Recommendation of Sea-Level Rise Planning Scenarios for Delaware

Technical Report

Prepared by:
Delaware Sea-Level Rise
Technical Committee

Recommendation of Sea-Level Rise Planning Scenarios for Delaware: Technical Report

November 2017

Developed by

Delaware Sea-Level Rise Technical Committee

Coordinated by the

Delaware Geological Survey

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November 2017

Delaware SLR Technical Committee

- John Callahan (chair), Research Scientist, Delaware Geological Survey, University of Delaware
- David Wunsch, Director and Delaware State Geologist, Delaware Geological Survey, University of Delaware
- Tom McKenna, Research Scientist, Delaware Geological Survey, University of Delaware
- Daniel Leathers, Professor and Delaware State Climatologist, Department of Geography, University of Delaware
- Robert Scarborough, Program Manager II, DNREC Delaware Coastal Programs
- Danielle Swallow, Planner, DNREC Delaware Coastal Programs
- Benjamin Horton, Professor, Sea Level Research, Department of Marine and Coastal Sciences, Rutgers University and Earth Observatory of Singapore, Asian School of the Environment Nanyang Technological University, Singapore.
- Daria Nikitina, Associate Professor, Department of Earth and Space Sciences, West Chester University
- Holly Michael, Associate Professor and Unidel Fraser Russell Chair for the Environment, Department of Geological Sciences, University of Delaware
- Christopher Sommerfield, Professor, School of Marine Science and Policy, Oceanography Program, University of Delaware
- Jennifer Volk, Extension Specialist, Department of Plant and Soil Science, University of Delaware
- Kim McKenna, Research Coordinator, DNREC Shoreline and Waterway Management
- Mike Powell, Natural Hazards Program Manager, DNREC Division of Watershed Stewardship

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List of Acronyms

AIS	Antarctic Ice Sheet
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Oceanic Circulation
AO	Arctic Oscillation
CE/BCE	Common Era/Before Common Era
CMIP5	Coupled Modeled Intercomparison Project, 5th Phase
CO-OPS	Center for Operational Oceanographic Products and Services, NOAA
DEMA	Delaware Emergency Management Agency
DNREC	Department of Natural Resources and Environmental Control
EAIS	East Antarctic Ice Sheet
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GMSL/GMSLR	Global mean sea level/Global mean sea-level rise
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
LGM	Last Glacial Maximum
LWS	Land Water Storage
MICI	Marine Ice-Cliff Instability
MISI	Marine Ice-Sheet Instability
MMSL	Monthly mean sea level
MSL	Mean sea level

NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCA	National Climate Assessment
NOAA	National Oceanic and Atmospheric Administration
NOC	National Ocean Council
NRC	National Research Council
NWLON	National Water Level Observation Network, NOAA
PDO	Pacific Decadal Oscillation
PNA	Pacific/North American (Oscillation)
RCP	Representative Concentration Pathway
SLR	Sea-level rise
SLRAC	Sea-Level Rise Advisory Committee
SRES	Special Report on Emission Scenarios
RCP	Representative Concentration Pathway
RSL/RSLR	Relative sea level/Relative sea-level rise
USACE	United States Army Corps of Engineers
USGCRP	United States Global Change Research Program
VLM	Vertical land movement
WAIS	West Antarctic Ice Sheet
WMO	World Meteorological Organization

Executive Summary

Sea-level rise (SLR) is a significant consequence of climate change. Its effects are global, crossing political and geographic boundaries, and may result in major economic and sociodemographic consequences for a wide range of public and private interests through shoreline erosion, inundation of wetlands and uplands, saltwater contamination, changes to natural habitat, and flood damage to infrastructure. For at least the past 4,000 years, we have experienced only modest global mean sea-level changes (< 2 mm/yr) (Engelhart et al., 2009; Lambeck et al., 2014). Since the mid to late 19th century, however, much higher rates (> 3 mm/yr) have been observed at most locations throughout the world (Kemp et al., 2011; Church and White, 2011; Zervas, 2013; Kopp et al., 2016a), with the increase in rate due to ocean thermal expansion and transfer of water to the sea from melting land-based glaciers and ice sheets.

Monitoring and planning for SLR is important for the U.S. mid-Atlantic coastal region, including Delaware, due to its high concentration of population and development, critical natural ecosystems, and public infrastructure. In addition to global mean sea-level rise (GMSLR), processes in this region add positively to the increase of sea-surface height relative to the land surface, such as 1) geologic land subsidence due to the glacial isostatic adjustment from the Laurentide ice sheet during the last Ice Age; 2) changing nearby ocean circulation patterns; and 3) gravitational effects from melting ice sheets of Greenland and Antarctica. Due to multiple factors contributing to relative sea-level rise (RSLR), this region has become known as a hotspot for potential damage and vulnerability to SLR (Sallenger et al., 2012; Boon, 2012; Kopp, 2013; Ezer and Corlett, 2012; Kopp et al., 2015a; Davis and Vinogradova, 2017).

This is worrisome for the state of Delaware as it lies directly in this hotspot zone of SLR, is extremely flat with very low mean elevation, and experiences frequent minor, as well as extreme coastal flooding from both tropical and extra-tropical (nor'easters) storm systems. The primary effects of SLR to Delaware occur on both long-term and short-term time scales. Long-term effects include coastal erosion and conversion of tidal wetlands to mud flats and open water; loss of low-lying agricultural fields, coastal impoundments, and forested wetlands; damage to public infrastructure (e.g., roads, septic tanks, water supply lines) and private property due to repeated flooding from saltwater from the bay or ocean; saltwater intrusion into groundwater aquifers affecting water supply for domestic use and irrigation systems; and increases of salinity in marshes altering the species and behavior, and ultimately the long-term health, of the flora and fauna in the system. Short-term effects include the damage to public infrastructure (e.g., roads, septic tanks, water supply lines) and private property due to waves and inundation from coastal storms; rapid erosion of beach sand from coastal storms; saltwater infiltration on agricultural fields and forested lands due to overtopping of dunes from storm surge; inundation of roads due to monthly high tides; all of which are made worse by the gradually rising water level.

Of particular interest are the impacts on the tidal wetlands and effects of beach erosion. Tidal wetlands provide important benefits to people and the environment by improving water quality by removing contaminants, providing protection to inland communities and public infrastructure by buffering the impacts of costal storms, providing habitat for beneficial and unique plants and animals, capturing and storing large amounts of carbon dioxide, and providing recreational opportunities. Delaware has over 73,000 acres of tidal wetlands. However, many are continuously stressed from human land use activities and sea-level rise. Currently, an active area of research is how the vertical accretion and transgression of Delaware Bay marshes will behave under various sea-level rise scenarios. As well, beaches and dunes are beneficial to Delaware as they provide protection to critical public infrastructure, commercial establishments, and private property from coastal flooding and also serve an important role in tourism and recreational activities. Waves and currents from coastal storms, exacerbated by sea-level rise, can severely degrade or breach the dune and berm structure of a beach or transport away a significant amount of sand. Delaware has spent approximately $200 million in the past 15 years mitigating beach and dune erosion, which will continue to be a costly endeavor for the state.

SLR will also have secondary effects in the state, such as economic impacts on coastal tourism and commercial activities; public safety through regular flooding of local community roads and property; and housing developments through increased flood insurance rates and modification of building codes. It is critical that local, county and state government agencies in Delaware incorporate sea-level rise in all long-term planning activities along the coast.

In 2008, the Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs (DCP) section instituted the Delaware Sea-Level Rise Initiative, a comprehensive, multi-year effort designed to help the state assess, prepare for and minimize the potential impacts of sea-level rise. This was accomplished by providing scientific and technical support for decision-making, stakeholder partnerships, providing educational and outreach opportunities, and developing and improving sea-level rise policies (DNREC, 2011). A result of the initiative was the formation of the Sea-Level Rise Technical Workgroup in 2009, which identified three scenarios of SLR of 0.5, 1.0, and 1.5 meters by the year 2100 (relative to the base year of 1992) that DNREC should use in its planning activities (DNREC, 2009).

Since those SLR planning scenarios were released, the Intergovernmental Panel on Climate Change (IPCC) released their Fifth Assessment Report (AR5) in 2013 (Church et al., 2013) and the U.S. Global Change Research Program (USGCRP) released the second and third U.S. National Climate Assessments in 2009 and 2014, respectively (Melillo et al., 2014). These reports and many other science-based research articles conclude that GMSL gradually rose in the 20th century and is currently rising at an increased rate.

In 2016, the Delaware Geological Survey (DGS) began working with DNREC Delaware Coastal Programs and others as part of the Delaware SLR Technical Committee, to determine if the SLR planning scenarios for Delaware released in 2009 should be updated. This technical report is a product of that effort. Its purpose is two-fold:

1) To summarize the scientific peer-reviewed literature, technical reports, and international/national assessments, published since 2009 though until May 2017, regarding past and projected sea-level change, globally and within the Delaware region;
2) To recommend scenarios of future sea-level rise based on sound scientific methodologies that state, county, and local agencies in Delaware can use for incorporating SLR into their planning activities.

Figure ES-1. Flooding in Bowers Beach during November 2009 Nor'easter (Veterans Day Storm). Source: DNREC Delaware Coastal Programs.

Global mean sea-level rise (GMSLR) and relative sea-level rise (RLSR) in Delaware. There are many factors that contribute to the changing of sea-surface heights. The dominant factors are divided into three categories:

- Global mean sea-level rise (GMSLR) refers to the increase that is currently observed in the average sea-surface height of all the Earth's oceans. GMSLR is primarily attributed to changes in ocean volume due to two factors: 1) land-based ice melt, and; 2) ocean thermal expansion. Melting of land-based glaciers and the continental ice masses such as the Greenland and Antarctic ice sheets, which are linked to changes in atmospheric temperature, can contribute significant amounts of freshwater input to the Earth's oceans. A steady increase in global atmospheric temperature also increases the temperature of the ocean's sea water, increasing the energy of the water molecules and the resulting volume of space the ocean assumes, therefore raising the height of the sea surface. Additionally, the amount of liquid water storage on land (e.g., lakes, rivers, groundwater) can affect the amount of water mass in the oceans: a reduction in land water storage, for example due to groundwater pumping for water supply needs or natural precipitation patterns, causes an increase in the amount of water in the oceans. For the time period 1993 – 2010, satellite altimetry estimates of GMSLR agree with the sum of contributions from these three processes: thermal expansion, land-sea mass exchange, land water storage (Church et al., 2013).

- Regional differences from GMSL – these processes can raise or lower the local sea surface as compared to the global mean. These processes include: 1) the weakening of the Gulf Stream causing a buildup of water along the U.S. mid-Atlantic coast (Rahmstorf et al., 2015; Ezer et al., 2013; Ezer, 2015); 2) weakening of the gravitational force of the Greenland and Antarctic ice sheets as they lose mass, causing sea-level rise to be greater along coastlines distal from the ice sheets (Mitrovica et al., 2011; Hay et al., 2015), and; 3) ocean-atmosphere climate patterns that can cause cyclic patterns of warmer water movement or storm surge (Kopp et al., 2015b).

- Vertical Land Motion (VLM) – rather than increase the height of the ocean surface, processes also may change the elevation of the land surface, thereby causing an increase or decrease in the observed relative sea-level rise. The dominant process here is glacial isostatic adjustment (GIA), which has been causing land subsidence in the mid-Atlantic region since the Last Glacial Maximum (LGM) (Kopp et al., 2015a). More localized VLM processes are the consolidation of coastal plain sediments due to groundwater withdrawal (i.e., pumping) from lower aquifers and natural sediment compaction. Anecdotal evidence suggests Bowers Beach and the Dover area in Delaware may be experiencing possible land subsidence due to this process.

Reconstruction of past sea levels.

The Holocene epoch has the most abundant and highly resolved relative sea level (RSL) reconstructions in comparison to previous time periods. GMSL has risen at varying rates since the Last Glacial Maximum approximately 20,000 years ago, as shown in Figure ES-2. Over the last 5,000 years, RSL has fallen in many areas that were formerly covered by major ice sheets because of GIA, while RSL beyond the ice margins reflects changes in GMSL, proglacial forebulge collapse, and hydro-isostatic loading, with deltaic regions being further influenced by compaction (Engelhart et al., 2011; Dutton et al., 2015). For the past 5,000 years until the mid to late 19th century, Delaware has experienced a gradual rise in relative sea levels, primarily due to GIA. From reconstructions throughout the Delaware Bay region using salt-marsh sediments that preserve the elevation and age of past sea level, it is estimated that the historic SLR rate for the past 5,000 years is approximately 1.25 ± 0.27 mm/yr (Nikitina et al., 2014).

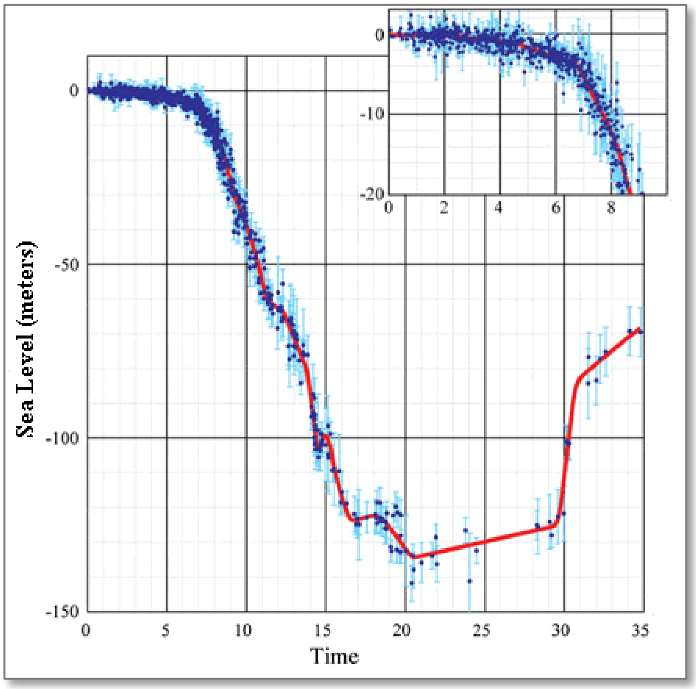


Figure ES-2. Historic far-field sea level data points and age uncertainty bars over the past 35,000 years. Inset focuses on the past 9,000 years. Modified from Lambeck et al. (2014).

Tide gauge and satellite observations. Since the late 19th century, tide gauges and satellite altimetry missions have been monitoring sea levels across the globe. Numerous studies have analyzed the long-term tide gauge record, correcting for regional and local effects as well as gaps and discontinuities in the spatial distribution, to determine the rate of GMSLR (Ray and Douglas, 2011; Church and White, 2011; Jevrejeva et al., 2014b; Hay et al., 2015). Most global tide gauge studies compute linear trends of GMSLR in the range of 1.6 – 1.9 ± 0.2 - 0.3 mm/yr for the time period of late 19th century to the early 21st century, with the value of 1.7 mm/yr from Church and White (2011) commonly used in many reports. Acceleration in GMSLR also has been identified in the tide gauge data for the latter part of the century. Since 1992, satellite altimetry missions have been able to continuously monitor large areas over the global oceans, apart from the coastal areas monitored by the tide gauges. Estimates of GMSLR among tide gauge and satellite altimetry studies for the same time period (approximately 1993 to present) are in relatively close agreement, as depicted in Figure ES-3 below.

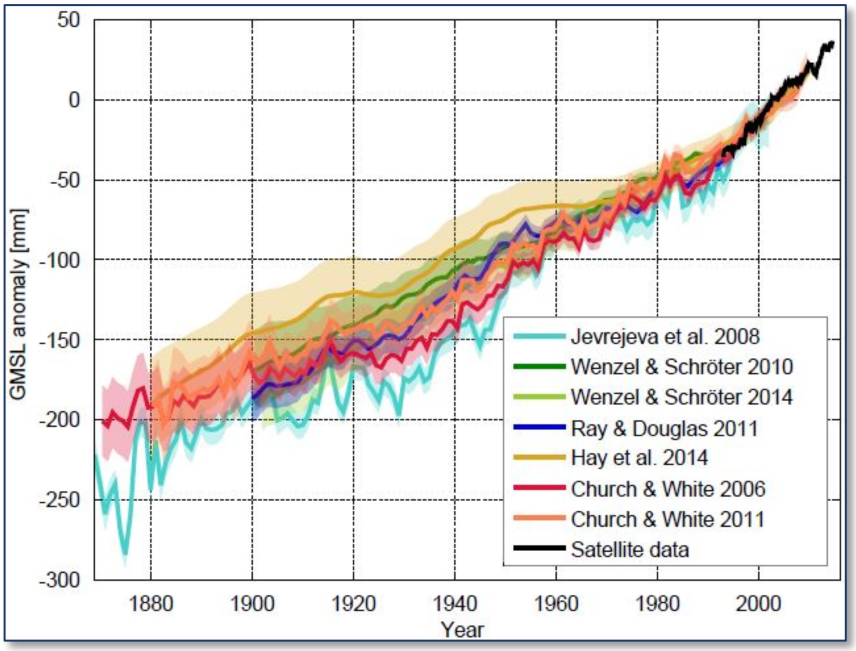


Figure ES-3. Comparison of GMSL curves from the later part of the 19th century to present from several tide gauge studies. GMSL values are relative to satellite-era average. Shaded regions represent error bars, where possible, which decrease as the number of observation points increases in later years. Source: http://www.realclimate.org/index.php/archives/2015/01/a-new-sea-level-curve/

Table ES-1 lists the linear trend and confidence intervals for stations in the Delaware region, calculated from tide gauge monthly MSL records for the stations' period of record following Zervas (2009). Only included are stations with periods of record of 40 years or more (except for Wachapreague, VA, which has 39 years). Note that all the listed gauges have experienced significantly higher RSLR rates (and wider uncertainty ranges) than the 20th century GMSLR rate, primarily due to vertical land subsidence effects and weakening in the Gulf Stream, making this area of the U.S. East Coast a hotspot of sea-level rise.

Table ES-1. SLR rates and confidence intervals for NOAA NWLON stations near the Delaware coast. Stations are listed approximately from north to south. Source: NOAA Tides and Currents Sea Level Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Station Name	Period of Record	Number of Years	Liner SLR Trend and 95% Confidence Interval (mm/yr)
Philadelphia, PA	1900-2016	117	2.93 ± 0.19
Atlantic City, NJ	1911-2016	106	4.07 ± 0.16
Cape May, NJ	1965-2016	52	4.55 ± 0.53
Lewes, DE	1919-2016	98	3.42 ± 0.24
Reedy Point, DE	1956-2016	61	3.53 ± 0.49
Annapolis, MD	1928-2016	89	3.55 ± 0.20
Cambridge, MD	1943-2016	74	3.70 ± 0.32
Ocean City Inlet, MD	1975-2016	42	5.58 ± 0.92
Wachapreague, VA	1978-2016	39	5.38 ± 0.79

Figures ES-4 and ES-5 show the monthly variation and long-term trend of sea level at the Lewes and Reedy Point tide gauges. At the Lewes tide gauge, the linear rate of 3.42 mm/yr equates to about 0.335 m / 13.2 in of sea-level rise since 1919 and about 0.400 m (15.7 in) since 1900 (through to 2016.) This is about twice the rate, and therefore twice the amount, of GMSLR observed since 1900.   Likewise, at the Reedy Point tide gauge, the linear rate of 3.53 mm/yr equates to about 0.215 m (8.5 in) since 1956. The observed SLR linear rate at Reedy Point should not be extended backward to 1900 due to the large number of years between the start of the station period of record and the start of the century.

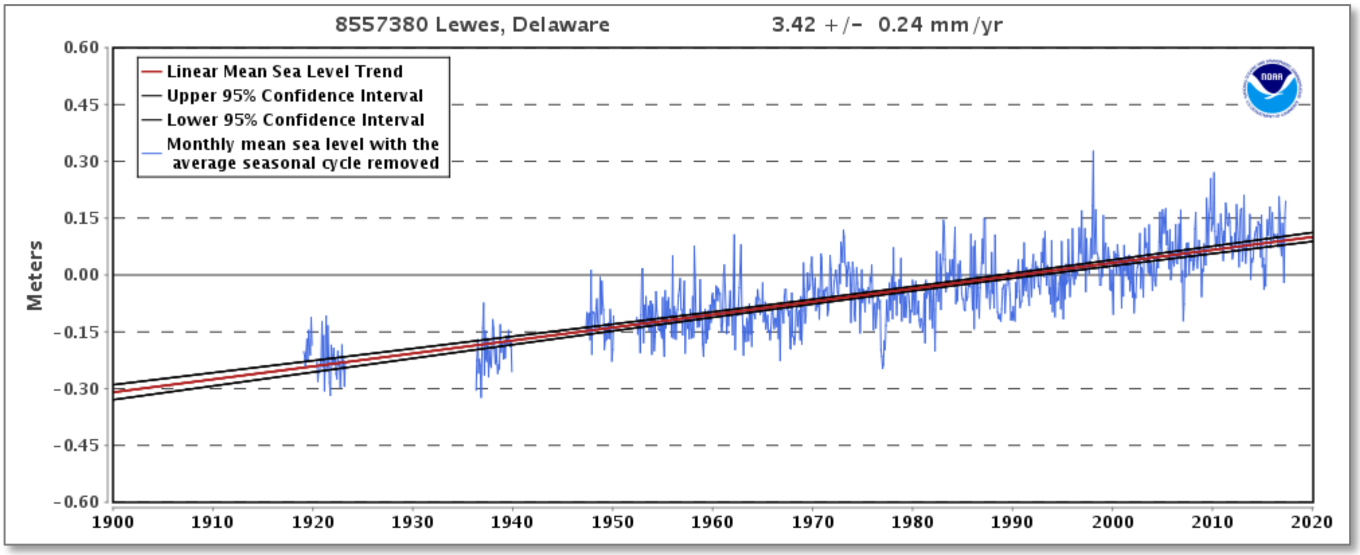


Figure ES-4. Monthly mean sea level for NOAA Lewes tide station from 1919 through 2016. Linear MSL trend and 95% confidence interval shown in red and black, respectively. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

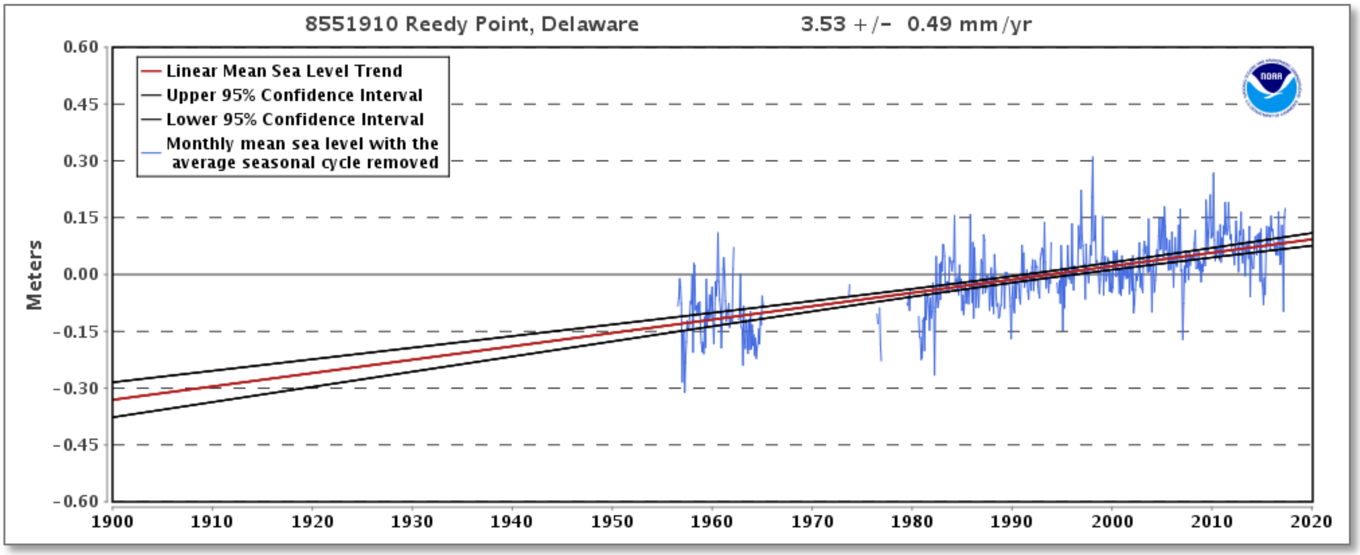


Figure ES-5. Monthly mean sea level for NOAA Reedy Point tide station from 1956 through 2016. Linear MSL trend and 95% confidence interval shown in red and black, respectively. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

Although SLR gradually raises the mean sea level of an area, large-scale oceanic-atmospheric conditions, such as ENSO (Hamlington et al., 2015), can further increase or decrease the mean sea level. For example, for the time period 1990 through 2016 at the Lewes tide gauge, deviations from the mean sea level for that period reached up to 0.30 m (0.98 ft), much larger than the expected increase due to the linear SLR trend alone. Regional meteorological conditions that develop from strong onshore winds, mid-latitude cyclones, or tropical storm systems, can cause water levels to be much higher, by up to several feet, than mean sea level. In areas where mean sea level has been rising, so too does inundation frequency relative to fixed-elevation infrastructure on land, including minor/nuisance flood levels as well as extreme water levels from storms or strong winds (Hall et al., 2016). Extreme water levels can cause significant damage and degradation to public/private property and public safety as well as to the natural environment along the shoreline. Although planning for the eventual, gradual increase in mean sea level is important, planning for the changes in frequency, duration, and intensity of extreme water levels is just as important in many cases. Sea-level rise will continue to increase the frequency and duration of nuisance flooding and exacerbate the impacts of extreme coastal flooding (Sweet et al., 2014; Tebaldi et al., 2012; Wahl et al., 2015; Little et al., 2015; Lin et al., 2016).

Delaware SLR Planning Scenario Recommendations. After review of the latest technical reports, national and international assessments, and peer-reviewed academic literature regarding future projections of SLR, it is the recommendation of the Delaware SLR Technical Committee that the framework described in Kopp et al. (2014), *Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites*, be used as the scientific basis for incorporating sea-level rise into Delaware coastal planning activities. This probabilistic approach, conditional upon selection of a greenhouse gas future Representative Concentration Pathway (RCP) emission scenario, was preferred over the scenario-based approach used previously in Delaware (DNREC, 2009), as well as by USACE (2013) and the 3rd NCA (Melillo et al., 2014), as a probabilistic approach provides more complete information throughout time and on each component contributing to SLR, allowing planners to more thoroughly assess and identify which SLR level to plan for. It also allows for assignment of a probability of likelihood among the Low, Intermediate, and High scenarios. By comparison, in the scenarios-based approach, no such likelihood can be given.

Kopp et al. (2014) calculates a complete probability distribution of SLR out to year 2200 (although Delaware only uses data out to year 2100) under each RCP emission scenario. It computes the relative contributions from ocean thermal expansion and regional processes, Greenland and Antarctic ice sheets surface mass balance and ice-sheet dynamics, mountain glaciers and ice caps surface mass balance, land water storage, vertical land movement, and other background (e.g., tectonic) effects. The projections are informed by a combination of expert community assessment, expert elicitation (regarding ice-sheet dynamics), and process modeling (directly from the IPCC AR5 Atmosphere/Ocean GCMs) which can be combined to generate local or global future SLR estimates. Figure ES-6 diagrams the logic flow of each of the input sources of information.

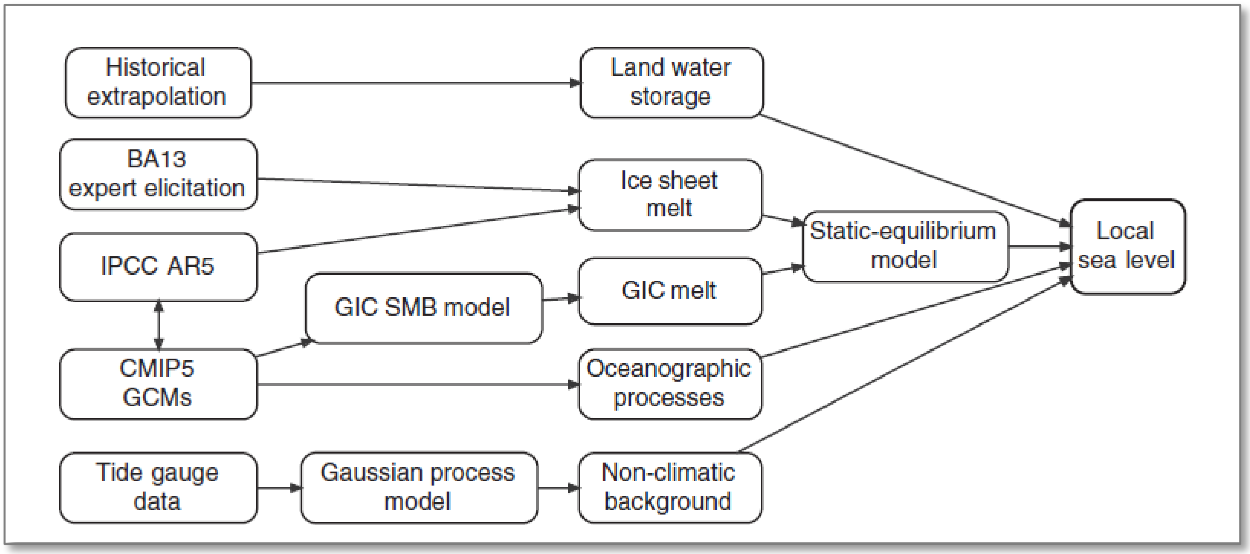


Figure ES-6. Logic flow of sources of information used in local SLR projections. GIC = glaciers and ice caps; SMB = Surface mass balance, BA13 = Bamber and Aspinall, 2013. Source: Kopp et al. (2014).

Recommendation: It is the recommendation of the SLR Technical Committee to use the 5, 50, and 95 percent probability levels of sea-level rise in Delaware, determined by the Kopp et al. (2014) methodology under the IPCC AR5 RCP 8.5 emission scenario, as the Low, Intermediate, and High SLR planning scenarios, respectively. This equates to 0.52 m, 0.99 m, and 1.53 m of SLR by 2100, relative to year 2000 MSL. Depending on time horizon and sensitivity to coastal flooding, projects also may benefit by planning for SLR scenarios greater than the High (95%) planning scenario.

SLR Planning Scenario	SLR by 2100	
Low Scenario (5%)	**0.52 m**	**1.71 ft**
Intermediate Scenario (50%)	**0.99 m**	**3.25 ft**
High Scenario (95%)	**1.53 m**	**5.02 ft**

The Kopp et al. (2014) methodology provides numerous benefits:

- A complete probability distribution of SLR projections is provided, not just single values or limited ranges. For example, IPCC AR5 provides projections of GMSLR by 2100 in the likely (17-83 percent) and very likely (5-95 percent) probability ranges; no information is provided on SLR outcomes outside of this range. NCA and USACE provide single values of GMSLR at 2100 with no probabilities assigned as to how likely that scenario will occur. Understanding the likelihood of the high SLR estimates is important for assessing the likelihood of risks related to coastal flooding.
- The time evolution of projections is physically based; estimates of SLR for times earlier than year 2100 have a valid probability assigned. Therefore, state and local planners and management officials may use the projection curves to estimate SLR at a time most appropriate to their needs.
- Projections are based on an ensemble of numerous, sophisticated atmosphere-oceanographic global climate models (AOGCMs) and research methodology as in IPCC AR5, the current internationally accepted state of knowledge relating to climate change and sea-level rise.
- Regional processes, such as VLM (estimated through locally observed tide gauge data at NOAA Lewes Breakwater Harbor) and ocean circulation changes (AR5 models) are incorporated.
- Relative contributions and associated uncertainties are separated for the primary sources of sea-level rise, both globally and locally, which could help planners decide which scenario to plan for.
- Kopp et al. (2014) incorporated expert opinions (on ice-sheet dynamics) to refine model results.
- SLR projections of Kopp et al. (2014) were consistent with the historical relationship between temperature and rate of GMSLR over the last two millennia (Kopp et al., 2016a).
- Robustness of the results was tested against several varying assumptions and methods.

The Kopp et al. (2014) probabilistic framework, either whole or in part, has been used in several research-based analyses (Moftakhari et al., 2015; Sweet and Park, 2014; Little et al., 2015), U.S. economic analyses (CBO, 2014; Houser et al., 2015), federal multi-agency reports (Hall et al., 2016; Sweet et al., 2017), and state planning activities, such as in New Jersey (Kopp et al., 2016b), Washington (Peterson et al., 2015), and California (Griggs et al., 2017).

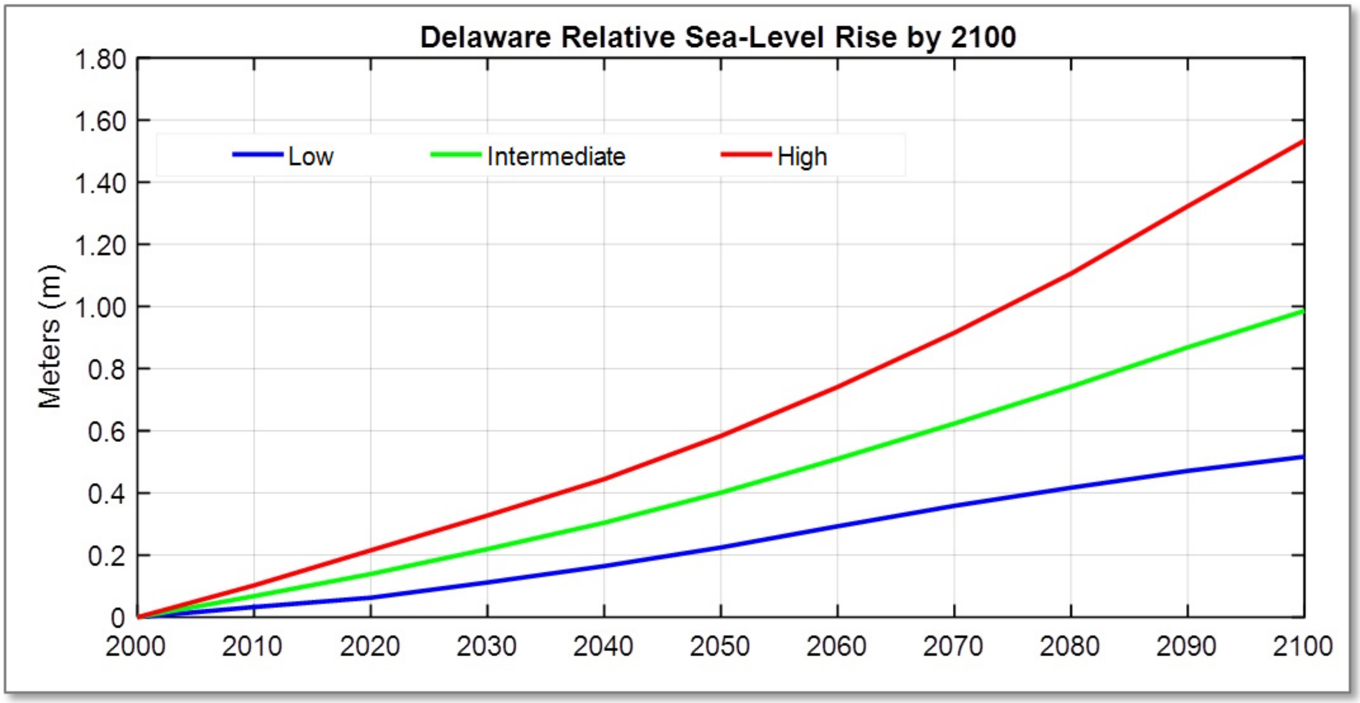


Figure ES-7. The 2017 Delaware SLR planning scenario curves to the year 2100. The Low, Intermediate and High planning scenarios correspond with the 5%, 50%, and 95% probability levels.

The probability levels associated with each Delaware SLR planning scenario represent the percent of modeled outcomes that the given scenario is greater than, within the Kopp et al. (2014) probabilistic framework, utilizing all of the various input sources from the IPCC AR5 models, observation data, and other model parameters outlined in Figure ES-6. For example, the 95 percent probability level represents the amount of SLR that is greater than the resultant amount of SLR in 95 percent of the model runs. The 50 percent probability level is the median SLR outcome, with an equal number of resultant SLR outcomes greater and less than this value. All three of the Delaware SLR planning scenarios use the Kopp et al. (2014) results under the RCP 8.5 "business as usual" future greenhouse gas emission assumption.

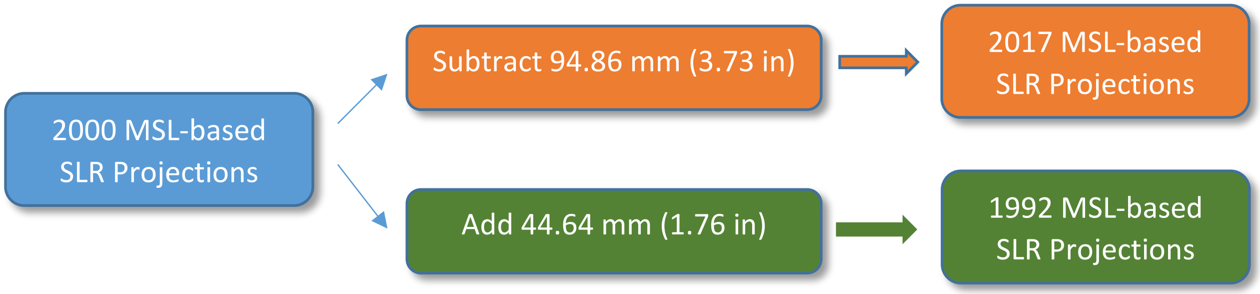
Table ES-2. The 2017 Delaware SLR planning scenarios for selected years 2030, 2050, 2080, and 2100. Data are in meters and feet relative to 2000 MSL.

Year	Delaware SLR Planning Scenarios		
	Low	**Intermediate**	**High**
2030	0.11 m / 0.36 ft	0.22 m / 0.72 ft	0.33 m / 1.08 ft
2050	0.22 m / 0.72 ft	0.40 m / 1.31 ft	0.58 m / 1.90 ft
2080	0.42 m / 1.38 ft	0.74 m / 2.43 ft	1.11 m / 3.64 ft
2100	0.52 m / 1.71 ft	0.99 m / 3.25 ft	1.53 m / 5.02 ft

Table ES-3. Probability that SLR in Delaware will meet or exceed column heading value for stated years. Based on Kopp et al. (2014) methodology under RCP 8.5 greenhouse gas emission scenario, relative to 2000 MSL. Gray shaded areas have less than 0.1% chance of occurrence.

	1.0 ft 0.30 m	2.0 ft 0.61 m	3.0 ft 0.91 m	4.0 ft 1.22 m	5.0 ft 1.52 m	6.0 ft 1.83 m	7.0 ft 2.13 m	8.0 ft 2.44 m	9.0 ft 2.74 m	10.0 ft 3.05 m
2020	0.1%									
2030	12%									
2040	51%	0.4%								
2050	80%	5.5%	0.2%							
2060	92%	25%	1.7%	0.2%	0.1%					
2070	96%	52%	8.2%	1.1%	0.2%	0.1%				
2080	98%	71%	24%	4.1%	1.0%	0.3%	0.1%	0.1%		
2090	98%	82%	43%	13%	3.2%	1.1%	0.4%	0.2%	0.1%	0.1%
2100	98%	87%	58%	25%	8.5%	2.7%	1.2%	0.5%	0.3%	0.2%

SLR projections starting point of year 2000. Kopp et al. (2014) projections are referenced to the year 2000, which is estimated as the average sea level over the decadal time period 1991 – 2009. The average rate of SLR at the Lewes gauge over these two decades is 5.58 ± 1.79 mm/yr (95 percent confidence interval); the high uncertainty range is based on the low number of years (20) and the variability within the time period. If we assume this same linear rate moving forward, the mean sea level in 2017 would be (17 x 5.58 =) 94.86 mm (3.73 in) higher than it was in 2000. Therefore, to modify the Kopp et al. (2014) SLR projections to reference the 2017 MSL (present day) as the baseline instead of 2000 MSL, subtract 94.86 mm (3.73 in) from the projections. The same calculation can be done backwards to 1992, which is the mid-point of the tidal epoch used to calculate the official NOAA NTDE 1983 – 2001 tidal datums as well as the year the previous Delaware SLR scenarios were referenced. Assuming the same linear rate moving backwards in time from 2000 to 1992, the difference in mean sea level would be (8 x 5.58 =) 44.64 mm (1.76 in) Therefore, to modify the Kopp et al. (2014) SLR projections to reference the 1992 MSL as the baseline instead of 2000 MSL, add 44.64 mm (1.76 in) to the projections.



Mean sea-level observations at the Lewes tide gauge since 2000 have been highly variable. Figure ES-8 shows monthly and annual mean sea-level data, computed after first removing the seasonal cycle following the methodology in Zervas (2009), plotted against the three Delaware SLR planning scenarios. The tide gauge data were referenced to the year 2000 MSL to match the reference year of the SLR projections. Since 2000, the mean sea level for each month has extended to greater than the High SLR planning scenario curve and lower than the Low SLR planning scenario curve on several occasions. However, the net trend still indicates rising sea level. The observed variability, discussed more in section 2.2 of this report, is larger than changes in the mean sea level following any of the three planning scenario curves, as well as larger than the difference among the curves for much of the past 17 years. A longer time period is needed to estimate if local sea levels are following any of the currently modeled scenarios.

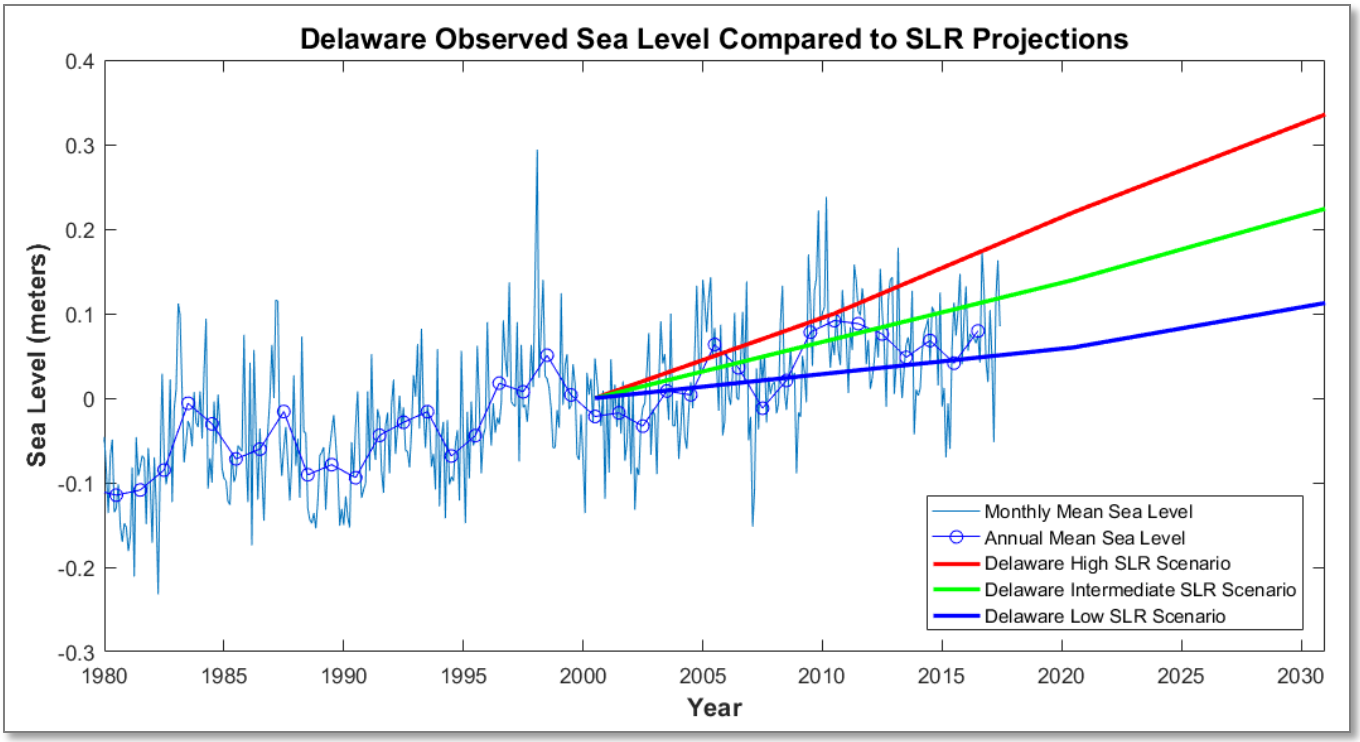


Figure ES-8. Monthly and annual mean sea levels observed at the NOAA Lewes tide gauge after removing the seasonal cycle, compared to the 2017 Delaware SLR planning scenarios. Data relative to 2000 MSL.

Comparison with other assessments. Figure ES-9 displays the likely ranges of projections of GMSLR by year 2100 from numerous studies and assessments compared with the global mean and Delaware-specific SLR projections made by Kopp et al. (2014). For the modelling or statistically based projections, the ranges presented here represent the likely (17 – 85 percent) or very likely (5 – 95 percent) probability ranges. Data from National Research Council (NRC, 2012), Parris et al. (2012), USACE (2013), and NOAA (Sweet et al., 2017) reports represent the full scope of scenarios used within their approach. The range of the GMSLR projections from Kopp et al. (2014) represents the very likely (5 – 95 percent) probability of occurrence and align well with the other studies. Not shown on the graph but described in section 4-3 of this report, the GMSLR 99.9 percent probability of occurrence from Kopp et al. (2014) is 2.47 m, nearly identical to the maximum GMSLR scenario used in the latest Sweet et al. (2017) report. As would be expected, the 2017 Delaware SLR planning scenarios, based on the Kopp et al. (2014), are higher than GMSLR but still consistent with the other studies.

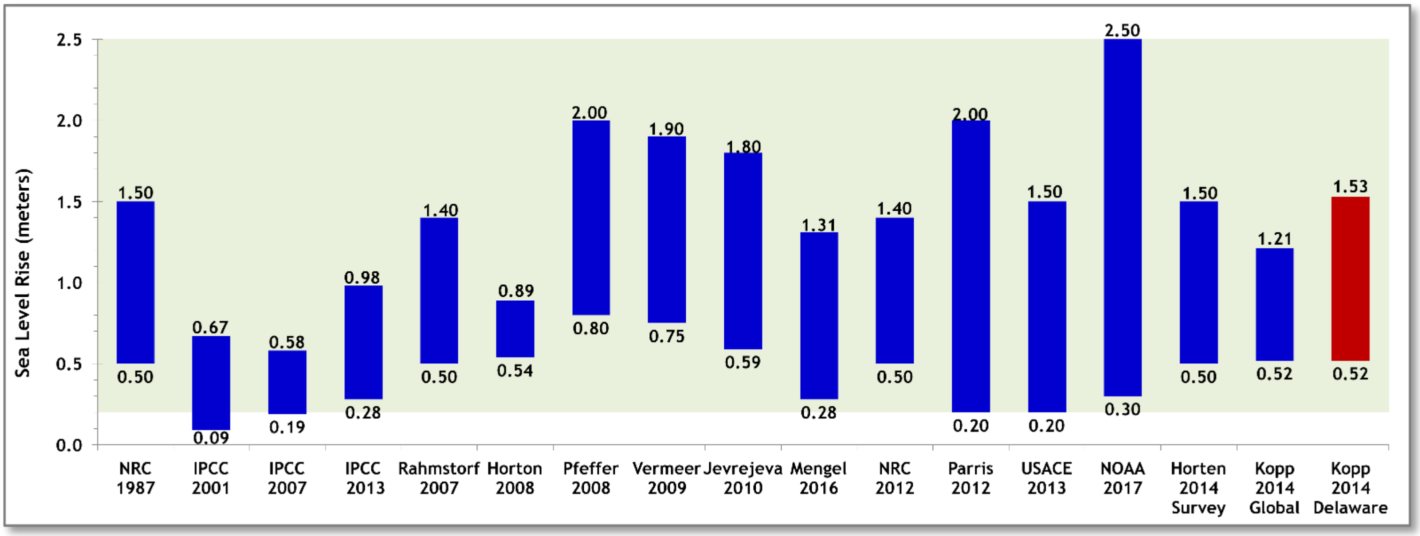


Figure ES-9. Comparison of the recommended 2017 Delaware SLR planning scenario range (shown in red) to the likely ranges of GMSLR by 2100 across scenarios of other well-known research studies, semi-empirical models, IPCC assessments, and the U.S. NCA. Source: Modified from Figure 2 in USACE (2014).

The 5 – 95 percent probability of occurrence range recommended for the Delaware Low – High SLR planning scenarios still leaves 5 percent probability for sea level to be greater than the High planning scenario of 1.53 m (5.02 ft.) For some cases, such as planning for construction of critical, long-lived infrastructure (e.g., waste-water treatment facility, power plant), 5 percent may be too high of a risk to assume. The upper end/low probability events carry a disproportionate level of risk with potentially disastrous damaging effects, the consequences of which should be carefully considered when deciding for which future sea level to plan.

One of the likely ways sea levels could reach greater than the High SLR planning scenario is the rapid melting and ice loss from the Greenland and Antarctica ice sheets into the ocean. Based on the recent observations, ice loss from mountain glaciers and ice caps have been contributing similar amounts to GMSLR as Greenland and Antarctica, although they are on different future paths. Contributions from mountain glaciers and ice caps are expected to decrease as they melt and disappear, whereas the Greenland and Antarctic ice sheets have been melting faster than anticipated. Contributions from the rapid melting of the ice sheets were included in the IPCC AR5 models as a scenario-independent constant value. Recent research since IPCC AR5 was released has taken into account multiple processes that ice sheets lose mass into the oceans, such as marine ice-sheet instability (MISI), crevassing and hydrofracturing, and calving. It is estimated that the Antarctic ice sheet can contribute significantly higher amounts to GMSLR by 2100 (up to a meter) than previously estimated (Hansen et al., 2016; DeConto and Pollard, 2016).

In addition to the significant uncertainty in modeling the future contributions of the Greenland and Antarctic ice sheets to GMSLR, the threat of storminess with extreme coastal flooding is projected to increase due to climate change. In order to plan for future SLR out to 2100, large, persistent uncertainties must be taken into account and balanced against the sensitivity and time horizon of the project. Table ES-4 lists GMSLR and relative SLR for Delaware for the high end probabilistic values from Kopp et al. (2014) under RCP 8.5 emission scenario.

Table ES-4. High-end projections for GMSLR and relative SLR for Delaware from Kopp et al. (2014) methodology under RCP 8.5 emission scenario. Data relative to year 2000 MSL.

	Probability Level 99.0%	Probability Level 99.5%	Probability Level 99.9%
Global	1.55 m / 5.09 ft	1.76 m / 5.77 ft	2.47 m / 8.10 ft
Delaware (Lewes)	1.93 m / 6.19 ft	2.13 m / 6.99 ft	3.01 m / 9.88 ft

Depending upon the sensitivity to coastal flooding of the project, Delaware agencies and organizations may want to plan for sea levels by 2100 that would be greater than the Delaware High (1.53 m, 5.02 ft) SLR planning scenario. In those cases, it is recommended to use one of the Kopp et al. (2014) 99.0, 99.5, or 99.9 percent probability levels of SLR by 2100, which corresponding to 1.93 m (6.19 ft), 2.13 m (6.99 ft), and 3.01 m (9.88 ft), respectively, relative to the year 2000 MSL. The Kopp et al. (2014) 99.9 percent probability level under the RCP 8.5 emission scenario is consistent with estimates of “maximum physically plausible” SLR derived through other methods.

General guidance in using Delaware SLR planning scenarios. Executive Order 41 directs state agencies to address both the causes and consequences of climate change. It recommends that planners and elected officials factor SLR projections into capital improvement projects and land-use decisions with long lifespans or some risk of flooding. Before selecting a SLR scenario for planning, it is important to understand that SLR is one component of overall flood risk in the state. Delaware communities experience flooding and damage from storms with heavy precipitation, wind, waves, and/or storm surge, as well as from perigean spring tides that cause localized, nuisance flooding. SLR will significantly exacerbate the risk of flooding from these events. Additionally, SLR can cause more gradual effects on the area, such as saltwater intrusion to groundwater supply, drowned coastal agricultural fields and forests, beach erosion and marsh migration, changes in the tourism and real estate industries, public safety, and more. This report does not analyze or offer projections regarding overall flood risk for Delaware towns. However, the SLR planning scenarios contained in this report should form a critical piece of the risk assessment and planning process at the state and local level.

Planners and officials should consider a range of factors when making land use and capital improvement decisions. Selecting the appropriate scenario (Low, Intermediate, High, or maximum projected) is a matter of understanding: 1) the time horizon or life cycle of a project, and; 2) tolerance for risk.

1. Time horizon – Some projects have a longer anticipated life span than others. Major capital improvement projects such as streets, bridges, and wastewater treatment plants have a design life of 15-50 years depending on the type of infrastructure and in the environment in which it is built. The first step in applying SLR projections to local decision-making is to select the appropriate time horizon for the project or land-use decision and understand how that correlates to the SLR projections for that particular timeframe. Table 4-3 and Figure 4-4 can be used to extract the appropriate SLR amount for any time period through 2100.

2. Risk Tolerance – Choosing which of the SLR scenarios to plan for should not be undertaken without understanding a project or land use's adaptive capacity and its potential value to the community. "Adaptive capacity" refers to the ability of a system (built, natural, or social) to recover from or withstand flooding from SLR or other hazards. It is important to understand how the project contributes to the community's way of life. This will help to inform the relative tolerance one has for accepting the risk of flooding from SLR. For example, projects that directly support public safety (e.g., a hospital or evacuation route) or are integral to the continued operation of a town (e.g., fire house or electric power substation) would likely carry a lower tolerance for risk to SLR compared to parking lots or retail establishments.

Knowing risk tolerance is absolutely crucial to decision making because SLR projections are not predictions; they do not forecast with absolute certainty how much SLR is expected in the future. Delaware's SLR projections are based on the best available data and scientific consensus concerning the major contributing factors. The relative confidence levels of each projection are noted, giving planners and decision makers latitude to choose the scenario they are most comfortable planning for.

In general, projects with longer lifespans that have low tolerances for risk will be best served by the High SLR scenario or the maximum possible SLR by 2100 (higher projection of SLR = less likelihood of exceeding it) and projects with shorter lifespans and higher tolerances for risk are well suited for the Low or Intermediate SLR scenarios.

Frequency of updates to this report. The latest IPCC AR5 report introduced significant improvements over previous IPCC studies regarding sea-level rise, particularly in integrating ice-sheet dynamics, albeit to a limited extent. New research is rapidly improving our understanding of the influences of global and local sea-level rise and on how best to incorporate this information into modeling and statistical frameworks. New data are currently being collected regarding the melting of the Greenland and Antarctic ice sheets (both of which are expected to be significant contributors to GMSLR later in the 21st century) as well as increased sampling of the ocean depths (0 - 2000 m) by the Argo floating network (Argo, 2016) and continued satellite observations of the global oceans, all of which should better inform GCMs in the next round (i.e., CMIP6) of model runs. Additional monitoring and research will advance our understanding of the frequency and intensity of extreme flooding from coastal storms, the effects of SLR on the impacts of groundwater, and on the response of coastal salt marshes and beach dune systems that cover a large portion of the Delaware coastline. DNREC Delaware Coastal Programs also has been recently working with the National Geodetic Survey (NGS) to improve our horizontal and vertical reference network through the NGS Height Modernization program, to refine our measurements of land subsidence. There may be changes in the priorities or policies regarding housing or public infrastructure development within the state that require reevaluation of the methodology to identify the likely and extremes of SLR projections. These considerations compel Delaware to continuously remain aware of national and international assessments of sea-level rise, especially along the U.S. mid-Atlantic coast, and to periodically review future SLR scenarios appropriate for Delaware planning activities.

Recommendation: It is the recommendation and intention of the Delaware SLR Technical Committee that SLR planning scenarios for the state of Delaware be reviewed and updated periodically as new information and federal guidelines become available. This is a continuation of the recommendation made by the 2009 DNREC SLR Technical Workgroup.

End of Executive Summary.

1. Introduction

Sea-level rise (SLR) is a significant consequence of climate change. Its impacts are both global and local, crossing political and geographic boundaries, and may result in major economic and sociodemographic consequences for a wide range of public and private interests through shoreline erosion, inundation of wetlands and uplands, saltwater contamination, changes to natural habitats, and flood damage to infrastructure. Rising sea levels can affect a region's economy, tourism, natural resources, recreational activities, and public health and safety. It can also affect a community's way of life, regularly flooding backyards or streets people take to work each day. SLR is an easily identifiable aspect of a changing climate with potentially severe consequences across all geographic scales and is a major threat facing coastal regions today.

For at least the past 4,000 years, we have experienced only modest global mean sea-level rise (GMSLR, < 2 mm/yr) (Engelhart et al., 2009; Lambeck et al., 2014). Since the mid to late 19th century, however, much higher rates (> 3 mm/yr) have been observed at most tide gauge locations throughout the world (Kemp et al., 2011; Church and White, 2011; Zervas, 2013; Kopp et al., 2016a). Rising seas are a direct consequence of a warming Earth. Surface air temperatures have increased about 1.7°F averaged over the globe since the late 19th century, with 16 of the warmest 17 years on record occurring since 2001 (NASA, 2017). As the atmosphere continues to warm, as much as 90 percent of the additional heat energy goes into the oceans (Church et al., 2011; IPCC, 2013), raising sea levels through ocean thermal expansion. The increased warming of the Earth also melts land-based ice sheets and glaciers, adding more water to the oceans. Both global atmospheric warming and subsequent sea-level rise are virtually certain to increase into the future (IPCC, 2013).

Coastal regions throughout the world will be the hardest hit. Unfortunately, these are also areas of great natural resources, food sources and breeding grounds of wildlife, hubs of economic and transportation activity, and dense population centers. In fact, 14 of the world's 17 largest cities are located along the coastline (Creel, 2003). In the United States, more than 50 percent of Americans (164 million people) live in coastal counties with another 180 million visiting the area each year as tourists (Melillo et al., 2014). Based on 2010 U.S. Census data, approximately 2.2 million people live in coastal areas with elevations below 0.9 m (3 ft) above high tide and 6.6 million below 1.8 m (6 ft) above high tide. Taking into account population growth projections to the year 2100, the number of people potentially impacted if mean sea level (MSL) reaches these elevations rise to 4.3 ± 0.9 million and 13.1 ± 2.6 million, respectively (Hauer et al., 2016). Likewise, between $66 billion and $106 billion worth of current coastal property will likely be below MSL by 2050 and between $238 billion to $507 billion by 2100, unless protective measures are taken (Houser et al., 2015).

The U.S. mid-Atlantic region is of particular concern. This region supports high concentrations of population and development, with about 60 percent of land below elevations of one meter above mean sea level (MSL) planned for further development (Tebaldi et al., 2012), as well as numerous critical natural ecosystems and major public infrastructure. In addition to global mean sea-level rise (GMSLR), processes in this region add positively to the increase of sea-surface height relative to the land surface, such as 1) geologic land subsidence due to the glacial isostatic adjustment from the Laurentide ice sheet during the last Ice Age; 2) changing nearby ocean circulation patterns; and 3) gravitational effects from melting ice sheets of Greenland and Antarctica. Due to multiple factors contributing to relative sea-level rise (RSLR), this region has become known as a hotspot for potential damage and vulnerability to SLR (Sallenger et al., 2012; Boon, 2012; Ezer and Corlett, 2012; Kopp, 2013; Kopp et al., 2015b; Davis and Vinogradova, 2017).

This is worrisome for Delaware as a state that lies directly in this hotspot zone of SLR. Delaware's location is positioned latitudinally such that it experiences coastal flooding from extratropical (e.g., nor'easters) and tropical storm systems, together numbering about 30-35 coastal storms per year (Leathers et al., 2011). Delaware is also small in size and the coastal areas play a large role in the economy, culture, history, wildlife, ecosystem services, and recreational activities of the state. All three of Delaware's counties are federally designated as coastal by the Coastal Zone Management Act, and no part of the state is more than 8 miles away from tidal waters. Topologically, Delaware is extremely flat and very near sea level where small vertical changes in the water surface can infiltrate large distances horizontally. It has the lowest average elevation of any state in the country, with 381 miles of shoreline and 8 – 11 percent of land area could be inundated by sea-level rise of 0.5 – 1.5 meters above mean high tide, respectively (DNREC, 2012). A greater proportion of Delaware's land area than any of the lower 48 U.S. states except Florida and Louisiana, is at risk of a 1 percent coastal flooding event (States at Risk, 2015). Across the state, 17 percent of Delaware's land area lies within the FEMA Special Flood Hazard Area (SFHA, known as the 1 percent annual chance floodplain) (DFAW, 2016). However, FEMA maps were developed from past information (the latest FEMA maps were developed from data prior to Hurricane Sandy) and do not take into account projected climate change. As a result, Delaware is significantly vulnerable to rising sea level and its effects on the coast.

1.1 Effects of Sea-Level Rise in Delaware

There are numerous effects of sea-level rise to the coastal regions of Delaware. Described more thoroughly in DNREC's 2012 report, *Preparing for Tomorrow's High Tide: Sea-Level Rise Vulnerability Assessment for the State of Delaware*, a brief overview is included here. Primary effects can be thought of as happening on two time scales: 1) long-term effects that happen gradually, and; 2) short-term effects that happen rapidly at irregular intervals. Gradual effects include processes that may be exacerbated by higher sea levels, such as coastal erosion and conversion of tidal wetlands to mud flats and open water; loss of low-lying agricultural fields, coastal impoundments, and forested wetlands; damage to public infrastructure (e.g., roads, septic tanks, water supply lines) and private property due to repeated flooding from saltwater from the bay or ocean; saltwater intrusion into groundwater aquifers affecting water supply for domestic use and irrigation systems; and salinity increases in marshes altering the species and behavior, and ultimately the long-term health, of the flora and fauna in the system. Short-term effects include damage to public infrastructure (e.g., roads, septic tanks, water supply lines) and private property due to waves and surge from coastal storms; enhanced rapid erosion of beach sand; saltwater infiltration on agricultural fields and forested lands due to overtopping of dunes from storm surge; and frequent inundation of roads due to monthly high tides.

Of special interest are the impacts of SLR on tidal wetlands, which provide important benefits to people and the environment by 1) improving water quality through the removal of contaminants; 2) providing protection to communities and public infrastructure by buffering the impacts of coastal storms; 3) providing habitat for beneficial and unique plants and animals; 4) capturing and storing (i.e., sequestering) large amounts of carbon from the atmosphere, and; 5) providing recreational opportunities. Delaware has over 73,000 acres of tidal wetlands, which is almost a quarter of all wetlands within the state (DNREC, 2015). Tidal marshes grow through vertical sediment accretion, capturing sediments brought in by the tides or from upland streams, and through lateral expansion/migration landward (if appropriate space is available for them to move in adjacent lands) converting low marsh to mudflats and open water, and high marsh to low marsh.

However, the health and growth of these areas are continuously stressed by land-use practices, coastal development, waves and inundation from coastal storms, and sea-level rise. Kreeger and Padeletti (2013) found that most of the Delaware Estuary marshes surveyed between 2009 and 2012 were moderately or severely stressed, with 63 percent of marshes examined for shoreline stability were found to have experienced net erosion. By examining Delaware imagery from 1992 to 2007, Tiner et al. (2011) found a net loss of 238 acres of estuarine vegetated wetlands and a net gain of 2,285 acres of ponds (i.e., open water) and mudflats, resulting in a net decrease in wetland function.

Figure 1-1. Murderkill River Estuary, Bowers Beach, DE. Source: McKenna/Delaware Geological Survey, UD.

Tidal wetlands can thrive only in a narrow band of marsh platform elevation, relative to the water-surface elevation (Raposa et al., 2016). Across the state of Delaware, 97 – 99 percent of tidal wetlands will be impacted by 0.5 – 1 .5 m of sea-level rise by 2100, respectively, resulting in damaging or reducing many of the services they provide (DNREC, 2012) although not all marshes will respond equally to sea-level rise. The rate of growth or transgression of a tidal marsh is based on a balance of constructive (e.g., sediment transport and deposition) and destructive (e.g., erosion) forces. Raposa et al. (2016) assessed numerous marsh sites on the east and west coasts of the United States that are part of the National Estuarine Research Reserve (NERR) program, including the St. Jones Reserve along the Delaware Bay, in categories of marsh resilience: marsh elevation distribution, marsh elevation change, sediment supply/accretion, tidal range, and local rate of sea-level rise. Measures in these categories affect the interplay between the constructive and destructive forces. The St. Jones Reserve received a 4 out of 5 score, with sediment supply as its biggest strength and tidal range and rate of sea-level rise as its biggest threats.

Fortunately, the Delaware Estuary has always been a tidal wetland dominated ecosystem, naturally muddy and rich in sediments (Kreeger and Padeletti, 2013), potentially allowing the natural constructive processes within the marsh to counter at least some of the losses due to sea-level rise. The ability of a tidal marsh to dynamically respond (i.e., adapt naturally) to sea-level rise is an important component in guiding natural resource managers and state officials in long-term planning of coastal areas (Lentz et al., 2016). This is an active area of research within the Delaware Estuary and should be revisited when evaluating the effects of sea-level rise in Delaware.

Another primary SLR impact of concern to Delaware is beach erosion. Beaches and dunes provide protection to critical public infrastructure, commercial establishments, and private property from coastal flooding but also serve an important role in tourism and recreational activities. Delaware maintains 24 miles of Atlantic Ocean shoreline and 357 miles of river and bay shoreline (DNREC, 2012). Similar to tidal wetlands, natural processes redistribute the beach sand, causing the beach/dune system to transgress. However, with hardened infrastructure and other human activities around the beaches preventing migration, sand is eroded and carried alongshore or offshore away from the beach (DNREC, 2012). Waves and currents from coastal storms can severely degrade or breach the dune and berm structure of a beach or transport away a significant amount of sand.

Figure 1-2. Beach erosion in South Bethany from winter storm Jonas, January 2016. Source: Delaware Online, http://www.delawareonline.com/story/news/2016/01/24/blizzard-recovery-dunes-washed-away-debris-litters-streets/79171696/

Beach nourishment and dune restoration are constant ongoing activities in Delaware, especially after major storms. For example, beach nourishment along the Atlantic Coast and Delaware Bay beaches was a key part of recovery after Hurricane Sandy, costing about $38 million to replenish the Sussex County ocean beaches (Wakefield et al., 2017). Overall, Delaware has spent approximately $200 million in the past 15 years mitigating beach and dune erosion (Powell, personal communication, 2016). Gradual and episodic erosion will continue to hit the Delaware beaches, exacerbated by sea-level rise, and may be a losing battle in the long run.

In addition to the many primary short-term and long-term effects of SLR on Delaware's natural and man-made environments, there is potential for significant social and economic impacts. For example, most evacuation plans in Delaware require vehicle transportation along roads into and out of coastal areas. Between 1 percent and 6 percent of evacuation routes in Delaware could be inundated by 2100, mostly located in coastal Sussex County (DNREC, 2012). As well, many non-evacuation roads leading to and from local communities experience regular flooding due to spring high tides alone. The increased frequency of road inundation and increased severity (depth and extent) of coastal flooding during storms affects daily plans as well as emergency preparations for Delaware's citizens living along the coast.

Tourism and coastal recreation are important components of Delaware's economy and quality of life and also may be significantly impacted by SLR. Based on 2014 data, tourism contributes $3 billion annually to Delaware's economy and is its fourth largest private employment sector, accounting for 17 percent of the total statewide workforce, with the vast majority of workers along Sussex County beach communities (Delaware Tourism Office, 2016; Wakefield et al., 2017). The effects of SLR can cause damage to historic sites located along coastal roadways and tributaries; flood state parks and wildlife refuges; interrupt travel to and from Delaware Bayshore and beach communities; damage piers and equipment used for fishing and other marine-based industries; significantly increase the cost and time required for beach maintenance; and deter beach goers and tourists from visiting Delaware, which could be detrimental to the livelihood and employment opportunities of seasonal businesses. For example, 40 percent of state parks in Sussex County would be inundated if sea levels rose by only 0.5 m (Wakefield et al., 2017).

Figure 1-3. Beachgoers at Dewey Beach during summer 2016. Source: Gene Shaner, DNREC.

Additionally, SLR will have an adverse effect on the housing industry along densely populated coastal areas. Population and development have significantly increased in coastal Delaware over recent decades. Coastal population grew by more than 50 percent, with some areas doubling their population, in the single decade from 1990 to 2000 (SSC, 2011). Within the Delaware Inland Bays watershed, which includes most of Delaware's tourism and seasonal coastal activities, population doubled from 1990 to 2010, with developed lands replacing agricultural lands, upland forests, and wetlands (CIB, 2016). The real estate boom that began in the mid-1990s led to a major increase in both residential and commercial development and associated infrastructure, such as parking lots, roads, and utilities (Tiner et al., 2011). Currently, according to 2010 U.S. Census Bureau data, over 19,000 people and 20,000 homes, with property values of approximately $1.1 billion, are located within only 5 ft of mean high tide (Strauss et al., 2014). Increased coastal flooding in these densely populated areas will increase losses of private and public property.

For the past 40 years in Delaware, local floodplain building codes have generally required new developments to build the lowest living floor levels at or above the 1 percent annual chance storm base flood elevation (BFE). Large portions of coastal Delaware have been built to the minimal flood protection standard possible, and therefore have very little freeboard to withstand changing flood levels. As an example, using the latest FEMA Flood Insurance Rate Maps (FIRMs), the difference between the 10 percent annual chance (10-year) flood height and 1 percent annual chance (100-year) flood height in Rehoboth Bay and Indian River Bay region is 1.0 ft. Therefore, an increase of 1.0 ft in mean sea level would increase the probability of flooding by 10 times for a building designed within regulation to withstand a current 1 percent flood event, and likewise increase National Flood Insurance Program (NFIP) flood insurance rates. A similar analysis was performed for New York City using Hurricane Sandy storm surge levels measured at The Battery NOAA tide gauge. Based on the historical record, Hurricane Sandy's return period increased from about a 1200-year flood in 1800 to 398-year flood in 2000, and estimated to be a 90-year flood in 2100 accounting for moderate sea-level rise (Lin et al., 2016). This may underestimates the risk potential of flooding since rising sea levels are likely to diminish coastal dune and barrier island protection levels, further elevating inland bay and marsh flood heights and wave action.

Overall, SLR will have an impact on Delaware in many ways, through both short-term and long-term effects. It will affect Delaware's economy (tourism, housing industry, commercial properties), natural environment (agriculture, wildlife, wetlands, beaches), public infrastructure (roads, utilities), private property, and public health and safety (water supply, evacuation routes, coastal flooding.) It is critical that local, county, and state government agencies in Delaware incorporate sea-level rise in all long-term planning activities along the coast.

1.2 Background on Sea-Level Rise Planning in Delaware

In 2008, the Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs (DCP) instituted the Delaware Sea-Level Rise Initiative, a comprehensive, multi-year effort designed to help the state assess, prepare for, and minimize the potential impacts of sea-level rise. This was accomplished by providing scientific support for aiding decision makers, stakeholder partnerships, providing educational and outreach opportunities, and developing and improving sea-level rise policies (DNREC, 2011). The Sea-Level Rise Technical Workgroup was formed to provide DNREC with scientifically based planning scenarios of SLR to year 2100. The workgroup, coordinated by the DNREC DCP, was composed of scientists from the University of Delaware, Delaware Geological Survey, Center for the Inland Bays, Partnership for the Delaware Estuary, and multiple sections within DNREC. They reviewed the historical data observed at nearby tide gauges and the scientific literature for future global and regional sea-level rise projections (DNREC, 2009). Due to the complex nature of all factors affecting changing sea levels, including both GMSLR and regional processes within and near Delaware, the workgroup focused much of its attention on the published summaries and technical reports from international and national sea-level rise expert panels, rather than on a specific individual researcher (DNREC, 2009).

The DNREC SLR Technical Workgroup in 2009 identified three scenarios of sea-level rise of 0.5, 1.0, and 1.5 meters by the year 2100, relative to the base year of 1992 (shown in Fig. 1-4), that DNREC should use in its planning activities (DNREC, 2009), with the appropriate scenario to use determined by the project's sensitivity to coastal flooding risk. Each planning scenario was denoted by the total cumulative relative sea-level rise along Delaware's coasts by the year 2100, with the time evolution of SLR generated by a simple quadratic model (USACE, 2009; NRC, 1987). These SLR values were based on the National Research Council (NRC, 1987) planning scenarios and used by the U.S. Army Corps of Engineers (USACE, 2009) for incorporating SLR into civil works programs. The fourth scenario (0.36 m by year 2100) was included only as reference to represent the linear extrapolation of the historic tide gauge record at Lewes.

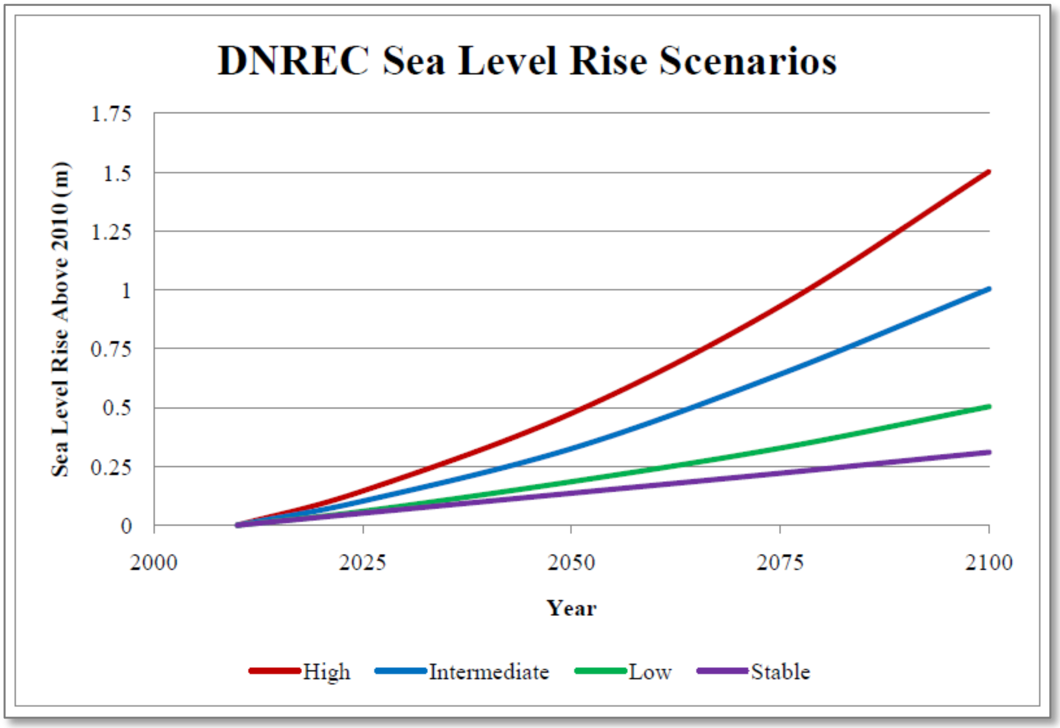
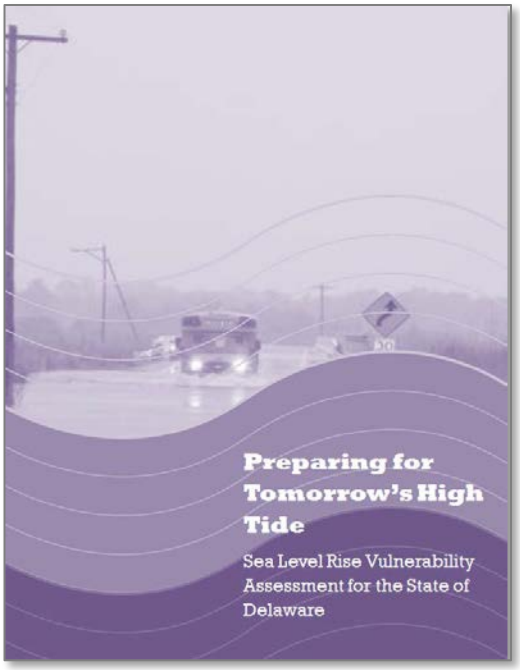


Figure 1-4. SLR planning scenarios for Delaware recommended by DNREC in 2009.



The three SLR planning scenarios identified in 2009 have been used throughout Delaware state and local government management and planning activities. The Delaware SLR Advisory Committee (SLRAC) was formed in 2010 and comprised of members from a wide variety of interest groups, including state agencies, local governments, citizen organizations, business organizations, and environmental organizations. The goals of the SLRAC were to: 1) assess Delaware's vulnerability to current and future inundation problems that may be exacerbated by sea-level rise, and; 2) to develop a set of recommendations for state agencies, local governments, businesses, and citizens to enable them to adapt programs, policies, and business practices and make informed decisions (DNREC, 2012). The SLRAC developed inundation maps for each of the Low (0.5 m), Intermediate (1.0 m), and High (1.5 m) scenarios and intersected those layers with locations of 79 different state resources. It was found that between 8 percent and 11 percent of the state's land area (including wetlands) could be inundated under the Low and High scenarios, respectively. The SLRAC ranked each state resource according to the potential impacts that could result from SLR and their relative importance to the state. For resources ranked as high risk concern, inundation would cause it to no longer function as designed and/or cause impacts statewide. For those of moderate risk concern, inundation would cause some loss of function and/or cause impacts on an approximately county-wide scale. Tables 1-1 and 1-2 list the state resources SLRAC found to be of high and moderate risk concern.

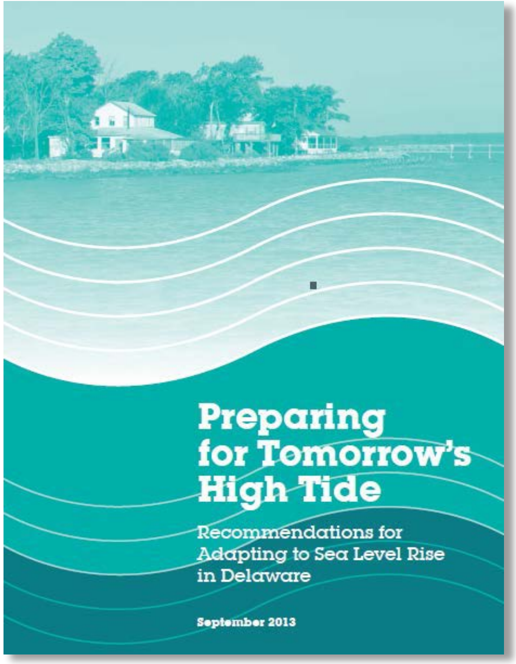
Table 1-1. State resources listed as high risk concern due to sea-level rise. Source: DNREC, 2012.

Heavy Industrial Areas	U.S. Fish & Wildlife Property	Port of Wilmington
Future Development Areas	Railroad Lines	Tourism and Coastal Recreation
Roads and Bridges	Tidal and Freshwater wetlands	Beaches and Dunes
Evacuation Routes	Coastal Impoundments	Dams, Dikes, and Levees
Habitats of Conservation Concern	Wells	Protected Lands Statewide

Table 1-2. State resources listed as moderate risk concern due to sea-level rise. Source: DNREC, 2012.

Residential Areas	Landfills and Nature Preserves	Septic Systems
Agricultural Land Conservation Easements	Wastewater Facilities	

Using information gathered from the SLR vulnerability assessment of state resources and other aspects of the Delaware Sea-Level Rise Initiative, the SLRAC developed a set of 55 recommendations that focused on building the necessary capacity for Delaware agencies, local governments, businesses and individuals to plan for and put into place strategies for responding to sea-level rise, described in the report, *Preparing for Tomorrow's High Tide: Recommendations for Adapting to Sea-Level Rise in Delaware* (DNREC, 2013). Rather than focus on any specific adaptation measures to act upon in Delaware (such as raising structures in flood-prone areas or identifying which communities should begin to relocate new development), the SLRAC focused on improving Delaware's adaptive capacity (i.e., to improve Delaware's ability to adapt as needed.) These include actions such as enhancing data collection, improving cooperation and communication across government levels, increasing regulatory flexibility, and expanding funding opportunities, among others. The SLRAC also held a workshop in March 2014 to develop specific implementation actions for each of the adaptation recommendations published in the 2013 report, results of which are documented in *Preparing for Tomorrow's High Tide: 2014 Workshop Proceedings and Interim Implementation Plan* (DNREC 2014a).



The 2009 SLR planning scenarios have been used in the Town of Lewes Hazard Mitigation and Climate Adaptation Action Plan, the Delaware Emergency Management Agency (DEMA) State Multi-Hazard Mitigation Plan, Wilmington Area Planning Council (WILMAPCO) Sea-Level Rise Transportation Vulnerability Assessment, and the Delaware Climate Change Impact Assessment, and are routinely referenced in documents and utilized in workshop and meetings throughout the state.

More immediately, the SLR planning scenarios identified by DNREC are included in *Executive Order 41: Preparing Delaware for Emerging Climate Impacts and Seizing Economic Opportunities from Reducing Emissions* by Governor Jack Markell in September 2013, Section 4c (full text included in Appendix A):

> *All state agencies shall consider and incorporate the sea level rise scenarios set forth by the DNREC Sea Level Rise Technical Committee into appropriate long-range plans for infrastructure, facilities, land management, land-use, and capital spending. DNREC shall periodically update the scenarios with the best scientific data available and distribute new guidance to state agencies.*

Delaware's efforts are proving beneficial to the education and preparedness of the state. In a 2014 poll conducted by DNREC DCP, 70 percent of Delawareans are completely or mostly convinced that sea-level rise is happening and is a threat, and 72 percent think action should be taken to address sea-level rise (Responsive Management, 2014). States at Risk: America's Preparedness Report Card, a collaboration of Climate Central and ICF International, assesses the level of action states have taken to deal with climate risks (States at Risk, 2015). Delaware received a combined B+ grade when evaluated on climate threat categories of Extreme Heat, Inland Flooding, and Coastal Flooding. Specifically in the Coastal Flooding category, which includes sea-level rise planning, Delaware received a "strong" score in addressing current risks and conducting vulnerability assessments, an "extensive" score in planning for adaptation, and a "fair" score in implementing resilience actions.

1.3 SLR Planning Scenario Update and Purpose of this Document

Specifically mentioned within the recommendations of the 2009 SLR Technical Workgroup and in Executive Order 41 (EO41), is the periodic update of the SLR planning scenarios. Since the SLR planning scenarios were released in 2009, the Intergovernmental Panel on Climate Change (IPCC) released their Fifth Assessment Report (AR5) in 2013 (IPCC, 2013) and the U.S. Global Change Research Program (USGCRP) released the second (2009) and third (2014) U.S. National Climate Assessments (Melillo et al., 2014). Reports on SLR analysis and risk assessments were also released by the National Oceanic and Atmospheric Administration (Sweet et al., 2017), the U.S. Army Corps of Engineers (USACE, 2011 and 2013), the U.S. Department of Defense (Hall et al., 2016), and the National Research Council (NRC, 2012). These reports and many other science-based research literature conclude that GMSL gradually rose in the 20th century and is currently rising at an increased rate.

In 2016, DNREC DCP and the Delaware Geological Survey (DGS) began a project to perform the first update of the Delaware SLR planning scenarios released in 2009. The project fit well within the mission of the DGS, which is, by statute, geologic and hydrologic research and exploration, and dissemination of information through publication and public service. This technical report is a product of that effort.

The purpose of the current technical report is two-fold:

1) To summarize the scientific peer-reviewed literature, technical reports, and international/national assessments, published since the 2009 Delaware SLR planning scenarios were released, regarding past and projected sea-level change, globally and within the Delaware region;
2) To recommend scenarios of future SLR based on sound scientific methodologies that state, county, and local agencies in Delaware can use for incorporating SLR into their planning activities.

Information in this document was gathered and reviewed by the Delaware Sea-Level Rise Technical Committee (TC), newly formed in 2016 organized by the DGS for the primary purpose of updating the 2009 SLR planning scenarios. The new SLR TC is comprised of scientists and planners, representing academia and state government, with knowledge and experience in Delaware coastal issues relating to sea-level rise, several of which had been members of the first Delaware SLR Technical Workgroup in 2009.

It is important to keep in mind the context of the question this report is designed to answer. Future SLR planning scenarios presented here are based on the best scientifically supported projections of future sea-level rise for the Delaware region that would be most appropriate for planning activities, given the current state of knowledge and uncertainty that exists. These are not predictions or forecasts of future SLR as realistic estimates would depend heavily on global greenhouse gas emissions for many years into the future, and therefore impossible to predict reliably or to assign meaningful probabilities. Nonetheless, these “scenario projections” can help planners, developers, coastal managers, and state regulatory agencies make more informed decisions based on the level of risk each project is willing to assume.

This technical report opened with an introduction on the effects of SLR on Delaware’s environment and economy and background on the planning activities that have previously occurred in the state. Chapter 2 discusses past sea-level rise observations, regionally and globally, and summarizes the latest scientific literature that has contributed to those observations. Chapter 3 reviews reports, academic articles and government assessments for future projections of sea-level rise to the year 2100. Chapter 4 distills the information down to a single set of future SLR scenarios recommended to be used in planning activities in Delaware, including some guidance on how to make the best use of these recommendations. Lastly, the report concludes with some remarks on when this topic should be revisited. FAQ boxes also are included throughout the report that provide supporting information to the main chapters.

FAQ 1. What are the contributing factors to sea-level change?

Change in sea-surface height is the combined result of a multitude of concurrent, ongoing processes. Some of the processes are global while others are more regionally or locally dependent. Time scales of these processes also significantly influence the measured sea-surface heights and vary greatly, from a few seconds (e.g., waves, currents) to hours (e.g., tides, storms), to months (e.g., lunar cycle, seasonal cycles) to even decades (e.g., sea-surface temperature and atmospheric circulation oscillations.) Although we typically treat it as such, sea level is far from temporally or spatially uniform (Kopp et al., 2015b; Meyssignac and Cazenave, 2012). However, major factors that influence sea level variations may be divided into three categories: 1) global mean sea-level rise, 2) regional differences to GMSLR, and 3) vertical land movement.

1) Global mean sea-level rise (GMSLR) refers to the increase that is currently observed in the average sea-surface height of all the Earth’s oceans. GMSLR is primarily attributed to changes in ocean volume due to two factors: land-based ice melt and ocean thermal expansion. 1) Melting of land-based glaciers and the continental ice masses such as the Greenland and Antarctic ice sheets, which are linked to changes in atmospheric temperature, can contribute significant amounts of freshwater input to the Earth's oceans; 2) a steady increase in global atmospheric temperature also increases the temperature of the ocean’s sea water, increasing the energy of the water molecules and the resulting volume of space the ocean assumes, therefore raising the height of the sea surface. Additionally, the amount of liquid-water storage on land (e.g., lakes, rivers, groundwater) can affect the amount of water mass in the oceans: a reduction in land water storage, for example due to groundwater pumping for water supply needs or natural precipitation patterns, causes an increase in the amount of water in the oceans. For the time period 1993 – 2010, satellite altimetry estimates of GMSLR agree with the sum of contributions from these three processes: thermal expansion, land-sea mass exchange, and land water storage (Church et al., 2013).

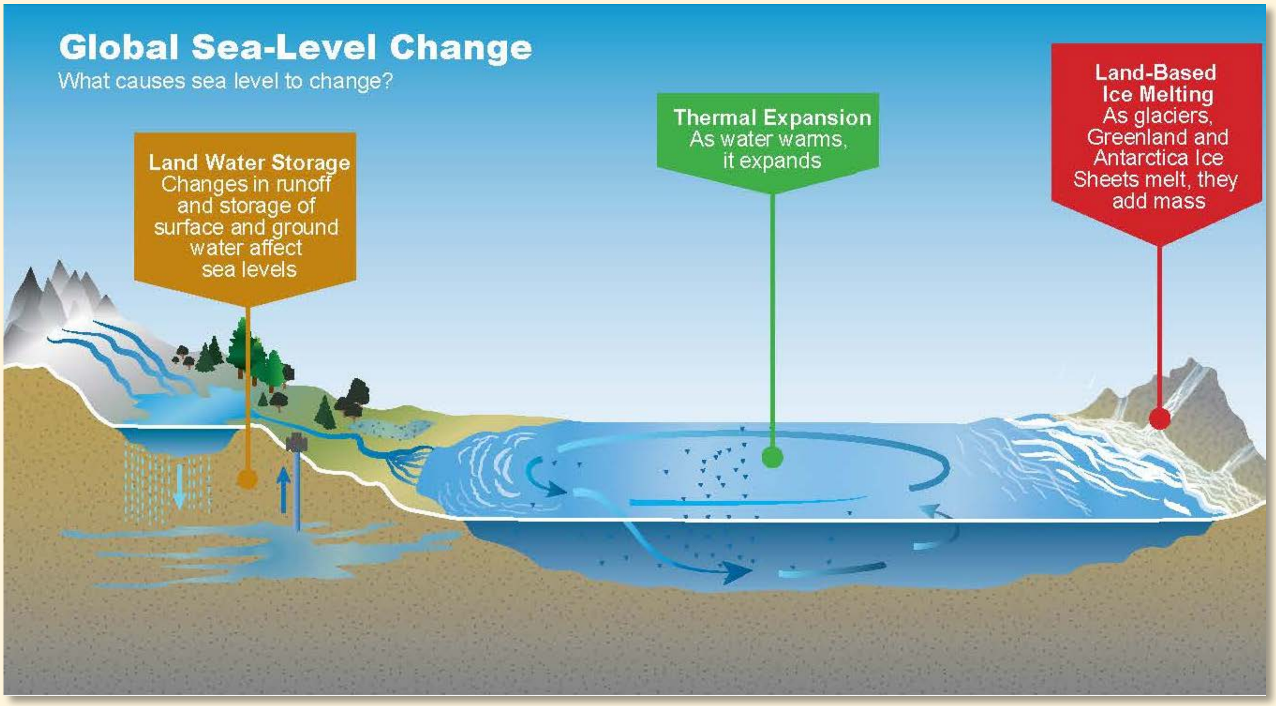


Figure FAQ1-1. Processes affecting changes in GMSL. Source: Hall et al. (2016).

2) Regional differences from GMSL – these processes can raise or lower the local sea surface as compared to the global mean. These processes include: 1) the weakening of the Gulf Stream causing a buildup of water along the U.S. mid-Atlantic coast (Rahmstorf et al., 2015; Ezer et al., 2013; Ezer, 2015); 2) weakening of the gravitational force of the Greenland and Antarctic ice sheets as they lose mass, causing sea-surface heights to rise along coastlines distal from the ice sheets (Mitrovica et al., 2011; Hay et al., 2015), and; 3) ocean-atmosphere climate patterns that can cause cyclic patterns of warmer water movement or storm surge (Kopp et al., 2015b).

There are many cyclical oscillations in ocean-atmosphere circulation patterns that could affect regional variability of sea-surface height. The El Niño Southern Oscillation (ENSO), occurring approximately every 3-7 years, causes significant changes in sea-surface heights through movement of warm tropical ocean waters and has a strong positive correlation to land water storage, when it typically rains more over the tropical oceans than over land (Nerem et al., 2010). Similar effects are felt during sea-surface temperature cycles of La Niña, Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). Likewise, coupled atmospheric circulation and sea-level pressure patterns, such as the North Atlantic/Arctic Oscillation (NAO/AO), Pacific-North American (PNA) pattern, and seasonal poleward-equatorward motion of the Intertropical Convergence Zone (ITCZ), can also affect sea-surface height variability. These types of processes significantly contribute to the interannual and interdecadal variability of sea levels and typically must be removed or approximated in order to discern other, underlying SLR signals.

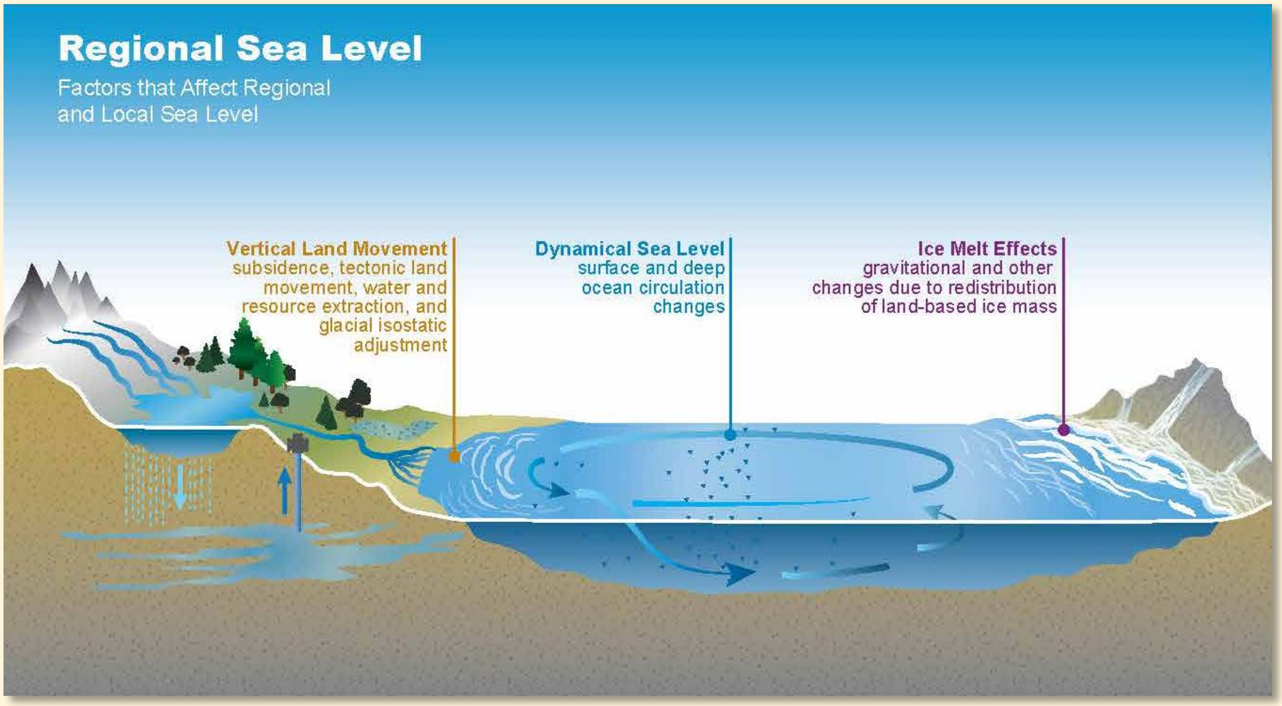


Figure FAQ1-2. Regional and local processes affecting sea level. Source: Hall et al. (2016).

3) Vertical Land Motion (VLM) – rather than increase the height of the ocean surface, terrestrial processes may also change the elevation of the land surface, thereby causing a relative increase or decrease in the observed sea-level rise. The dominant process here is glacial isostatic adjustment (GIA), which has been causing land subsidence in the mid-Atlantic region since the Last Glacial Maximum (Kopp et al., 2015a). More localized VLM processes are related to the consolidation of coastal plain sediments due to groundwater withdrawal (i.e., pumping) from lower aquifers and natural sediment compaction (Galloway and Burbey, 2011).

The Atlantic Coastal Plain, including Delaware, is relatively young geomorphic province that exhibits few erosional features. Relatively flat lying sediments are drapped over an underlying bedrock surface that dips to the southeast. Just south of the Delaware Piedmont, layered sediments are only a few hundreds of feet or less above bedrock, but thicken to several thousands of feet in southern Delaware. Thus, the sediment cover in northern Delaware generally too thin to show significant naturally compression under its own weight. However, in southern Delaware, there may be some subsidence due to compression and compaction of sediment, as well as subsidence due to groundwater withdrawal within Delaware and the adjacent Chesapeake Bay region (Holdahl and Morrison, 1974; Eggleston and Pope, 2013; Karegar et al., 2016; Andreasen, 2016). As water is extracted from an aquifer, the hydraulic pressure decreases, which induces flow inward from adjacent layers of mud, clays, or other aquifers. This process can lead to sediment consolidation, with the amount of net vertical displacement determined by the amount of water extracted, the compressibility of sediment, and thickness of the layers of sediment (Eggleston and Pope, 2013).

In Delaware, land subsidence due to groundwater pumping has been noted in the towns of Bowers Beach and Dover. Several previous studies have documented this phenomenon (Holdahl and Morrison, 1974; Davis, 1987; Galloway et al., 1999; Holzer and Galloway, 2005) but were not able to assign a reliable quantification of its influence.

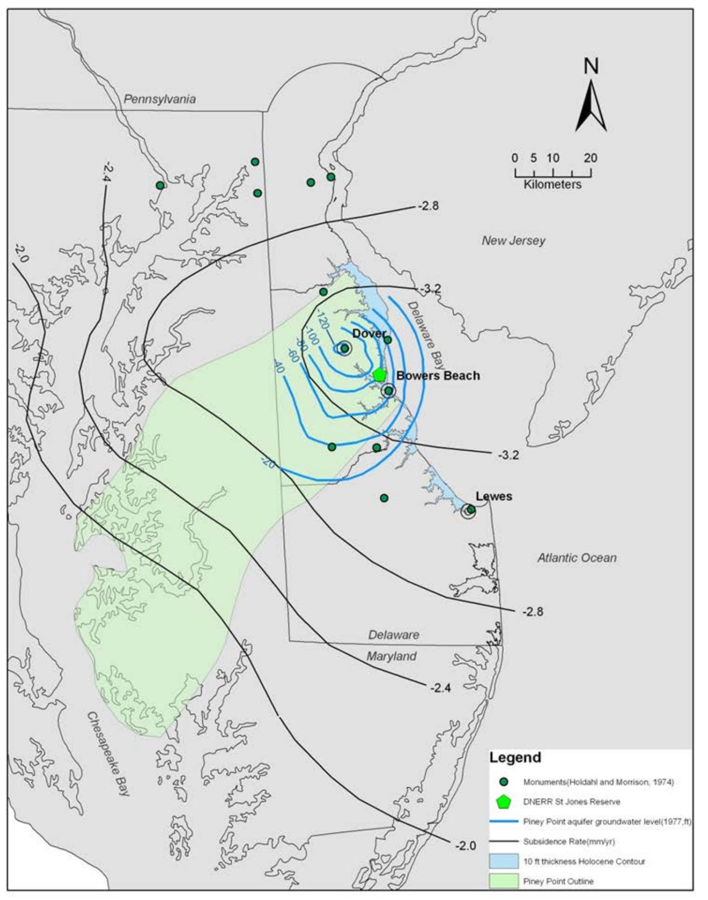


Figure FAQ1-3. Bowers Beach and Dover, DE region. Adapted from Holdahl and Morrison (1974).

Figure FAQ1-3 shows the Bowers Beach and Dover areas. Gray contour lines are taken from original research from Holdahl and Morrison (1974) showing vertical land displacement based upon extensive land-surveying over multiple years. The green polygon outlines the Piney Point aquifer, from which pumping has occurred. The dot centered within the blue contours is a groundwater monitoring well maintained by the Delaware Geological Survey, and the blue contours represent the modeled cone of depression.

Attempts to measure the land subsidence through GPS measurements has been an area of active research. In past studies (Snay et al., 2007; Sella et al., 2007; Karegar et al., 2016; NASA JPL, 2013), the uncertainties in vertical velocities were too large to reliably discern the impact of sea-level change. Research from Woppelmann and Marcos (2016) and Karegar et al. (2016) are using longer time series of GPS measurements and improved methods for accurately assessing VLM in relation to sea-level change.

There are, of course, many additional processes that affect sea levels on regional and local scales, for example, regional tectonic uplift, gravitational deformation to ocean basins due to changing masses of groundwater and surface water, discharge of freshwater from tributaries, sediment deposition, geomorphologic changes along the coast, and others. Most have little effect on sea-level change, particularly when compared to the influences of the aforementioned global and regional processes.

Looking into the future, trends in SLR along Delaware's coasts will be determined by a combination of all three factors (GMSLR, regional processes, and VLM) and is discussed more thoroughly in subsequent chapters in this report.

2. Observations of Sea-Level Change

2.1 Proxy Reconstructions of sea levels

Relative sea-level (RSL) reconstructions prior to the tide gauge instrumental period are important for predicting future trends, calibrating and constraining geophysical models of Earth's rheology and glacio-isostatic adjustment (Engelhart et al., 2011). To reliably predict future SLR, accurate records from the pre-instrumental era are needed to robustly test relationships with climate (Kopp et al., 2016a). Longer time series of proxy sea–level reconstructions are the fundamental basis for comparison with historical and present-day changes because they provide a benchmark against which the rates of SLR that have occurred over the last 100 to 150 years can be compared (Kemp et al., 2011; Nikitina et al., 2014).

The major cause of sea-level changes on millennia scales is exchange of water between the land and ocean. Glacial and interglacial cycles are characterized by temperature changes of ~ 10ºC. As temperature falls, water is removed from the oceans and stored on the land in the form of ice sheets and glaciers, resulting in a eustatic lowering of sea level. Sea level is further lowered through the reduced volume of ocean waters caused by lower temperatures. Upon deglaciation, these processes are reversed and sea level rises. Figure 2-1 shows global mean sea level, temperature, and CO_2 for the past 450,000 years, displaying oscillations between glacial and interglacial phases. Elevations are relative to current sea level.

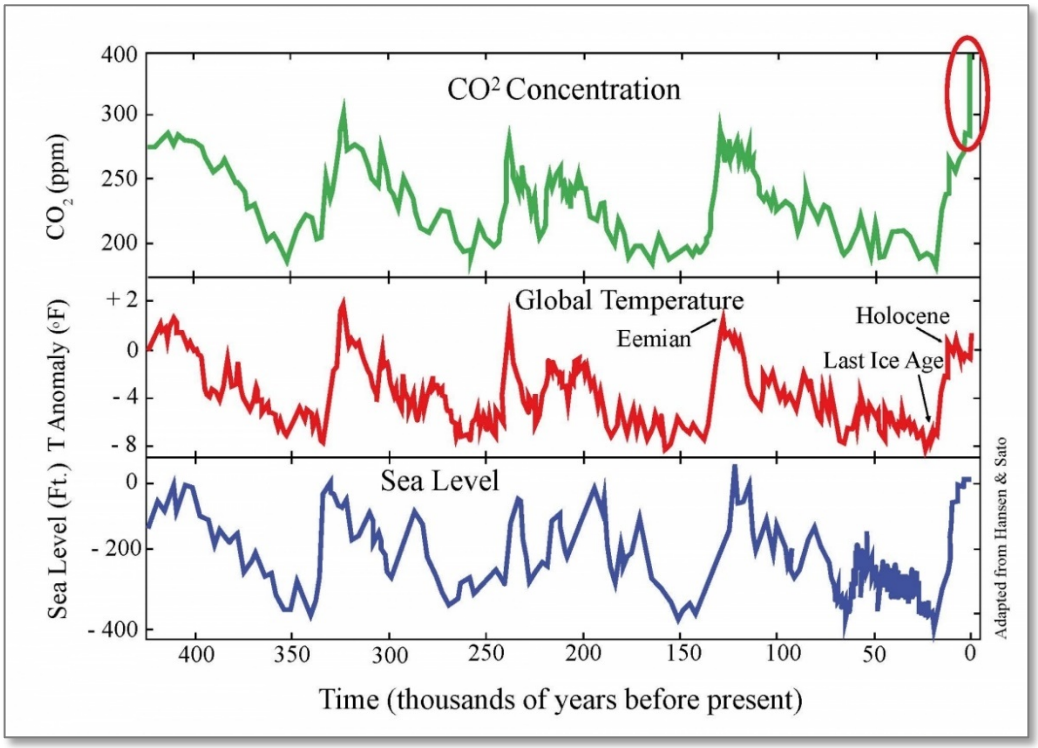


Figure 2-1. Global mean sea level, temperature, and CO_2 concentrations, showing several glacial-interglacial cycles over the past 450,000 years, based on Antarctic Vostok ice-core data. The red oval highlights the most recent increases in CO_2. Source: John Englander, http://www.johnenglander.net.

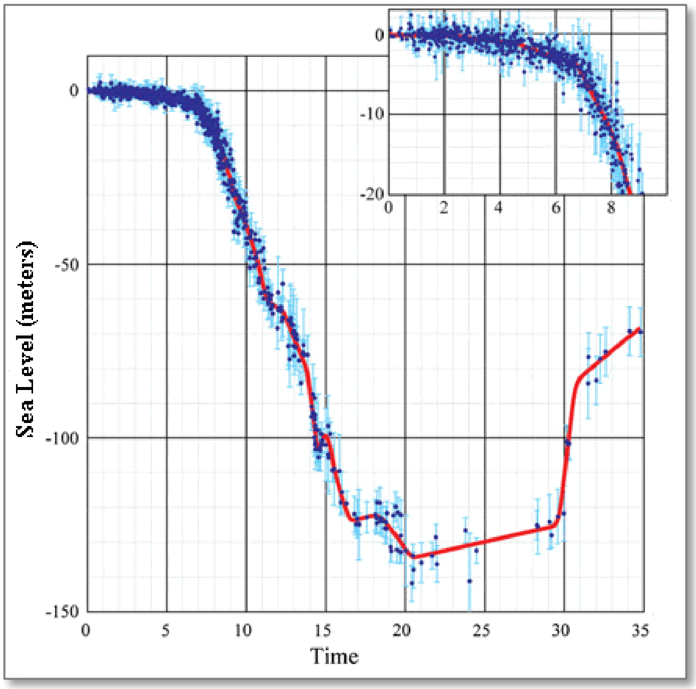


Figure 2-2. Historic far-field sea-level data points and age uncertainty bars over the past 35,000 years. Inset focuses past 9,000 years. Modified from Lambeck et al. (2014).

Loading and unloading of the Earth's crust as a consequence of ice sheet growth and decay can introduce large vertical movements in land level, known as isostatic movement (Engelhart et al., 2011). Since the LGM, ~20,000 – 26,000 years ago when the Laurentide ice sheet reached its maximum lateral extent covering much of North America, approximately 50 million km^3 of ice have melted from land-based ice sheets (about two-thirds of the ice existing at that time), raising RSL in regions distant from the major glaciation centers (far-field sites) by approximately 120 m (Peltier and Fairbanks, 2006). Sea levels did not rise uniformly throughout this time period; SLR was quicker than usual during meltwater pulses. Figure 2-2 shows the variable rate of SLR for the past 35,000 years based on reconstructed data observed at several sites far-field from ice margins (Lambeck et al., 2014). Elevations are relative to current sea level.

The massive Laurentide ice sheet had thicknesses up to 4 km (Dyke, 2004). Areas under this thick ice cover were depressed while the ice sheet was in place, but subsequently experienced uplift as the ice sheet melted. Conversely, at the margins of the ice sheet and beyond, land was uplifted during the glaciations as a forebulge, which subsequently collapsed during deglaciation (i.e., GIA). Due to the nature of Earth's slow response to loading, this compensatory adjustment of land level continues to be an important factor today, several thousand years after the Laurentide ice sheet vanished (Peltier, 2004). The general process is diagramed in Figure 2-3.

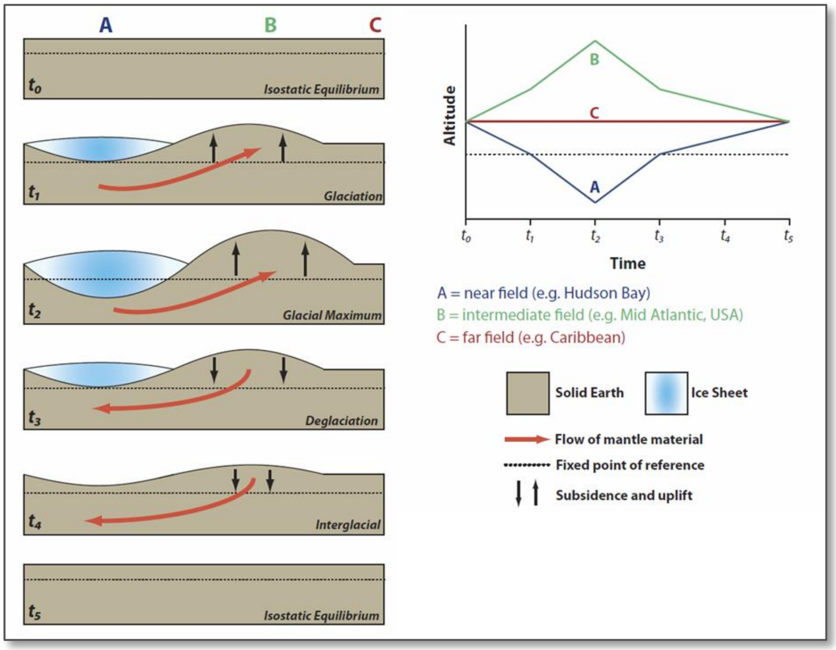


Figure 2-3. Diagram of glacial isostatic adjustment (GIA), which has been occurring since the retreat of the Laurentide ice sheet. Source: Khan et al. (2015).

Delaware is close to the southern limit of the Laurentide ice sheet and records a general trend of rising RSL throughout the last 10,000 years as gradual GIA subsidence from the collapse of the forebulge complemented the eustatic increase in ocean volume (Khan et al., 2015). The Delaware sea-level history has been reconstructed using salt-marsh sediments that preserve the elevation of past sea level and sea-level indicators, such as plant macrofossils and microfossils (Nikitina et al., 2014). Nikitina et al. (2014) focused on the last 2,200 – 150 years before present (BP) and improved upon existing data by using high-resolution surveying methods, AMS radiocarbon dating of *in-situ* plant macrofossils collected immediately above the basal contact between pre-Holocene sand and salt-marsh sediments, foraminifera microfossils as sea-level indicators, and by accounting for tidal range changes through time (Hall et al., 2013). Nikitina et al. (2014) estimated the rate of RSL rise in the upper (1.26 ± 0.33 mm/yr) and lower (1.30 ± 0.36 mm/yr) Delaware Bay during the past 2,000 years, depicted in Figure 2-4. Correction for changes in tidal range through time removed the disparity in rate between the upper and lower Delaware Bay that had previously been postulated (Engelhart and Horton, 2012). After paleotidal correction, the rates of RSL rise estimated for the Delaware Bay (1.25 ± 0.27 mm/yr) correlate with the ~1.3 mm/yr rate reported for New Jersey, Maryland, and Virginia, and confirm that the maximal ongoing forebulge collapse along the U.S. Atlantic coast is focused on the mid-Atlantic region (Nikitina et al., 2014).

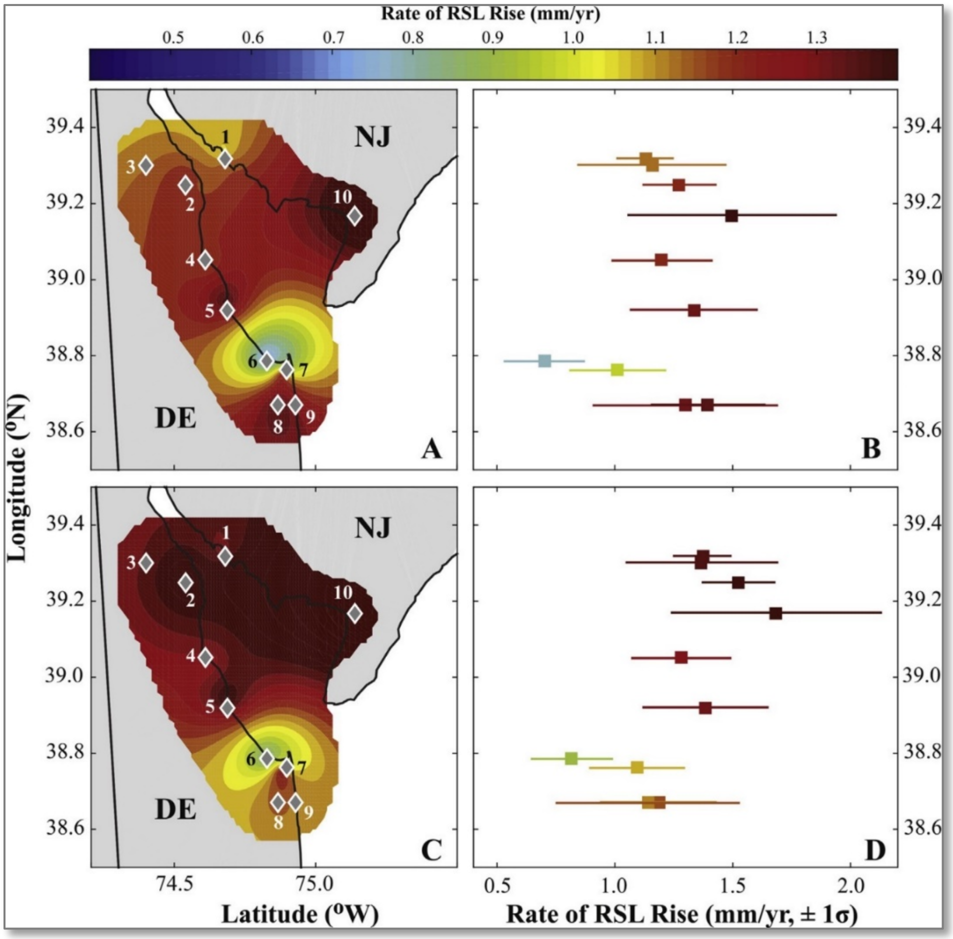


Figure 2-4. Average relative sea-level rise field (2200 - 150 years BP) estimated for the entire study area (A) without and (C) with paleotidal range correction. Uncolored areas exhibit a posterior variance >10% of the prior variance. (B, D) This field is sub-sampled to obtain rates for individual sites. (1) Sea Breeze; (2) Smyrna; (3) Leipsic River; (4) Bowers; (5) Slaughter Beach; (6) Great Marsh/Broadkill Beach; (7) Cape Henlopen; (8) Horse Island Marsh/Marsh Island; (9) Rehoboth Bay; (10) Jake's Landing. Source: Nikitina et al. (2014).

2.2 Tide Gauge Observations of SLR

Global Observations

For the time period from the late 19th century through to present time, commonly referred to as the instrumented period, sea levels have been monitored by a network of tide gauges throughout the world, although some individual gauges go back as far as the early 1700s (Jevrejeva et al., 2008; Church and White, 2011; Jevrejeva et al., 2014b). Data from tide gauges are influenced by any process that changes the relative difference between the water surface and a reference level physically marked on the tide gauge, such as surge and waves from storms, land subsidence, changes in the geomorphic environment, ocean thermal expansion, and many other processes. Tide-gauge data are considered direct measurements of relative sea-level heights and can be statistically temporally aggregated or spatially interpolated to compute long-term rates of change or gridded continuous water surfaces.

Many studies have analyzed the global tide gauge network to determine estimates of GMSLR rates. When computing the long-term rates of change in the tide gauge record, it is important to understand additional signals that may be inherent within the record. To minimize influences on the long-term trend of SLR from long-period atmospheric-oceanographic cycles (e.g., ENSO, PDO, AMO), a 50- to 60-year period of record, or longer, would be ideal to determine long-term linear trends (Zervas, 2009; Chambers et al., 2012). Additionally, numerous studies have noted a near-linear background VLM signal in the U.S. mid-Atlantic region occurring over the past couple of millennia from glacial isostatic adjustment, tectonics, and natural coastal plain compaction (Nikitina et al., 2014; Kopp et al., 2016; Kemp et al., 2013; Engelhart et al., 2011; Zervas et al., 2013, Miller et al., 2013). These background signals should be accounted for in the sea-level time series record in order to identify other ocean or climate forcing that may be driving variations in sea levels.

Table 2-1 and Figure 2-5 shows various research studies that analyzed long-term tide gauge records and compare linear rates of GMSLR for the early part of the century to the later part. Disagreements among analyses in the estimates of GMSL, especially in the early part of the century, could result from 1) differences in analysis and/or reconstruction techniques, and; 2) differences in tide gauge selection and quality control of the data (Hamlington and Thompson, 2015).

Table 2-1. Linear GMSLR rates since the beginning of the 20th century based on tide gauge data. Included are GMSLR rates for the years 1993 to present to compare against satellite estimates. Uncertainties represent 95% confidence interval, unless otherwise specified. SLR rates are in mm/yr.

Tide Gauge Study	**Date Range**	**GMSLR rate**	**Satellite Era Date Range**	**Satellite Era SLR rate from tide gauges**
Church et al. (2013)	1901-2010	1.7 ± 0.2	1993-2010	3.2 ± 0.4
Church and White (2011)	1900-2009	1.7 ± 0.2	1993-2009	2.8 ± 0.8
Ray and Douglas (2011)	1900-2008	1.7 ± 0.2	1993-2007	2.8
Jevrejeva et al. (2014b)	1900-1999	1.9 ± 0.3	1993-2010	3.1 ± 0.6
Hay et al. (2015)	1901-1990	1.2 ± 0.2 (90%)	1993-2010	3.0 ± 0.7 (90%)
Dangendorf et al. (2017)	1902-1990	1.1 ± 0.3 (1σ)	1993-2012	3.1 ± 1.4 (1σ)

The calculation of Church and White (2011) of a GMSLR rate of 1.7 ± 0.2 mm/yr for 1900 – 2009 is the commonly cited value in many assessments and reports (USACE, 2013, 2014; Parris et al., 2012; Church et al., 2013). The rate of GMSLR is significantly larger in recent years than in the earlier part of the century. IPCC AR5 states that it is very likely (90 percent confidence) that global sea levels rose at the rate of 1.7 ± 0.2 mm/yr from 1901-- 2010 on average, and 3.2 ± 0.4 mm/yr from 1993 – 2010 (referencing the values given by Church and White (2011).) The difference in rates derived from tide gauges versus satellite altimetry is partly due to the different time periods over which these measurement systems average GMSL, and partly due to the higher interannual variability of coastal sea levels, which are averaged-out when computing the global mean. When carefully selected tide records are compared to satellite data for the same time period, they predict similar trends in global mean sea level (Prandi et al., 2009; Dean and Houston, 2013; Ezer, 2013).

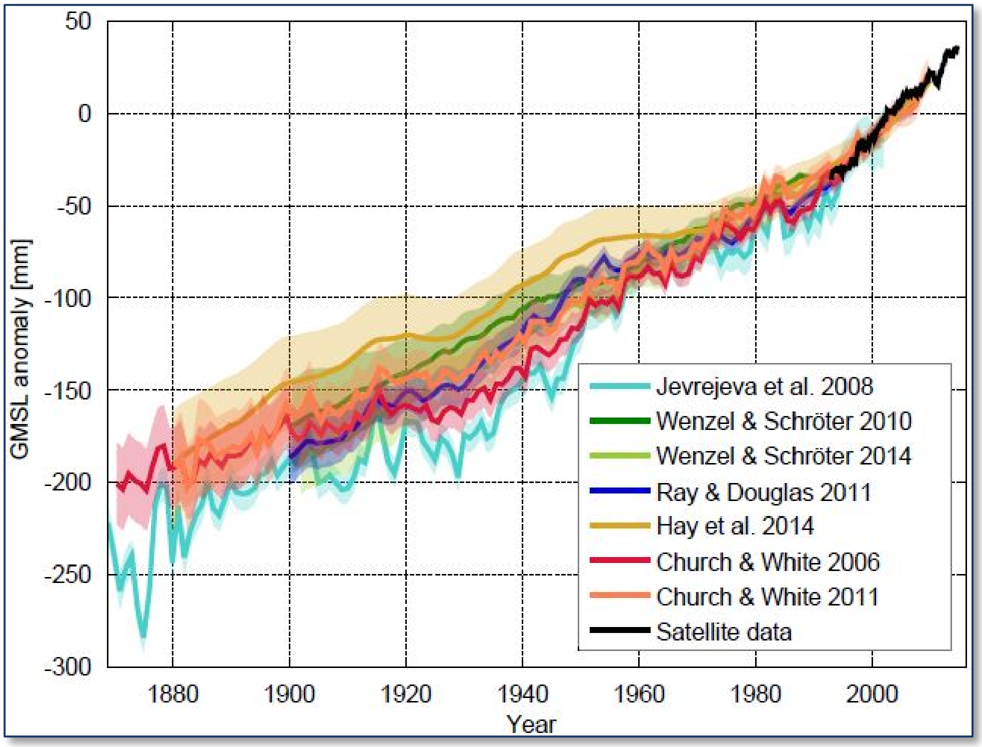
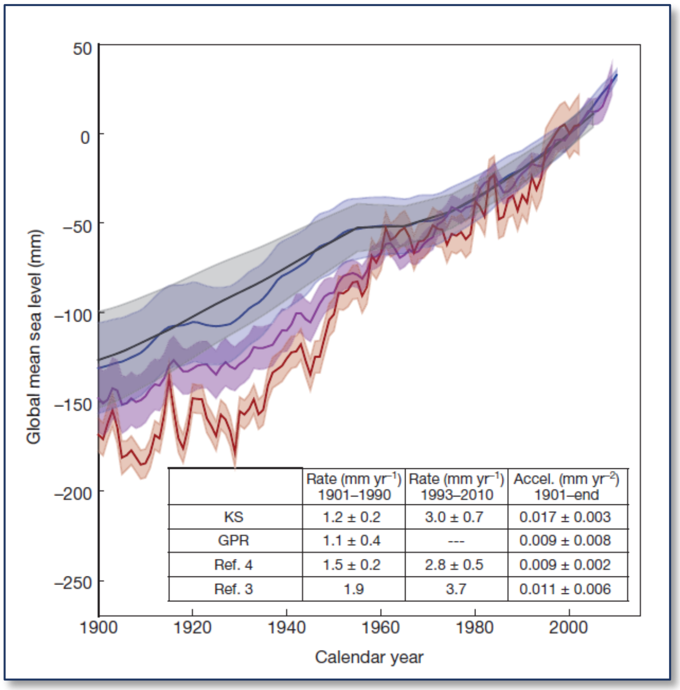


Figure 2-5. Comparison of GMSL curves from the later part of the 19th century to present from several tide gauge studies. GMSL values are relative to satellite-era average. Shaded regions represent error bars (where possible) which decrease as the number of observation points increases in later years. Source: http://www.realclimate.org/index.php/archives/2015/01/a-new-sea-level-curve/

In their analysis of tide gauge records, Church and White (2011) found a statistically significant acceleration in GMSLR from 1900 through 2009 of 0.009 ± 0.003 mm/yr, an observation supported by the work of Ray and Douglas (2011), Jevrejava et al. (2008, 2014), Hogarth (2014), Hay et al. (2015), and Dangendorf et al. (2017). Extending this to the Atlantic coast of North America, recent studies indicate that rates of SLR along the U.S. mid-Atlantic region have accelerated in recent decades faster than the global mean, possibly due to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and hence weakening of the Gulf Stream (Boon, 2012; Ezer and Corlett, 2012; Sallenger et al., 2012; Ezer et al., 2013). Low-lying coasts in the mid-Atlantic region have also experienced a significant increase in the frequency of coastal flooding in recent years, perhaps related to processes associated with the increase in SLR (Sweet et al., 2014). The existence of a mid-Atlantic hotspot was statistically validated by Kopp (2013), although he determined that we would need “about two decades of additional observations” in order to determine if the hotspot is due to a long-term trend or part of an oceanographic or atmospheric cyclical pattern. Davis and Vinogradova (2017) investigated U.S. East Coast SLR accelerations by modeling the separate and combined effects of primary sources of SLR, all of which vary geographically, such as the melting of the Antarctic and Greenland ice sheets, ocean dynamic processes, and variations in atmospheric surface pressure. Significant correlations of acceleration were found for coastal areas south of 40° N latitude to melting of the Greenland ice sheet, and areas north of 40° N latitude to ocean dynamic processes. (Delaware lies at approximately 39° N latitude and the local tide gage record may be influenced by both.)



	Rate (mm yr^{-1}) 1901–1990	Rate (mm yr^{-1}) 1993–2010	Accel. (mm yr^{-2}) 1901–end
KS	1.2 ± 0.2	3.0 ± 0.7	0.017 ± 0.003
GPR	1.1 ± 0.4	---	0.009 ± 0.008
Ref. 4	1.5 ± 0.2	2.8 ± 0.5	0.009 ± 0.002
Ref. 3	1.9	3.7	0.011 ± 0.006

Figure 2-6. Tide gauge reconstructions showing linear trend and acceleration. Shaded regions represent uncertainty. Source: Hay et al. (2015).

However, Hay et al. (2015) note that summing the estimates of the contributing factors to GMSLR during the past century (ocean thermal expansion, glacier and ice sheet mass loss, and changes in land water storage), falls short of the 1.6 – 1.9 mm/yr estimates of GMSLR derived from most previous tide gauge studies. They developed a probabilistic framework, combining tide gauge data with physics-based and model-derived geometries of the contributing signals. Benefits are: 1) it accommodates spatially sparse and temporally incomplete sampling of records; 2) it is a probabilistic framework for uncertainty propagation, and; 3) it can correct for a distribution of GIA and ocean models. Estimates of GMSLR are 1.2 ± 0.2 mm/yr for 1900 – 1990 using a Kalman Smoothing (KS) technique, significantly lower than previous estimates but consistent with values determined by summing the individual contributions (i.e., it closes the 20th century global mean sea-level budget.) The rate of GMSLR over the satellite era (1993 – 2010) was found to be 3.0 ± 0.7 mm/yr, consistent with numerous other current estimates, resulting in acceleration of 0.017 ± 0.003 mm/yr^2, implying GMSLR acceleration has been underestimated in previous works.

In an attempt to reconcile tide gauge analysis with historical reconstructions of GMSLR, Cahill et al. (2015) employed a new statistical technique, Errors-In-Variables Integrated Gaussian Process (EIV-IGP), to model the past 2000 years integrating proxy reconstructions and tide gauge records. This takes into account the continuous and dynamic evolution of sea-level change with full consideration of all sources of uncertainty in both datasets. Using the same tide gauge dataset as in Church and White (2011), the age uncertainties are small enough to use a Simple Integrated Gaussian Process (S-IGP) model, resulting in modeled GMSLR rates as displayed in Figure 2-7. GMSLR rates show continuous acceleration during the 20th century and are consistent with the generally lower estimates of Hay et al. (2015) over the 1900 – 1990 time period, although estimates during the satellite era seem to be less than Hay et al. (2015) and other studies.

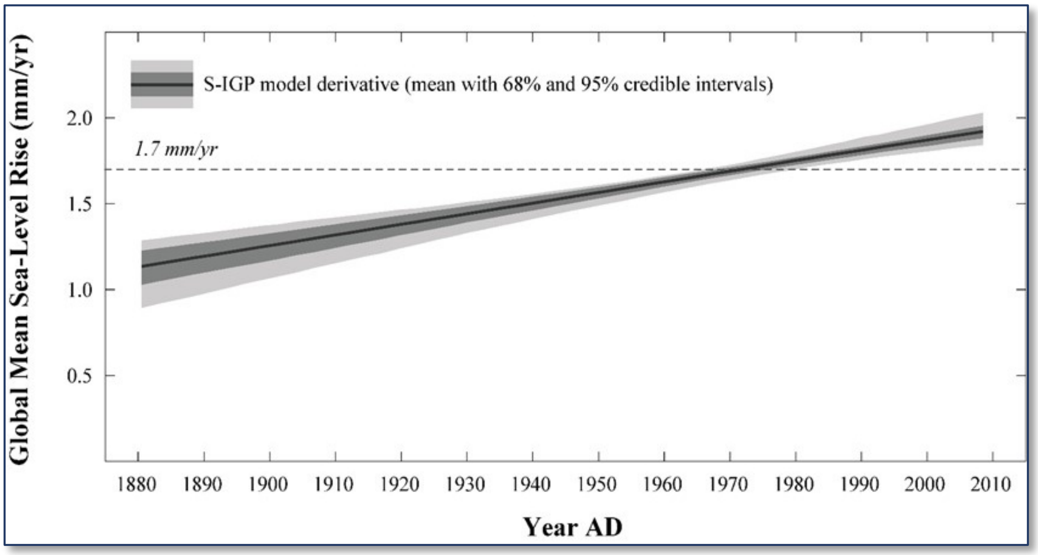


Figure 2-7. Rate of GMSLR calculated as the derivative of the S-IGP model. Shading denotes 68% and 95% credible intervals for the posterior mean of the rate process. Source: Cahill et al. (2015).

Delaware Regional Observations

In the United States, the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) has been monitoring water levels along the coasts for over 150 years. Stations part of the National Water Level Observation Network (NWLON), have been placed in locations to minimize the effects of waves and currents. They are continuously resurveyed to nearby vertical benchmarks and include a high level of quality control on operational maintenance and data products. Although NWLON's primary purpose is for marine safety and ship navigation, a significant number of these stations have period of records long enough to perform statistical analysis of the trends and patterns of observed sea levels.

Distribution of NOAA tide gauges generally uniformly covers both the Atlantic and Pacific coasts, the northern Gulf of Mexico, the southern coast of Alaska, and the Hawaiian Islands. Figure 2-8 maps the locations of the NOAA tide gauges with at least 30 years of record, colored by the relative SLR rate during that time. Dots colored green represent small rates of SLR (less than 3 mm/yr). Yellow (3 – 6 mm/yr), orange (6 – 9 mm/yr), and red (9 – 12 mm/yr) show graduated increases in sea levels, whereas the blue and violet colors (negative trends) represent decreases in sea levels. The differences in SLR rates are predominantly due to changes in the rates of land subsidence or land uplift (NOAA, 2016b). Along the U.S. East Coast, SLR rates in the mid-Atlantic are higher, on average, than rates in the Northeast and Southeast regions, demonstrating the hotspot moniker explained in the previous section of this report.

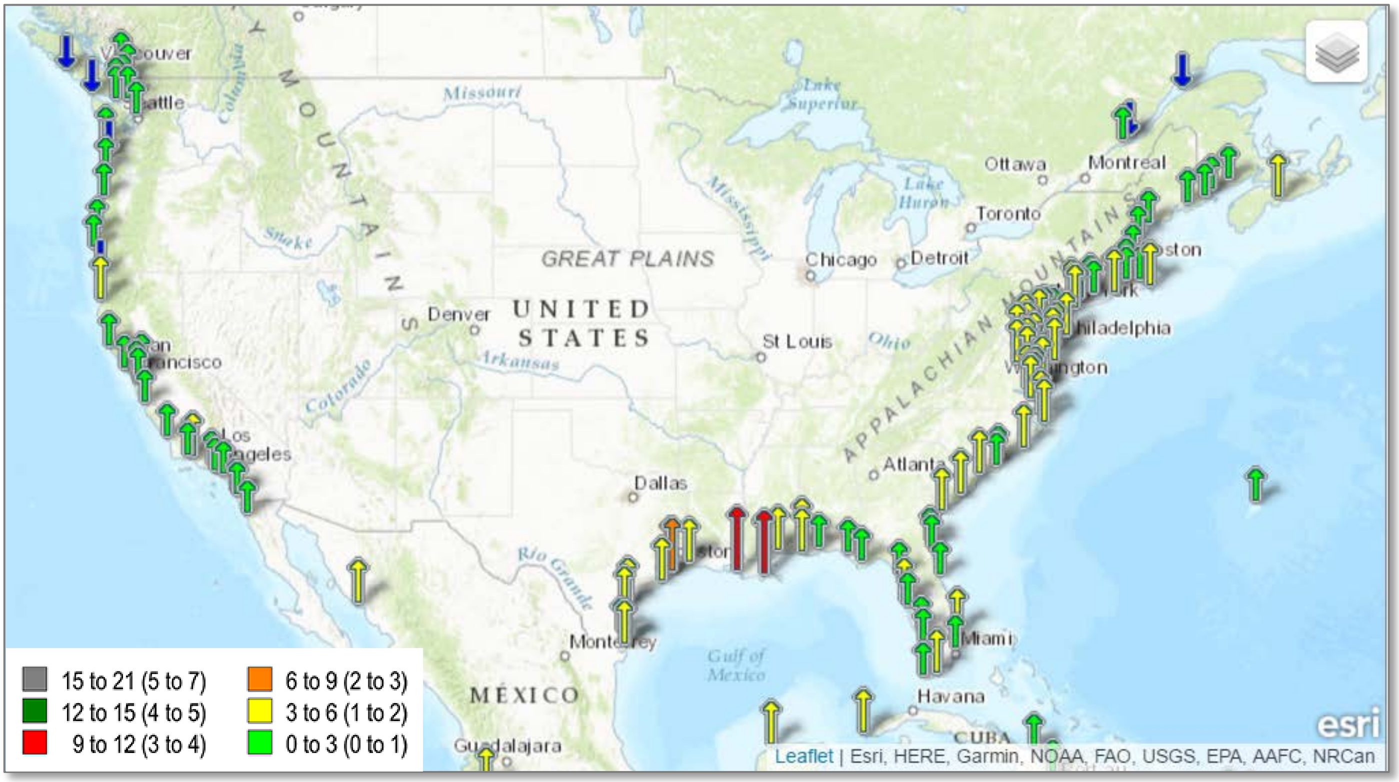


Figure 2-8. Map above illustrates U.S. regional trends in sea level, with the colored arrows representing the direction and magnitude of change. Units are in mm/yr (feet/century). Rates of SLR are computed over the period of record at each station. Differences are primarily due to changes in the rates and sources of regional or local land surface vertical motion. Source: NOAA CO-OPS Tides and Currents Sea Level Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

Table 2-2 lists the long-term linear trend and confidence intervals for NOAA stations with periods of record of 39 years or more in the SLR hotspot region around Delaware. All of these stations are experiencing SLR rates greater than the GMSLR rate of 1.7 mm/yr. The linear rates were computed using monthly mean sea levels following the methodology in Zervas (2009) throughout the station's entire period of record. This methodology takes into account the seasonality and autocorrelation of the monthly mean sea-level time series. Confidence intervals are determined by a combination of variance in the monthly records and by the number of years of record. In general, the longer the record, the narrower the uncertainty range. Ocean City Inlet, MD, and Wachapreague, VA, measure the highest SLR rates as well as the most recent periods of record in this region, aligning with increases in GMSLR in recent years. However, they also have the shortest periods of record leading to broad uncertainty ranges.

Table 2-2. SLR rates and confidence intervals for NOAA NWLON stations near the Delaware coast. Stations are listed in approximate order from north to south. Source: NOAA CO-OPS Tides and Currents website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Station Name	Period of Record	Number of Years	Liner SLR Trend and 95% Confidence Interval (mm/yr)
Philadelphia, PA	1900-2016	117	2.93 ± 0.19
Atlantic City, NJ	1911-2016	106	4.07 ± 0.16
Cape May, NJ	1965-2016	52	4.55 ± 0.53
Lewes, DE	1919-2016	98	3.42 ± 0.24
Reedy Point, DE	1956-2016	61	3.53 ± 0.49
Annapolis, MD	1928-2016	89	3.55 ± 0.20
Cambridge, MD	1943-2016	74	3.70 ± 0.32
Ocean City Inlet, MD	1975-2016	42	5.58 ± 0.92
Wachapreague, VA	1978-2016	39	5.38 ± 0.79

Figures 2-9 and 2-10 display the monthly mean sea-level observations and the computed linear trend throughout the period of record for both of the NOAA NWLON tide stations in Delaware, namely Lewes Breakwater Harbor and Reedy Point. The average seasonal cycle was first removed from the monthly mean observations and the linear trend calculated following the methodology in Zervas (2009). The SLR rate at Lewes is 3.42 ± 0.24 mm/yr over the past 98 years; Reedy Point is 3.53 ± 0.49 mm/yr over the past 61 years.

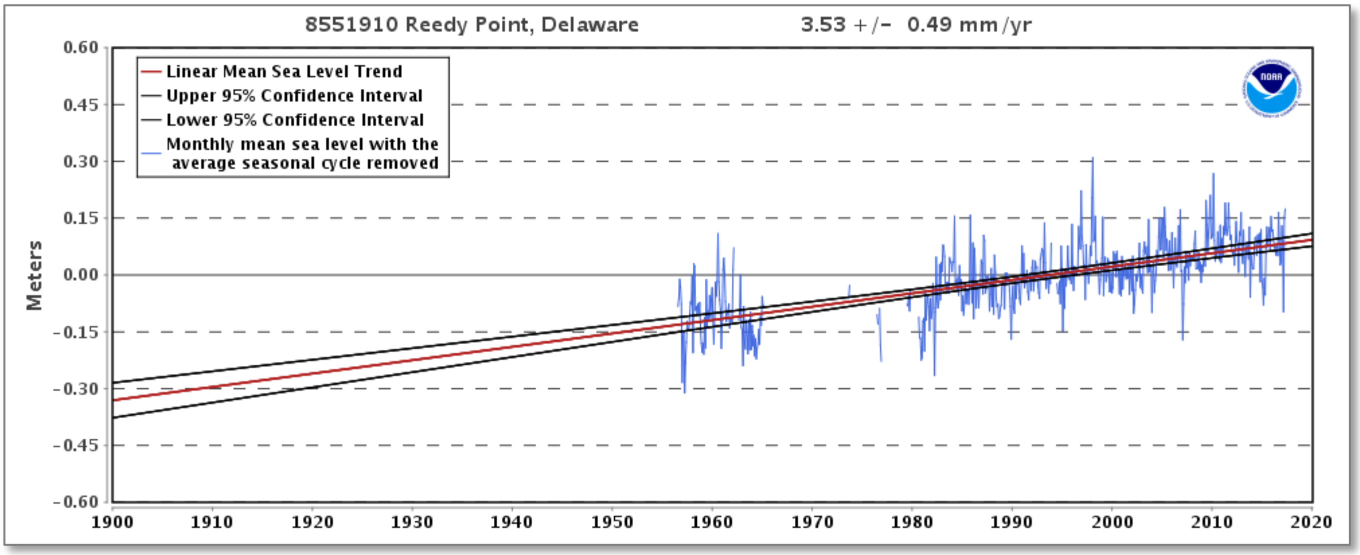


Figure 2-9. Monthly mean sea level for NOAA Reedy Point tide station from 1957 through 2016. Linear MSL trend and 95% confidence intervals shown in red and black, respectively. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents Sea Level Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

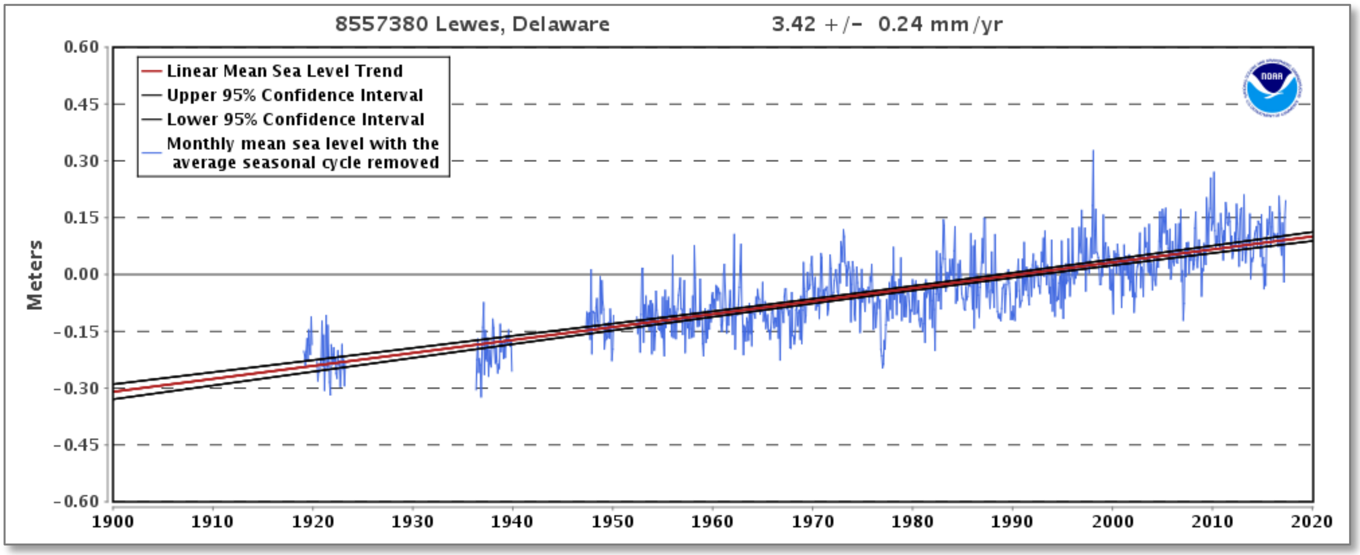


Figure 2-10. Monthly mean sea level for NOAA Lewes tide station from 1919 through 2016. Linear MSL trend and 95% confidence interval shown in red and black, respectively. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

At the Lewes tide gauge, the linear rate of 3.42 mm/yr equates to about 0.335 m (13.2 in) of sea-level rise since 1919 and about 0.400 m (15.7 in) since 1900 (through to year 2016.) This is about twice the amount of GMSLR observed during that same time period. At the Reedy Point tide gauge, the linear rate of 3.53 mm/yr equates to about 0.215 m (8.5 in) since 1956. The observed SLR linear rate at Reedy Point is also approximately twice the GMSLR rate but should not be extended backward to 1900 due to the large gap of years between the start of the station period of record and year 1900.

In addition to long-term gradual change in mean sea level, it is important to note the considerable variability of sea level at other temporal scales. On very short time scales, sea-level changes can be significantly large caused by the tides, storm surge, winds, waves, discharge from nearby tributaries, and many other factors. To identify longer term trends, observed sea levels are averaged to monthly time steps. Figure 2-11 shows the average monthly cycle (commonly referred to as the seasonal cycle) for the Lewes tide gauge throughout its period of record. This underlying seasonal cycle emerges from the regular fluctuations that occur seasonally each year in factors such as coastal atmospheric and ocean temperatures, ocean salinities, ocean currents, river discharge from precipitation, and prevalent wind direction and speed (Zervas, 2009). The seasonal cycle at Lewes peaks in late summer/early fall (September) and drops to a minimum in mid-winter (January.) This general pattern is consistent among other tide gauges along the mid-Atlantic region, primarily driven by local thermal expansion of coastal waters. In statistical analysis investigating interannual and longer time period patterns, the seasonal cycle is usually removed first to improve the accuracy of trend estimation and other statistical model parameters (Foster and Brown, 2014).

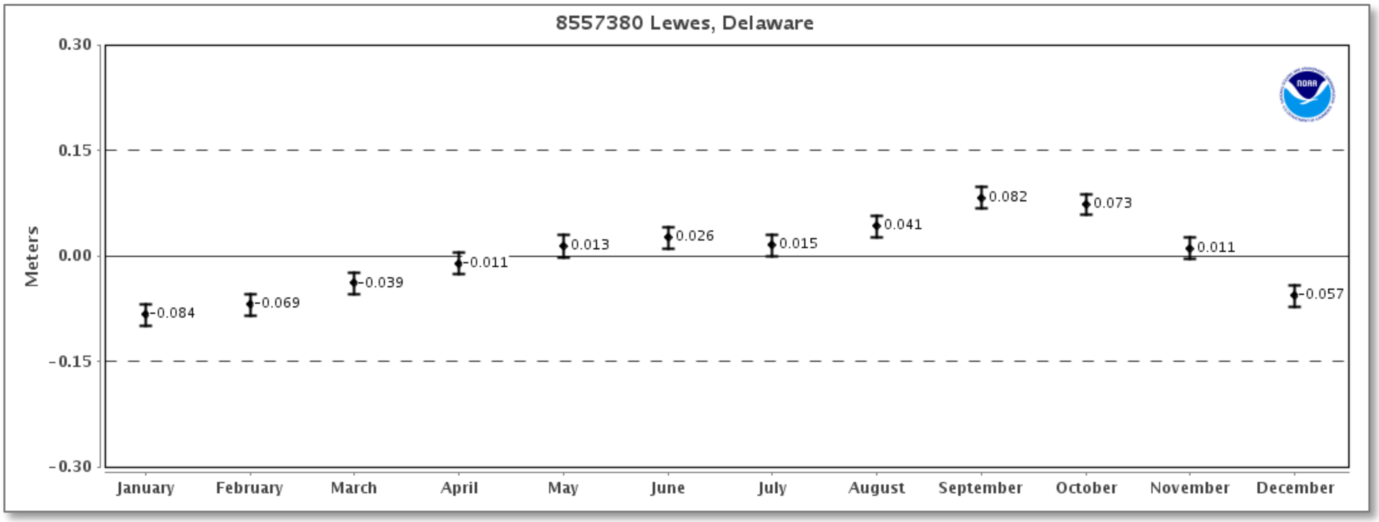


Figure 2-11. Average seasonal cycle of sea level for NOAA Lewes tide gauge. Vertical bars represent 95% confidence interval. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

For the time period 1990 through 2016, monthly mean sea level observations at the Lewes tide gauge deviated from the seasonal cycle up to 0.30 m / 0.98 ft, as depicted in Figure 2-12. The deviations are computed after first removing the seasonal cycle as well as the linear trend as derived from Zervas (2009), and plotted relative to NTDE 1983-2001 MSL. Even if we ignore the one event that reached 0.30 m, since it happened during the extraordinarily strong El Niño of 1997-98, deviations from the monthly mean reached or nearly reached ± 0.15 m / 0.66 ft on multiple occasions, which is significantly larger than what would be expected following the SLR linear trend alone. Therefore, when interpreting long-term trends in sea-level observations, it is important to realize that the variability in monthly or annual mean sea levels, influenced by variations in large-scale oceanographic or atmospheric conditions, can easily mask the expected sea-level rise from the trend alone.

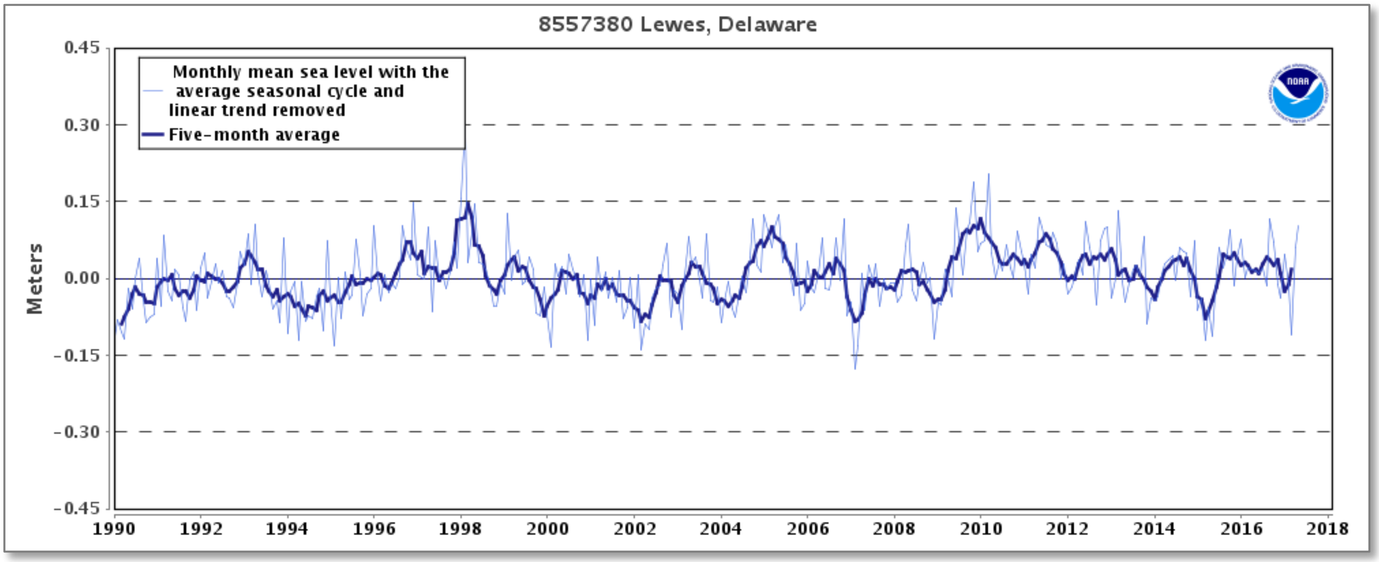


Figure 2-12. Interannual variability for NOAA Lewes tide gauge from 1990 through 2016 after seasonal cycle and linear trend are removed. Dark line shows running 5-month average. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

Combining tide gauge and historical reconstructions

Specifically for this report, new models were run to reconstruct historical RSL in the Delaware Bay using local tide gauge data, paleotidal-corrected information from Nikitina et al. (2014), and other sea-level indicators preserved in salt marsh sediments. A new sea-level evolution reconstruction was produced by the Bayesian hierarchical model developed in Cahill et al. (2015), which showed that the rate of RSL rise varied in time and space in this region. Reconstructions were produced for the past 4,000 – 5,000 years for both the Inner Delaware Bay and Outer Delaware Bay regions, as spatially defined in Engelhart and Horton (2012), shown in Figure 2-13.

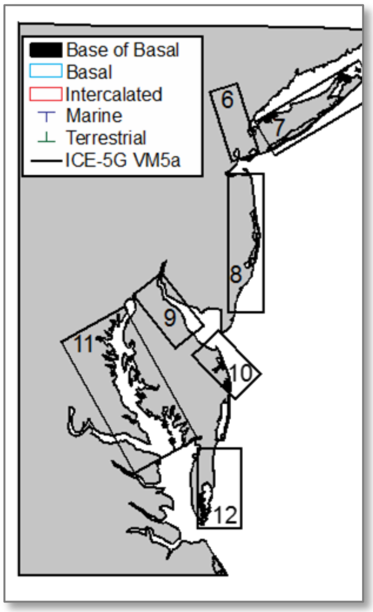
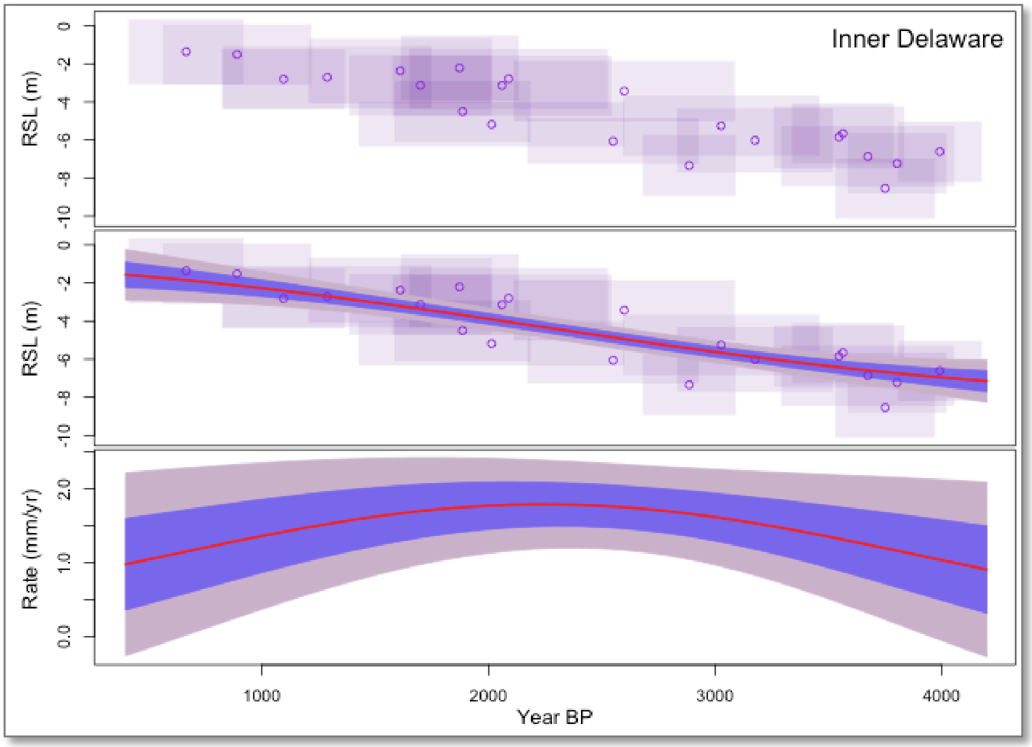
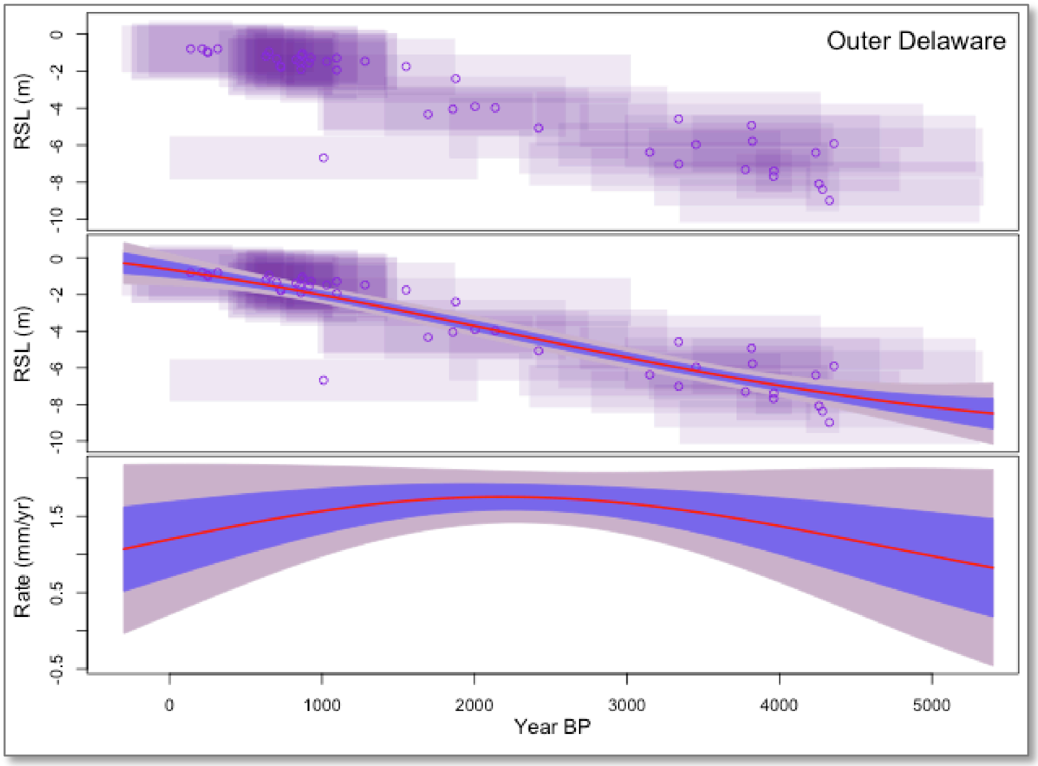


Figure 2-13. Inner (box #9) and Outer (box #10) Delaware Bay regions. Source: Engelhart and Horton (2012).

The Inner Delaware RSL data covers the period from the early Holocene to present. Relative sea level rose from -21 m at 9,000 years ago to -17 m at 6,000 years ago (Engelhart and Horton, 2012). Relative sea level then rose to about -8 m at 4,000 years ago, at an average rate of ~4.5 mm/yr, and likewise from 4,000 years ago to 1900 AD at the rate of ~1.8 mm/yr (Figure 2-14). Outer Delaware was -20 m at 8,500 years ago (Engelhart and Horton, 2012). RSL rose by ~2.8 mm/yr from 8,000 to 4,000 years ago and at a reduced rate of ~1.7 mm/yr from 4,000 years ago to AD 1900 (Figure 2-15).





Figures 2-14 and 2-15. Reconstruction of RSL for the Inner and Outer Delaware Bay produced from local tide gauge and marsh sediments data from Nikitina et al. (2014) using the Gaussian process model from Cahill et al. (2015). Boxes represent 2σ vertical and calibrated age errors.

The interagency report, *Global and Regional SLR Scenarios for the U.S.* (Sweet et al., 2017), plotted global mean sea levels over the past 2,500 years using combined sources of historic reconstructions and recent observations. Note the scale is in centimeters demonstrating a very modest change over this time period, less than in the previous few thousand years dating back to the LGM (see section 2.1 for more information on past sea level reconstructions.) GMSL data from 500 BCE to 1900 CE was taken from Kopp et al. (2016a) geologic and tide gauge-based reconstruction (black line with blue uncertainty ranges), from 1900 to 2010 from Hay et al. (2015) tide gauge-based reconstruction (black line), and from 1992 to 2015 updated from Nerem et al. (2010) satellite-based reconstruction (magenta). The rate of sea-level rise during the 20th Century is the highest throughout this time period and the highest in at least the past 2,800 years (Kopp et al., 2016a).

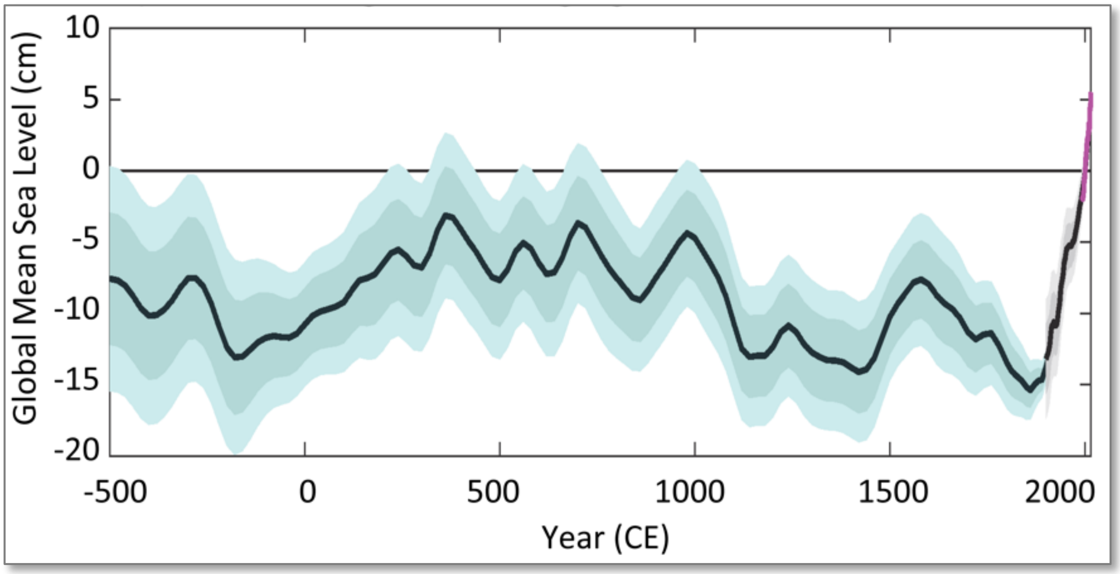


Figure 2-16. Geologic, tide gauge, and satellite altimeter reconstruction of GMSL for years 500 BCE to 2015 CE. Data relative to year 2000 MSL. Source: Sweet et al. (2017).

FAQ 2. What are vertical datums and how are they used?

According to the National Geodetic Survey (NGS), a vertical datum is, “a surface of zero elevation to which heights of various points are referred in order that those heights be in a consistent system. More broadly, a vertical datum is the entire system of the zero elevation surface and methods of determining heights relative to that surface.” For any type of elevation data, it is critical to understand which vertical datum they are referenced to. For example, if the measured height of a building was 50 ft, you first need to know if that means 50 feet above the ground level, or 50 feet above the base of the building, or 50 feet above mean sea level. Those are examples of vertical datums.

There are two main types of vertical datums: geodetic datums and tidal datums. A geodetic datum measures height as referenced to an ellipsoid, fit to the Earth’s gravitational potential surface, or geoid. This height is known as its orthometric height, and its relationship among the geoid and ellipsoid surfaces is shown in Figure FAQ2-2. In the U.S., the primary geodetic datum in use is the North American Vertical Datum of 1988 (NAVD88). NAVD88 is based upon the Geodetic Reference System of 1980 (GRS80) ellipsoid, and was developed after re-leveling numerous benchmarks across North America. One benchmark remained fixed, the tide gauge station at Father Point, Rimouski, Quebec, Canada. The local mean sea level measured at Father Point was the zero reference level used for NAVD88.

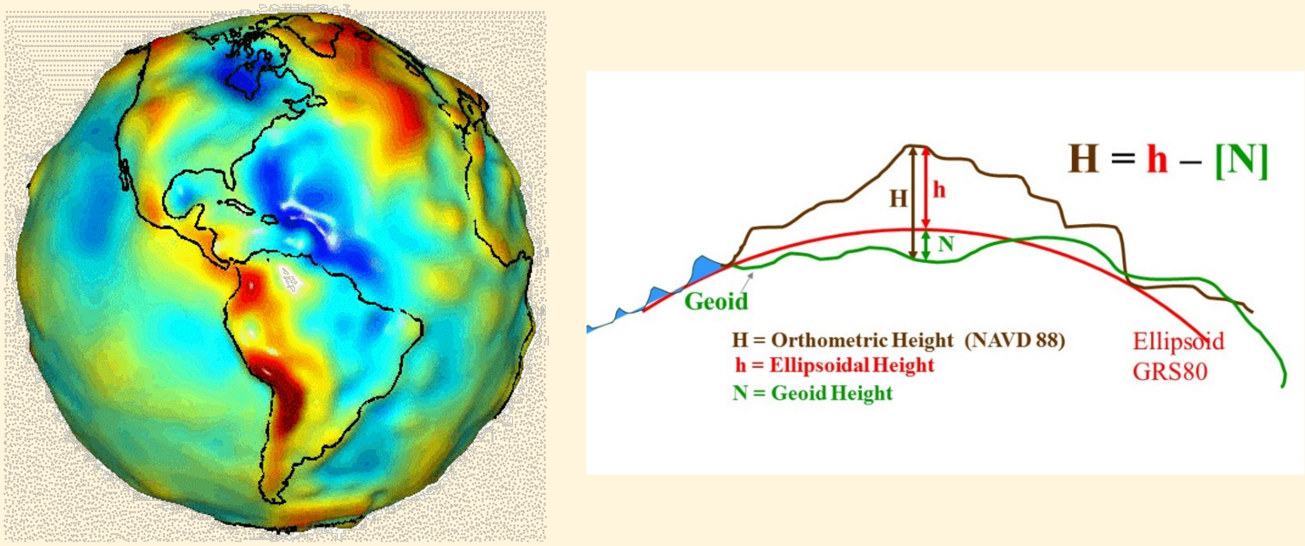


Figure FAQ2-1 and FAQ2-2. Geoid surface of Earth (left) and a diagram of the relationship among the geoid, ellipsoid, and orthometric height (right.) Source: NGS (2009).

Tidal datums are very different. They are based on continuously measuring the water surface at a single tide gauge. NOAA calculates tidal datums using hourly water-level measurements over a period of 19 years. Hourly measurements are used to reduce noise from winds, surge, instrument error and other biases in the measurements. The 19-year period represents the National Tidal Datum Epoch (NTDE), which is the period of time that spans all the orbital variations among the sun, moon, and Earth. The current NTDE over which official tidal datums are computed by NOAA is 1983-2001.

The most common tidal datums in use for most applications in Delaware are mean sea level (MSL = average of all hourly measurements over the NTDE), mean higher-high water (MHHW = average of all of the higher of the daily high tides), and mean lower-low water (MLLW = average of all of the lower of the daily low tides.) Figure FAQ2-3 shows the relationship among the tidal datums.

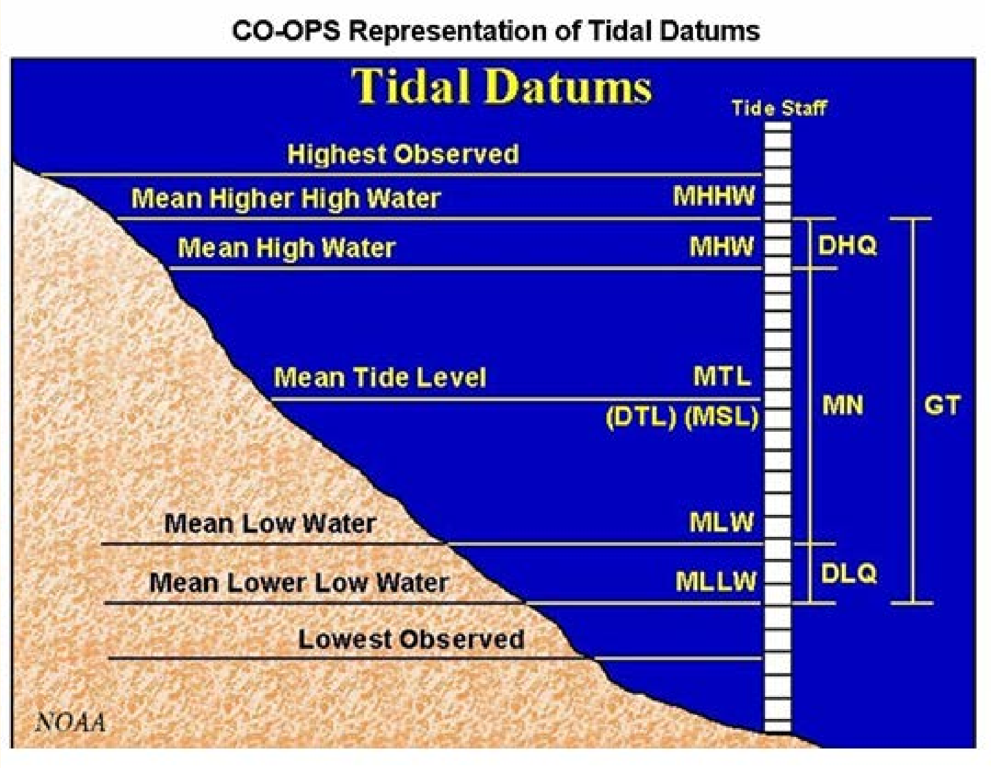


Figure FAQ2-3. Tidal datum relationships. Source: NOAA (2016a).

MLLW is used for marine safety to make sure ships do not run aground. MHHW datum is used often when mapping flood levels, such as from storm surge or sea-level rise scenarios, since the existing MHHW represents the flood level communities are accustomed to experiencing. The Great Diurnal Range (GT = the difference between MHHW and MLLW) is also important as it relates to health and extent of marsh vegetation. Note that tidal datums are valid only for that tide gauge's location.

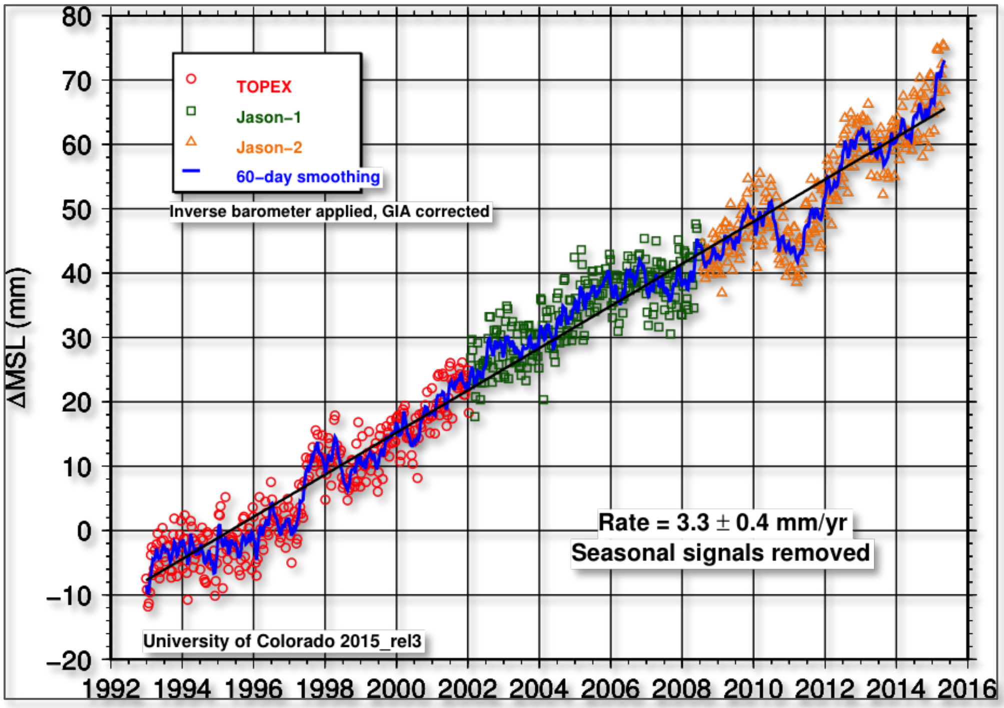
NOAA makes free software available for conversion among vertical datums, aptly named VDatum (http://vdatum.noaa.gov/). VDatum also includes the best estimates of tidal datums interpolated over areas that do not have tide gauge measurements. Common vertical datum conversion values at the Lewes Breakwater Harbor and Reedy Point tide gauges are listed in Table FAQ2-1. Values in feet relative to that gauge's station datum over NTDE 1983 – 2001.

	MLLW	MSL	MHHW	GT	NAVD88
Lewes	2.78	5.01	7.43	4.65	5.41
Reedy Point	1.35	4.27	7.19	5.84	4.32

2.3 Satellite Altimetry of SLR

Satellite-based sea-level data are available since 1993, starting with the TOPEX/Poseidon launch in 1992 and continuing with the Jason-1 (2001–2013), Jason-2 (2008–present), and Jason-3 (2016–present) missions. The orbital configurations of these missions provides nearly global (± 66° latitude) sea-level measurements, covering over 90 percent of the globe's ice-free oceans, at 10-day intervals (Church et al., 2013). The high-accuracy radar altimeters aboard these satellites yield an average accuracy value of 3-4 mm and are commonly used together for continuity for global time series estimates (NOAA, 2014).

Estimates of global mean sea level from satellite data have been rising at a rate of around 3.2 – 3.4 mm/yr, after corrections made for the inverse barometer (i.e., pressure) effect and GIA, with errors in the range of 0.4 – 0.6 mm/yr (CU SLR Research Group, 2017), depending on the precise processing methodology and time period of analysis. Figure 2-17 plots the continuous time series of GMSL (after removing the seasonal signal) as measured by the TOPEX/Poseidon and Jason missions and shows very good agreement among them. IPCC AR5 (Church et al., 2013) reports GMSLR rate as 3.2 ± 0.4 mm/yr with the precision derived from assessments of all errors affecting altimetry measurements and tide gauge comparisons. These observations are consistent with tide gauge analyses over the same time period.



Figures 2-17. GMSL from 1993 through 2015 as derived from multiple satellite altimetry missions. Source: CU SLR Research Group (2017).

Remote sensing by satellite offers the advantage of continuous, large spatial coverage, including areas in the central tropical oceans where it's difficult to maintain field sensors. The method works well for large-scale spatial variability or time series averaged globally or in large basins. Figure 2-18 maps the coverage and variability of sea-level change from 1993-2015 obtained from the TOPEX/Poseidon and Jason missions. To achieve this type of coverage, the nature of remote sensing data is as spatially continuous, gridded fields, at 0.25 degree resolution for sea-surface altimetry data, and works best when the land cover is uniform (i.e., open ocean) throughout each grid cell, rather than for small areas, individual point locations, or along continental coastlines with complex hydrology over mixed land cover.

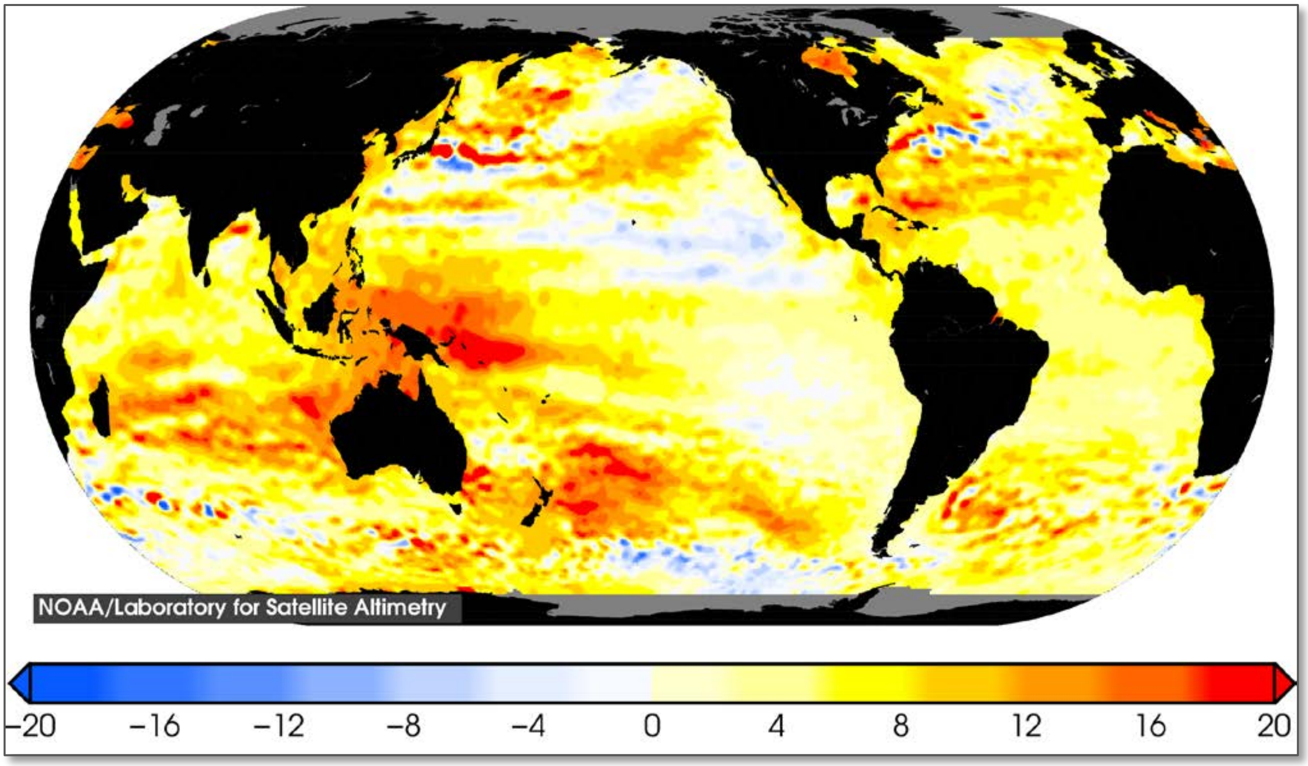


Figure 2-18. Map of total sea-level change (cm) from 1993 through 2014 from TOPEX/Jason-1/Jason-2 satellite altimetry missions. Reds/Blues indicate an increase/decrease in sea level. Source: NOAA Laboratory for Satellite Altimetry, http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/

Cazenave et al. (2014) specifically address the decrease in GMSLR acceleration (about 30 percent decrease) found in the satellite altimetry record when comparing data from 1993 – 2002 to 2003 – 2012. They attribute the difference to interannual variability, the most prominent signal of which comes from the El Niño-Southern Oscillation. The ENSO variability is captured in the water cycle through land water storage which can be estimated through a hydrologic model (before 2003) or through measurements from the Gravity Recovery and Climate Experiment (GRACE) satellite (2003 and afterward). After correcting for the interannual variability, the slowdown in the GMSLR disappears, leading to a new rate of 3.3 ± 0.4 mm/yr for the 1994-2011 time period. Fasullo et al. (2016) did similar work but found the Mt. Pinatubo eruption in June 1991 to be the primary culprit for the change in GMSLR. The global cooling effect of the eruption lowered oceanic heat content and therefore decreased global mean sea level at the start of the satellite era and gradually recovered throughout the 1990s decade. The authors emphasize the importance of quantifying and removing the short-term natural variability to more reliably extract a long-term trend.

Figure 2-19 shows the same global sea-level dataset as Figure 2-18 but zoomed in and centered on the U.S. mid-Atlantic coastal region. The satellite-based maps easily depict the spatial variability in sea-surface height changes in the open ocean that would be difficult to obtain from tide gauge point measurements. Reds/Blues indicate an increase/decrease in sea level, using the same scale as in Figure 2-18.

The northward migration of the Gulf Stream and resultant increases in sea level along the U.S. mid-Atlantic coast (i.e., the hotspot) can easily be seen, as would be expected with a weakening AMOC under Arctic warming and infusion of freshwater from melting of the Greenland ice sheet.

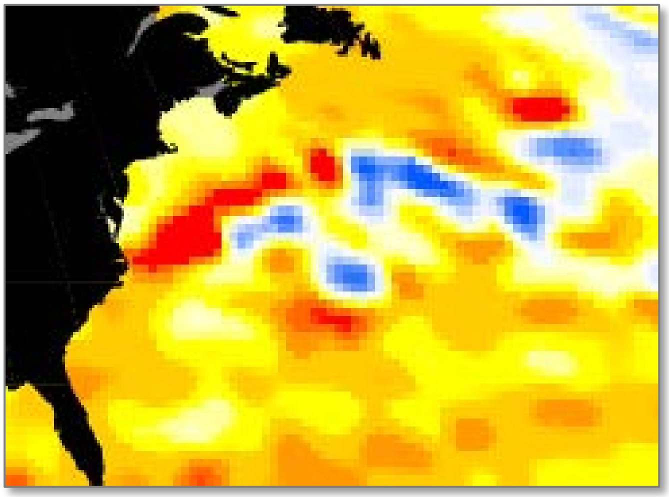


Figure 2-19. Same map data and color scale as in Figure 2-18 but zoomed in and centered on the U.S. mid-Atlantic coast.

2.4 Effects of SLR on the Impacts of Coastal Flooding

As described above, tide gauges have recorded increases in mean sea level at sites in Delaware and the surrounding region throughout the past century, at rates nearly twice as fast as the global average. Meteorological conditions (e.g., strong onshore winds, mid-latitude cyclones, and tropical storm systems) can cause water levels to be much higher than mean sea level. The impacts of these processes are exacerbated by sea-level rise. In areas where mean sea level has been rising, so too does inundation frequency relative to low fixed-elevation infrastructure, but extreme water levels also begin flooding higher elevations (Hall et al., 2016). Extreme water levels can cause significant damage and degradation to public/private property and public safety as well as to the natural environment along the shoreline. Although planning for the eventual, gradual increase in mean sea level is important, planning for the changes in frequency, duration, and intensity of both minor and extreme water levels is just as critical.

Figure 2-20. Flooding in Bowers Beach during November 2009 nor'easter (Veterans Day Storm). Source: DNREC Delaware Coastal Programs.

Recent studies have investigated the changes in frequency and duration of both minor and major coastal flooding events. NOAA's report, *Sea Level Rise and Nuisance Flood Frequency Changes around the United States*, utilized water-level data from tide gauges throughout the coastal regions of the U.S. with long periods of record to analyze changes over time of peak high tides, regardless of the meteorological or astronomical conditions occurring at the time (Sweet et al., 2014). The report gained wide attention and in general, popularized the term “nuisance flooding” to be synonymous to minor flooding that can cause public inconvenience, business interruption, substantial economic losses, and public safety issues due to road closures and degradation of infrastructure (Moftakhari et al., 2015). The authors define the nuisance flood level to match the National Weather Service (NWS) Minor Flood Advisory threshold for each tide gauge. This level does not necessarily mean that flooding will occur at this location during an event but rather represents at what level, on average, would the effects of flooding begin to occur as noted by the NWS local office. This level is also useful as a reference to quantify changes in total water level over time.

For the NOAA Lewes Breakwater Harbor tide gauge, the nuisance flood level corresponded to 6.0 ft MLLW, which equates to 1.03 m NAVD88, or 0.41 m MHHW. For the NOAA Reedy Point tide gauge, nuisance flood level was 7.2 ft MLLW, which equates to 1.30 m NAVD88, or 0.43 m MHHW. At both Delaware gauges and throughout the mid-Atlantic region, they found significant increases in the number of flood events and duration (cumulative hours) the total water level remained above nuisance flood levels, the majority of these events being minor flood events. The increases were largely in response to relative SLR and many of the gauges experienced acceleration in the number of days above the nuisance threshold.

Figure 2-21 (left panels) shows the number of days and hours above the nuisance threshold for each year of station data (along with annual mean sea level in blue) at each of the Delaware stations. Spikes in the cumulative number of hours are typically due to large events which keep water levels high over multiple tide cycles. Figure 2-21 (right panels) show the average seasonal cycle of the number days and hours above nuisance level. The lowest number of days/hours above the nuisance flooding threshold is during the summer months, when the number of tropical and extratropical (i.e., nor’easters) storms are at a minimum. The larger number of days/hours occur during times when the coastal oceans are at their warmest and tropical systems frequently develop (late summer/early fall) and when nor’easters frequently affect the region (early/mid spring).

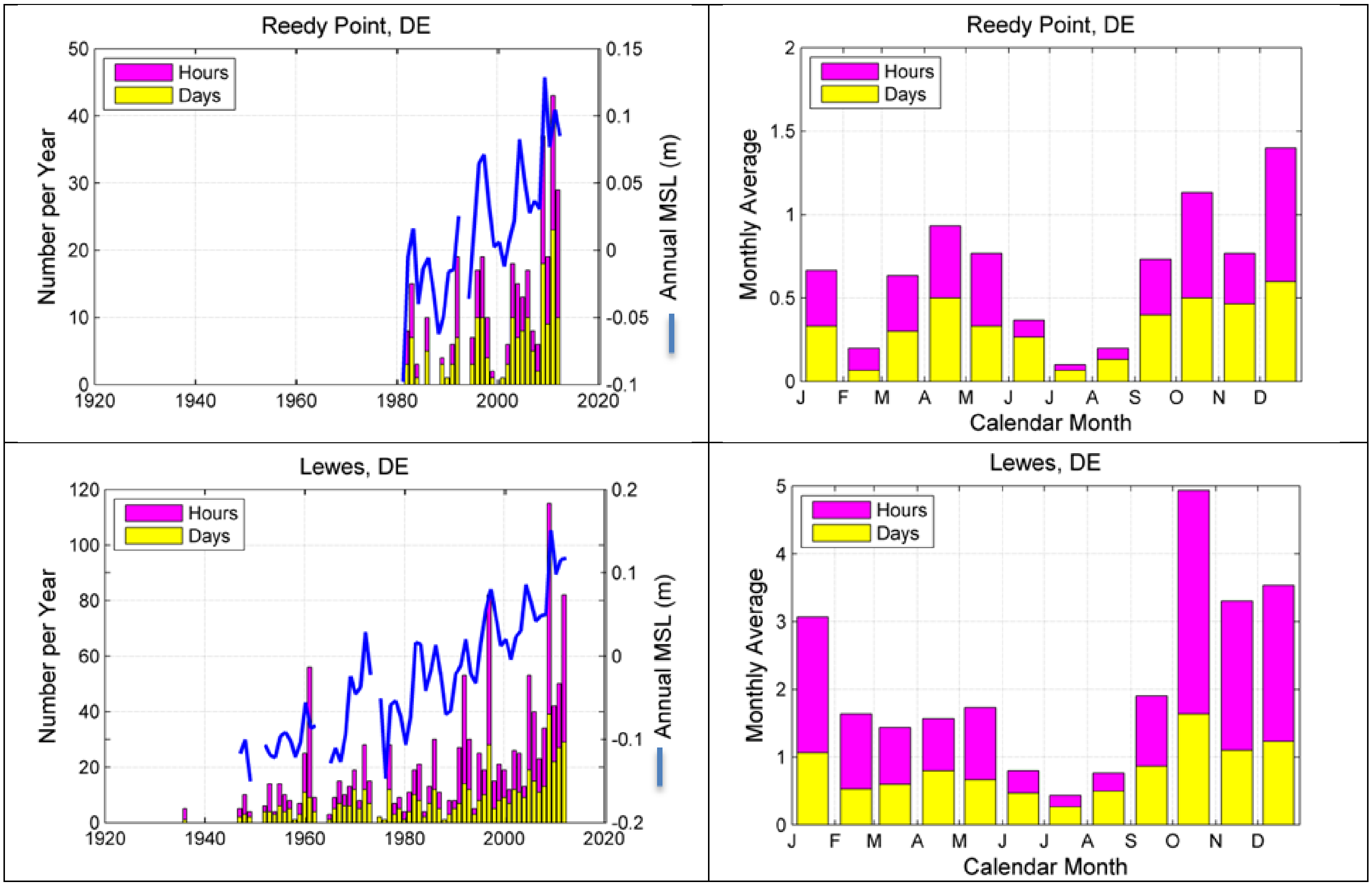


Figure 2-21. Frequency and duration of nuisance flood events for Lewes and Reedy Point tide gauges. Graphs on the left show annual counts, with the blue line representing annual mean sea level. Graphs on the right show average seasonal distribution of nuisance flood events. Source: Sweet et al. (2014).

Sweet and Marra (2015) and Sweet and Park (2014) looked closer at flood frequency variability and found significant increases in El Niño years and generated new equations to forecast the number of flood days and hours over the NWS Minor Flood Advisory ("nuisance") level. Based on the comparison of the sea-level variance during 1950 to 2012, they find that relative sea-level rise is a major contributing factor to the increasing nature of nuisance flood frequency. In Ezer and Atkinson (2014), the authors defined three flood threshold (0.3, 0.6, and 0.9 m) increments above MHHW and found correlation between flood frequency and the NAO and Gulf Stream strength. For the Lewes station, the authors found a 186 percent increase when comparing pre-1971 and post-1990 number of hours/year over the MHHW + 0.3 m threshold. The number of minor flood events and cumulative hours about nuisance thresholds have been accelerating (Sweet et al., 2014; Sweet and Park, 2014; Sweet and Marra, 2015; Moftakhari et al., 2015; Strauss et al., 2016; Dahl et al., 2017; Sweet et al., 2017) with estimates of between 55-83 percent of the increase attributed to anthropogenic sea-level rise (Strauss et al., 2016).

Rising sea levels also provide a higher base for more extreme water levels due to storm surge. There has been recent evidence for increase in storminess and extreme weather events in the United States (Houser et al., 2015; Melillo et al., 2014; Hartmann et al., 2013; Wahl et al., 2015). Winter storms (including nor'easters) have increased in frequency and intensity since the 1950s, and their tracks have shifted northward over the United States. The U.S. Northeast region has experienced a 70 percent increase in the amount of precipitation falling during heavy precipitation events, defined as the heaviest 1 percent of all daily events (Melillo et al., 2014). Colle et al. (2015) reviewed numerous past studies of extra-tropical storms along the U.S. East Coast, and although no trend was found in the number of storms, they did find large interannual and interdecadal variability associated with both atmospheric (i.e., NAO/AO, ENSO) and oceanic (i.e., AMO, PDO) teleconnections. As well, at Delaware meteorological stations, seasonal totals of precipitation accumulation did not show a statistically significant increase through the 21st century, except for autumn-only precipitation (DNREC, 2014a).

Sea-level rise will continue to increase the frequency and duration of nuisance flooding and exacerbate the impacts of extreme coastal flooding (Tebaldi et al., 2012; Sweet et al., 2013; Wahl et al., 2015; Little et al., 2015; Lin et al., 2016; Sweet et al., 2017). It is very likely that the frequency of heavy precipitation events will increase into the late 21st century over most mid-latitude land masses. Hurricanes and tropical cyclones also will likely become more intense, though not necessarily more frequent, into the 21st century in the North Atlantic basin (IPCC, 2013; Melillo et al., 2014; Colle et al., 2015; Sweet et al., 2017). In Delaware, the projected increases in intense storms combined with SLR makes it very likely for future sea-level extremes to increase, including extremes in storm surge, winds, waves, scour, erosion, and greater swings in salinity (DNREC, 2014b). This projected increase in extreme water levels combined with the already accelerating pace of increased minor (nuisance) flooding, needs to be recognized by coastal planners and state resource managers to prevent critical-system degradation due to climate change and sea-level rise.

2.5 Effects of SLR on the Impacts of Groundwater

Three important impacts on groundwater from SLR are: 1) saltwater intrusion into aquifers; 2) water-table rise, and; 3) changes in groundwater discharge rates and locations (Figure 2-22). Because of the long time span of SLR process and the uncertainty in the rates of future SLR, the majority of current insights on the impact of SLR on groundwater systems are derived from modeling studies.

Researchers have only started to address these SLR impacts in earnest over the last decade (Werner and Simmons, 2009; Rotzoll and Fletcher, 2012; Michael et al., 2013; He and McKenna, 2014; Ketabchi et al., 2016). Saltwater intrusion occurs when salt water in an aquifer near the shoreline moves inland due to an increase in base level (i.e., SLR), a decrease in recharge, or an additional stress on the system (e.g. pumping). It can also be caused by vertical infiltration into the aquifer during marine incursions like storm events (Yu et al., 2016; Yang et al., 2013; Holding and Allen, 2015).

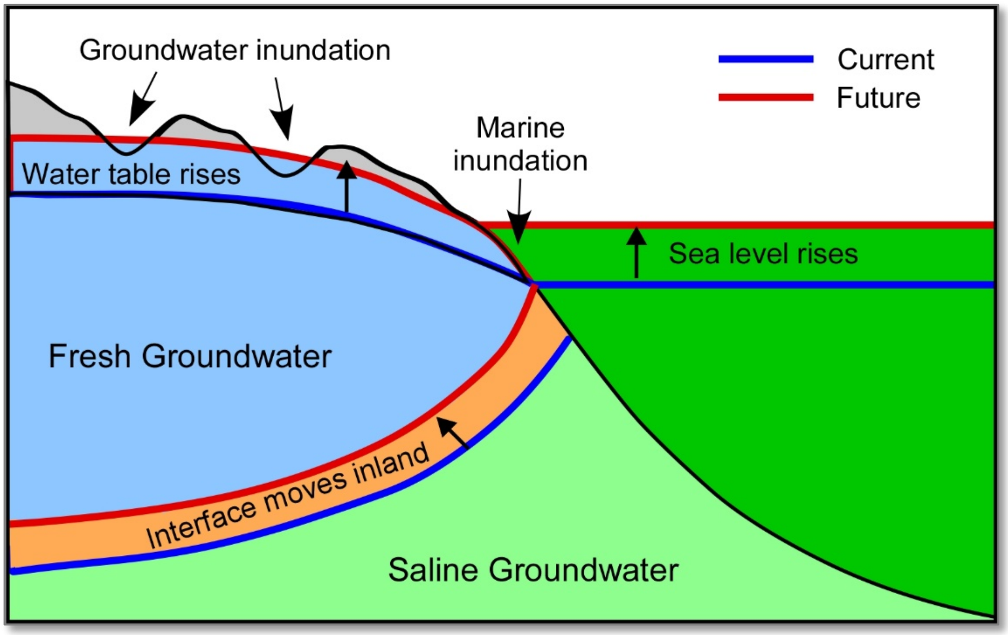


Figure 2-22. Effects of SLR on groundwater depth and salinity. Adapted from Michael et al. (2013).

Sea-level rise raises the base hydrologic level, resulting in associated rise in water tables. In areas where the unsaturated zone is thick, the water-table rise can balance the sea-level rise, limiting lateral seawater intrusion (e.g., Michael et al., 2013). Where the unsaturated zone is thin, water-table rise is limited by the ground-surface elevation, causing groundwater inundation (soil saturation and pooling of water) and greater runoff. These systems are more vulnerable to lateral seawater intrusion because the water table cannot balance the sea-level rise (Michael et al., 2013; Werner and Simmons, 2009). Figure 2-23 shows areas along the Delaware Bay that would experience groundwater inundation under various SLR scenarios (He and McKenna, 2014). Changes in rates and locations of fresh and saline groundwater discharge depend primarily on recharge of the aquifer in the uplands, aquifer permeability, and the position of the salt water interface.

Rising water tables, groundwater inundation, increased salinity in onshore aquifers, and changes in rates and locations of groundwater discharge will result in:

- increased susceptibility of water supply, irrigation, industrial and domestic wells to saltwater intrusion
- increased rates of local flooding and standing water from groundwater inundation due to the decrease in storage capacity in the soils as the water table rises (Michael et al., 2013)
- impacts on agriculture including loss of arable land due to groundwater inundation, hindrances to planting and harvesting due to waterlogged soils, and decrease in crop yield due to water table levels above the effective rooting depths of local crops (0.6m to 0.9m for soybeans and corn, respectively, the dominant crops in Delaware soils) (He and McKenna, 2014)
- impacts on water and wastewater infrastructure including decreased efficiencies or failures of septic tanks and wastewater spray fields and rapid infiltration basins because of the decreased

thickness of the unsaturated zone due to water-table rise, backup of water in storm sewer pipes as hydraulic gradients in the pipes decrease with SLR, increased flow of water into leaky storm and sewer pipes that will decrease capacity to carry storm flows and sanitary sewage, and corrosion of underground pipes and other underground infrastructure due to higher salinity groundwater (Flood and Cahoon, 2011; Rotzoll and Fletcher, 2012)

- geotechnically engineered infrastructure (e.g., transportation infrastructure) where saturated soils and/or salt-water corrosion must be taken into account
- ecological habitats in wetlands and uplands due to changing subsurface moisture and salinity conditions (Baldwin and Mendelssohn, 1998; James et al., 2003; Masterson et al., 2014)
- ecosystems due to changes in fresh and saline water discharge locations in upland springs, streams, and lakes (Michael et al., 2013) and increased evaporation (Rotzoll and Fletcher, 2012)
- mobilization of contaminants previously sequestered in the current unsaturated zone due to changes in redox and salinity (Borch et al., 2010; Personna et al., 2015; Wong et al., 2015; Pardue et al., 2005)

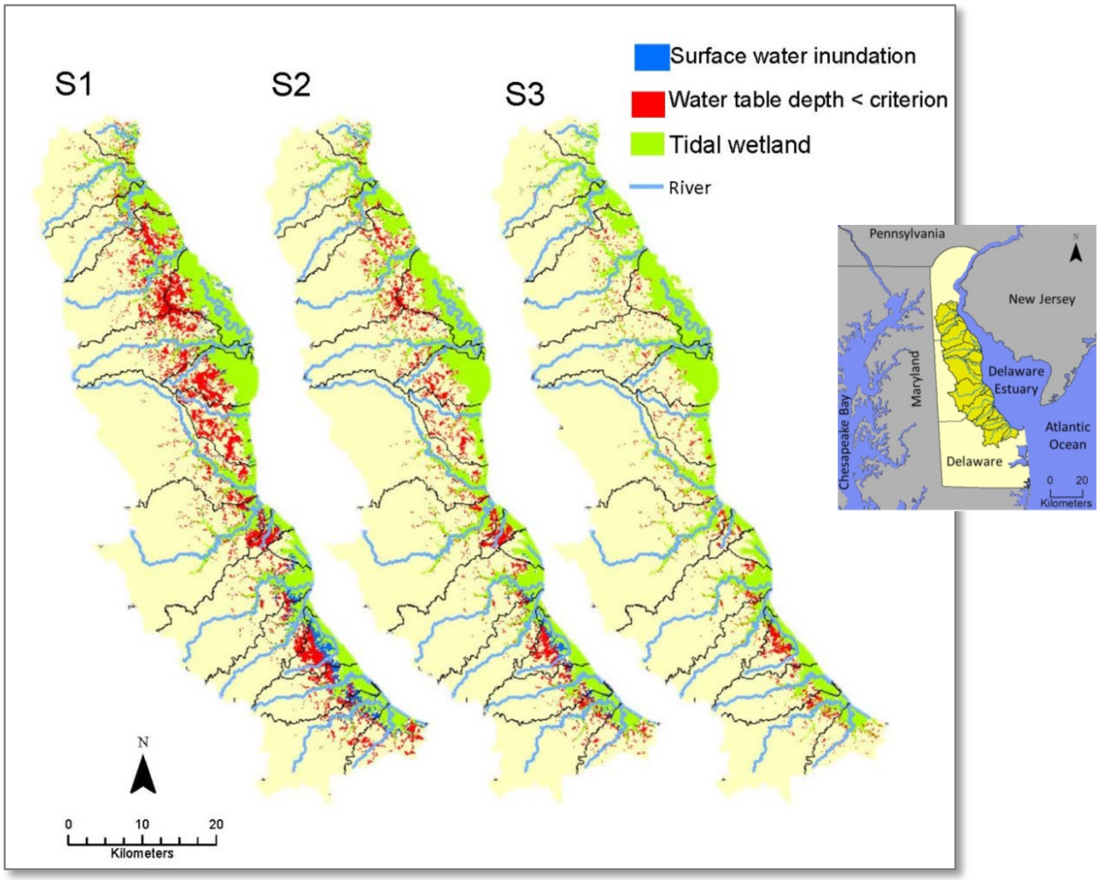


Figure 2-23. Areas of surface-water inundation and depth to water of less than 0.5m. S1, S2, and S3 indicate SLR of 0.5, 1.0 and 1.5m in year 2100, respectively, for the Delaware Bay watersheds within Delaware. Source: He and McKenna (2014).

3. Future Projections of 21st Century Sea-Level Rise

There have been numerous projections of sea-level rise described in peer-reviewed academic journals, technical reports, and international and national assessments. In the United States, federal government agencies and most, if not all, coastal states have performed their own evaluation of SLR projections. This chapter will review several common SLR projections, globally and regionally, that may provide a scientific basis for identifying a set of projections for SLR in the Delaware region.

3.1 Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)

The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. The IPCC was set up in 1988 by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation (IPCC, 2013). The IPCC released its Fifth Assessment Report (AR5) in four parts from September 2013 through November 2014. About 30 different global model representations were used for various types of analyses during AR5 development, as part of the Coupled Modeled Intercomparison Project, 5th Phase (CMIP5), at spatial resolutions varying from 62 to 125 miles. AR5 is the latest comprehensive assessment of scientific knowledge regarding climate change.

In addition to updated peer-reviewed research, and new environmental data based on improved hardware and model, AR5 makes two new contributions in the area of sea-level change: 1) the introduction of Representative Concentration Pathways (RCPs) to replace the Special Report on Emission Scenarios (SRES) greenhouse gas emission scenarios used in AR4, and; 2) a chapter dedicated to sea-level change in addition to the chapter on oceans. RCPs represent the different scenarios of future global emissions of greenhouse gases, and therefore depict different net amounts of greenhouse gases present in the atmosphere. The four RCPs described in IPCC AR5 are RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, with the numeric value in the name representing the radiative forcing of that pathway by year 2100 relative to pre-industrial values. RCPs are described more thoroughly in FAQ 3.

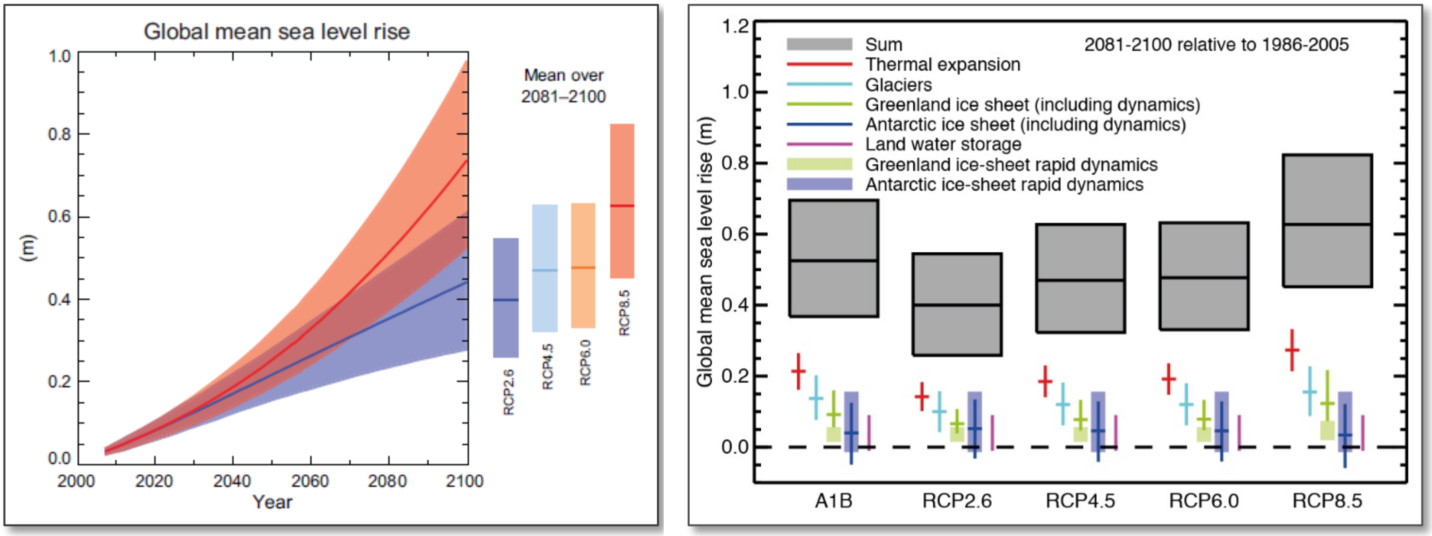
Since AR4 was released in 2007, the amount of observation data obtained and the understanding of past sea-level change and processes that contribute to total sea level has improved significantly (Church et al., 2013.) The biggest difference in IPCC AR5 modeling efforts of future sea-level change over AR4 is the addition of rapid ice-sheet dynamics modeling (which is separate from the long-term surface mass loss via sublimation/ablation of melted snow/ice that AR4 and AR5 already included). Research has shown that the land-ice outflow (breaking off or sliding of land-ice into the sea) plays an important role in global and regional sea-level change, with both uncertainty and relative contribution increasing in the second half of the 21st century and beyond. However, AR5 does not quantify the dependence of the new rapid ice-sheet dynamical modeling based upon RCP scenario. Land water storage (LWS) is also a new SLR component that was not included in AR4. The LWS component has been shown to correlate well with interannual sea-level variability and is closely tied to atmospheric processes, such as ENSO.

Projections of sea-level rise by 2100 in AR5 are consistently higher than in AR4 by about 60 percent. Although the greenhouse gas emission scenarios in AR5 (i.e., RCPs) were constructed differently than what was used in AR4 (i.e., SRES), a direct comparison was performed for the AR4 SRES A1B "middle of the road" emission scenario. The comparative modeled SLR by 2100 projection medians and 5 – 95 percent ranges were 0.37 m (0.22 – 0.50 m) under AR4, 0.43 m (0.22 – 0.60 m) under AR4 with a scaled up ice-sheet discharge, and 0.60 m (0.42 – 0.80 m) under AR5 (Church et al., 2013, Table 13-6.)

Table 3-1 and Figure 3-1 show the AR5 estimates of GMSLR by 2100 and the mean GMSLR for 2081 – 2100. Likely ranges of SLR amounts by the year 2100 are 0.28 – 0.61 m for RCP 2.6, and 0.52 – 0.98 m for RCP 8.5. Note that RCP 4.5 and RCP 6.0 have very similar probability distributions by 2081 – 2100. Estimates are calculated from projections as ensemble 5-95 percent ranges (i.e., a net 90 percent probability of occurrence within this range) from physical process-based model results. However, after consideration of the additional uncertainties (e.g., glacier mass loss, ice-sheet dynamics) and confidence levels within the models, these projections were adjusted to the lower confidence likely range, representing the 17 – 83 percent probability range (i.e., a net 66 percent probability of occurrence within this range.) Projections of GMSLR in AR5, therefore, have medium confidence, an improvement over AR4 where no confidence level was given at all.

Table 3-1. GMSLR projections from AR5 process-based models of the median and very likely range for the time periods 2081–2100 and for the year 2100. Likely range represents 17–83%, a net 66% probability of occurrence. Data in meters relative to 1986–2005 MSL.

Pathway	Mean GMSLR 2081-2100	Likely Range of GMSLR 2081-2100	GMSLR by 2100	Likely Range of GMSLR by 2100
RCP 2.6	0.40	0.26-0.55	0.44	0.28-0.61
RCP 4.5	0.47	0.32-0.63	0.53	0.36-0.71
RCP 6.0	0.48	0.33-0.63	0.55	0.38-0.73
RCP 8.5	0.63	0.45-0.82	0.74	0.52-0.98



Figures 3-1 (left) and 3-2 (right). The plot on the left shows global MSL projections averaged over the time period 2081 – 2100 from IPCC AR5 process-based models under the four RCPs scenarios. The plot on the right shows relative contributions from the major processes affecting sea-level change during 2081-2100 with the AR4 SRES A1B scenario for the same time period. Box plots show median and likely range. Source: Church et al. (2013).

Figure 3-2 shows projections of median values of GMSLR from AR5 process-based models with likely ranges (66 percent probability of occurrence) along with relative component contributions averaged over the years 2081–2100 compared to 1986–2005 for the four RCP scenarios, as well as the SRES A1B scenario used in AR4. In all scenarios, thermal expansion is the largest contributor to GMSLR, accounting for 30-55 percent. Glaciers and mountain ice caps are next largest with 15-35 percent, although many of these outside Antarctica (15-55 percent under RCP 2.6 and 35-85 percent under RCP 8.5) are expected to be eliminated by the year 2100, thereby reducing their relative contributions for years afterward. Rapid dynamics of the Antarctica and Greenland ice sheets represent ice outflow that may occur over shorter time scales (years to decades) as compared to surface-mass loss (decades to centuries) processes. AR5 also states that based on current understanding, only the collapse of marine-based sectors of Antarctic ice sheet could cause global MSL to rise substantially above the likely range.

Even with these improvements over previous reports, AR5 does not address regional spatial variability, such as GIA and ocean circulation effects, other than to state that it is very likely (90 percent probability of occurrence) that future sea-level rise will have strong regional patterns.

Additionally, AR5 also does not include results from semi-empirical models (SEMs, described in section 3.5) in their estimates of future GMSLR. In sea level studies, SEMs are statistical models that refer specifically to transfer functions formulated to project future GMSL change from future global mean surface temperature change or greenhouse gas radiative forcing. SEMs generally produce higher results than process-based models. The IPCC declared it had low confidence in projections made from SEMs and used results from the process-based models for their GMSLR projections.

FAQ 3. What are Representative Concentration Pathways (RCPs)?

The exact amount of sea-level change experienced globally is highly correlated to the increase of Earth's mean atmospheric surface temperature. In turn, this is largely dependent upon amount of greenhouse gas emissions released to the atmosphere. In AR5, the IPCC introduced the concept of Representative Concentration Pathways (RCPs) to represent radiative forcing (i.e., increased energy at the Earth's surface) responses to different atmospheric greenhouse gas concentrations (van Vuuren et al., 2011). The higher the greenhouse gas concentration in the atmosphere, the higher the radiative forcing response, and therefore the higher resulting temperature of the Earth's surface.

Each pathway actually describes a different model of future global greenhouse gas emissions, dependent upon worldwide economic and political strategy of managing fossil fuels (i.e., greenhouse gas energy sources) and technological innovation. These are integrated into global climate model forecasts via different amounts of the net concentration of greenhouse gases present in the atmosphere through time, such as CO_2, CH_4, and N_2O. The four RCPs described in IPCC AR5 are RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5, the numeric value in the name representing the radiative forcing (in Watts per square meter, W/m^2) of that pathway by year 2100 relative to pre-industrial values. Figure FAQ3-1 shows the corresponding global average surface temperature change from present day for each RCP as quantified in the GCM model runs.

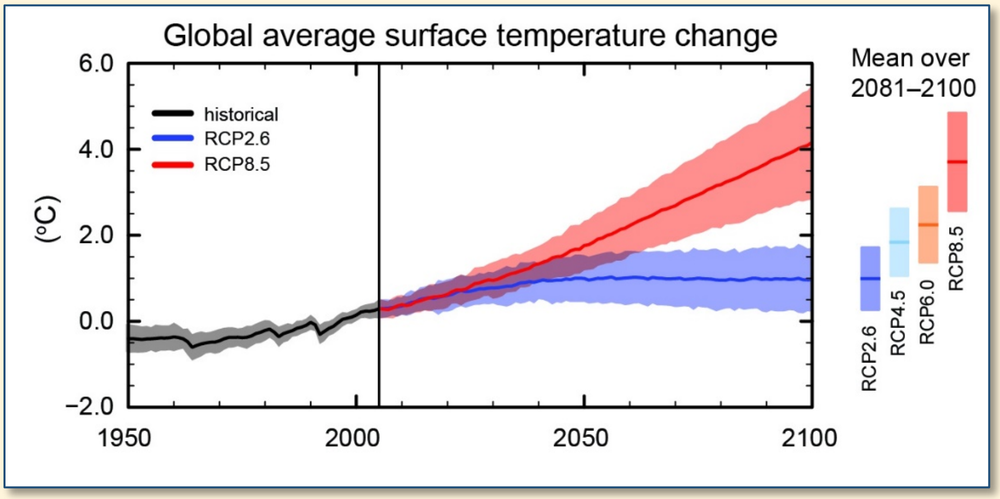


Figure FAQ3-1. Past and projected global average surface temperature from 1950 to 2100. Future projections use the RCP 2.6 and RCP 8.5 emission scenarios. Shaded area around each curve represent confidence interval. Source: IPCC (2013).

The RCP 2.6 pathway is representative of a future with an immediate drastic policy change toward a global priority on clean energy sources, resulting in very low greenhouse gas emissions, with net-negative emissions in the second half of the century. It is a "peak-and-decline" scenario where the radiative forcing will continue to increase in the near future to 3.1 W/m^2, then drop gradually to 2.6 W/m^2 by 2100. It was specifically designed to demonstrate how aggressive mitigation could limit temperature rise to 2°C.

RCP 4.5 and RCP 6.0 pathways are mid-range emissions scenarios representing a future where the control of greenhouse gas emissions is eventually stabilized, possibly through advances in clean technology and/or changing economic strategies. RCP 8.5 is termed as the “business as usual” scenario with continued increase in fossil fuel burning and unabated greenhouse gas emissions.

It is difficult to compare exact forecasted values reported in AR5 with those in the IPCC Fourth Assessment Report (AR4) released in 2007, since AR4 and previous reports used different emission scenarios, called Special Report on Emission Scenarios (SRES). AR5 also brought in an improved modeling structure, representation of ice-sheet dynamics (albeit limited), and was calibrated to more recent, and higher, sea-level observations. However, based upon globally averaged temperature anomalies, RCP 8.5 can be compared to SRES A1FI (“FI” stands for “fossil-intensive”), RCP 6.0 to SRES B1, and RCP 4.5 to SRES B2. The peak-and-decline RCP 2.6 does not have a counterpart in AR4.

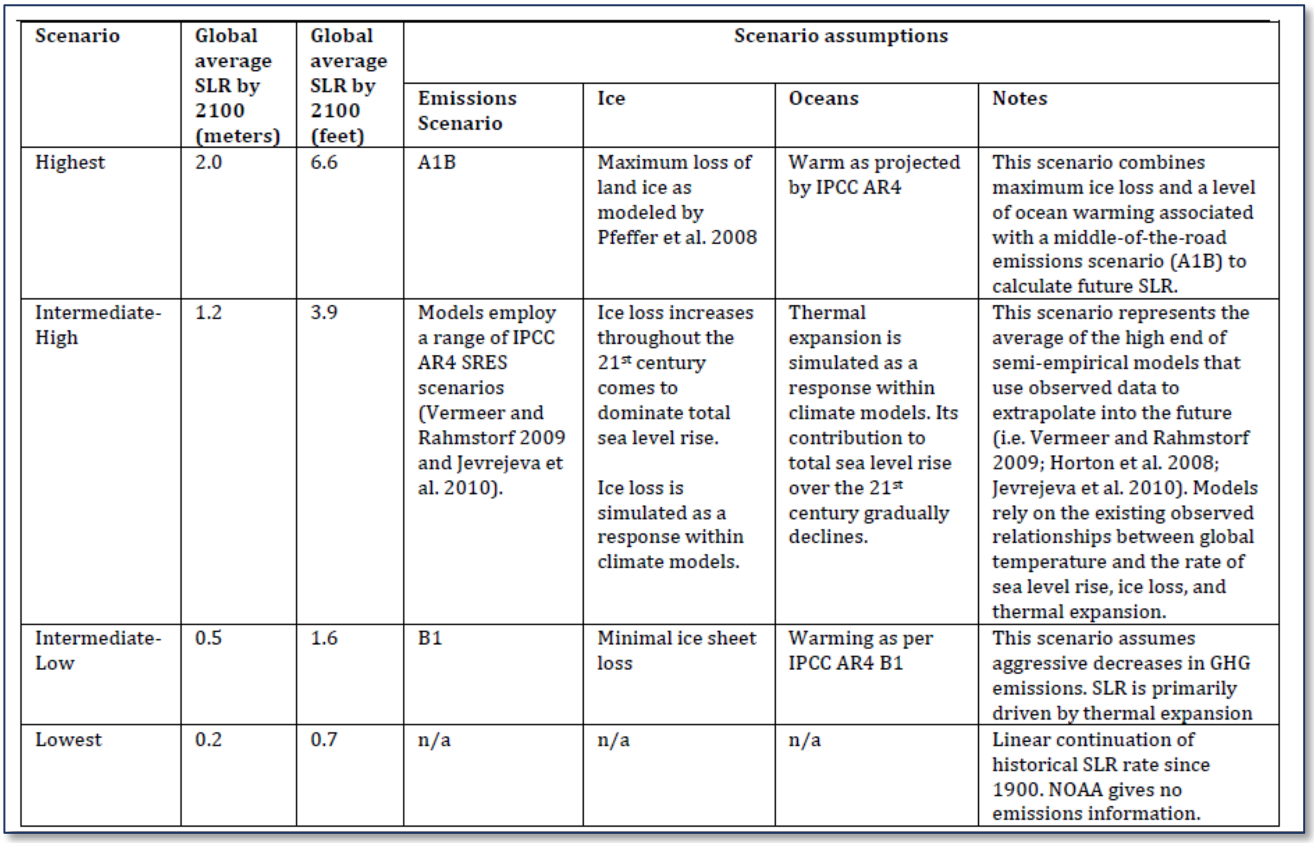
RCPs represent different futures or scenarios of greenhouse gas emissions. They are not projections or forecasts and cannot be assigned probabilities as to which is more likely to occur. Each RCP scenarios is independent of each other. They are designed to be used for planning and decision-making under a variety of possible emission futures.

3.2 U.S. National Climate Assessment (NCA)

The U.S. Global Change Research Program (USGCRP) released the third U.S. National Climate Assessment (NCA) in 2014. The first and second NCAs were released in 2000 and 2009, respectively, under the USGCRP’s previous name of the U.S. Climate Change Science Program (CCSP), from which information was used by DNREC to generate the previous Delaware SLR planning scenarios in 2009. The NCA assesses the science of climate change and its impacts across the United States, now and throughout this century, with the goal of better informing public and private decision-making at all levels. For the third NCA, a team of more than 300 experts produced the report, guided by a 60-member Federal Advisory Committee as well as decision-makers from the public and private sectors, resource and environmental managers, researchers, representatives from businesses and non-governmental organizations, and the general public. The report, which was extensively reviewed by the public and experts form federal agencies and a National Academy of Sciences panel, categorized information by U.S. region and by topic, such as extreme weather, human health, infrastructure, agriculture, ecosystems, and the oceans (Melillo et al., 2014.)

To assess sea-level rise, the third NCA used information put forth by the report, *Global Sea Level Rise Scenarios for the United States National Climate Assessment* (Parris et al., 2012), a synthesis of an extensive scientific literature review on global sea-level rise research at the request of the Federal Advisory Committee charged with developing the NCA. The report provided a set of four GMSLR scenarios derived by consensus from federal agencies, universities, and others that describe future conditions for the purpose of planning and assessing potential vulnerabilities and impacts. Prior to that report, there was no coordinated, interagency effort in the U.S. to identify agreed upon GMSLR estimates for the purpose of coastal planning, policy, and management (Parris et al., 2012).

The consensus GMSLR scenarios in Parris et al. (2012) do not represent probabilistic projections of future conditions as “no widely accepted method is currently available for producing probabilistic projections of sea level rise at actionable scales (i.e. regional and local).” Rather, it focused on multi-scenario planning and highlighted the need for experts and decision makers to consider multiple future conditions (based on wide array of approaches, such as statistical trends, process modeling, semi-empirical approaches, etc.) and to develop multiple response options that frame the range of uncertainties. A key advance of Parris et al. (2012) was to evaluate the available science from a user needs perspective, supporting a wide variety of decision contexts and risk tolerances (Sweet et al., 2017). Table 3-2 lists each of the chosen SLR consensus scenarios and the corresponding assumptions and estimates of GMSLR reached by 2100.



Scenario	Global average SLR by 2100 (meters)	Global average SLR by 2100 (feet)	Scenario assumptions			
			Emissions Scenario	Ice	Oceans	Notes
Highest	2.0	6.6	A1B	Maximum loss of land ice as modeled by Pfeffer et al. 2008	Warm as projected by IPCC AR4	This scenario combines maximum ice loss and a level of ocean warming associated with a middle-of-the-road emissions scenario (A1B) to calculate future SLR.
Intermediate-High	1.2	3.9	Models employ a range of IPCC AR4 SRES scenarios (Vermeer and Rahmstorf 2009 and Jevrejeva et al. 2010).	Ice loss increases throughout the 21st century comes to dominate total sea level rise. Ice loss is simulated as a response within climate models.	Thermal expansion is simulated as a response within climate models. Its contribution to total sea level rise over the 21st century gradually declines.	This scenario represents the average of the high end of semi-empirical models that use observed data to extrapolate into the future (i.e. Vermeer and Rahmstorf 2009; Horton et al. 2008; Jevrejeva et al. 2010). Models rely on the existing observed relationships between global temperature and the rate of sea level rise, ice loss, and thermal expansion.
Intermediate-Low	0.5	1.6	B1	Minimal ice sheet loss	Warming as per IPCC AR4 B1	This scenario assumes aggressive decreases in GHG emissions. SLR is primarily driven by thermal expansion
Lowest	0.2	0.7	n/a	n/a	n/a	Linear continuation of historical SLR rate since 1900. NOAA gives no emissions information.

Table 3-2. GMSLR scenarios and inherent assumptions concerning the treatment of greenhouse gas emissions, ice and oceans in the third NCA. Source: Parris et al. (2012).

Very high confidence (> 9 in 10 chance) was found that GMSL will rise at least 20 cm but no more than 2.0 m by the year 2100 relative to the NTDE 1983-2001. The 20 cm increase, noted as the Lowest scenario, was calculated by a linear extrapolation of the 1.7 mm/yr trend from 20th century global tide gauge records. At the time, the linear trend of global mean sea-level rise calculated from the satellite altimetry record (1992 – 2010) of 3.2 mm/yr was considered too short for projecting SLR through to 2100, and therefore was not used in deference to the 1.7 mm/yr value. The Highest scenario of 2.0 m by 2100 was derived from a combination of estimated ocean warming from IPCC AR4 GMSLR projections and a calculation of maximum possible glacier and ice-sheet loss by 2100 from Pfeffer et al. (2008). The Intermediate-High scenario of 1.2 m by 2100 was based on an average of the high-end SEM estimates of GMSLR, whereas the Intermediate-Low scenario of 0.5 m by 2100 was based on the upper end of IPCC AR4 process-models using the B1 emission scenario (Parris et al., 2012). Note that these are based on GMSLR projections and do not take into account regional (e.g., GIA, ocean circulation changes) or local (e.g., compaction, consolidation) effects.

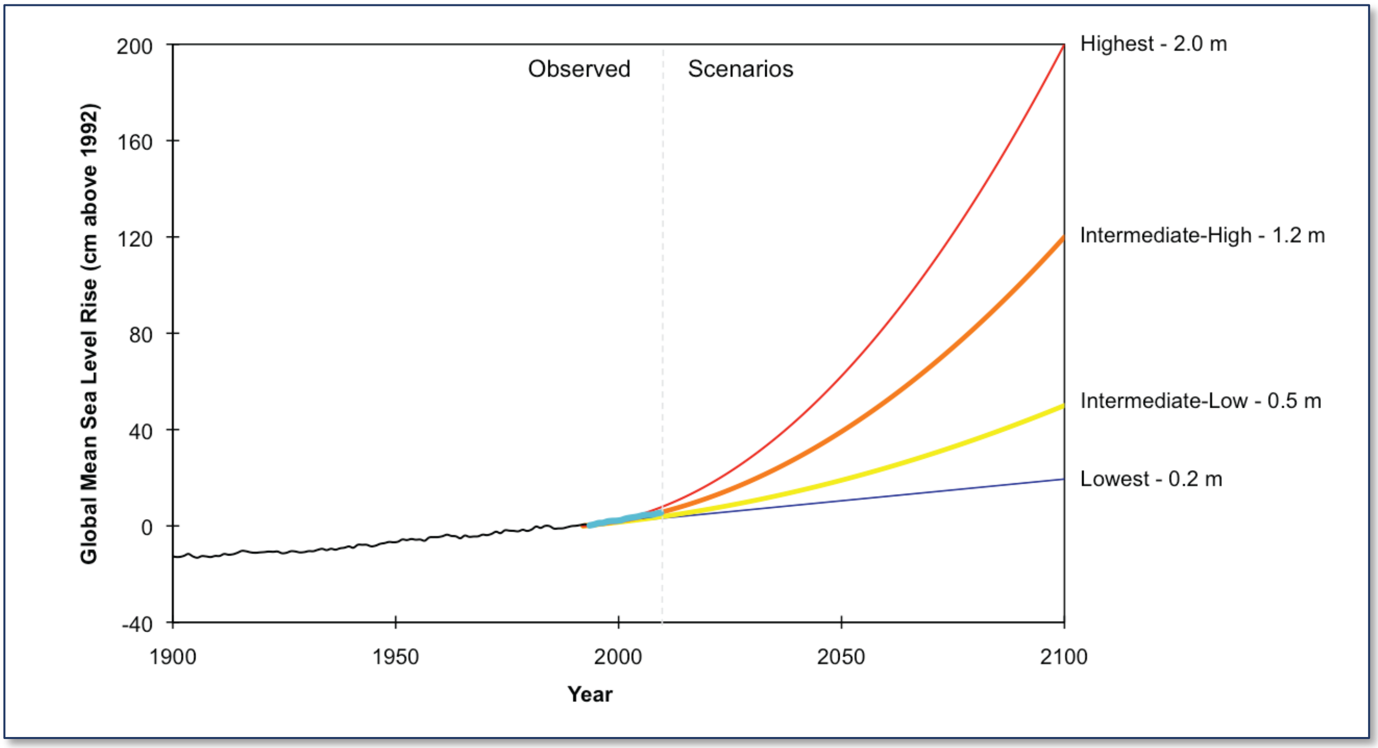


Figure 3-3. Global mean sea-level curves in *Global Sea Level Rise Scenarios for the United States National Climate Assessment*. Source: Parris et al. (2012).

To represent the non-linear trajectory of sea-level rise from present to 2100, Parris et al. (2012) adopted the methodology employed by the engineering reports of NRC (1987) and USACE (2011). The time evolution of the scenarios is described using the equation

$$E(t) = 0.0017t + bt^2 \qquad \text{(Eq. 3-1)}$$

where t is years since 1992 (mid-point of NTDE 1983-2001), *E(t)* is the mean sea-level rise since 1992 in meters, 0.0017 represents a constant GMSLR rate in mm/yr (Church and White, 2011), and *b* represents constant of acceleration. Fitting Eq. 3-1 to GMSLR values of 0.2 m, 0.5 m, 1.2 m, and 2.0 m at the year 2100, yields the colored curves plotted in Figure 3-3. Computed values of b for each scenario are 1.56E-04, 8.71E-05, 2.71E-05, and 0.0 for the Highest, Intermediate-High, Intermediate-Low, and Lowest scenarios, respectively.

Other than the Lowest scenario, the other three SLR scenarios are determined solely by the amount of increased GMSL by 2100. Mathematical curves were fit between sea-level observations in 1992 and those projected at 2100 under each of the scenarios. Therefore, the time evolution of projected sea-level rise was not designed to represent actual global mean sea levels at times before 2100. Parris et al. (2012) states, “It should be emphasized that this straightforward quadratic approach to the time evolution is chosen in part for its simplicity; there is no scientific reason or evidence to assume that SLR will evolve in precisely this smooth manner.”

Based on this information, the third NCA kept the same Highest and Lowest Scenarios as in Parris et al. (2012) but approximated the two middle scenarios, again noting that these scenarios are not based on probabilistic model simulations but rather reflect the range of possible scenarios based on other scientific studies (Walsh et al., 2014). Under the lowest emission scenarios, the ocean thermal expansion and melting of mountain glaciers alone would result in at least 11 inches of global mean SLR by 2100 over 1992 levels. Therefore, 1.0 ft (0.3 m) would be a realistic minimum scenario for planning. As well, 4.0 ft (1.2 m) is also a plausible value based on semi-empirical models to take into account ice-sheet dynamics (Rahmstorf et al., 2012; Jevrejava et al., 2012). The third NCA notes there is medium confidence for GMSLR by 2100 to be between 0.3 and 1.2 m (1 and 4 ft), and very high confidence it would be between 0.2 and 2.0 m (0.7 and 6.6 ft). Figure 3-4 shows past observations and future GMSL changes for each of the planning scenarios from the year 1800 through 2100.

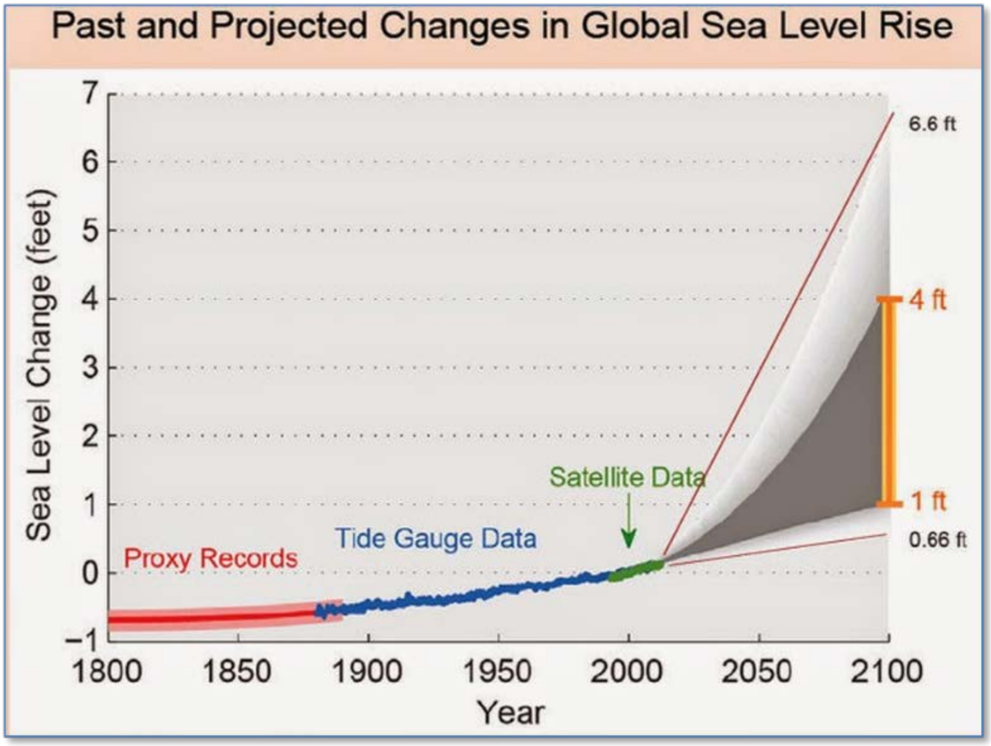


Figure 3-4. Estimated from proxy records, observed from tide gauges and satellites, and amounts of GMSLR based on each of four scenarios from 1800 to 2100. Source: Walsh et al. (2014).

Although the third NCA was released after the IPCC AR5 report in 2013, CMIP5 model results were not available in time for NCA impact analyses. However, NCA does note that existing climate models underestimate global sea-level rise due to ice-sheet dynamics. Ice-sheet melt has been occurring faster than what was accounted for previously and the wide range of sea-level change forecasts reflect the lack of understanding (Walsh et al., 2014).

The NCA advises that the choice of scenarios involve interdisciplinary scientific experts as well as coastal managers and planners, and that three decision factors should be taken into account: location, time horizon (life-span of projects), and risk tolerance (lower tolerance equates to planning for higher scenarios.) For example, coastal planners may want to use the highest forecasted sea-level rise scenario for projects with a low tolerance of risk and long life span. A large drawback of the Parris et al. (2012) scenarios in the third NCA was the lack of regionalization. When planning for specific projects, GMSLR scenarios must be adjusted for processes relevant to that region, such as vertical land movement and ocean circulation dynamics.

3.3 U.S. Army Corps of Engineers (USACE)

U.S. Army Corps of Engineers (USACE) missions, operations, programs, and projects must be resilient to coastal climate change effects, beginning with sea-level change (USACE, 2014). USACE has developed several documents to provide guidance on incorporating the direct and indirect physical effects of projected future sea-level change on a broad range of projects and activities. The USACE Circular 1165-2-211, entitled *Incorporating Sea-Level Change Considerations in Civil Works Programs*, released July 1, 2009 (USACE, 2009), requires the incorporation of sea-level change projections into planning, engineering design, construction, operating, and the maintenance of projects. This document was updated, with assistance from NOAA National Ocean Service and USGS, in circulars EC 1165-2-212 (USACE, 2011) and ER 1100-2-8165 (USACE, 2013).

The USACE used a scenario-based approach, similar to the third NCA report, considering a Low, Intermediate, and High scenario of GMSLR, selection of which should be based on project sensitivity relative to human health and safety, economic costs and benefits, environmental impacts, and other social effects. For the Low scenario, USACE uses the linear extrapolation of the historical SLR trend out to year 2100 calculated from tide gauges. For the Intermediate scenario, they follow NRC (1987) Curve I, which equates to GMSLR of 1.0 m and b coefficient of 2.71E-5. For the High scenario, they follow NRC (1987) Curve III, which equates to GMSLR of 1.5 m and b coefficient of 1.13E-4. The USACE follows the same mathematically-based quadratic form of the time-evolution curve as in Parris et al. (2012), shown in Equation 3-1.

In many coastal locations, a significant portion of relative sea-level rise comes from VLM, which must be taken into account. USACE (2013) guidance states that to estimate projected SLR at a particular tide gauge, a modified rate based on VLM on that gauge should be applied, as calculated from NOAA technical report, *Estimating Vertical Land Motion from Long-Term Tide Gauge Records* (Zervas et al., 2013). The rate to use in the first (linear) term in Eq. 3.1, would be the GMSLR rate (1.7 mm/yr) + VLM rate. The GMSLR rate of 1.7 mm/yr is the same value used in the third NCA, derived from the work of Church and White (2011), although other values could be used as new research is conducted. The acceleration (b) term would stay the same. At Lewes, the VLM rate was found to be 1.66 mm/yr. At Reedy Point, the rate was found to be 1.71 mm/yr. Therefore, the equations become:

Lewes: 1.7 mm/yr GMSLR + 1.66 mm/yr VLM = 3.36 mm/yr RSLR
Reedy Point: 1.7 mm/yr GMSLR + 1.71 mm/yr VLM = 3.41 mm/yr RSLR

The historic rate of SLR estimates at both gauges have been updated as new data have been collected since the report. The SLR rate at Lewes has increased by 0.21 mm/yr (from 3.20 to 3.41 mm/yr) and at Reedy Point by 0.15 mm/yr (from 3.46 to 3.61 mm/yr). GMSLR will also likely be higher in the future than the long-term average. These changes are not accounted for in the USACE scenario estimates.

Table 3-3. Global and relative sea-level rise amounts by 2100 for USACE planning scenarios. All data are in meters relative to 1992 MSL. Calculations are available at the USACE Sea Level Change Curve Calculator, http://www.corpsclimate.us/ccaceslcurves.cfm.

Scenario	b coefficient	NRC Curve	GMSLR by 2100	Reedy Point SLR by 2100	Lewes SLR by 2100
USACE Low	0 (linear)	Linear	0.184	0.368	0.363
USACE Intermediate	2.71E-5	NRC Curve I	0.50	0.684	0.679
USACE High	1.13E-4	NRC Curve III	1.50	1.686	1.681

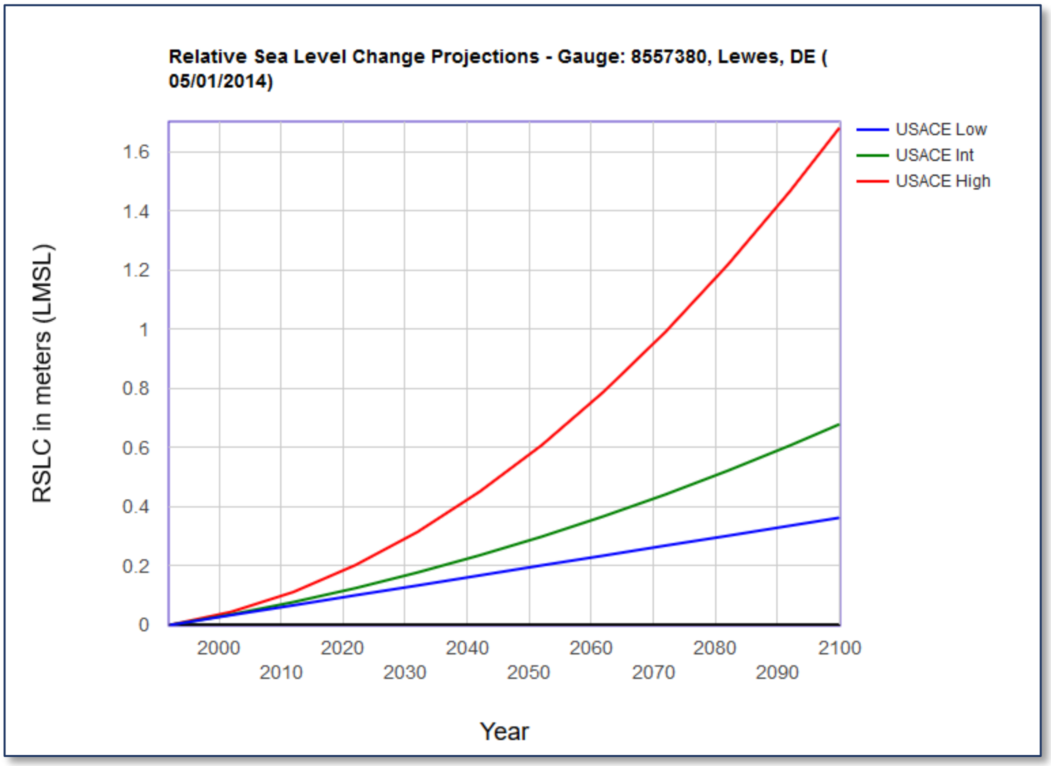


Figure 3-5. Relative sea-level rise by 2100 for Lewes, DE. Source: USACE Sea Level Change Curve Calculator, http://www.corpsclimate.us/ccaceslcurves.cfm.

3.4 NOAA Report on Global and Regional SLR Scenarios for the United States

In 2015, the White House Council on Climate Preparedness and Resilience called for the establishment of the Federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Task Force, a joint task force of the National Ocean Council (NOC) and the U.S. Global Change Research Program (USGCRP) (Sweet et al., 2017). The Task Force's charge is to develop and disseminate, through interagency coordination and collaboration, future RSL and associated coastal flood hazard scenarios and tools for the entire United States. The Task Force has focused its efforts on three primary tasks: 1) updating scenarios of GMSLR; 2) integrating the GMSLR scenarios with regional factors contributing to sea-level change for the entire U.S. coastline, and; 3) incorporating these regionally appropriate scenarios within coastal risk management tools and capabilities deployed by individual agencies in support of the needs of specific stakeholder groups and user communities (Sweet et al., 2017). The NOAA Technical Report NOS CO-OPS 083, *Global and Regional Sea Level Rise Scenarios for the United States*, authored by researchers from NOAA, Rutgers University, the Environmental Protection Agency, South Florida Water Management District, Columbia University, and USGS, focuses on the first two of these three tasks.

The GMSLR scenario-approach in this report essentially represents an update to the work of Parris et al. (2012) used in the third NCA, which put forth a set of four scenarios that spanned the range of scientific GMSLR estimates that could be used for assessment and planning. In a similar manner, the Sweet et al. (2017) report presents six scenarios that span scientific GMSLR estimates that can be used for assessment and planning and will serve as input to the fourth NCA due in 2018. However, it improves on the Parris et al. (2012) work in two distinct ways: 1) it incorporates the most up-to-date science, specifically the improved understanding of complex behaviors of the large, land-based ice sheets of Greenland and Antarctica, and; 2) it utilizes the most up-to-date methodologies for regionally adjusting each given GMSLR scenario.

The scenarios in Sweet et al. (2017) are broader and have a higher limit than those from Parris et al. (2012); the six scenarios (and associated estimates of GMSLR by 2100) are: Low (0.3 m), Intermediate-Low (0.5 m), Intermediate (1.0 m), Intermediate-High (1.5 m), High (2.0 m), and Extreme (2.5 m). The upper limit (i.e., worst-case scenario) was increased from 2.0 m in Parris et al. (2012) to 2.5 m, primarily due to the potential of accelerated mass loss from Antarctica and to be consistent with worst-case scenarios in many other studies. The lowest scenario was also increased, from 0.2 m in Parris et al. (2012) to 0.3 m, mainly because of the higher GMSL data observed in recent years at tide gauges and in satellite altimetry records since Parris et al. (2012) was released. The remaining four scenarios, from Intermediate-Low (0.5 m) to High (2.0 m), were simply placed at 0.5 m intervals in between. The six scenarios are displayed in Figure 3-6 alongside historical reconstruction of GMSL since the year 1800 from Hay et al. (2015) and boxplots that provide a measure of the increased contribution to GMSLR that Antarctica could have based on the modeled estimates from DeConto and Pollard (2016).

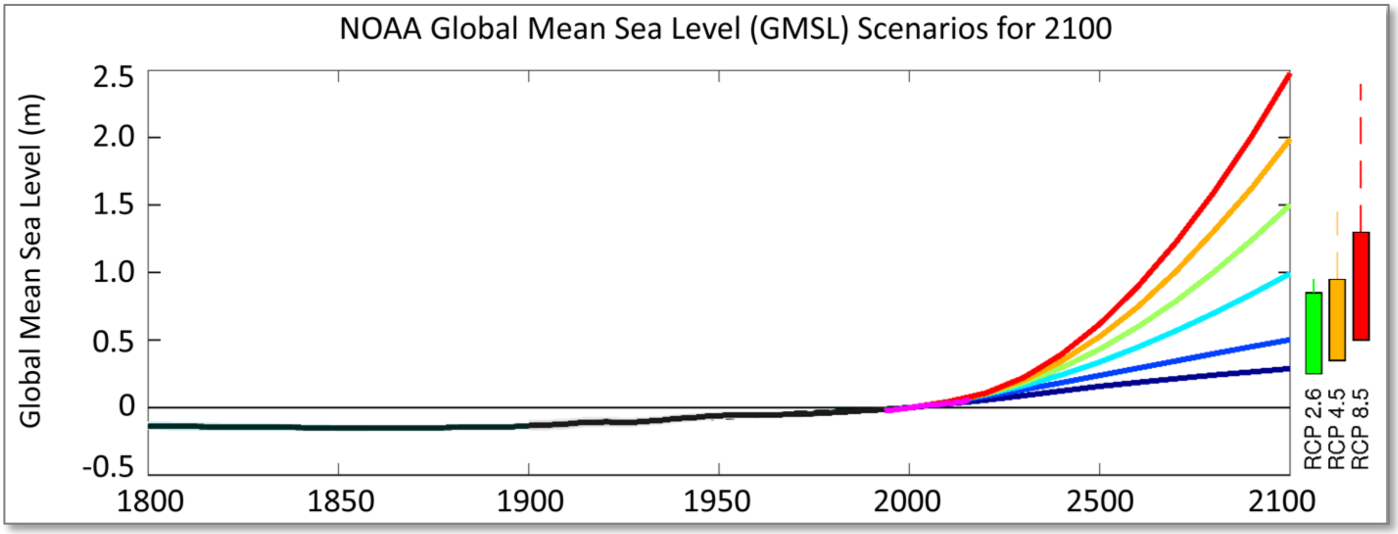


Figure 3-6. GMSLR scenarios to 2100 for six representative scenarios (colored curves: Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme) relative to historical geological, tide gauge, and satellite altimetry reconstructions from 1800 – 2015. The boxes to the right represent GMSLR 90% probability ranges from several recent studies for each RCP scenario. The dashed lines represent the difference between the median Antarctica contributions to GMSLR by 2100 from the SLR projection methodology used in this study (Kopp et al., 2014) and that of DeConto and Pollard (2016). Source: Sweet et al. (2017).

In addition to the scenarios of GMSLR by 2100, a downscaled 1° x 1° gridded product of regional adjustments covering the coastlines of the United States also was produced following the same basic approach of Kopp et al. (2014). Regional SLR probability distributions were developed by separating the influences from climatic and non-climatic background processes and utilized results from the IPCC AR5 process-based models, local and regional tide gauge analysis, expert opinions, and other methods. The distributions were then sampled using Monte Carlo simulations for each of RCP 2.6, RCP 4.5 an RCP 8.5 emission futures and then tied to the six GMSLR scenarios. Estimates of relative SLR for each GMSLR scenario were then assigned to each 1-degree grid cell. The adjustments to GMSLR take into account factors such as glacial isostatic adjustment, ocean circulation patterns, changes in the Earth’s gravitational field, and more.

Table 3-2 gives the estimates of relative SLR by 2100 at the NOAA Lewes tide gauge in Delaware for each GMSLR scenario. Values represent the medians within the regional probability distribution developed for each scenario. Figure 3-7 shows the gridded result along the U.S. coastlines of the difference between relative SLR estimates and the GMSLR estimate for each scenario.

Table 3-2. Estimates of GMSLR and Delaware SLR by 2100 for six representative scenarios: Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme. Source: Sweet et al. (2017).

Scenario	GMSLR by 2100	Delaware SLR by 2100
Low	0.3 m	0.50 m
Intermediate-Low	0.5 m	0.65 m
Intermediate	1.0 m	1.32 m
Intermediate-High	1.5 m	2.01 m
High	2.0 m	2.81 m
Extreme	2.5 m	3.44 m

The methodology used in this report attempts to support both scientific assessment and decision making by combining the scenario approach with probabilistic analysis in a consistent manner. Probabilistic distributions were developed to model all the key processes, individually and cumulatively, that contribute to SLR. The main six scenarios presented here, although representing scientifically plausible upper and lower bounds of GMSLR by 2100, were not necessarily chosen to be relevant for any specific planning or decision-making process, nor to meet the needs of any specific decision-maker or other user (Sweet et al., 2017).

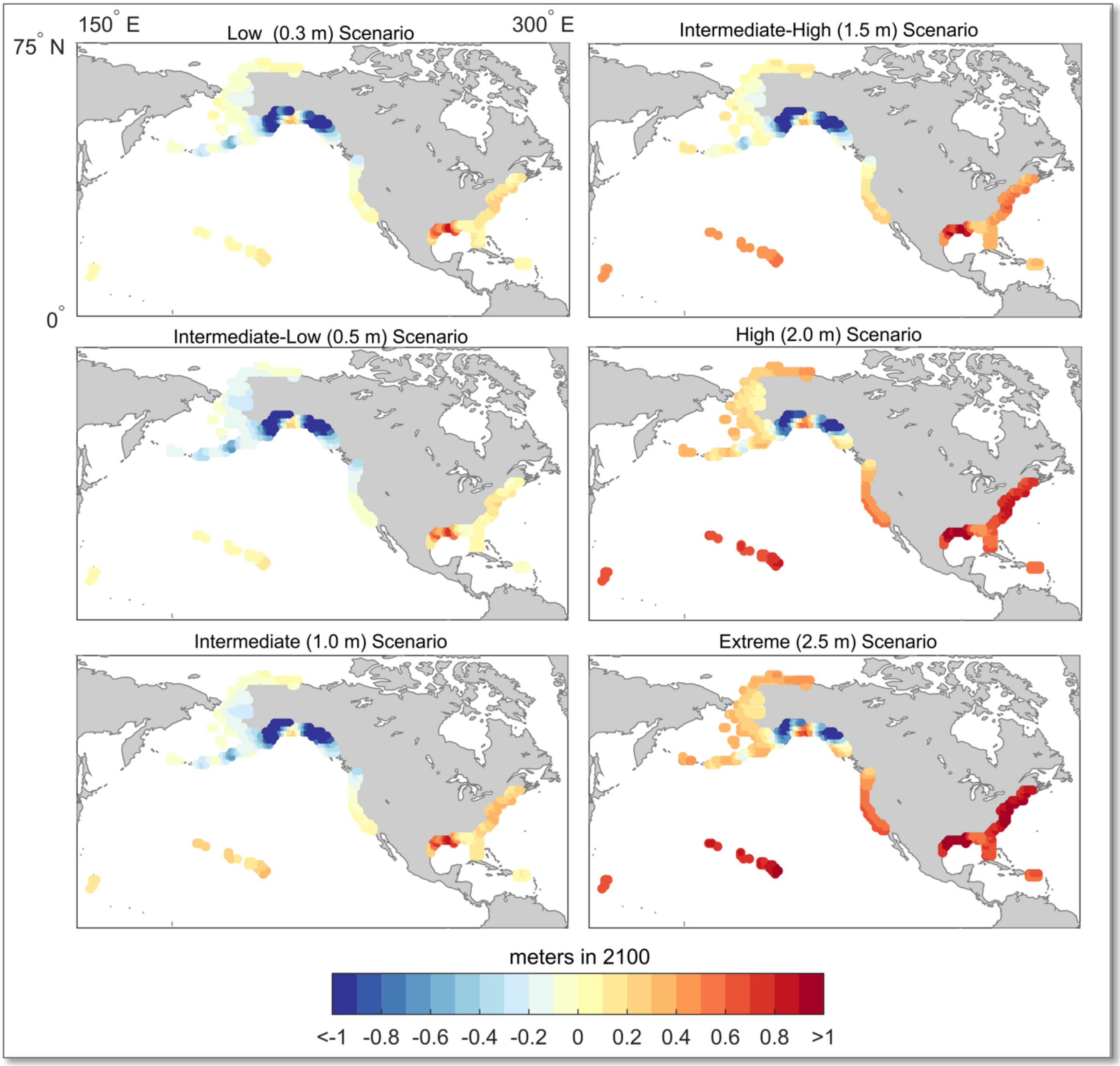


Figure 3-7. Total sea-level rise change, relative to the corresponding GMSLR amount by 2100 for that scenario at the 1-degree resolution grid. To determine the total RSLR by 2100 at each location, add the GMSLR scenario amount to the value shown. Red colors represent relative SLR amounts higher than GMSLR; blue colors represent relative SLR amounts lower than GMSLR. Source: Sweet et al. (2017).

3.5 Semi-Empirical Models (SEMs)

The lack of integrated ice-sheet dynamics models caused the AR4 estimates of GMSLR to be lowest of all IPCC reports and set the stage for the rise of semi-empirical models (SEMs), which estimate GMSLR using past observational data correlations. The basic idea is to develop a statistical relationship between GMSLR (output) and some forcing mechanism (input) from past observational data and exploit that relationship for making projections of the future (Rahmstorf et al., 2012.) SEMs consider sea-level rise as an integrated response of the entire climate system to changes in global mean temperature (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Grinsted et al., 2009; Kemp et al., 2011; Schaeffer et al., 2012; Mengel et al., 2016) or to radiative forcing (Jevrejeva et al., 2009; Jevrejeva et al., 2010). The form of the relationship is based on physically plausible models of reduced complexity, while the parameters of that relationship are determined by a known training dataset, hence the name "semi-empirical" which is in contrast to process-based physical modeling approaches that estimate contributions from each component through modeling and summation of the results (Rahmstorf et al., 2012; Moore et al., 2013).

An example of the relationship between GMSL and global mean temperature, can be expressed in the following equation from Vermeer and Rahmstorf (2009):

$$\frac{d}{dt}H(t) = a\,(T(t) - T0) + b\frac{d}{dt}T(t), \qquad \text{(Eq. 3-2)}$$

where *H(t)* is global mean sea level at time *t*, *T* is global mean temperature, and *T0* is the baseline temperature where sea level is stable in respect to temperature. Constants *a* and *b* are coefficients the long-term and short-term (up to a few decades) sensitivity. Model parameters *a*, *b*, and *T0* can be found through a general least-squares fit of the integral of Equation 3-2.

An advantage of treating GMSLR as a response to a complete system is that it does not require quantifiable knowledge of all forces influencing upon sea-surface heights. If the process-based modeling approach misses accounting for an unknown driving force of sea-level change or misrepresents the physics of a known process affecting SLR, the GMSLR budget would not be closed and estimates could have significant errors. Derivation is performed on existing, long-term datasets of global sea level, either from tide gauges or proxy reconstruction, and temperature/radiative forcing data without the need for supercomputers or spinning up sophisticated models.

One big disadvantage is that it is still unknown if past relationships between sea-level changes and global surface temperature/radiative forcing will hold true into the future (Rahmstorf, 2007), for example, if additional unaccounted forces come into play once sea levels (or oceanic heat content, temperature, etc.) reach a certain threshold. Although there is robustness to the choice of input data (Rahmstorf et al., 2012), the bias and confidence intervals of SEM results are still dependent upon the dataset used for calibration as well as the techniques used for removal of regional and local non-climate effects (e.g., GIA, groundwater pumping, oceanic and atmospheric circulation patterns) from the highly autocorrelated data (Moore et al., 2013; Bitterman et al., 2013).

Jevrejeva et al. (2014) make the argument that by their very nature, with the ability to generate millions of potential SLR projections through random selection of model parameters, SEMs are ideal for exploring a wide range of uncertainties and extreme upper/lower bounds. However, IPCC AR5 did not include SEM results in the SLR projection because there was disagreement on the reliability of SEMs. Figure 3-8 shows SEM results of GMSLR estimates using different calibration time periods. Poor performance was found calibrating the SEM to data only up to 1860, whereas using calibration data ending in 1880 and up to present day collapsed the wide range of predictions.

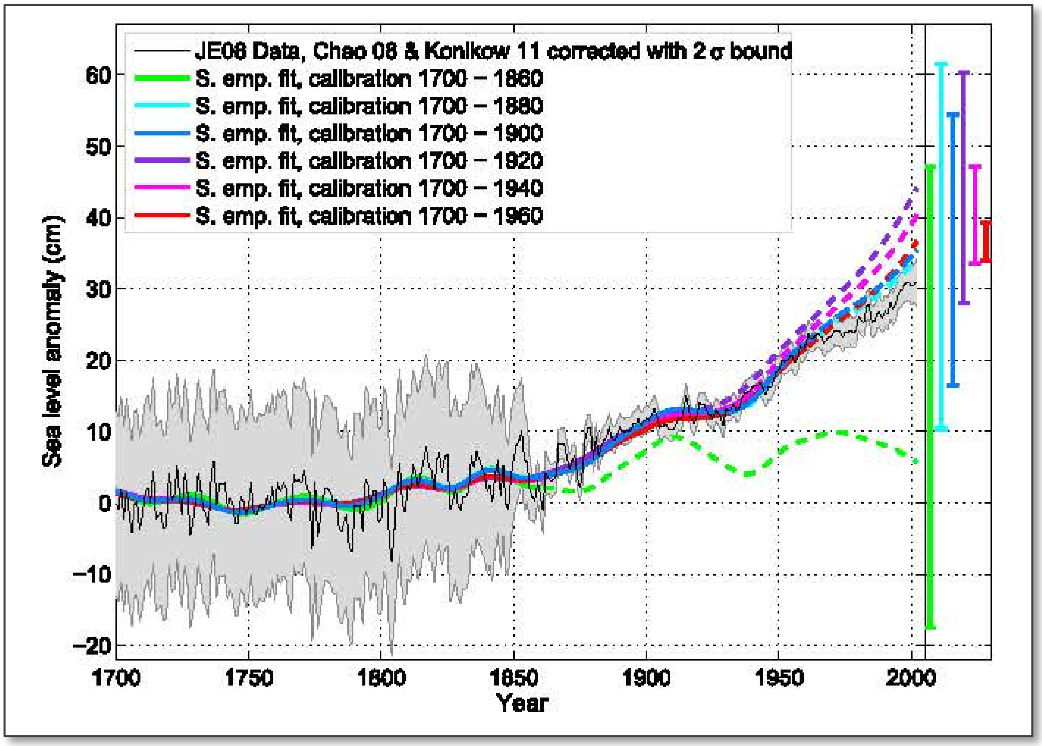


Figure 3-8. SEM sea-level projections and model fit using the tide gauge dataset from Jevrejeva et al. (2008) and using different calibration time periods. Dashed lines indicate projected data; solid lines represent model fit to observed data used for calibration. The bars on the right hand side give the 90% confidence of the forecast, starting from the last year of calibration onwards. Source: Bitterman et al. (2013).

Many of the SEMs projected much higher GMSLR by 2100 than the process-based models in IPCC AR4 under similar emission scenarios (Church et al., 2013; Horton et al., 2014). Process-based model results of GMSLR by 2100 from AR5 were closer to the SEM projections, although the improvement in agreement was largely due to the increased contributions and higher uncertainties in modeled estimates of ice-sheet mass loss within AR5 (Moore et al., 2013) rather than changes in the SEMs. Mengel et al. (2016) developed SEMs for each contributing factor to GMSLR, then combined the results and corresponding uncertainties to create probability ranges for SLR by 2100. Each component can then have its own calibration dataset and response time parameter, perhaps further justifying the extrapolation to future conditions. Resultant 5-95 percent ranges overlapped those of the IPCC AR5 process-based models: 28-56 cm under RCP 2.6, 37-77 cm under RCP 4.5, and 57-131 cm under RCP 8.5. Kopp et al. (2016a) further closed the gap between SEMs and process-based modeling projections by calibrating a more sophisticated, probabilistic-based SEM to ~3,000 years of GMSLR data and adjusting for non-climatic regional and background noise. Although research in SEMs continues alongside process-based modeling, it is unknown the role that SEMs will play in future IPCC and national assessments.

3.6 Horton et al. (2014) - Expert Assessments

Horton et al. (2014) surveyed 90 international experts on sea-level change who were among the most active scientific publishers on the topic of sea level in recent years. Participants were provided with global mean surface temperature projections under two contrasting emissions scenarios (RCP 2.6 and RCP 8.5) and asked to provide their best estimates for likely (17-83 percent) and very likely (5-95 percent) probability ranges of GMSLR by years 2100 and 2300. They were not asked to judge the likelihood of either RCP scenario, just to provide their best estimates of global sea-level rise if either one occurred. Figure 3-10 shows the temperature projections out to 2300 for each scenario and was included in the survey.

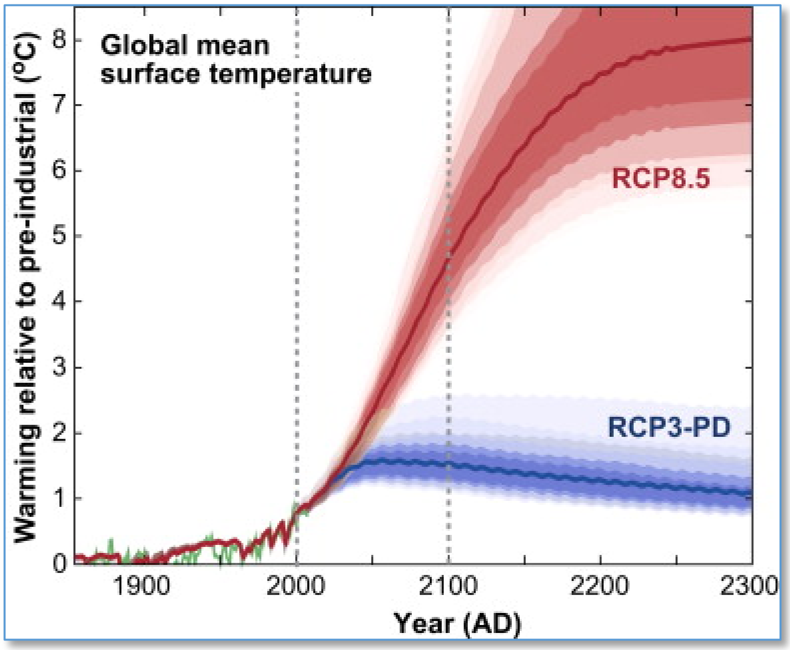


Figure 3-9. Scenarios of global temperature changes up to year 2300 provided to survey participants; scenarios were produced from Meinshausen et al. (2011).

The authors describe two types of expert elicitations: deep and broad. Deep elicitations compile views from a small number of experts in considerable detail while a broad elicitation compiles views from a large number of experts through a small number of questions designed for wide participation and to minimize time investment of the participant. The current survey is a broad elicitation from the professional scientific community, all of which published at least six articles on “sea level” since 2007. Overall, 46 percent of respondents were from North America, 46 percent from Europe, and 8 percent combined from Brazil, China, Japan, and Australia. North American experts reported slightly higher estimates than European counterparts but the differences were not statistically significant. When answering the question regarding estimates of GMSLR by 2100, 82 and 84 participants provided at least a partial response under the RCP 8.5 and RCP 2.6 scenarios, respectively. Likewise regarding GMSLR by 2300, 72 and 74 participants provided at least a partial response under the RCP 8.5 and RCP 2.6 scenarios, respectively.

Table 3-6 and Figure 3-10 summarize the GMSLR estimates compiled from the survey. The likely (17-83 percent) and very likely (5-95 percent) probability ranges of GMSLR by 2100 under RCP 2.6 are 40 – 60 mm and 25-70 mm, respectively. Under RCP 85, the estimates of GMSLR by 2100 are 70-120 mm and 50-150 mm, respectively. Although the maximum (95 percent probability level) values are lower than the high scenarios from the third NCA and other semi-empirical models, they are higher than (but still generally consistent with) estimates from IPCC AR5 and Kopp et al. (2014). The box plots in Figure 3-10 show that in the upper bounds of the probability ranges for the RCP 8.5 emission scenario, several estimates were provided that exceeded the median value of 1.2 and 1.5 m, with some between 2 and 7 m. The authors conclude that the survey reflects a substantial uncertainty remains in predicting the magnitude in future SLR.

Table 3-6. Summary of estimates of global mean sea-level rise by 2100 from Horton et al. (2014) compared with others. Data in cm relative to 1986-2005 MSL.

Method	AR5 Process-based		Schaffer et al. (2014) Semi-empirical		Horton et al. (2014) Survey		Kopp et al. (2014)		
	50%	**17-83%**	**50%**	**5-95%**	**17-83%**	**5-95%**	**50%**	**17-83%**	**5-95%**
RCP 2.6	43	28-60	75	52-96	40-60	25-70	50	37-65	29-82
RCP 4.5	52	35-70	90	64-121	-	-	59	45-77	36-93
RCP 8.5	73	53-97	-	-	70-120	50-150	79	62-100	52-121

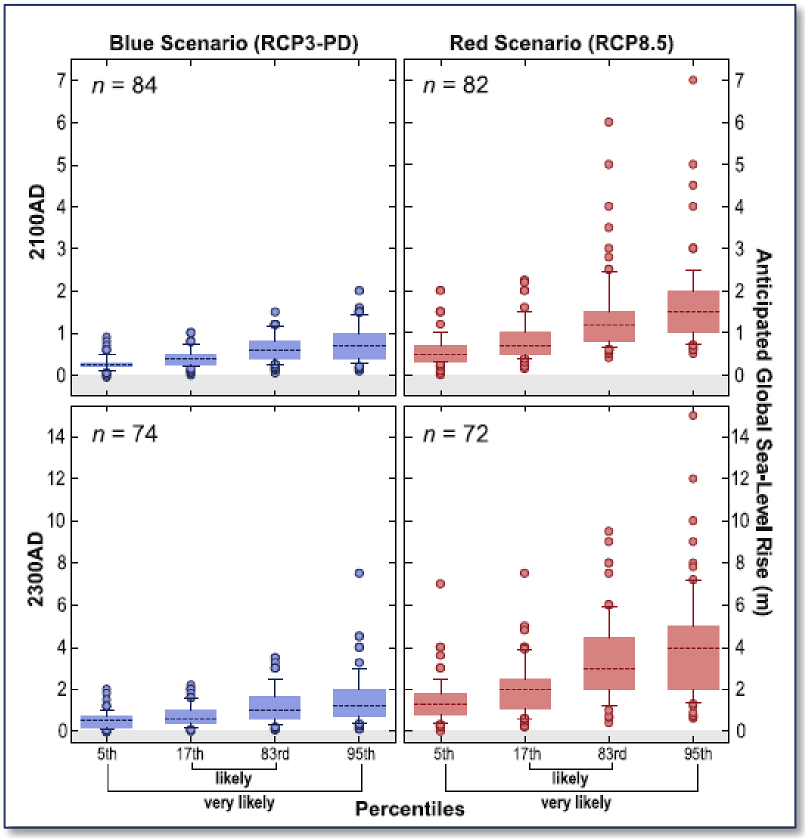


Figure 3-10. Boxplot summary of estimates of GMSLR by 2100 and by 2300, under both RCP 2.6 and RCP 8.5 emission scenarios, from expert assessment survey in Horton et al. (2014).

FAQ 4. Can we extrapolate past linear trends to forecast future sea-level rise?

No. Extrapolation of the century-long linear trend from tide gauge data assumes the rate of SLR was constant during the 20th century and will remain constant throughout the 21st century. FAQ 1 in this report describes each of the primary forces that shape future sea levels, all with likely non-linear responses, such as: 1) the ocean thermal expansion response to increased tropospheric temperature; 2) self-gravitational effects of ice-sheet melting, and; 3) Atlantic Ocean circulation changes due to the weakening and migration of the Gulf Stream. Numerous tide gauge analyses have demonstrated increasing SLR linear trends when comparing the past 100 – 150 years of data to recent decades, many of which have also identified acceleration in the record (refer to section 2-2 in this report for more information.) Extrapolating outside the range of the input data using a quadratic (or higher polynomial) trend is bad practice as these techniques are designed to extract signals within an existing data range; a simple example as a test is to extrapolate a quadratic fit backward in time and note the differences (Baart et al., 2012). Additionally, it is unrealistic to assume the amount and rate of global ice melt added to the oceans, and associated warming feedback mechanisms, will be the same in the next century as it was during the previous one.

4. Recommendations of Delaware SLR Planning Scenarios

4.1 Kopp et al. (2014) Probabilistic Projections

It is recommended that the framework described in Kopp et al. (2014), *Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites*, published in the journal *Earth's Future*, be used as the scientific basis for incorporating sea-level rise into Delaware coastal planning activities. This methodology is a comprehensive probabilistic approach, conditional upon selection of a RCP scenario of greenhouse gas emissions. This was preferred over the scenario-based approach used previously in Delaware (DNREC, 2009) and in the third NCA (Melillo et al., 2014), as it provides more complete information on each SLR contributing component throughout the time period leading up to year 2100, allowing planners to more thoroughly assess and identify which SLR level is most appropriate. This approach also allows for assignment of a probability of likelihood among the Low, Intermediate, and High scenarios, rather than in the scenarios-based approach in which no such likelihood can be given.

Kopp et al. (2014) calculate a complete probability distribution out to year 2200 separately for each of the primary SLR contributing processes, namely: ocean thermal expansion and regional processes, Greenland and Antarctic ice sheets surface mass balance and ice-sheet dynamics, mountain glaciers and ice caps surface mass balance, land water storage, vertical land movement, and other background (e.g., tectonic) effects. The projections are informed by a combination of expert community assessment, expert elicitation (regarding ice-sheet dynamics), and process modeling (results of which come directly from the IPCC AR5 Atmosphere/Ocean GCMs), which all can be combined to generate future local SLR or GMSLR estimates. Figure 4.1 diagrams the logic flow of each of the input sources of information.

Regarding ice sheets, IPCC AR5 is used to characterize the median and likely ranges of sea-level rise due to ice-sheet melting, while the research of Bamber and Aspinall (2013) is used to calibrate the shape of the tails of the probability distribution. This is required because AR5 incorporation of ice-sheet dynamics was limited and not RCP-scenario dependent. The changing mass of the ice sheets also causes self-gravitational effects (decreased gravitational force from reduced mass), which are regionally varying and included in Kopp et al. (2014) through a separate static-equilibrium model. Ocean thermal expansion and regional influences from changing circulation processes are grouped together and informed from IPCC AR models. Changes in GMSLR due to land water storage is based on its relationship to changing population, and includes the cumulative water mass from groundwater and surface-water reservoirs (e.g., lakes, ponds, rivers.)

Historical tide gauge records are included through a sophisticated Gaussian process model that decomposes tide gauge data into three parts: 1) a globally uniform process; 2) a regionally varying, temporarily linear process, and; 3) a regionally varying, temporarily autocorrelated non-linear process, as described in Kopp (2013). The second (linear) term is used for forward projection of local background processes, such as GIA, tectonic processes, and other non-climatic local effects. Local SLR can then be made by combining GMSLR and local/regional observations.

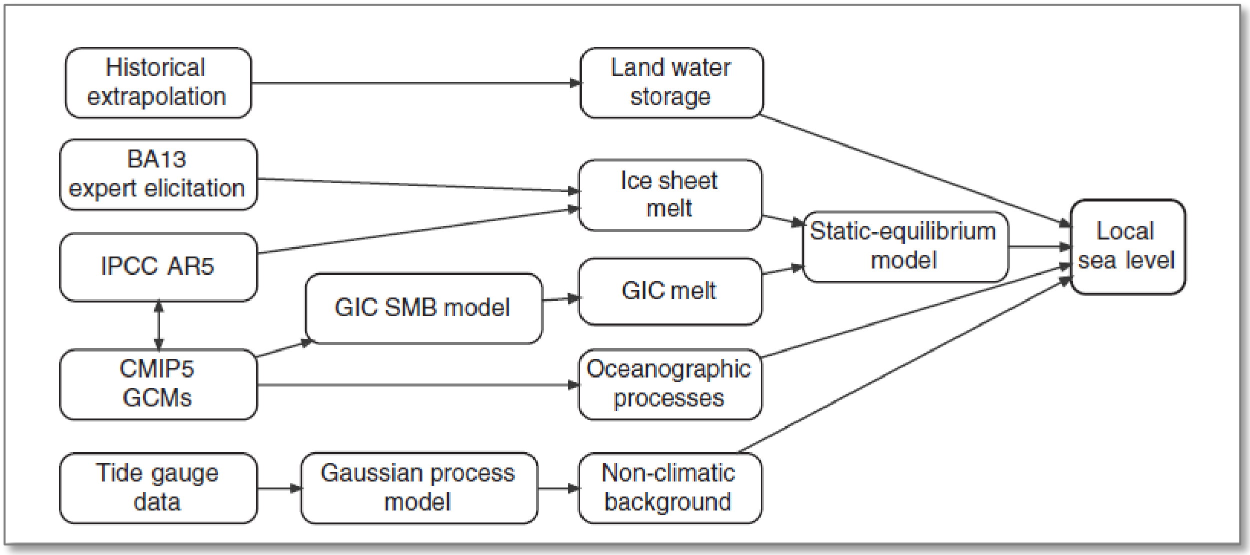


Figure 4-1. Logic flow of sources of information used in local SLR projections. GIC = glaciers and ice caps; SMB = Surface mass balance, BA13 = Bamber and Aspinall, 2013. Source: Kopp et al. (2014).

Although four different RCPs were run during IPCC AR5 study, Kopp et al. (2014) considers only three of these: RCP 2.6, RCP 4.5, and RCP 8.5. They do not use the RCP 6.0 pathway as the projections are nearly identical to those for RCP 4.5, and few CMIP5 model runs for RCP 6.0 extend beyond 2100. As in AR5, the RCP 8.5 pathway can be viewed as the high-end, business-as-usual emissions scenario, whereas RCP 4.5 pathway includes moderate global emissions policies and RCP 2.6 requires intense mitigation strategies to achieve a net-negative carbon emissions budget for the second half of the 21st century.

Table 4-1 lists the GMSLR and local SLR (Lewes and Reedy Point, Delaware) projections by 2100 for each RCP scenario at the 50 percent level (median), likely (17–83 percent) and very likely (5–95 percent) probability ranges. Figure 4-2 shows the GMSLR projection curves produced for the 20th century for each RCP scenario. Solid lines represent median values, dashed lines represent the 5–95 percent probability range, and dotted lines represent the 0.5–99.5 percent probability range. Since the basis for the growth of these curves come from a physical process-based model, the time evolution represents a physical meaning, as opposed to the mathematical constructs employed by the USACE and NCA planning scenario approach. Projections, and their associated probabilities, are valid at times along the curve (conditional upon an RCP selected.)

Table 4-1. Projections of GMSLR and Delaware SLR by 2100 based on Kopp et al. (2014). Data relative to 2000 MSL.

	Global Mean SLR by 2100 (cm)			Reedy Point SLR by 2100 (cm)			Lewes SLR by 2100 (cm)		
Quantile	**50%**	**17-83%**	**5-95%**	**50%**	**17-83%**	**5-95%**	**50%**	**17-83%**	**5-95%**
RCP 2.6	50	37-65	29-82	63	44-85	30-105	66	47-89	33-109
RCP 4.5	59	45-77	36-93	75	53-100	38-120	79	57-103	42-124
RCP 8.5	79	62-100	52-121	95	67-125	48-150	99	70-129	52-153

Note how close the curves are for each RCP scenario. There is a much broader interval in the 5-95 percent probability range of a single RCP than variation in the medians across all three. The curves do not diverge until approximately the year 2045, which is slightly later than in the quadratic fits adopted by USACE and NCA. This is consistent with Lyu et al. (2014) that the time the anthropogenic signal of increasing sea levels exceeds that from natural variability has little to do with future greenhouse gas emissions.

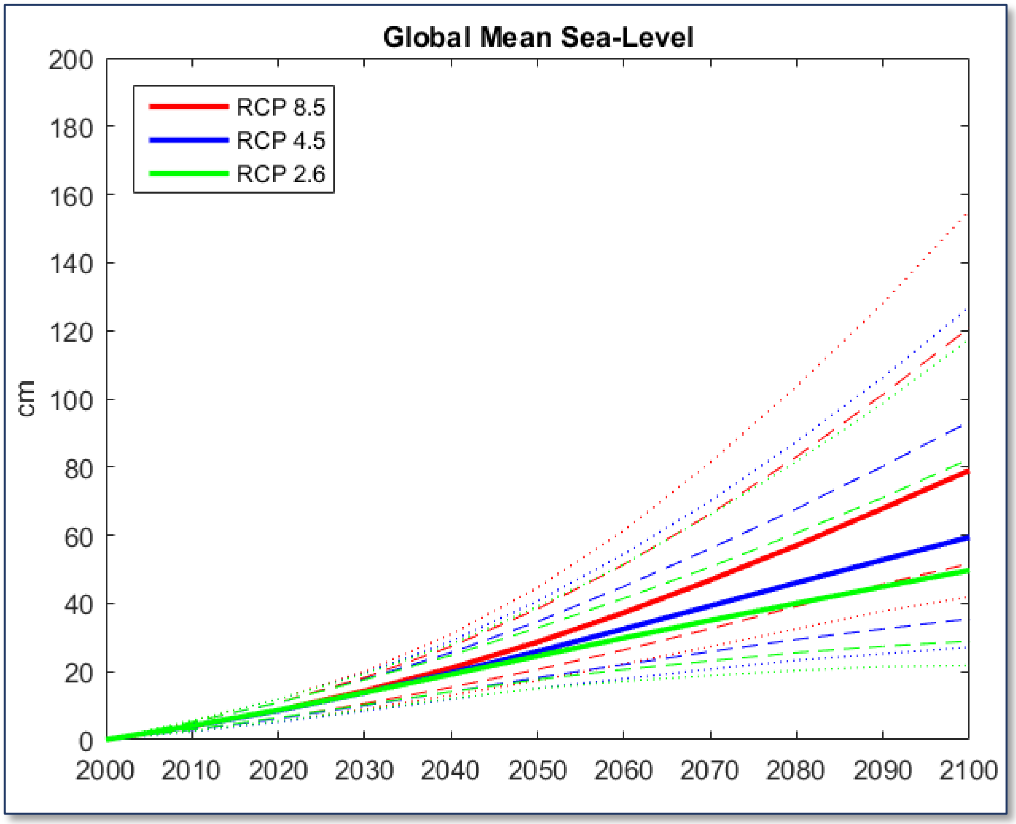


Figure 4-2. GMSLR by 2100 produced by Kopp et al. (2014) for RCP 2.6, RCP 4.5 and RCP 8.5 emission scenarios. Solid lines represent median (50%) values, dashed lines represent 5-95% range, and dotted lines represent 0.5-99.5% range. Note the minimal difference among RCP scenarios until mid-century. Data relative to year 2000 MSL.

Table 4-2 and Figure 4-3 show the decomposition of the magnitude and relative uncertainty (as fraction of variance) of individual process contributions to GMSLR by 2100. The ocean contribution, which is mostly composted of thermal expansion but also includes effects of ocean circulation changes, makes up approximately 50 percent of the total cumulative contribution, with mountain glaciers and ice caps contributing about the same as the combined Greenland and Antarctic ice sheets, as the next largest components. This is consistent with IPCC AR5 since the both projections come from the CMIP5 models. However, the Greenland and Antarctic sources have very large uncertainty ranges, biased to the positive, due to additional expert elicitation included in the Kopp et al. (2014) methodology. The IPCC AR5 estimates did not include additional information to modify the process-based model results, which include ice-sheet dynamics only to a limited extent. As the century progresses, the overall uncertainty increases with Antarctic ice sheet remaining the largest unknown.

Contributing Component	Global Mean SLR by 2100 under RCP 8.5 (cm)		
	50%	**17-83%**	**5-95%**
Antarctic Ice Sheet	4	-8-15	-11-33
Greenland Ice Sheet	14	8-25	5-39
Ocean	37	28-46	22-52
Glaciers and Ice Caps	18	14-21	11-24
Land Water Storage	5	3-7	2-8

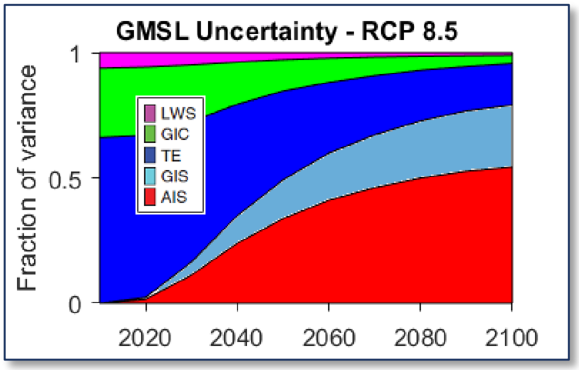


Table 4-2 and Figure 4-3. Decomposition and uncertainty of GMSLR by 2100 projections based Kopp et al. (2014). Data relative to year 2000 MSL.

The Kopp et al. (2014) methodology provides numerous benefits:

1) A complete probability distribution of SLR projections is provided, not just single values or limited ranges. For example, IPCC AR5 provides projections of GMSLR by 2100 in the likely (17-83 percent) and very likely (5-95 percent) probability ranges; no information is provided on SLR outcomes outside of this range. NCA and USACE provide single values of GMSLR at 2100 with no probabilities assigned as to how likely that scenario will occur. Understanding the likelihood of the high SLR estimates is important for assessing the likelihood of risks related to coastal flooding.
2) The time evolution of projections is physically based; estimates of SLR for times earlier than year 2100 have a valid probability assigned. Therefore, state and local planners and management officials may use the projection curves to estimate SLR at a time most appropriate to their needs.
3) Projections are based on an ensemble of numerous, sophisticated atmosphere-oceanographic global climate models (AOGCMs) and research methodology as in IPCC AR5, the current internationally accepted state of knowledge relating to climate change and sea-level rise.
4) Regional processes, such as VLM (estimated through locally observed tide gauge data at NOAA Lewes Breakwater Harbor) and ocean circulation changes (AR models) are incorporated.
5) Relative contributions and associated uncertainties are separated for the primary sources of sea-level rise, both globally and locally, which could help planners decide which scenario to plan for.
6) Kopp et al. (2014) incorporated expert opinions (on ice-sheet dynamics) to refine model results.
7) SLR projections of Kopp et al. (2014) were consistent with the historical relationship between temperature and rate of GMSLR over the last two millennia (Kopp et al., 2016a).
8) Robustness of the results was tested against several alternate assumptions and statistical techniques performed in the Kopp et al. (2014) analysis.

The Kopp et al. (2014) probabilistic framework, either whole or in part, is currently being used in several research-based analyses (Moftakhari et al., 2015; Sweet and Park, 2014; Little et al., 2015), U.S. economic analyses (CBO, 2014; Houser et al., 2015), federal multi-agency reports (Hall et al., 2016; Sweet et al., 2017), and state SLR planning activities, such as in New Jersey (Kopp et al., 2016b), Washington (Peterson et al., 2015), and California (Griggs et al., 2017).

4.2 Delaware SLR Planning Scenario Recommendations

It is the recommendation of the Delaware SLR Technical Committee to use the 5, 50, and 95 percent probability levels of sea-level rise in Delaware, determined by the Kopp et al. (2014) methodology under the IPCC AR5 RCP 8.5 greenhouse gas emission scenario, as the Low, Intermediate, and High SLR planning scenarios, respectively. This equates to 0.52 m, 0.99 m, and 1.53 m of SLR by 2100, relative to year 2000 MSL. The 5 and 95 percent values represent the upper and lower limits of the 90 percent probability range of SLR by 2100. Depending on time horizon and sensitivity to coastal flooding, projects may also benefit by planning for SLR amounts above the High (95 percent) SLR planning scenario.

SLR Planning Scenario	SLR by 2100	
Low Scenario (5%)	**0.52 m**	**1.71 ft**
Intermediate Scenario (50%)	**0.99 m**	**3.25 ft**
High Scenario (95%)	**1.53 m**	**5.02 ft**

Table 4-3. Selected SLR probability levels based on the Kopp et al. (2014) methodology under the RCP 8.5 greenhouse gas emission scenario applied to the NOAA Lewes Breakwater Harbor tide gauge for years 2030, 2050, 2080, and 2100. The 5/50/95% probability corresponds to the 2017 Delaware Low/Intermediate/High SLR planning scenarios. Data in meters and feet relative to year 2000 MSL.

Year	**SLR Probability Levels under Kopp et al. (2014) for Delaware**				
	5% (Low)	**17%**	**50% (Inter.)**	**83%**	**95% (High)**
2030	0.11 m / 0.36 ft	0.16 m / 0.53 ft	0.22 m / 0.76 ft	0.28 m / 0.92 ft	0.33 m / 1.08 ft
2050	0.22 m / 0.72 ft	0.30 m / 0.98 ft	0.40 m / 1.31 ft	0.50 m / 1.64 ft	0.58 m / 1.90 ft
2080	0.42 m / 1.38 ft	0.55 m / 1.80 ft	0.74 m / 2.43 ft	0.95 m / 3.12 ft	1.11 m / 3.64 ft
2100	0.52 m / 1.71 ft	0.70 m / 2.30 ft	0.99 m / 3.25 ft	1.29 m / 4.23 ft	1.53 m / 5.02 ft

Table 4-4. Probability that SLR in Delaware will meet or exceed column heading value for stated years. Based on Kopp et al. (2014) methodology under the RCP 8.5 greenhouse gas emission scenario, relative to 2000 MSL. Gray shaded areas have less than 0.1% chance of occurrence.

	1.0 ft 0.30 m	2.0 ft 0.61 m	3.0 ft 0.91 m	4.0 ft 1.22 m	5.0 ft 1.52 m	6.0 ft 1.83 m	7.0 ft 2.13 m	8.0 ft 2.44 m	9.0 ft 2.74 m	10.0 ft 3.05 m
2020	0.1%									
2030	12%									
2040	51%	0.4%								
2050	80%	5.5%	0.2%							
2060	92%	25%	1.7%	0.2%	0.1%					
2070	96%	52%	8.2%	1.1%	0.2%	0.1%				
2080	98%	71%	24%	4.1%	1.0%	0.3%	0.1%	0.1%		
2090	98%	82%	43%	13%	3.2%	1.1%	0.4%	0.2%	0.1%	0.1%
2100	98%	87%	58%	25%	8.5%	2.7%	1.2%	0.5%	0.3%	0.2%

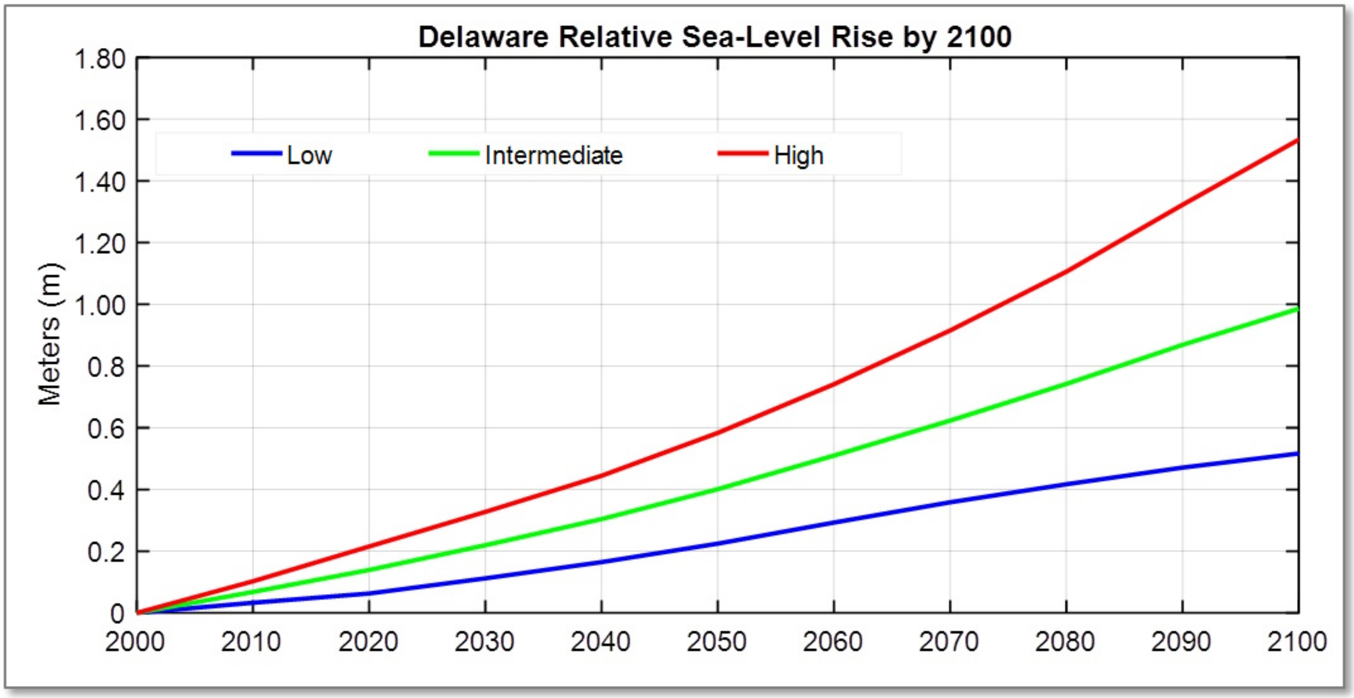
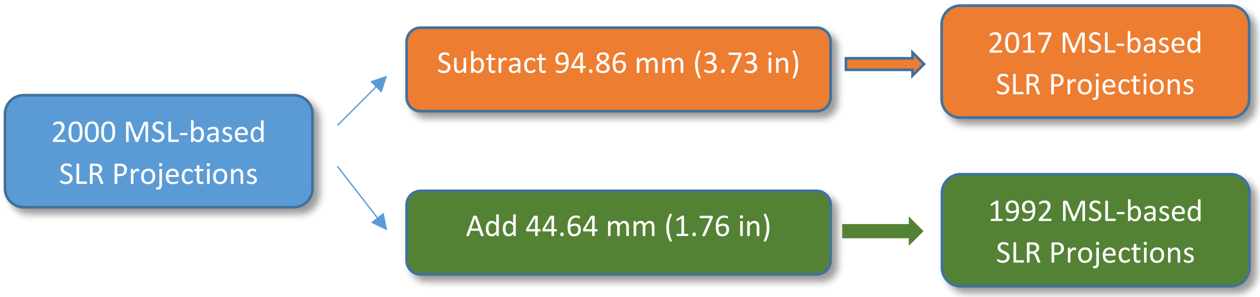


Figure 4-4. The 2017 Delaware SLR planning scenario curves to the year 2100, relative to 2000 MSL.

SLR projections starting point of year 2000. Kopp et al. (2014) projections are referenced to the year 2000. The average rate of SLR at the Lewes gauge over these two decades (1990 through 2010) is 5.58 ± 1.79 mm/yr (95 percent confidence interval); the high uncertainty range is based on the low number of years (20) and the observed variability within the time period. If we assume this same linear rate moving forward in time, the mean sea level in 2017 would be (17 x 5.58 =) 94.86 mm (3.73 in) higher than it was in 2000. Therefore, to modify the Kopp et al. (2014) SLR projections to reference the estimated 2017 MSL (present day) as the baseline instead of 2000 MSL, subtract 94.86 mm (3.73 in) from the projections. The same calculation can be done backwards in time to 1992, which is the mid-point of the tidal epoch used to calculate the official NOAA NTDE 1983 – 2001 tidal datums as well as the year the previous Delaware SLR scenarios were referenced. Assuming the same linear rate moving backwards in time from 2000 to 1992, the difference in MSL would be (8 x 5.58 =) 44.64 mm (1.76 in) Therefore, to modify the Kopp et al. (2014) SLR projections to reference the 1992 MSL as the baseline instead of 2000 MSL, add 44.64 mm (1.76 in) to the projections.



Mean sea level observations at the Lewes tide gauge since 2000 have been highly variable. Figure 4-5 shows monthly and annual mean sea level data, computed after first removing the seasonal cycle following the methodology in Zervas (2009), plotted against the three Delaware SLR planning scenarios. The tide gauge data were referenced to the year 2000 MSL to match the reference year of the SLR projections. Since 2000, the mean sea level for each month has extended to greater than the High SLR planning scenario curve and lower than the Low SLR planning scenario curve on several occasions. The observed variability, discussed more in section 2.2 of this report, is larger than changes in the mean sea level following any of the three planning scenario curves, as well as larger than the difference among the curves for much of the past 17 years. A longer time period is needed to estimate if local sea levels are following any of the currently modeled scenarios.

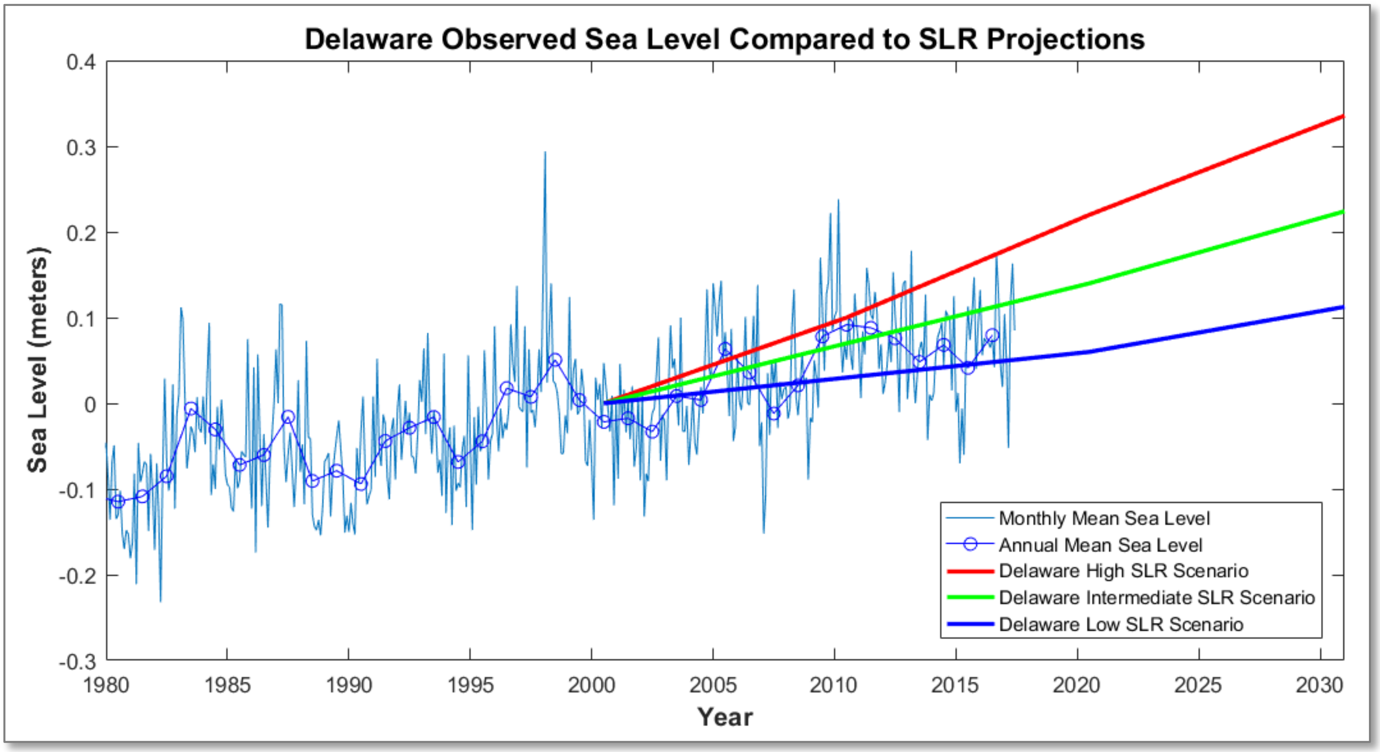


Figure 4-5. Monthly and annual mean sea levels observed at the NOAA Lewes tide gauge after removing the seasonal cycle, compared to the 2017 Delaware SLR planning scenarios. Data relative to 2000 MSL.

Selection of RCP 8.5 emission scenario. It is difficult, if not impossible, to assess the likelihood of any one particular IPCC AR5 RCP global greenhouse gas emission scenario over another, i.e., probabilities of occurrence cannot be assigned to each RCP scenario. Under the Kopp et al. (2014) probabilistic framework, the SLR values and the probability of occurrence are valid only within a single RCP emission scenario. RCP 8.5 was chosen for the Delaware SLR planning recommendations as it represents the continuation of current global emission growth, with atmospheric concentrations of CO_2 eventually reaching 940 ppm by 2100, and has been considered the “business as usual” case (Houser et al., 2014).

Figure 4-6 (left) shows the amount of gigatons of carbon released in the atmosphere globally following each RCP emission scenario. Figure 4-6 (right) shows how the past actual carbon emissions compare to the AR5 RCP emission scenarios as well as the IPCC AR4 SRES scenarios for comparison. Note that as shown in Table 4-1 and Figure 4-2 in the previous section of this chapter, there is very little difference in the amount of sea-level rise among the different RCP scenarios until the second half of the century. This is because sea-level rise is a slowly responding, cumulative aspect of climate change. However, recent data appear to be tracking along the RCP 8.5 curve. Particularly for planning purposes, due to the higher potential of severe damage to property with significant impact to public safety, RCP 8.5 emission scenario seems to be the most appropriate scenario to use for future SLR impacts due to projected climate change.

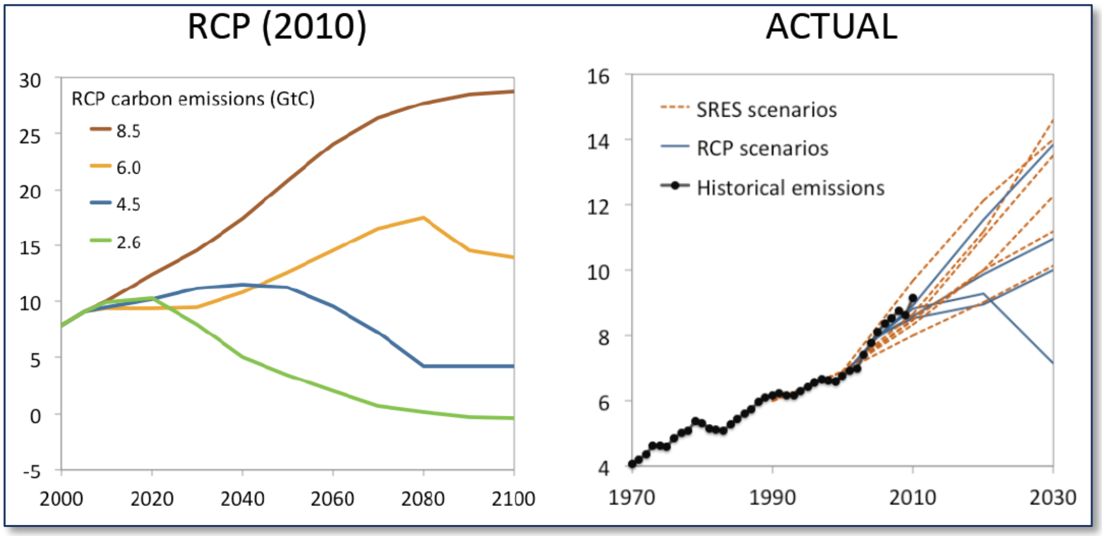


Figure 4-6. (left) Global carbon emissions in gigatons of carbon (GtC) assumed under each IPCC AR5 RCP emission scenario. (right) RCP and IPCC AR4 SRES emission scenario curves compard to historic observations of carbin emissions. Source: IPCC (2013).

Selection of the Lewes tide gauge. To define a single set of SLR planning scenarios for Delaware, the NOAA tide gauge at Lewes Breakwater Harbor was selected over the tide gauge at Reedy Point to apply the Kopp et al. (2014) methodology. Lewes is more centrally located to the coastal areas most affected by SLR, and the tide gauge has a much longer period of record. As well, both gauges have very similar projection curves under the Kopp et al. (2014) methodology. For example, the difference in SLR at 2100 between the Lewes and Reedy Point tide gauges under the RCP 8.5 emission scenarios at the 95 percent probability level is only 4 cm.

Comparison with other assessments. Figure 4-5 displays the likely ranges of projections of GMSLR by year 2100 from numerous studies and assessments compared with the global mean and Delaware-specific SLR projections made by Kopp et al. (2014). For the modelling or statistically based projections, the ranges presented here represent the likely (17 – 85 percent) or very likely (5 – 95 percent) probability ranges.

Data from the NRC (2012), Parris et al. (2012), USACE (2013), and NOAA (Sweet et al., 2017) reports represent the full scope of scenarios used within their approach. The range of the GMSLR projections from Kopp et al. (2014) represents the very likely (5 – 95 percent) probability of occurrence and align well with the other studies. Not shown on the graph but described in section 4-3 of this report, the GMSLR 99.9 percent probability of occurrence from Kopp et al. (2014) is 2.47 m, nearly identical to the maximum GMSLR scenario used in the latest Sweet et al. (2017) report. As would be expected, the 2017 Delaware SLR planning scenarios, based on the Kopp et al. (2014), are higher than GMSLR but still consistent with the other studies.

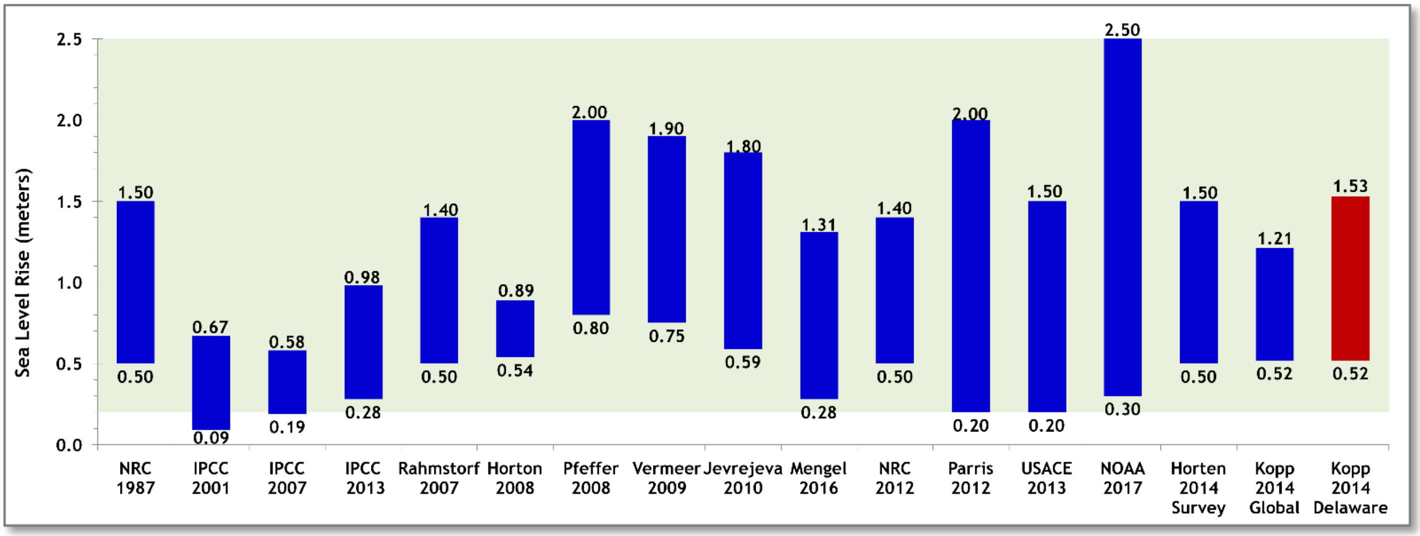


Figure 4-5. Comparison of the recommended 2017 Delaware SLR planning scenario range (shown in red), based on the Kopp et al. (2014) methodology, to the ranges of GMSLR by 2100 across scenarios of other well-known research studies, semi-empirical models, IPCC assessments, and the U.S. NCA. Data from Church et al. (2013) report represent likely range, 17 – 83% probability of occurrence. Modified from Figure 2 in USACE (2014).

Component breakdown of SLR in Delaware. The breakdown of contributing components and their associated uncertainties of relative SLR in Delaware in Table 4-5 and Figure 4-8 is similar to their influence on GMSLR with a few differences. Oceanographic processes contribute more to the SLR around Delaware with a broader uncertainty range, mainly due to the AR5 modeled results of the changes in location and intensity of the Gulf Stream. Contribution from the Greenland ice sheet is slightly lower, offset somewhat by the self-gravitational effects. Background values (which include processes such as GIA, tectonics, and other non-climatic effects) are generated by the regional linear term computed from regional tide gauge data. Contribution from Antarctica remains about the same although its relative uncertainty is much smaller than regional ocean processes.

Table 4-5. Individual component decomposition under RCP 8.5 emission scenario projection of SLR by 2100 for Delaware based on Kopp et al. (2014). Negative values indicate a potential lowering of sea levels. Values for Greenland and Antarctic ice sheets include both surface mass loss and ice-sheet dynamics. Data in cm relative to year 2000 MSL.

SLR at Delaware (Lewes) by 2100	RCP 8.5		
	50%	**17-83%**	**5-95%**
Antarctic Ice Sheet	4	-8-18	-12-38
Greenland Ice Sheet	7	4-13	3-20
Ocean (thermal + circulation changes)	48	25-72	8-90
Glaciers and Ice Caps	15	11-18	9-20
Land Water Storage	5	3-7	2-8
Background (including GIA)	17	16-19	15-20

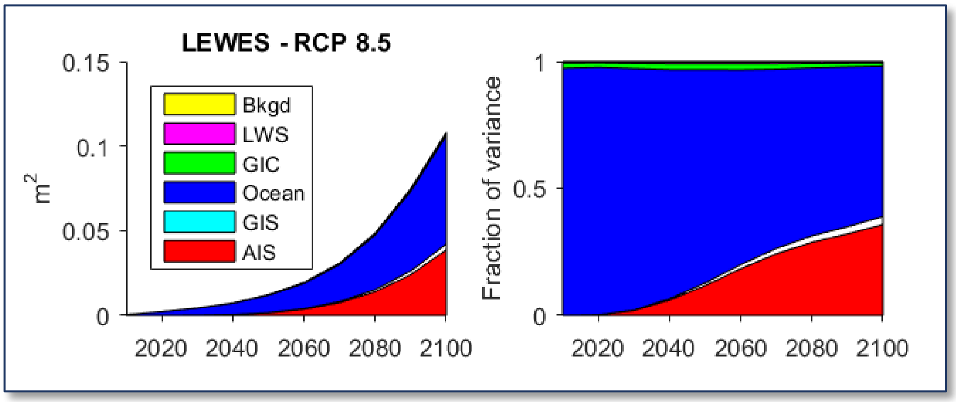


Figure 4-8. Relative contribution (left) and uncertainty (right) for each component under RCP 8.5 emission scenario projection of SLR by 2100 for Delaware (Lewes) based on the Kopp et al. (2014).

FAQ 5. The uncertainty of the Greenland and Antarctic ice sheets

For most of the 20th century, sea-level rise has been dominated by thermal expansion from a globally warming ocean. However, the transfer of ice from land to the sea has recently taken over as the primary contributor to GMSLR (Griggs et al., 2017). Since the 1970s, observed sea levels have risen through a combination of thermal expansion, ice loss from mountain glaciers and ice caps, ice loss from the Greenland and Antarctic ice sheets, and changes in land water storage (Church et al., 2011) confirmed by various observational studies since the 1990s (Church et al., 2013; Griggs et al., 2017; AMAP, 2017; Sweet et al., 2017). Figure 4-9 shows recent relative acceleration of ocean mass increase (due to the addition of land ice) compared to thermal expansion. Similarly, Figure 4-10 shows the contributions from thermal expansion, Greenland ice sheet (GIS) and Antarctic ice sheet (AIS), land water storage, and mountain glaciers, with emphasis on the Arctic region, from 2004 to 2010. Summing the individual components, about one-third of GMSLR contribution is from thermal expansion and two-thirds from land ice loss.

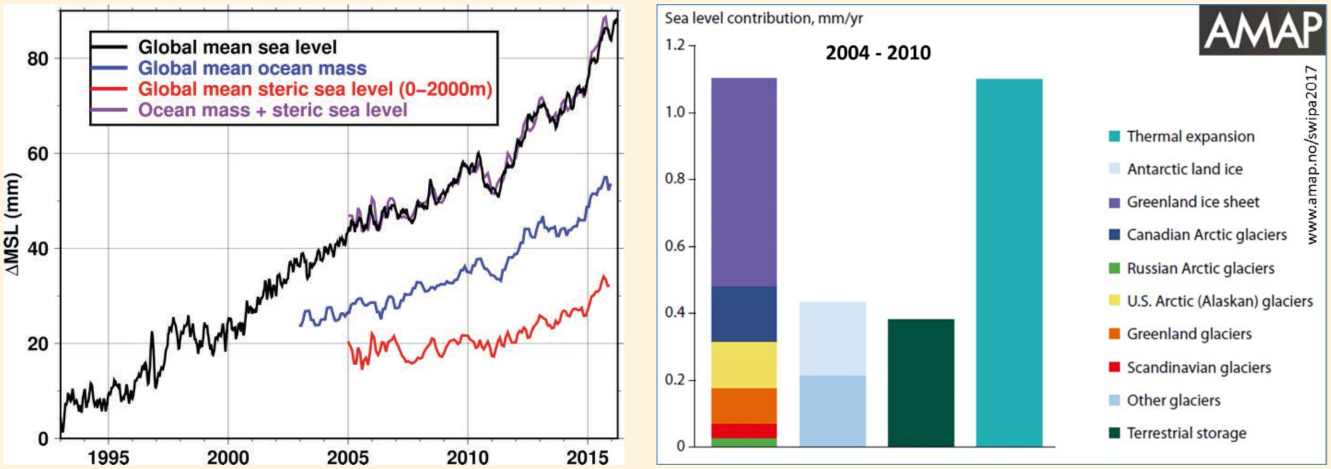


Figure 4-9 (left) and 4-10 (right). On the left, GMSLR from satellite altimetry (plotted in black) compared against individual contributions of 1) ocean mass changes due to melting land-based ice and liquid water storage (blue), and 2) thermal expansion from upper ocean from Argo floats (red). Source: Leuliette and Nerem (2016). On the right, components of GMSLR averaged over 2004-2010. Source: AMAP (2017).

Based on recent observations, loss of ice from mountain glaciers and ice caps is contributing similar amounts to GMSLR than from Greenland and Antarctica, although they are on different future paths. Contributions from mountain glaciers and ice caps are expected to decrease as they melt and disappear, whereas the Greenland and Antarctic ice sheets have been melting faster than anticipated. There is enough ice locked in the GIS to raise GMSLR by about 7 meters, and within the AIS to raise GMSLR about 60 meters. Although it will take many hundreds to thousands of years for these ice sheets to disappear completely, many glaciers on the edges of these massive ice sheets contribute significantly to global sea levels and are retreating at an accelerated pace, such as the Jakobshavn glacier in Greenland and the Pine Island glaciers around the Amundsen Sea in Antarctica. One of the causes of accelerated grounding line retreat and subsequent increased flow of ice into the sea is the breakup of sea ice shelves, which, when fully intact, typically block the seaward flow of the glacier (buttressing effect).

Despite their substantial potential contributions to GMSLR, dynamical modeling of ice sheets is still in its infancy and currently a very active field. For instance, ice-sheet dynamic processes were not included in the IPCC AR4 and only in a limited extent (as a constant additive value) in AR5. There are several instabilities inherent in the melting of the glaciers that produce positive feedback effects that must be modeled. These include marine ice sheet instability (MISI, retreat of the grounding line on an inverted slope and thinning of the glacier due to warm deep ocean water), crevassing and hydrofracturing (meltwater and precipitation run-off that crevasse into the glacier, causing calving/fracturing of the glacier as well as reducing bottom friction enhancing retreat), vertical marine ice-cliff instability (MICI, as the glacier thins and calves, pieces of the vertical ice cliffs break away in large chunks), and albedo darkening (ponding on the surface and mixing of rock/dirt increases absorption of radiation and therefore temperature) (Pollard et al., 2015; DeConto and Pollard, 2016; Tedesco et al., 2016; Griggs et al., 2017). Figure 4-11 diagrams these processes, except albedo darkening, more thoroughly.

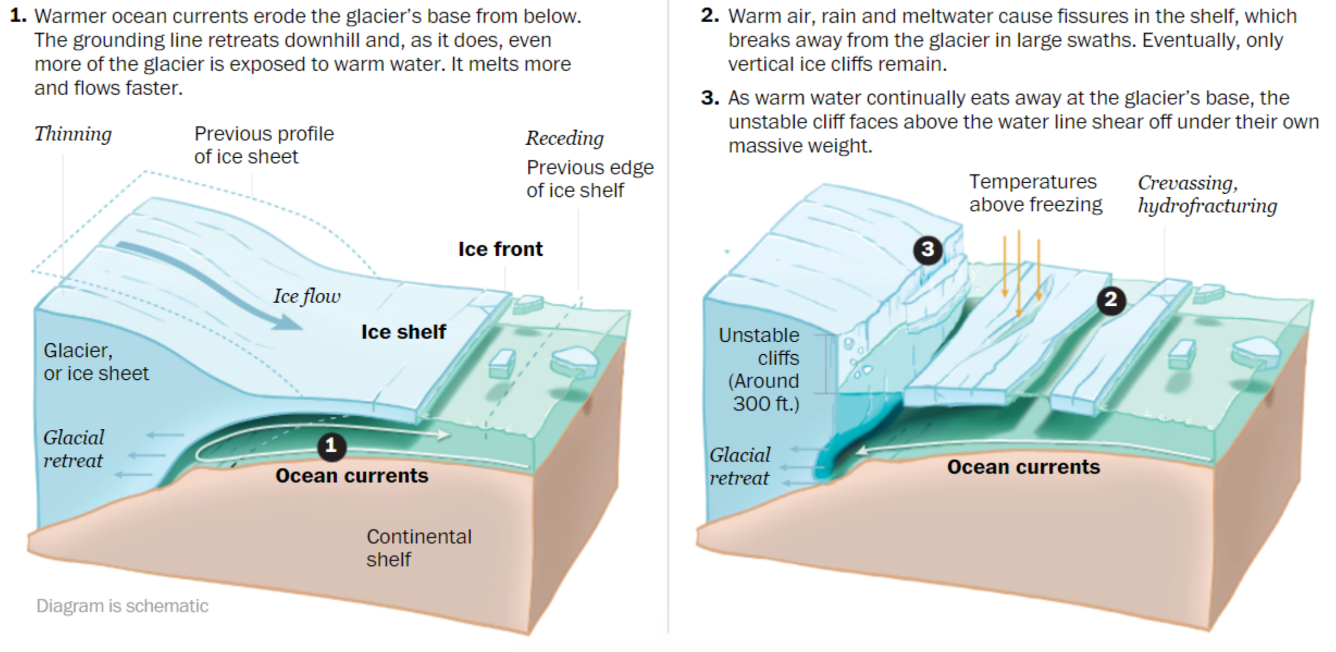


Figure 4-11. Diagram of dynamic processes occurring from glacier melt. Source: DeConto and Pollard (2016). Accessed from https://www.washingtonpost.com/news/energy-environment/wp/2016/03/30/antarctic-loss-could-double-expected-sea-level-rise-by-2100-scientists-say/

Hansen et al. (2016), in a comprehensive study, used numerical climate modeling of both paleoclimate and modern observations to study the effect of growing ice melt from Antarctica and Greenland directly and through feedback mechanisms. Their fundamental question regarding sea level was, "whether ice-sheet melt in response to rapid global warming will be nonlinear and better characterized by a doubling time for its rate of change or whether more linear processes dominate." They conclude that a 2°C global warming above the preindustrial level could be dangerous, and continued high fossil-fuel emissions this century would yield, among other things, nonlinearly growing sea-level rise, reaching several meters over a timescale of 50–150 years. Doubling times of 10, 20 or 40 years would yield multi-meter sea-level rise in about 50, 100 or 200 years, although they also concede that the empirical data are too brief to confirm their hypothesis. This study represents a catastrophic case that may be possible due to the rapid nature of positive feedback mechanisms.

DeConto and Pollard (2016) modeled past and future contributions to GMSLR from Antarctica by coupling climate and ice-sheet dynamics, including the three sea-ice dynamic processes described in Figure 4-6 (the first paper to do so). The model was calibrated against two warm periods in geologic history: 1) the Last Interglacial (LIG), about 130,000 – 115,000 years ago when GMSL was about 6.0-9.3 m higher than it is today, atmospheric concentrations were about 280 ppm, and global mean

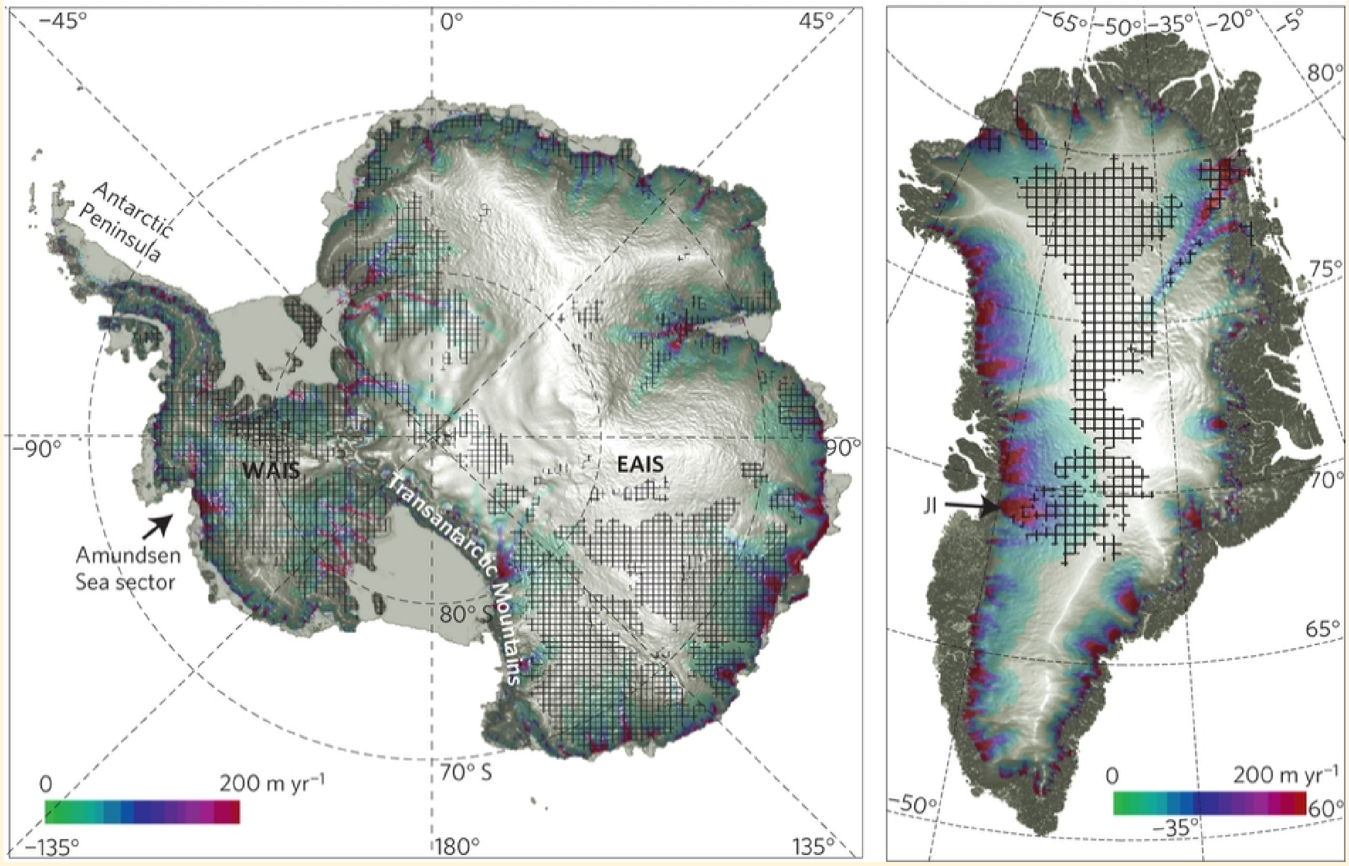


Figure 4-11. Shaded relief of Antarctica and Greenland ice sheets. Colored areas show regions of high glacier flow. Hatched areas show regions where the grounding line is below MSL. Nearly all of the West Antarctic ice sheet bedrock is below MSL, much of it also backward sloping (not shown).

temperatures were only 0-2°C warmer than today, and; 2) during the Pliocene epoch, about three million years ago, when atmospheric CO_2 concentrations were comparable to today (about 400 ppm) but sea levels were 10 – 30 m higher. The LIG reconstruction required approximately 3.6 – 7.4 m contribution from Antarctica and 1.5 – 2.0 m from Greenland, while the Pliocene reconstruction required the complete loss of Greenland and West Antarctic Ice Sheet (WAIS) and partial loss of the East Antarctic Ice Sheet (EAIS). The authors applied the calibrated set of parameterizations to future GMSLR. Under the RCP 8.5 high emission scenario, Antarctic-only contributions to GMSLR by 2100 can be 0.78 – 1.50 m, significantly higher than other estimates and nearly double the projections in IPCC AR5.

Due to the overall instability and potential tipping point of West Antarctic glaciers as the grounding line retreats downslope, the unpredictability of the breakup of sea ice shelves buttressing land-based glaciers, and the fragile nature of hydro-fracturing and ice-cliff instability dependence on increasing atmospheric temperature, it is extremely difficult to reliably predict the rate and amount of SLR these ice sheets will cause in the future. Models are only beginning to incorporate these processes; the DeConto and Pollard (2016) study being the first to incorporate the new dynamic processes. In order to plan for future SLR out to 2100, large, persistent uncertainties must be taken into account and balanced against the sensitivity and time horizon of the project.

4.3 Planning for Higher Levels of SLR

Many times the scientific assessment of risk hazard may not be completely adequate for determining appropriate levels of decision-making and planning activities. For example, bounds provided in IPCC AR5 GMSLR projections only cover the likely (17-83 percent) probability range and therefore only medium confidence is assigned to that likelihood, leaving a large 34 percent chance that sea levels will be outside that range by 2100. The above recommendations of the three Delaware SLR planning scenarios fall within the 5-95 percent probability range of SLR possibilities using the Kopp et al. (2014) methodology under RCP 8.5 emission future. In particular, the High planning scenario (1.52 m, 5.02 ft) represents the SLR amount of which greater than 95 percent of modeled SLR outcomes are below. This leaves 5 percent of modeled SLR outcomes above the High scenario level. For some cases, such as planning for construction of critical, long-lived infrastructure (e.g., waste-water treatment facilities, power plants), 5 percent may be too high of a risk to assume. The upper end/low probability events carry a disproportionate level of risk with potentially disastrous damaging effects, the consequences of which should be carefully considered when deciding for which future sea level to plan.

It also may be prudent to plan for higher levels of SLR due to changing conditions in the future environment. The RCP 8.5 emissions scenario developed by the IPCC for modeling purposes does not represent the highest possible amount of greenhouse gas emissions. Riahi (2013) suggests the resulting radiative forcing could be 10 percent higher under rapid economic growth scenarios.   As described in FAQ 5, there is significant uncertainty in the future contributions to SLR from the melting ice sheets of Greenland and Antarctica, potentially causing a meter or more of additional SLR by 2100 on top of current planning scenario recommendations. Knowledge of the magnitude and range of SLR that may occur above the likely or recommended bounds may be critical for projects with high sensitivity to coastal flooding and other impacts from high sea-level rise or extreme storm surge.

The USGCRP third NCA report states there is very high confidence (greater than 90 percent confidence) that GMSLR will be at least 0.2 meters and no more than 2.0 meters by 2100 (Parris et al., 2012). The 2.0 m Highest scenario in the NCA was based on work by Pfeffer et al. (2008), who considered the glaciological conditions required for large sea-level rise by 2100 and concluded that an increase of SLR above 2.0 m is “physically untenable.” Hall et al. (2016), in a study of the vulnerability to SLR of U.S. military installations worldwide, also used the same 2.0 m maximum GMSLR. USACE (2013) used 1.5 m as the highest scenario for incorporating into their civil works program activities, but also states that 2.0 m is a credible upper limit for GMSLR by year 2100. These studies were designed as worst case scenarios for national and regional planning and do not have specific probabilities assigned to them.

However, recent research has indicated that contributions from thermal expansion and melting ice sheets in Pfeffer et al. (2008) 2.0 m worst-case scenario could be exceeded. Nor did Pfeffer et al. (2008) include the possibility of a net decrease in land water storage due to groundwater withdrawal (Sweet et al., 2017). Miller et al. (2013) and Sweet et al. (2017) expounded upon the work by Pfeffer et al. (2008) by increasing the contributions from land water storage, Antarctic and Greenland ice-sheet melting, and thermal expansion, and calculated upper bounds of 2.7 m and 2.5 m, respectively.

Jevrejeva et al. (2014a) constructed probability distributions for each of the major components that contribute to GMSLR, namely thermal expansion, melting of land-based glaciers and ice sheets, and land water storage. To focus on the 5 percent upper tail of occurrences, they combined a process modeling approach, extracting samples from the uncertainty distributions, with expert assessments and evaluation of semi-empirical model results. The authors suggest that there is a 95 percent chance that GMSLR will not exceed 1.8 meters above present day levels by year 2100. As well, 1.9 m of GMSLR by 2100 may be possible if the high end estimates of all process-based modeled components, led by large contributions from the Greenland and Antarctic ice sheets, come to fruition, although these estimates should not be considered definitive due to large uncertainties. Jackson and Jevrejeva (2016) developed a similar probabilistic distribution methodology for regional SLR and GMSLR projections, incorporating a high-end scenario of RCP 8.5 plus increased ice-sheet contributions. The authors found a 99 percent probability level of 2.22 m of GMSLR by 2100.

Following Kopp et al. (2014), amounts of sea-level rise can be computed for any percentage range (since it builds a complete cumulative probability distribution.) Under the RCP 8.5 emission scenario for SLR by year 2100, there is a 99.0 percent chance SLR would not exceed 1.55 m in Delaware. Likewise, the 99.5 percent and 99.9 percent probability levels correspond to SLR of 1.76 m and 2.47 m, respectively

Table 4-6 lists GMSLR for the upper end probabilistic values from Kopp et al. (2014), upper limit SLR planning scenario from NCA and NOAA reports, and upper limits of other studies mentioned above. Values for Delaware are computed using the NOAA Lewes Breakwater Harbor tide gauge and should be considered relative SLR. The Delaware values are larger than GMSLR estimates, attributing to the regional GIA land subsidence and ocean effects. These values do not take into account additional subsidence due to groundwater extraction, natural compaction, or changes in coastal geomorphology.

Table 4-6. Upper limit and high-end projections for GMSLR and relative SLR for Delaware under various studies and reports. Data in meters relative to year 2000 MSL. Kopp et al. (2014) 99.9% could be also considered maximum physically plausible SLR.

	USGCRP NCA (2014) Max	NOAA SLR Report (2017) Max	NOAA SLR Report (2017) 99.9%	Miller et al. (2013) Max	Jevrejeva et al. (2014a) Max	Jackson and Jevrejeva (2016) 99%	Kopp et al. (2014) 99.0%	Kopp et al. (2014) 99.5%	Kopp et al. (2014) 99.9%
Global	2.00	2.50	2.40	2.70	1.90	2.22	1.55	1.76	2.47
Delaware		3.44	3.28				1.93	2.13	3.01

Therefore, agencies in Delaware may want to consider upper end (greater than 95 percent probability of occurrence) projections of SLR as an additional planning scenario depending upon the sensitivity to coastal flooding of the project. In those cases, it is recommended to use one of the Kopp et al. (2014) 99.0, 99.5, or 99.9 percent probability levels of SLR by 2100, which correspond to 1.93 m (6.33 ft), 2.13 m (6.99 ft), and 3.01 m (9.88 ft), respectively. Kopp et al. (2014) notes that the 99.9 percent probability level under RCP 8.5 is consistent with "maximum physically plausible" GMSLR derived through other methods.

4.4 General Guidance on Using Delaware SLR Planning Scenarios

It is recommended that planners and elected officials factor SLR projections into capital improvement projects and land-use decisions with long lifespans or some risk of flooding. Before selecting a SLR scenario to plan from, it is important to understand that SLR is one component of overall flood risk. Delaware communities may experience flooding from storms with heavy precipitation, wind, and/or storm surge, as well as perigean spring tides that cause localized, nuisance flooding. If SLR is added to the mix, it exacerbates the risk of flooding from these events. Consider, for example, FEMA's floodplain management standards. They require that the lower levels of homes and businesses in a community be built at least to 1 percent annual chance flood protection elevations in order to be eligible for national flood insurance, and recommend that development be built above this level (i.e., freeboard.) These standards are based on hydrologic modeling often calibrated to historic patterns of flooding; future projections of SLR and other projected future climate trends are not part of FEMA's calculations. Thus, coastal homes and businesses built to the minimum standard may see their risk of flooding increase over time because of SLR. SLR also can exacerbate the impacts of flooding experienced at the local level. What was once a high tide with little consequence, now forces temporary road closures because of the addition of SLR. This report does not analyze or offer projections regarding overall flood risk for Delaware towns. However, the SLR projections contained in this report should form a critical piece of the risk assessment and planning process at the state and local level.

Planners and officials should consider a range of factors when making land use and capital improvement decisions. Sometimes there are trade-offs that must be made between the costs and benefits of a project. When incorporating future SLR in planning, it is important to choose the right scenario. Selecting the appropriate scenario (Low, Intermediate, High, or maximum possible) is a matter of understanding: 1) the time horizon or life cycle of a project and 2) tolerance for risk. Sometimes, scenario selection is further influenced by the cost of design and implementation and identification of co-benefits.

1. Time horizon - Some projects have a longer anticipated life span than others. Major capital improvement projects such as streets, bridges and wastewater treatment plants have a design life of 15-50 years depending on the type of infrastructure and the environment in which it is built. In Delaware, land-use planning is informed by comprehensive plans. By law, Delaware communities and counties must update and certify their comprehensive plans every 10 years but the implementation of the Plan, in the form of zoning, design and construction of neighborhoods, business districts, and schools, is based on much longer timeframes. Therefore, the first step in applying SLR projections to local decision-making is to select the appropriate time horizon for the project or land-use decision and understand how that correlates to the SLR projections for that particular timeframe. Table 4-1 and Figure 4-2 can be used to extract the appropriate SLR amount for any time period through 2100.

2. Risk Tolerance – Choosing which of the SLR scenarios to plan for should not be undertaken without understanding a project's adaptive capacity and its potential value to the community. "Adaptive capacity" refers to the ability of a system (built, natural or social) to recover from or withstand

> flooding from SLR or other hazards. Some well-designed parks such as Canal Front Park in Lewes, can be repaired (i.e., have its function restored) from damages caused by storm surge more readily than a historic home or museum. The park is more resilient in this case, and therefore has a higher adaptive capacity to flooding. Next, it is important to understand how the project contributes to the community's way of life. This will help to inform the relative tolerance one has for accepting the risk of flooding from SLR. For example, projects that directly support public safety (a hospital or evacuation route) or are integral to the continued operation of a town (fire house or electric power substation) would likely carry a lower tolerance for risk to SLR compared to parking lots or retail establishments.

Knowing risk tolerance is absolutely crucial to decision-making because SLR projections are not predictions: they do not forecast with absolute certainty how much SLR is expected in the future. Delaware's SLR projections are based on the best available data and scientific consensus concerning the major contributing factors. The relative confidence levels of each projection are noted, giving planners and decision makers latitude to choose the scenario they are most comfortable planning to. In general, projects with a longer lifespan that have low tolerance for risk will be best served by the High SLR scenario (higher projection of SLR = less likelihood of exceeding it) and projects with shorter lifespans and higher tolerances for risk are well suited for the Low or Intermediate SLR scenarios.

The cost of design and implementation of projects may be influenced by the SLR scenario chosen. Before planners and decision-makers consider making trade-offs between cost and risk tolerance, consider that there are many co-benefits of taking action. Co-benefits refer to added benefits or "win-win strategies" that arise out of adaptation and mitigation decisions. These co-benefits can serve the public good, ecosystem health, long-term cost reduction in insurance premiums or hazard recovery, and better compliance with federal and state initiatives. For example, choosing to elevate an existing home according to the High SLR projection carries a higher cost than designing to a lower standard, but it also results in better savings on federal flood insurance over time. Or, converting vulnerable city-owned land into a park with trails, bioswales and rain gardens supports public recreation and open space preservation in addition to hazard mitigation.

5. Recommendation for Future Updates

It is the recommendation and intention of the Delaware SLR Technical Committee that SLR planning scenarios for the state of Delaware be reviewed and updated periodically as new information and federal guidelines become available. This is a continuation of the recommendation made by the DNREC SLR Technical Workgroup in 2009.

The latest IPCC AR5 report introduced significant improvements over previous IPCC studies regarding sea-level rise, particularly in integrating ice-sheet dynamics, albeit to a limited extent. New research is rapidly improving our understanding of the influences of global and local sea-level rise and on how best to incorporate this information into modeling and statistical frameworks. New data are currently being collected regarding the melting of the Greenland and Antarctic ice sheets (both of which are expected to be more significant contributors to SLR later in the 20th century) as well as increased sampling of the ocean depths (0 - 2000 m) by the Argo floating network (Argo, 2016) and continued satellite observations of the global oceans, all of which should better inform GCMs in the next round (i.e., CMIP6) of model runs. Regarding the rapid ice-sheet dynamics, a quantitative assessment of its dependence upon the RCP scenario was not able to be included in the AR5 models, and hopefully will be in AR6. As well, the concept of the Representative Concentration Pathways (RCPs) was introduced in AR5 and may be modified in future reports based on current trends in fossil-fuel burning and geopolitical activities.

Specifically in Delaware, the DNREC Delaware Coastal Programs has been recently working with the National Geodetic Survey to improve our horizontal and vertical reference network through the NGS Height Modernization program. Many existing NGS benchmarks have been updated and several new benchmarks have been added. Once the process is complete, regular direct measurements at many of these locations can provide useful insight into VLM across the state.

Continued monitoring and data analysis of regional tide gauge datasets and coastal storms will take place, providing a better understanding of the observed trends of relative sea-level rise and coastal flooding frequency, intensity, and extent. Additional research will advance our understanding on the effects of SLR on groundwater and on the response of coastal salt marshes that cover a large portion of the Delaware coastline. There may be changes in the priorities or policy regarding housing or public infrastructure development within the state that require reevaluation of the methodology to identify the likely and extremes of SLR projections.

These considerations compel Delaware to continuously remain aware of national and international assessments of sea-level rise, especially along the U.S. mid-Atlantic coast, and to periodically re-evaluate future SLR scenarios appropriate for Delaware planning activities.

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Appendix A. Executive Order 41

STATE OF DELAWARE

EXECUTIVE DEPARTMENT
DOVER

EXECUTIVE ORDER
NUMBER FORTY-ONE

TO: HEADS OF ALL STATE DEPARTMENTS AND AGENCIES

RE: PREPARING DELAWARE FOR EMERGING CLIMATE IMPACTS AND SEIZING ECONOMIC OPPORTUNITIES FROM REDUCING EMISSIONS

WHEREAS, burning fossil fuels causes the release of heat-trapping greenhouse gases that contribute to a changing climate, which presents both economic opportunities for new jobs and industries, as well as challenges to protecting public health and safety, supporting a vibrant economy, and conserving natural resources; and

WHEREAS, Delaware's greenhouse gas emissions have decreased by more than any state in the nation (29.7% from 2000 to 2010) and recent investments to modernize our energy system and efforts by several of Delaware's major employers and institutions of higher learning will result in significant additional reduction, however more must be done; and

WHEREAS, initiatives to responsibly reduce greenhouse gas emissions and prepare Delaware for climate impacts present significant economic development and employment opportunities in infrastructure construction, energy efficiency, clean energy, and advanced transportation; and

WHEREAS, as a low-lying coastal state with the lowest average land elevation in the United States and significant population living along 381 miles of shoreline, Delaware is vulnerable to coastal erosion, storm surge, flooding, saltwater intrusion, and tidal wetland losses, all of which will be exacerbated by sea-level rise; and

WHEREAS, Delaware's critical infrastructure, including roads, bridges, dams, dikes, impoundments, energy distribution systems, emergency services, outdoor recreation facilities, drinking water and wastewater treatment facilities, industrial sites, and landfills are at-risk to climate change impacts; and

WHEREAS, Delaware's Bayshore and Inland Bays communities have experienced saltwater intrusion into drinking water supplies and irrigation systems, and climate impacts could negatively affect the availability and reliability of the groundwater aquifers that provide water to many municipalities, residents, and farmers; and

WHEREAS, agriculture in Delaware is an $8 billion industry which could be significantly impacted by increasingly variable temperatures, precipitation, extreme weather events, and droughts; and

WHEREAS, tourism in Delaware is an $6 billion industry supported by world-class beaches, parks, wildlife areas, cultural assets, and recreational waterways, all of which are vulnerable to more extreme storms and sea-level rise; and

WHEREAS, the State of Delaware was an original signatory to the Regional Greenhouse Gas Initiative and is working in collaboration with other states to reduce regional greenhouse gas emissions from power plants by more than 30% compared to 2008; and

WHEREAS, to coordinate the efforts of state agencies to create a clean energy economy and a sustainable natural environment, I signed Executive Order No. 18 on February 17, 2010; and

WHEREAS, under Executive Order No. 18, the State of Delaware, under the direction of and coordination by the Cabinet Committee on Energy, has reduced the number of state vehicle miles traveled by 25%; has increased its use of clean, renewable energy to 30% of its overall annual electric energy demand; and has taken important steps to reduce energy consumption, lower gas consumption and emissions from state vehicles, increase recycling, and implement environmentally-friendly procurement and building practices, resulting in millions of dollars of savings; and

WHEREAS, the State of Delaware, through the Department of Natural Resources and Environmental Control (DNREC), has developed a sea level rise adaptation policy that serves as a pilot for further statewide application; and

WHEREAS, a variety of entities—including, among others, the Floodplain and Drainage Advisory Committee, the Bay Beaches Working Group, the Wetlands Advisory Committee, the State Sea Level Rise Advisory Committee, and the Delaware Climate Change Steering Committee—have developed or are developing policies and recommendations to address various discrete issues related to our changing climate and rising sea levels; and

WHEREAS, it is important for the State of Delaware to continue to reduce greenhouse gas emissions cost-effectively, while preparing for current and emerging climate risks; and

WHEREAS, it is in the best interest of the State of Delaware to address climate change and rising sea levels in a coordinated and cost-effective manner, at the highest levels of government, using a structure similar to the one that has been employed so successfully in connection with Executive Order No. 18.

NOW THEREFORE, I, JACK A. MARKELL, by virtue of the authority vested in me as Governor of the State of Delaware, do hereby DECLARE and ORDER the following

1. There is hereby created a Governor's Committee on Climate and Resiliency (the "Committee"), which shall be comprised of the following members:

a. Each of the members of the Cabinet Committee on Energy as set forth in 29 *Del.C.* § 8054, including the Secretaries of the Department of Natural Resources and Environmental Control, Department of Agriculture, Department of Transportation, Department of Health and Social Services, Department of Safety and Homeland Security, and Department of State; the Director of the Delaware Economic Development Office; and the Director of the Office of Management and Budget;

b. The Director of the Delaware State Housing Authority;

c. The Director of the Office of State Planning Coordination; and

d. Such other persons as the Governor may from time to time appoint.

2. The Committee shall oversee development of an implementation plan to maintain and build upon Delaware's leadership in responsibly reducing greenhouse gas emissions, including identifying appropriate interim goals. The plan shall ensure that efforts have a positive effect on the State's economy, including advancing the strategy of securing cleaner, cheaper, and more reliable energy, improving public health outcomes, increasing employment in Delaware, strengthening Delaware's manufacturing capabilities, and enhancing Delaware's overall competitiveness. The Committee shall report to the Governor on the completed plan by December 31, 2014, and annually thereafter.

3. The Committee shall develop agency-specific actionable recommendations for improving Delaware's preparedness and resiliency to climate impacts on public health and safety, public infrastructure and facilities, water resources, natural ecosystems, agriculture, tourism, and other industries. The recommendations shall prioritize the use of natural systems or green infrastructure as the preferred means to improve resiliency. Recommendations shall be submitted to the Governor by December 31, 2014 and shall include, but not be limited to:

a. Actions state agencies can take both within their departments and with assisting residents to adapt to and prepare for more extreme storms and projected temperature and precipitation variations expected over the next several decades, based upon research conducted through the Delaware Climate Change Steering Committee;

b. Actions local governments can take to improve community resiliency, including assessment of infrastructure vulnerabilities, land use policies, and other adaptation strategies that may be integrated into Comprehensive Land Use Plans in coordination with the Office of State Planning Coordination; and

c. Outreach strategies to inform and prepare Delaware's residents and businesses about identified risks, vulnerabilities, adaptation strategies, and basics of climate change and its causes, with particular attention to providing strategies to help protect at-risk populations.

4. In addition to the foregoing, all state agencies shall adhere to the following requirements related to flood hazard mitigation and sea level rise:

a. All state agencies shall incorporate measures for adapting to increased flood heights and sea level rise in the siting and design of projects for construction of new structures and reconstruction of substantially damaged structures and infrastructure. Such projects shall be sited to avoid and minimize flood risks that would unnecessarily increase state liability and decrease public safety. Construction projects shall also incorporate measures to improve resiliency to flood heights, erosion, and sea level rise using natural systems or green infrastructure to improve resiliency wherever practical and effective;

b. Where avoidance is not practicable, structures within a Federal Emergency Management Agency (FEMA) designated Special Flood Hazard Area shall be designed and constructed with habitable space at least 18 inches above current base flood elevation on a foundation appropriate for anticipated flood risk factors. If the structures are within an area mapped by DNREC as vulnerable to sea level rise inundation the projects shall be designed and constructed to account for sea level changes anticipated during the lifespan of the structure, in addition to FEMA flood levels; and

c. All state agencies shall consider and incorporate the sea level rise scenarios set forth by the DNREC Sea Level Rise Technical Committee into appropriate long-range plans for infrastructure, facilities, land management, land-use, and capital spending. DNREC shall periodically update the scenarios with the best scientific data available and distribute new guidance to state agencies.

5. The Secretary of Natural Resources and Environmental Control shall serve as chair of the Committee and, with the cooperation of other state agencies, is responsible for managing and tracking implementation of this Order. In connection therewith, the chair and the Committee shall leverage the work of leading scientists and subject matter experts, as well as any research, studies, work groups, advisory councils, and committees as may be required to complete the tasks outlined herein. DNREC shall provide support to state agencies to meet the requirements of this Order, including the development of maps illustrating areas of combined flooding and sea level rise.

6. No provision of this Order shall create any individual right or cause of action that does not currently exist under state or federal law.

GREAT SEAL OF THE STATE OF DELAWARE • 1704 • 1776 • 1787 •

APPROVED this 12 day of September, 2013

Jack Markell

Governor

ATTEST:

Secretary of State