to 83% probability considered the Likely range and the 5 to 95% probability considered the Very Likely range, using the IPCC convention. Stated another way, by 2050 the relative sea level at Baltimore is likely to be between and

0.8 and 1.6 feet above year the 2000 level and there is only a 5% chance that it will exceed 2.0 feet higher. The near-term projections in Figure 3 are displayed



Likely means a two-thirds chance of sea-level rise within that range. There is a 5% chance that sea-level rise would exceed the Very Likely range.

Figure 3. Observed relative sea-level rise at the Baltimore tide gauge and probabilistic projection of relative sea-level rise through 2050.

in comparison with the sea level observed at the Baltimore tide-gauge station since the beginning of the 20th century. Its rise over the previous 50 years between 1950 and 2000 was about 0.6 feet, compared to mean estimated projection of 1.2 feet for the first half of the 21st century—very consistent with the extrapolation of the tide-gauge observations shown in Figure 2.

The projections in this report for sea-level rise in Maryland beyond 2050 use estimates based on the K14 methodology (Figure 4).²² The DP16 projections estimate more rapid sea-level rise during the later part of this century and during the next centuries under high emissions pathways. The rates of processes affecting the loss of Antarctic ice-sheets are highly uncertain and it is anticipated that a refined scientific consensus will be presented in the IPCC’s Special Report on the Ocean and Cryosphere scheduled to be finalized in September 2019. The judgment of the expert group is that best estimate projections under high emissions pathways are intermediate between those of K14 and DP16. These can better be taken into account in the next update of Maryland’s sea-level rise projections.

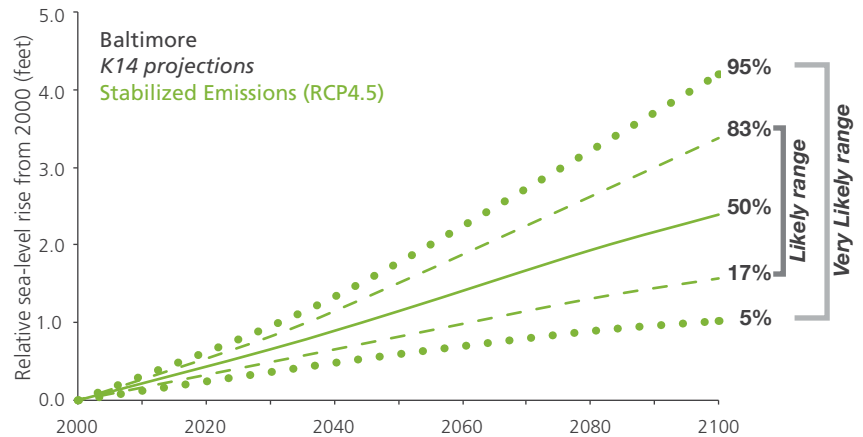


Figure 4. Probabilistic projection of sea-level rise through 2100 at Baltimore with the Stabilized Emissions pathway (RCP4.5).

Because the different emissions pathways result in an increasing spread among sea-level rise projections after 2050, emissions pathway-specific projections illuminate the critical importance of rapid reduction in emissions over the next several decades to limiting the amount of sea-level rise to which we must adapt. Probabilistic projections of sea-level rise at Baltimore through 2100 are presented for the Stabilized Emissions pathway in Figure 4. As one can see, sea-level rise continues to accelerate, but the probability distribution naturally broadens into the future. Even if global society were to stabilize and begin to reduce emissions during the second half of this century, the central estimate of sea-level rise during the 21st century is 2.4 feet, with the Likely range extending to 3.4 feet, compared to about 1 foot for the 20th century. The projections for all three emissions pathways extending to 2150 are summarized in Figure 5 and Table 2.

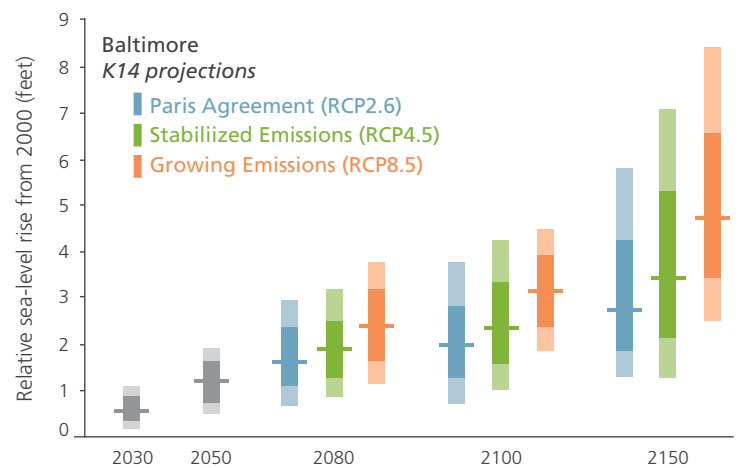


Figure 5. Median (horizontal line) and Likely (darker bars) and Very Likely (lighter bars) range of projections for relative sea-level rise at Baltimore at different time periods and the three greenhouse emissions pathways: Paris Agreement (RCP2.6), Growing Emissions (RCP4.5) and Growing Emissions (RCP8.5).

Table 2. Projected sea-level rise estimates above 2000 levels for Maryland based on the Baltimore tide-gauge station. Columns correspond to different projection probabilities and rows represent to time horizons and emissions pathways. See caveat in the text concerning potentially greater sea-level rise late this century under higher emissions pathways.

Year	Emissions Pathway	Central Estimate 50% probability SLR meets or exceeds:	Likely Range 67% probability SLR is between:	1 in 20 Chance 5% probability SLR meets or exceeds:	1 in 100 Chance 1% probability SLR meets or exceeds:
2030		0.6 ft	0.4 – 0.9 ft	1.1 ft	1.3 ft
2050		1.2 ft	0.8 – 1.6 ft	2.0 ft	2.3 ft
2080	Growing	2.3 ft	1.6 – 3.1 ft	3.7 ft	4.7 ft
	Stabilized	1.9 ft	1.3 – 2.6 ft	3.2 ft	4.1 ft
	Paris Agreement	1.7 ft	1.1 – 2.4 ft	3.0 ft	3.2 ft
2100	Growing	3.0 ft	2.0 – 4.2 ft	5.2 ft	6.9 ft
	Stabilized	2.4 ft	1.6 – 3.4 ft	4.2 ft	5.6 ft
	Paris Agreement	2.0 ft	1.2 – 3.0 ft	3.7 ft	5.4 ft
2150	Growing	4.8 ft	3.4 – 6.6 ft	8.5 ft	12.4 ft
	Stabilized	3.5 ft	2.1 – 5.3 ft	7.1 ft	10.6 ft
	Paris Agreement	2.9 ft	1.8 – 4.2 ft	5.9 ft	9.4 ft

An important caveat using these projections: In not accounting for the prospect of greater polar ice sheet loss, the K14 projections probably underestimate sea-level rise beyond 2050 under higher emissions pathways. While the DP16 projections might be over-estimates, they can serve to inform decisions for which risk aversion is relatively high. Under the Growing Emissions pathway the median (and Likely) sea-level rise projections are 3.6 feet (2.7-4.9 feet) for 2080 and 5.7 feet (4.2-7.9 feet) by 2100. Under the Stabilized Emissions pathway, DP16 projections begin to significantly diverge from K14 after 2080, with median (and Likely) sea-level rise of 3.7 feet (2.6-5.0 feet) for 2100.

VARIATIONS IN SEA-LEVEL RISE WITHIN MARYLAND

While there are some differences in projected relative sea-level rise among the tide-gauge stations in the Chesapeake Bay, they are relatively small and mainly reflect differences in vertical land motion among the their locations (Figure 6). There are no real differences among these relatively close-by sites in the polar ice fingerprints or dynamic ocean effects resolvable with the Global Climate Models used in climate projections. Even the rates of glacial isostatic adjustment, the main factor affecting vertical land motion, are also very similar. While the projected rise for Baltimore and Washington is virtually identical, relative rise at Norfolk (Sewell’s Point gauge station) is 10 cm greater by 2100 because of the higher rate of land subsidence, principally attributable to large groundwater withdrawals. Relative sea-level rise at Solomons Island and Cambridge, where there seems to be some groundwater withdrawal-induced subsidence is intermediate between Baltimore/Washington and Norfolk.

Assuming the subsidence rates are more-or-less constant over the century, adjustments can be made to customize the sea-level rise projections based on Baltimore for other coastal regions in Maryland as indicated in Table 3.

EFFECTS OF GREENHOUSE GAS EMISSIONS

As discussed earlier, controls on greenhouse gas emissions will make only a small difference in the projections of relative sea-level rise in Maryland through 2050. Delays in the aggressive reduction of global emissions of greenhouse gases until 2050 will have a much more consequential effect during the latter half of the century and, indeed for many centuries thereafter (Figure 7). If the goals of the Paris Agreement were met and global greenhouse gas emissions were reduced soon enough to hold the increase global mean temperature to less that 2°C above pre-industrial levels,

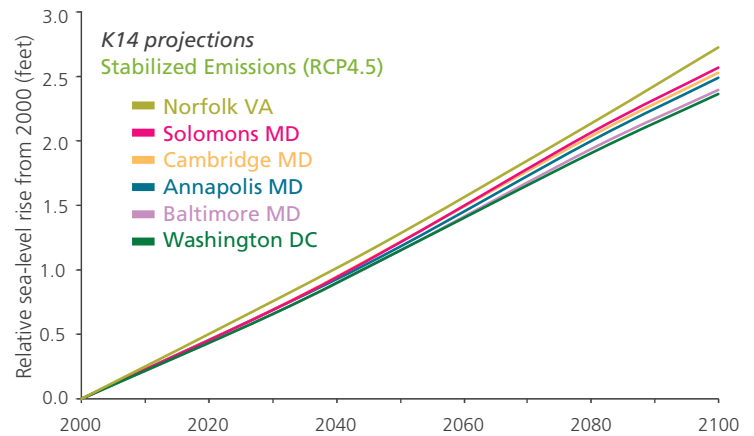


Figure 6. Median projections of sea-level rise at several tide-gauge locations in the Chesapeake Bay through 2100. Differences are attributable to different rates of vertical land motion.

Table 3. Adjustments to the Baltimore sea-level projection for other Maryland locations.

Location	2050	2080	2100
Annapolis	-	-	0.1 ft
Solomons	-	0.1 ft	0.2 ft
Cambridge	0.1 ft	0.1 ft	0.2 ft
Ocean City	0.1 ft	0.1 ft	0.3 ft

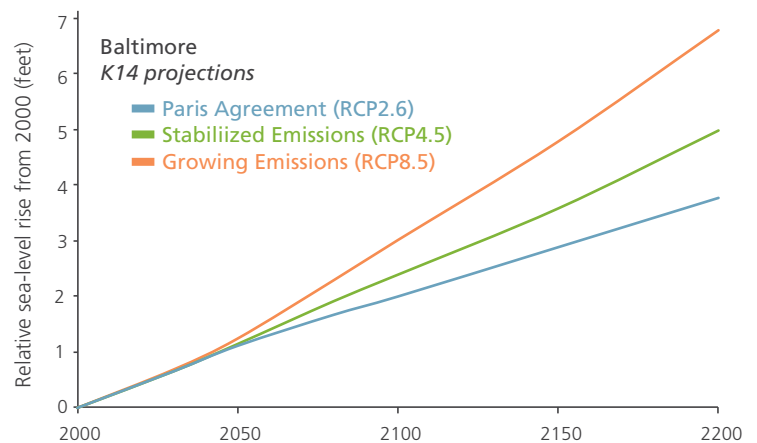


Figure 7. Median projections of relative sea-level rise at Baltimore through 2200 under the three greenhouse gas emissions pathways.

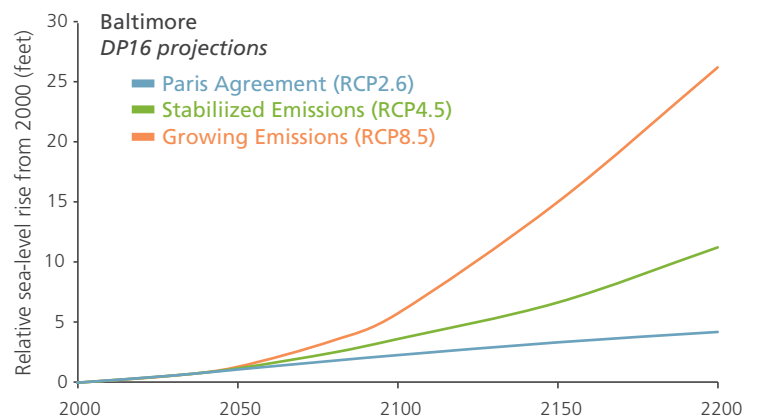
relative sea-level rise in Maryland would likely (87% probability) not exceed 3 feet by 2100 (central estimate 2 feet). If, on the other hand, greenhouse gas emissions were to continue to grow at the rates experienced during recent decades, the central estimate of relative sea-level rise in Maryland is 1 foot higher and the Likely range extends to 4.2 feet.

THE LONGER VIEW

The consequences of taking global action to reduce, then eliminate, greenhouse gas emissions for Maryland sea-level become even more starkly apparent beyond the 21st century (Figure 7), with median projections of 6.8 feet for the Growing Emissions pathway by 2200, compared to 3.8 feet under the Paris Agreement pathway. Even if global mean temperature is stabilized later this century, sea level will continue to rise for centuries to come. To some degree this is because the oceans will continue to absorb heat and expand, but mainly this is a result of the melting of ice on land that has already been initiated and continues to increase even if global mean temperature is stabilized. While mountain glaciers will eventually lose their frozen mass, the polar ice sheets are, in practical terms, inexhaustible. Humans can, however, constrain the rate of ice loss by limiting global warming.

ANTARCTIC ICE SHEET RISKS

The L14 probabilistic projections do not account for the potentially large contributions to the ocean volume of much more rapid loss of the polar ice sheets, such as the deterioration of Antarctic ice shelves and destabilization of seabed-founded glaciers discussed above. Thus, there is a risk of even greater sea-level rise toward the end of this century and beyond if greenhouse gas emissions continue to grow. Estimates for sea-level rise for the same emissions pathways over the same time span using the DP16 projections illustrate just how enormous the consequences of delaying reductions in emissions may be (Figure 8).



By 2200, the median projected rise under the Growing Emissions pathway is 26 feet, and even reaches 11 feet for the Stabilized Emissions pathway (compared to 4 feet for the Paris Agreement pathway). Furthermore, while the assumptions regarding Antarctic ice loss are very uncertain, it will very likely be well past the time when it could be limited by reducing emissions before the uncertainties are resolved.²⁹

Figure 8. Median DP16 projections of relative sea-level rise at Baltimore through 2200 under the three greenhouse gas emissions pathways incorporating new Antarctic physics. Compare with the projections consistent with the IPCC Fifth Assessment in Figure 7.

COMPARISON WITH PREVIOUS PROJECTIONS

The projections for Maryland presented in this update estimate greater relative sea-level rise from the 2000 baseline than the 2008 Comprehensive Assessment of Climate Change Impacts,⁴ but less than the 2013 update⁵ (Figure 9). The changes from 2008, for both low or stabilized emissions, and high or growing emissions pathways, reflect the increase in scientific evidence from the IPCC Fourth Assessment to the Fifth Assessment,

augmented by expert elicitation. The projections in 2013 update were based on a 2012 report⁶ containing the expert judgments of scientists empaneled by the National Research Council, prior to the 2014 publication of the probabilistic framework by Dr. Kopp and his colleagues.²³ The NRC panel did not consider the effects of different emissions pathways, assuming that emissions would continue to increase. Even so, the range and median for the 2013 projection are higher than the new estimates under the Growing Emissions pathway. The differences are not due to different assumptions in vertical land motion and other local factors, but rather reflect greater contributions from Antarctic ice sheets in the NRC panel's estimates of global sea-level rise than included by the IPCC. As indicated earlier, the DP16 projections based on more rapidly changing Antarctic ice-sheet physics produce an even higher Likely range of 4.2 to 7.9 feet by 2100.²⁹

With regard to the Interagency Task Force's six sea-level rise scenarios used in the Fourth National Climate Assessment, the 2018 probabilistic projections for Maryland span the three Intermediate scenarios, with the 2100 projections under the Paris Agreement emissions pathway centering around the Intermediate-Low scenario and the projections for the Growing Emissions pathway approximating the Intermediate scenario. If Growing Emissions would stimulate the more dynamic ice-sheet physics included in the DP16 model, the sea-level rise by 2100 would approximate the Intermediate-High scenario. Because they were developed using similar K14 methodology, the relative sea-level projections presented in this report are very consistent with those given for the Mid-Atlantic coast in the just released Fourth National Climate Assessment for its Lower Scenario (RCP4.5 pathway) and Higher Scenario (RCP8.5 pathway).³⁰

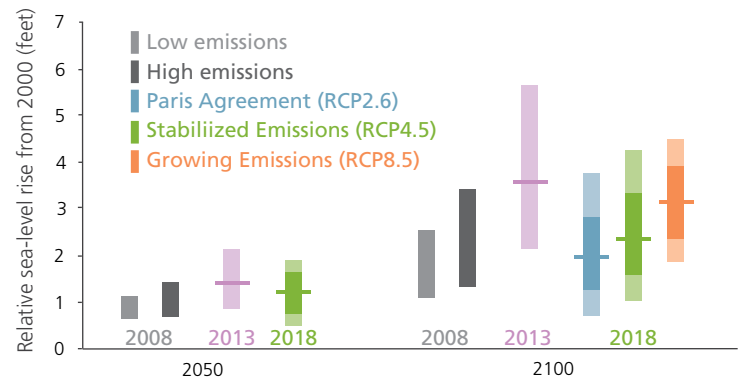


Figure 9. Comparison of sea-level rise projections for Maryland made in the Comprehensive Impacts report in 2008, the 2013 update, and present probabilistic estimates.

Practical Use for Adaptive Planning

AVOIDING THE UNMANAGEABLE

Actions taken over the next 60 years or so to limit global warming will affect the rate of polar ice-sheet melting and, thus, sea-level rise. But, even the reduction of greenhouse gas emissions sufficient to limit warming to between 1.5 and 2.0°C will not stop or reverse sea-level rise—the ocean warming and melting of glaciers that has already been initiated will cause sea level to continue its rise for centuries to come.³¹ If, on the other hand, the rate of emissions of greenhouse gases continues to grow until late this century, Earth's surface temperature will warm well above 2.0°C and increasingly rapid loss of polar ice sheets will be assured well into the future. Future generations will be powerless in stopping the accelerated rise by eliminating emissions or other actions.

This is why a foundational tenant of Maryland's efforts to prepare for the threats of sea-level rise must be an aggressive strategy to reduce its greenhouse gas emissions as the state's contribution to meeting the global goals of the Paris Agreement. John Holdren, who later served as President Obama's Scientist Advisor for eight years, and colleagues stated this dual challenge in confronting climate change succinctly in the title of their 2007 report: avoiding the unmanageable and managing the unavoidable.³² Sea-level rise is a prime example, requiring mitigation action now to constrain sea-level rise to levels to which we can adapt. The state of Maryland has already committed to the first leg of this course of avoiding the unmanageable through the 2016 extension of its Greenhouse Gas Reduction Act, requiring a 40% reduction in emissions by 2030. The sea-level rise projections presented here provide both strong incentives to take action and estimates for which we must plan during this century.

CONSEQUENCES FOR TIDAL RANGE AND STORM SURGE

Of course, the level of Maryland's coastal waters with respect to the land varies over hours to weeks as a result of the semi-diurnal tides, lunar cycles that accentuate or minimize the tidal range, and winds that drive water into our bays or push it offshore. Major storms, including hurricanes, tropical storms, and Nor'easters, can result in even more substantial storm surges. The sea-level rise driven by global warming will increase both high and low tide levels and storm surges by a generally similar amount as the increase in mean sea level.

Seizing this chance requires an immediate and major acceleration on two fronts:

- *mitigation measures to prevent the degree of climate change to become unmanageable; and,*
- *adaptation measures to reduce the harm from climate change that proves unavoidable.*

— Scientific Expert Group
on Climate Change

The standard datums by which the National Oceanic and Atmospheric Administration (NOAA) characterizes tidal water levels in Baltimore Harbor are depicted in Figure 10.³³ The North American Vertical Datum of 1988 (NAVD88), established for vertical control surveying, represents Mean Sea Level (MSL) at that time. Of course, relative sea level rose between 1988 and 2000—the baseline used for the projections in this report—by about 0.1 foot.

As the ranges of the two diurnal tides are unequal, the tidal range is the difference between the mean lower low water (MLLW) and mean higher high water (MHHW), 1.66 feet at the Baltimore tide-gauge station. Water depths indicated on NOAA’s navigation charts are the elevations below the MLLW mark. Tidal flooding exceeding 2.6 feet above the NAVD88 is considered a minor flood and a major flood if it exceeds 4.8 feet. The storm surge level of record in Maryland’s Chesapeake Bay was associated with Hurricane Isabel in 2003. It was 7.3 feet above the NAVD88 at the Baltimore tide-gauge station. Keep in mind that with respect to coastal inundation, the water level at high tide or associated with common tidal flooding events is of more consequence than mean sea level.

The tidal ranges at other locations in Maryland vary from 1.44 to 3.21 feet as a function of how the tides move up the estuaries (Table 4).³⁴ Tidal ranges are larger toward the head of the Chesapeake Bay and its tidal tributaries—such as the Potomac River at Washington DC—as tides become squeezed by diminishing cross-sectional area. In addition, tidal ranges are larger on the eastern side of the bay—such as at Bishops Head and Cambridge—as water piles up due to the rotation of the Earth.

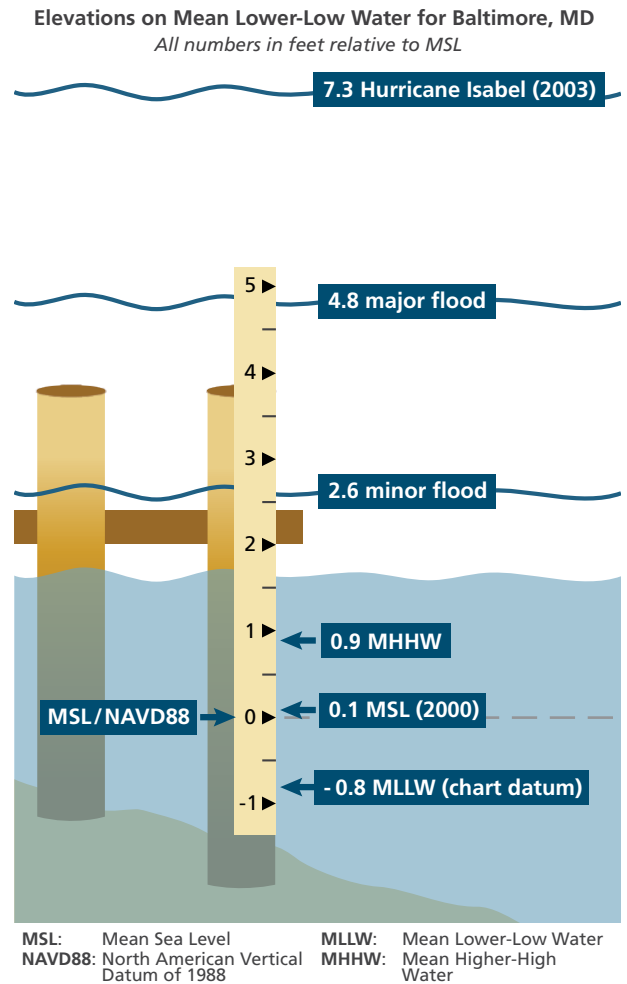


Figure 10. Key tidal datums for Baltimore. Minor and major flood levels are based on a nationally consistent approach; thus the minor flood level is higher than previously used to define nuisance flooding.

Table 4. Average diurnal tidal range at active gauge stations in Maryland.

Location	Tidal Range (ft)
Annapolis	1.44
Baltimore	1.66
Bishops Head	2.05
Cambridge	2.04
Chesapeake City	3.21
Ocean City	2.46
Solomons Island	1.47
Tolchester	1.73
Washington DC	3.17

How will these tidal ranges be affected by the sea-level rise projected in the future? Analysis of long-term trends in tidal amplitude in the Chesapeake Bay has indicated that 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.³⁵ This is consistent with the expectations along a narrowing estuary as sea level rises. The responses of tidal amplitude in the Maryland portion of the Chesapeake Bay 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 no new shoreline protection measures are installed and low-lying lands allowed to become permanently inundated by higher sea levels, the tidal range might actually decline by 2 to 3 inches.³⁶ If, on the other hand, shorelines are extensively armored, the higher tides would be prevented from flooding low-lying areas and the tidal amplitude may increase by as much as 0.3 feet. This is an additional impact to consider in designing and permitting shoreline management actions, including armoring and living shorelines, as Maryland adapts to sea-level rise.



C&D Canal, 2010. © Jane Hawkey, Integration & Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/mageilbrary/)

A hardened shoreline helps guard against shoreline erosion. However, it comes with the high price of reducing accessible habitat for aquatic species and preventing high tides from flooding low-lying areas.

How will storm surges be affected by climate change and sea-level rise? Maryland is vulnerable from storm surges generated by tropical storms and hurricanes. For storms moving northeastward just off the coast, such as Hurricanes Irene (2011) and Floyd (1999), northeast to northerly winds can cause dangerous storm surges along the state's Atlantic coast, but sea level may actually drop in the upper Chesapeake Bay.³⁷ For storms making landfall and moving inland, such as Hurricane Isabel (2003) and Sandy (2012), however, southeasterly to easterly winds drive water into the Chesapeake Bay. Isabel created significant tidal flooding in Washington DC, Baltimore, Annapolis, and Maryland's Eastern Shore, with surge levels about one foot higher than a 1933 hurricane that followed a similar path, approximating the relative sea-level rise.³⁸ Extratropical cyclones such as Nor'easters can also cause extensive storm surge flooding along the U.S. East Coast, as demonstrated in November 2009 when Nor'Ida generated storm surge heights in Norfolk, Virginia, approaching those of Hurricane Isabel.³⁹

The prevailing scientific consensus is that while global warming might not result in more frequent tropical and extratropical storms, the frequency of more severe storms will likely increase and such storms will maintain their strength as they reach the higher latitudes of the Mid-Atlantic.⁴⁰ Assuming the relative-sea level rise projected under the Growing Emissions pathway, coupled with the storm's ability to maintain its strength and propagate a greater storm surge up the Bay, a Category 2 storm following a path of Hurricane Isabel would result in water levels at Baltimore 10.6 feet above the MSL datum versus 7.3 feet during Isabel.⁴¹ The increase in inundation of the city around the Inner Harbor is striking (Figure 11). As with the case of tidal range, shoreline hardening around the Bay would have the effect of increasing storm surge height in Baltimore and elsewhere around Maryland's shores.



Figure 11. The combined effect of sea-level rise and increased storm surge on inundation from a Hurricane Isabel-like storm in 2100, under the Growing Emissions pathway, compared to 2003.

No less dramatic than these urban impacts is the increase in the extent and depth of storm surge inundation that would result for the wetlands and rural landscapes of Dorchester County on Maryland's Eastern Shore as a consequence of projected sea-level rise and potentially higher storm surges (Figure 12).⁴¹

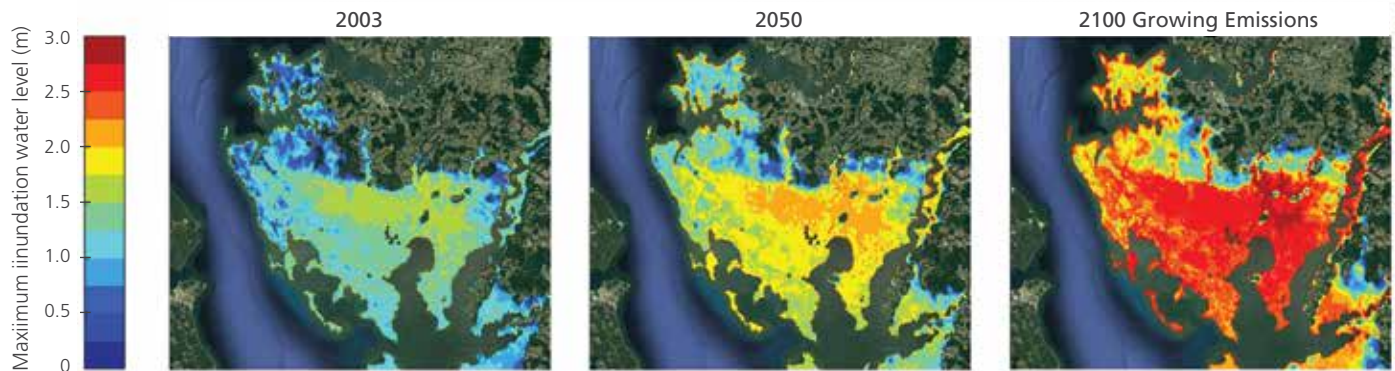


Figure 12. Model estimates of the maximum storm-surge inundation of Dorchester County resulting from a Hurricane Isabel-like storm in 2050 and in 2100 under the Growing Emissions pathway.

INUNDATION MAPS

The Maryland Commission on Climate Change Act of 2015, in addition to requiring this update in sea-level rise projections for the state, indicates that the projections shall include maps that indicate the areas of the state that may be most affected by storm surges, flooding, and extreme events. These should be made publically available on the Internet. There are several publically available online mapping tools, including NOAA's Sea Level Rise Viewer⁴⁰ and Climate Central's Surging Seas sea-level rise analysis.⁴¹ With these tools, one can select a given sea-level increase and storm surge level, and develop an accurate depiction of areas that would be inundated.

Rather than produce a set of static maps of selected scenarios and making judgments as to the areas most affected by storm surges and flooding, the University of Maryland Center for Environmental Science will collaborate with the Maryland Department of Natural Resources and other state agencies in incorporating the 2018 sea-level rise projections in the production of a uniform set of maps or mapping tools that accomplish this purpose. This is timely because 2018 amendments to the Coast Smart Council statute require that the Council develop new Coast Smart Design and Siting Criteria in 2019.

SEA-LEVEL RISE, NUISANCE FLOODING, AND SALTWATER INTRUSION

The aforementioned amendments to the Coast Smart Council statute includes new provisions that local jurisdictions develop plans to address nuisance flooding⁴⁴ and that state agencies establish a plan to adapt to saltwater intrusion.⁴⁴ Nuisance flooding is defined to mean high-tide flooding that causes public inconvenience. Incorporation of these 2018 sea-level rise projections should be an integral component in both nuisance flooding and saltwater intrusion planning.

As an example, Figure 13 depicts the observed number of days of high-tide or “nuisance” flooding— here defined as water levels exceeding 1.75 feet above the highest average tide (MHHW) in Baltimore.³³ These observations

are superimposed on the projected number of days in which water levels would exceed this minor flood threshold based on the 2018 sea-level rise projections included in this report. Note that this is based on the recently derived, nationally consistent threshold for minor flooding,³³ not the lower NOAA flood threshold represented in Figure 1.

What has recently been an event occurring less than 10 days per year is projected to occur 30 days per year on average by 2040 and nearly 100 days per year by 2050. Under any emissions pathway, high tides exceeding the nuisance level would be virtually a daily occurrence. While there will surely be variability in nuisance flooding from year to year, just in the past, these projections provide guidance as to the likely timing of the evolution of a highly disruptive frequency of tidal flooding—the inevitable result of accelerating sea-level rise.

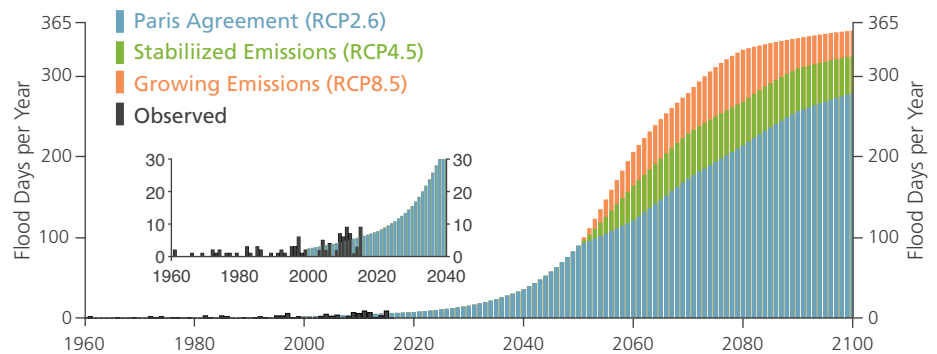


Figure 13. The observed projected frequency of high-tide or “nuisance flooding,” at Baltimore defined as days on which water levels are 1.75 feet above the highest average tide (MHHW) datum.

USING SEA-LEVEL PROJECTIONS IN PLANNING

There are myriad potential uses in coastal planning of the probabilistic sea-level rise projections presented here. These uses require consideration of multiple factors, including the type of decision to be made, planning timescale, and overall risk tolerance.²² Tolerance of risk depends on how critical an asset or how vulnerable an exposed population may be to permanent inundation, tidal flooding, and coastal storms.

Maryland's *Climate Change and Coast Smart Construction: Infrastructure Siting and Design Guidelines*⁴⁶ provides guidance for using the 2013 sea-level rise projections that remain appropriate considerations. The timescales for which capital project planning, design construction, maintenance, and operational decisions being made are characterized as short-term (design life less than 25 years), medium-term (design life less between 25 and 50 years), long-term (design between 50 and 100 years), and very long-term (design life over 100 years). Tolerance of infrequent flooding is another important consideration, as are the characteristics of location with regard to elevation and distance from exposed shorelines and other characteristics of the coast. Also, accounting for storm surge on top of sea level is necessary in specific project planning. A margin of safety may also be required; for example, current Coast Smart guidelines specify a two-foot freeboard above the mapped 100-year base flood elevation for structures.

Referring to Table 2, then, it would be imprudent to plan for just the central estimate of the projection of 1.2 feet sea-level rise above the 2000 level by 2050, even for short-term infrastructure. Rather, the upper end of the Likely range (1.6 feet) could be used with low risk aversion, or one-in-one hundred (2.3 feet) chance estimates for medium to high risk aversion should be employed as per the California guidance.²⁵ This is consistent with the advice provided in the 2013 update that it is prudent to plan for relative sea-level rise of 2.1 feet by 2050.⁵ Adjustments for differences in location within Maryland (Table 3) should also be included.

The selection of a specific sea-level rise projection for a given project is often a nuanced process, in which planners, engineers, and decision-makers evaluate the short- to long-term performance of project against the range of sea-level rise to determine impact over time. To account for uncertainty, decision-makers may also find it useful to assess risk in concert with an assessment of the benefit-cost of risk reduction action alternatives, including adaptation pathways and contingency plans.

Beyond 2050, the emissions pathway has an increasing influence on the sea-level rise projections. Because greenhouse gas emissions are still increasing close to the rate of the Growing Emissions pathway (RCP8.5), in planning medium-term projects it would be prudent to use the upper end of the Likely range in 2080 (3.1 feet) under low risk aversion and the 1% probability (4.7 feet) under high risk aversion. While in twenty to thirty years we should have a better understanding of the pathways of emissions and of sea-level rise, what should we assume now in planning long-term infrastructure? Using the upper end of the Likely range within the project lifetime may still be reasonable for projects with low risk aversion. However, with high risk aversion, one should consider both the 1% probability from the K14 projections (e.g., 6.9 feet in 2100) and the upper end of the Likely range from the DP16 projections (7.9 feet).



This property in Dorchester County, MD, flooded regularly during full-moon high tides and other tidal events. In 2017, it was raised 8 ft. David Harp/ChesapeakePhotos.Com.

Adapting to higher water and the increased erosion it will bring depends on where one lives, says Dr. William C. Boicourt, University of Maryland Horn Point Lab. "Part of the adaptation is recognizing what's going to happen in as accurate a projection as possible, and then planning for that".

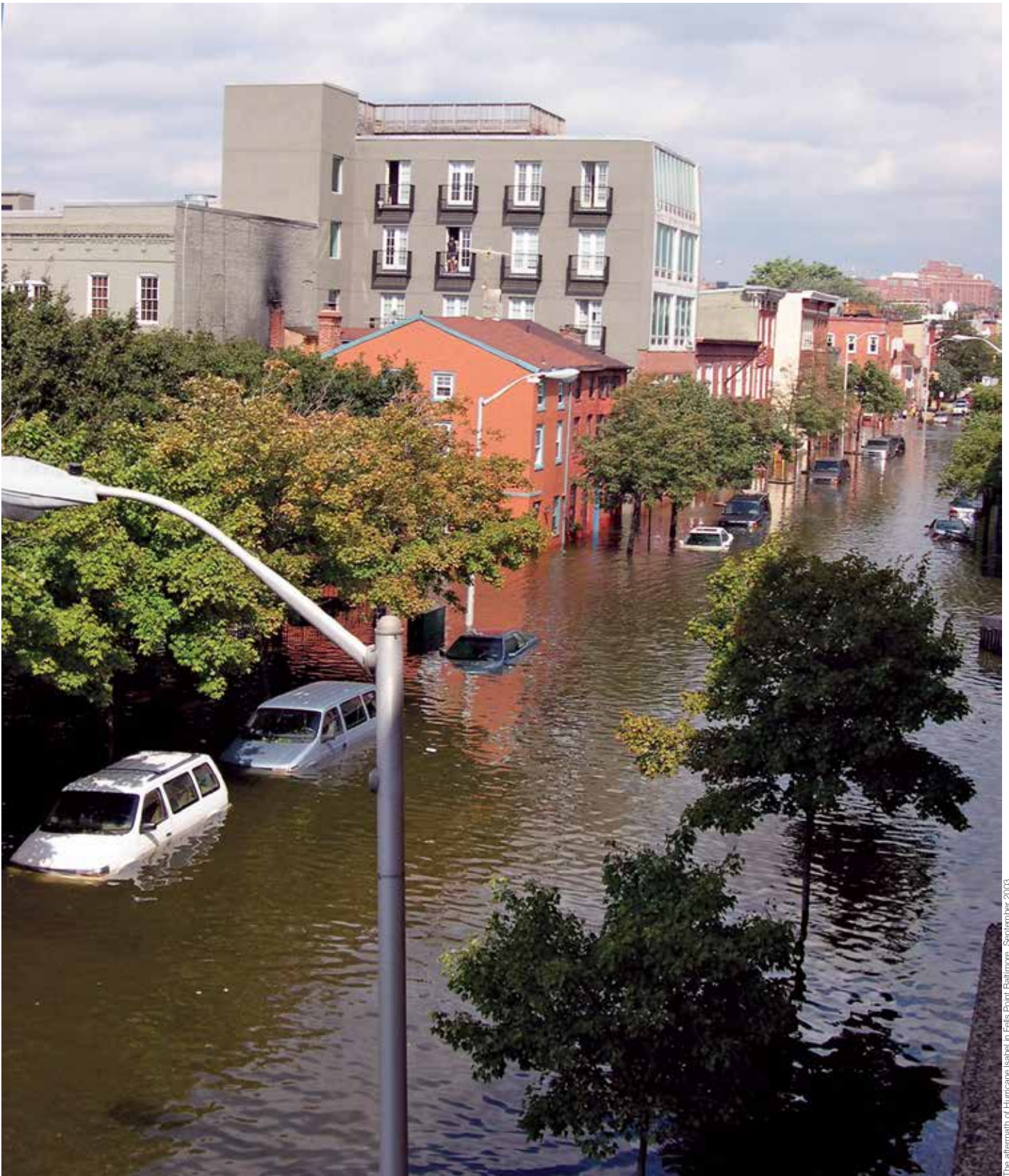
Conclusions

The probabilistic projections of relative sea-level rise in Maryland provided in this report offer a more scientifically sound and readily applicable basis for planning for adaptation and resilience than the best estimate and range approach used in the 2013 update or the six-scenario approach used in the National Climate Assessment. These projections take into account local and regional factors, such as land subsidence and distance from melting polar ice sheets, as well as the increasing volume of the global ocean. Comparable projections using these methods have been recently adopted in several other states and metropolitan areas, and in the recent Fourth National Climate Assessment.

The Likely range (66% probability) of the relative rise of mean sea level expected in Maryland between 2000 and 2050 is 0.8 to 1.6 feet, with about a one-in-twenty chance it could exceed 2.0 feet and about a one-in-one hundred chance it could exceed 2.3 feet. After 2050, rates of sea-level rise depend increasingly on the future pathway of global emissions of greenhouse gases during the next sixty years; thus, separate projections are provided for three emissions pathways. If emissions continue to grow well into the second half of the 21st century, the Likely range of sea-level rise experienced in Maryland is 2.0 to 4.2 feet over this century, two to four times the relative sea-level rise experienced during the 20th century. Moreover, there is a one-in-twenty chance that it could be over 5.2 feet. If, on the other hand, global society were able to bring net greenhouse gas emissions to zero sufficient to meet the goals of the Paris Climate Agreement to limit the increase in global mean temperature to less than 2°Celsius over pre-industrial levels, the Likely range for 2100 is 1.2 to 3.0 feet, with a 5% chance that it would exceed 3.7 feet.

Recent scientific research and analysis indicates that, without such rapid reductions in greenhouse gas emissions, the loss of polar ice sheets could be more rapid than assumed in the projections presented here. This might result in sea-level rise of as much as 20 feet during the next century, adding urgency to Maryland's commitment to substantially eliminate its net greenhouse gas emissions over the next thirty years. A special report on the Ocean and Cryosphere in a Changing Environment will be released by the Intergovernmental Panel on Climate Change (IPCC) in 2019 and provide a new scientific consensus on the risks of this catastrophic loss of polar ice. Revised IPCC projections of the effects on global sea-level rise will be taken into account in subsequent updates of sea-level rise projections for Maryland.

In addition to their use in planning and regulation, these sea-level rise projections should be used in assessments of changing tidal range and storm surge, the co-development of inundation maps and mapping tools by state government and the scientific community, and adaptation related to increasing high-tide or "nuisance" flooding and saltwater intrusion.



The aftermath of Hurricane Isabel in Fells Point, Baltimore, September 2003. future15pic/flickr Commons.

During Hurricane Isabel in 2003, residents in historic Fells Point canoed up and down the cobblestone streets after a record storm surge and flooding. Since then, the Baltimore Inner Harbor has flooded more than once, cutting off the city's main east-west artery.

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Dead trees reflected at Blackwater National Wildlife Refuge, 2017.
David Harp/ChesapeakePhotos.Com

“Ghost” pines, dead from salt water intrusion, line the marsh-upland edges. “I’ve been traveling the roads of southern Dorchester County all my life, and even now coming to work. I see a huge difference in the land. . . almost looks like the land is sinking. . . more water on the land all over the county,” says Steve Phillips, Phillips Packing Company in business since 1902.