Preliminary Phase 6 Watershed Model (WSM) and Chesapeake Bay Water Quality Sediment Transport Model (WQSTM) Climate Change Assessment Procedures for the 2017 Midpoint Assessment

STAC Peer Review
Documentation
06.30.17 Draft

Background

The Chesapeake Bay Program (CBP) partnership is undertaking a midpoint assessment of progress to ensure that the seven Chesapeake Bay watershed jurisdictions are on track to meet the 2025 Chesapeake Bay Total Maximum Daily Load (TMDL) goal. A key element of this effort is the incorporation of the latest science, data, tools, and BMPs into the partnership's decision support tools to help guide implementation and to use this new information to facilitate and optimize implementation of the jurisdictions' Watershed Implementation Plans (WIPs).

The impacts of climate change on the attainment of partnership goals has been a CBP concern since the issue was first highlighted in the Chesapeake 2000 Agreement. Assessing the influence of climate change on Chesapeake water quality was also a significant element of Executive Order 13508 (2009) as well as the 2014 Chesapeake Bay Agreement. However, a comprehensive quantitative exploration of the influence climate change has on Chesapeake water quality, as called for in the 2009, 2010, and 2014 CBP management documents is to be completed for the 2017 Midpoint Assessment. These assessments build on the limited analysis that was completed during the development of the Bay TMDL (U.S. EPA 2010a, 2010b).

The CBP's Scientific and Technical Advisory Committee (STAC) has conducted several assessments of climate science and recommended processes to integrate the consideration of climate change into the Bay Program's management framework (DiPasquale, 2014; Johnson et al 2016; Pyke et al 2008; Pyke et al 2012; STAC, 2011; Wainger, 2016). These reviews and recommendations assessed the latest climate science and impacts to the Chesapeake Bay watershed and highlighted the need to more effectively embed climate change among partnership goals in decision making, identify and prioritize vulnerabilities of restoration efforts and management actions, and utilize partners' ongoing research efforts to better assess and evaluate responses to changing climatic conditions. Throughout the period of reviews and responses provided by STAC, the importance of informing cross-cutting adaptation efforts based on changing environmental conditions was central. Additionally, building the capacity to better determine the sensitivity of loads and consequent management responses was determined to be of critical importance when planning restoration and adaptation measures for altered conditions that will affect Bay management efforts throughout the 21st century.

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CBP Midpoint Assessment Decision- Making Process

The Water Quality Goal Implementation Team (WQGIT) serves as the “lead systems integrator” for the Midpoint Assessment, working with STAR’s Modeling Workgroup and the WQGIT source sector workgroups to define the scientific and technical issues to be addressed and determining the schedule for partnership briefings and policy decisions.

A major component of the Midpoint Assessment is enhancing the CBP partnership’s decision support tools, including the Phase 6 Watershed Model (WSM) and the Chesapeake Bay Water Quality Sediment Transport Model (WQSTM). The incorporation of key elements of the latest science on climate change is one of the significant refinements to this modelling effort being conducted as part of the Midpoint Assessment. A number of CBP Workgroups and coordinating bodies are involved with defining the scientific and technical aspects of climate change for integration into the WSM and WQSTM modeling efforts. The CBP Scientific and Technical Advisory Committee (STAC) and the Climate Resiliency Workgroup (CRWG) have provided guidance on the climate data and information to support the Midpoint Assessment modeling effort including the following.

- STAC sponsored workshop, "The Development of Climate Projections for Use in Chesapeake Bay Program Assessments" conducted on March 7-8, 2016.
- CRWG recommendations on two specific climate-related data inputs and assessments, sea level rise projections and future tidal wetland loss, to inform the Midpoint Assessment modeling effort.

Midpoint Assessment Climate Modeling Timeline

The timeline for the integration of climate modeling components into the Midpoint Assessment is outlined below.

Table 1.

Deliverable/Decision	Decision- Making Lead(s)	Timeline
Technical Workshop on climate change projections for use in CBP assessments	STAC, STAR Modeling Workgroup	March 7-8, 2016
Recommend WQSTM model data inputs related to: sea level rise projections and tidal wetland loss assessment methodology	CBP Climate Resiliency Workgroup (CRWG)	May –August, 2016
Develop initial climate change analysis with all CBP models	CBP Modeling Team	June-July, 2016
Modeling Workgroup Quarterly Review (initial review of climate data and analysis)	STAR Modeling Workgroup	August 9-10, 2016
Modeling Workgroup Quarterly Review (review of climate data and analysis)	STAR Modeling Workgroup	October 4,13 2016
WQGIT Climate Webinar	CBP Modeling Team; CRWG	October 18, 2016
Review and approve CBP climate modeling approach	WQGIT	October 24-25, 2016
Approve WQGIT decisions concerning CBP climate modeling approach	Management Board (MB)	November, 2016
Approve proposed climate assessment procedures	Principle Staff Committee	December, 2016
Initial 2025 and 2050 WQSTM and Watershed Model preliminary runs presented to WQGIT (one set of climate scenarios run)	Modeling Team	May, 2017
Watershed Model Peer Review	STAC	Underway

Water Quality Sediment Transport Model Peer Review	STAC	Underway
Partnership's Fatal Flaw Review of the Phase 6 Modeling Tools	CBP Parternship	Underway
Phase 6 Water Quality Sediment Transport Model Calibration	Modeling Team	June 1 – June 30, 2017
Release of draft Water Quality Sediment Transport Model	Modeling Team	July 1, 2017
Additional climate change scenarios to be run through Phase 6 Model (WSM and WQSTM	Modeling Team	July – September 1, 2017
Resolution of Fatal Flaws Identified Through Partnership Review, Final Calibration (if appropriate), and Partnership Approval of Phase 6 Modeling Tools	Modeling Team	August 1 – August 30, 2017
WQGIT Revisits Midpoint Assessment Schedule based on Phase 6 Fatal Flaw Review Period	WQGIT	August 14, 2017
EPA releases final Phase III WIP Planning Targets	EPA	December, 2017

Midpoint Assessment Climate Change Analysis

In 2012, the CBP partnership identified climate change as one of the priorities of the Bay TMDL's Midpoint Assessment. As a result, the partnership developed the tools and procedures to quantify the effects of climate change on watershed flows and pollutant loads, storm intensity, increased estuarine temperatures, sea level rise, and ecosystem influences, including loss of tidal wetland attenuation with sea level rise, as well as other ecosystem influences in the Chesapeake Bay watershed.

A major component of the Midpoint Assessment relies upon enhancing the CBP partnership's decision support tools, including the Phase 6 Watershed Model (WSM) and the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM). The incorporation of key elements of the latest science on climate change is one of the more significant refinements applied to this modeling effort being conducted as a part of the 2017 Midpoint Assessment.

Watershed Sediment Model (WSM) Methodology[1]

The climate change assessment undertaken for the Phase 6 Watershed Model relied heavily upon prior recommendations and guidance provided by Linker et al. (2007, 2008) and the Chesapeake Bay Program's Climate Resiliency Workgroup (CBP, 2016). A STAC workshop of climate and

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[1] Text from this subsection can also be found in Chapter 12 of the Phase 6 Watershed Model Documentation

modeling experts was also convened to help further refine choices for modeling tools that would be needed to begin to simulate a more accurate representation of future climate scenarios based on the latest scientific tools available. "The Development of Climate Projections for Use in the Chesapeake Bay Program Assessments" (Johnson et al., 2016), outlined a series of recommendations related to the selection and application of climate data and projections to the Midpoint Assessment modeling process.

Climate Scenarios (Years 2025 and 2050)

To assess the altered precipitation patterns and temperatures in 2025 and 2050, several decisions were made by the Chesapeake Bay Program based on recommendations provided by a 2016 STAC workshop on Climate Change in the Chesapeake (Johnson et al., 2016). STAC recommended that an assessment of expected changes to precipitation in the year 2025 use long-term observed precipitation trends instead of climate model projections. For 2050, climate models used for assessing anticipated changes in precipitation were based upon the recommendations of STAC to utilize the Coupled Model Inter-comparison Phase 5 (CMIP5) set of Global Climate Models (GCMs) as outlined in the Intergovernmental Panel on Climate Change's Fifth Report (IPCC, 2013). It was also recommended that these models be employed in the assessment of changes in temperature for both 2025 and 2050 as the expected changes in temperature are in much better agreement in both the short and long-term projections. The GCMs utilize forcings based on potential future socio-economic and natural scenarios defined as Representative Concentration Pathways (RCPs). The RCPs are categorized according to the additional radiative forcing generated through each scenario measured in Watts per square meter (Wm^{-2}) by the year 2100, e.g., RCP 4.5.

To begin, analyses were conducted with the Watershed Model that assessed expected changes in 2025 precipitation based on historical observed trends within the watershed. Additionally, expected changes in 2025 temperatures as well as 2050 precipitation and temperatures were determined using RCP 4.5 model values. However, additional scenarios based upon different RCPs (namely RCP 2.6 and RCP 8.5) are planned to help develop a fuller assessment and a range of potential future climate scenarios. Additional RCP scenarios will be run through the WSM and selected high-value scenarios will be used to force the WQSTM (Summer 2017) to help provide bounds on model estimates of climate change impacts.

The development of climate scenarios was based upon the same decisions made in the development of the U.S. Climate Resilience Toolkit (CRT)[2] (U.S. Federal Government, 2014). Downscaled climate models and realizations were retrieved from an online archive accessed through the USGS Geo Data Portal (Reclamation, 2013). The decision to use an existent downscaled dataset rather than working to develop a tailored statistical climate downscaling process was based upon the recommendations of the STAC workshop (Johnson et al., 2016). The Bias Corrected Spatial Disaggregation (BCSD) downscaling methodology was chosen for initial assessments because of its commonality among numerous datasets including the U.S. Climate Resilience Toolkit and the NASA Earth Exchange (NEX) Downscaled Climate Projections (NEX-DCP30), its extensive review in peer-reviewed literature in comparison with other downscaling methodologies (Gutmann et al., 2014; Mizukami et al., 2016), and its relative ease of access and flexibility in choosing models and realizations to be incorporated into analyses. Still, it may benefit future regional climate

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[2] This approach followed the same models used for the U.S CRT with the exception of the inclusion of the BNU-ESM GCM, which was unavailable for download through the USGS Geo Data Portal.

analyses to consider other datasets based on downscaling techniques that are also capable of producing reliable correlations with observed precipitation and temperature such as the Multivariate Adaptive Constructed Analogs (MACA) or Localized Constructed Analogs (LOCA) methodologies (Demirel and Moradkhani, 2016; Pierce and Cayan, 2015).

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Application of Global and Downscaled Climate Models to CBP watershed modeling framework

With consistent RCP realizations and models chosen, anticipated changes in average monthly values of precipitation and temperature were calculated. The calculation was determined based upon a common analysis referred to as a delta approach, wherein downscaled climate model historical values are compared against future projected values and the average percentage or degree change is then applied to an observation dataset used in the model of study. Comparisons within each model and realization were derived from 30- year periods of historical and projected climate model output centered on the year of study. Because the calibration period of the CBP Watershed Model spans a time period from the year 1991 to 2000, the historical climate model data are centered on this time period (1981-2010), and future projections data are centered on 2050 (2036-2065) in order to determine expected changes between the calibration period (1991-2000) and

2050.

Changes in Temperature

Temperature changes were developed using the aforementioned delta approach with projected future climate models for both 2025 and 2050. The average change in degrees was calculated for each model, and the corresponding median of those calculations was chosen as the expected change estimated for the 50th percentile. Estimates for the 10th and 90th percentiles were also developed for both 2025 and 2050 in order to provide a larger confidence interval of anticipated changes in temperature. Based upon the median changes calculated, the relative annual increase in median temperatures for the watershed in 2025 and 2050 were 1.05^{0}C and 2.08^{0}C, respectively, using data derived from RCP 4.5.

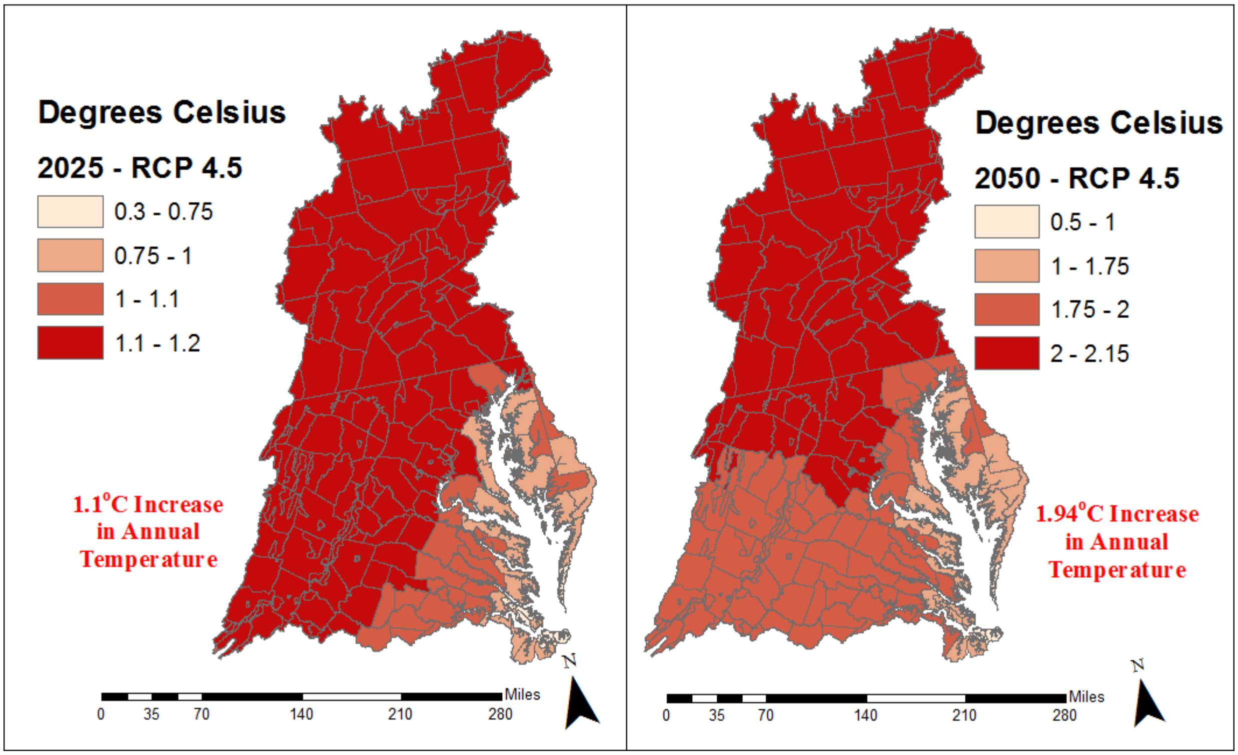

Figure 1. *Estimated annual degrees Celsius difference in temperature for counties within the Chesapeake Bay Watershed for climate projections of 2025 (left) and 2050 (right).*

Long-term Observed Trends in Precipitation (2025 projections)

The STAC Workshop Report, “The Development of Climate Projections for Use in the Chesapeake Bay Program Assessments” (Johnson et al., 2016) does not recommend the use of climate models for estimating changes in precipitation by 2025 relative to the Watershed Model’s calibration period. Instead, long term trends in annual precipitation on a county level were developed through the application of PRISM data and analysis provided and recommended by Jason Lynch, EPA, and Karen Rice, USGS. The PRISM dataset comprised an 87 year historical record of county data across all counties in the watershed, and a simple linear trend was fitted to the data in order to determine average annual percent change that might be expected to occur by 2025. This value was determined to be, on average for the watershed, an increase in annual precipitation of 3.1%.

Projections of Future Precipitation (2050 projections)

While there is fairly strong agreement among differing models and realizations regarding the number of degrees warming that are expected in each RCP for both 2025 and 2050, there are greater differences in the estimated magnitude of precipitation. Still, a large majority of precipitation projections anticipate an overall increasing trend in precipitation volume by 2050. In assessing precipitation trends for RCP projections, the modeling team again developed a confidence interval using the 10th and 90th percentiles of model estimates in conjunction with the calculation of median percent change. The median percentage change in annual precipitation for the watershed was determined to be an increase of 7.3% from the calibration period to the year 2050 for RCP 4.5.

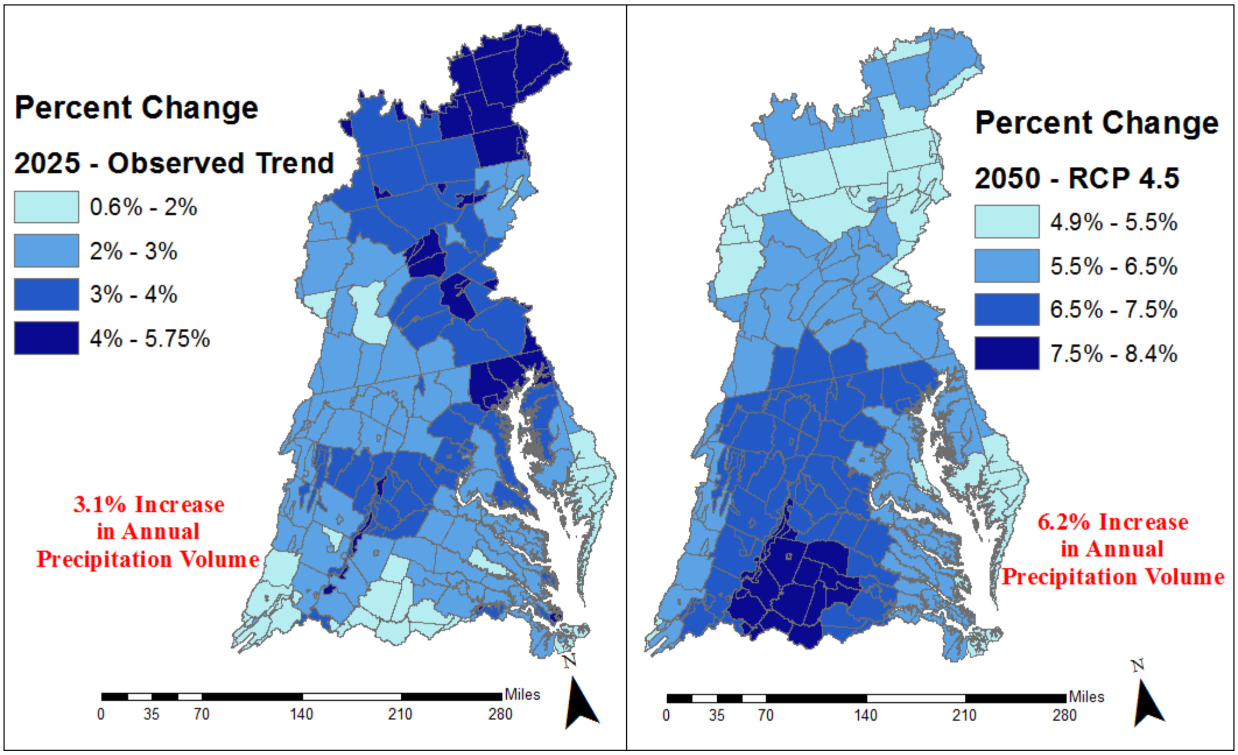

Figure 2. *Estimated annual percent change in precipitation volume of counties within the Chesapeake Bay Watershed for climate projections of 2025 (left) and 2050 (right).*

Projected Changes in Precipitation Intensity

The capacity to alter the simulation of precipitation patterns by deciles was built into the analysis as well based on expected changes to the intensity, frequency, and duration of precipitation events due to increasing greenhouse gas concentrations (Groisman, Pavel Ya, et al., 2004; Groisman et al., 2001; Karl and Knight, 1998, Gordon et al., 1992). The anticipated increases in larger precipitation events (Groisman, Pavel Ya, et al., 2004) was the basis for assigning the total percent change in volume of precipitation to different deciles in initial analyses. Essentially, increased volumes of precipitation were distributed throughout each year of the Watershed Model's observed record of precipitation unequally based on prior assessments of changes in this region (Groisman, Pavel Ya, et al., 2004). Further analysis will also explore the alteration of precipitation intensities based upon the downscaled projections used. There will also be additional study into improved methods of altering precipitation intensity, wherein volume added to the observed precipitation record will not implicitly bias the model simulation to produce events of greater precipitation in shorter time periods. Additionally, model simulations were also completed that did not alter the intensity distribution of added precipitation and additional volume was distributed evenly among all deciles. The final estimates of future climate scenarios in the WSM assumed an intensity change based upon literature values for this region (Groisman, Pavel Ya, et al., 2004).

Altered CO_2 Concentrations and Evapotranspiration Response

The simulation of potential evapotranspiration (PET) within the Phase 6 Watershed Model is controlled by temperature, stomatal resistance, and the choice of PET methodology.
In addition to modifying temperature and precipitation, a variable that controls the simulation of plant stomatal resistance in HSPF (lower vadose zone evapotranspiration, LZETP) was varied by increasing CO_2 concentrations as a result of continuing projections of atmospheric contributions from anthropogenic sources. Anticipated values of carbon dioxide concentrations in ppm were gathered from the IPCC's 5th Assessment Report, and increased to approximately 423 ppm and 486.5 ppm under the Representative Concentration Pathway (RCP) 4.5 for 2025 and 2050, respectively (IPCC, 2013: Annex II). Modifications to CO_2 concentrations based upon different RCP scenarios may also be simulated, depending upon the year and scenario of choice.

The simulation of potential evapotranspiration (PET) within the Phase 6 Watershed Model is controlled by temperature, stomatal resistance, and the choice of PET methodology. Originally, the Hamon method was used for simulating PET within climate scenarios in prior development stages of Phase 6. The Hamon method relies solely upon the temperature, the saturation pressure (a function of temperature), and the number of daylight hours as inputs in calculating PET. Analyses evaluated model performance with a number of PET methods. The Hargreaves-Samani approach to PET was found to exhibit an improved simulation of processes as it did not produce an unrealistic response to increased temperatures and was consistent with estimates from the more robust and first principle oriented Penman- Monteith method. The change in methodology of PET also relied upon guidance provided by P C. Milly in the STAC Climate Workshop *(Figures x and x,* Johnson et al., 2016).

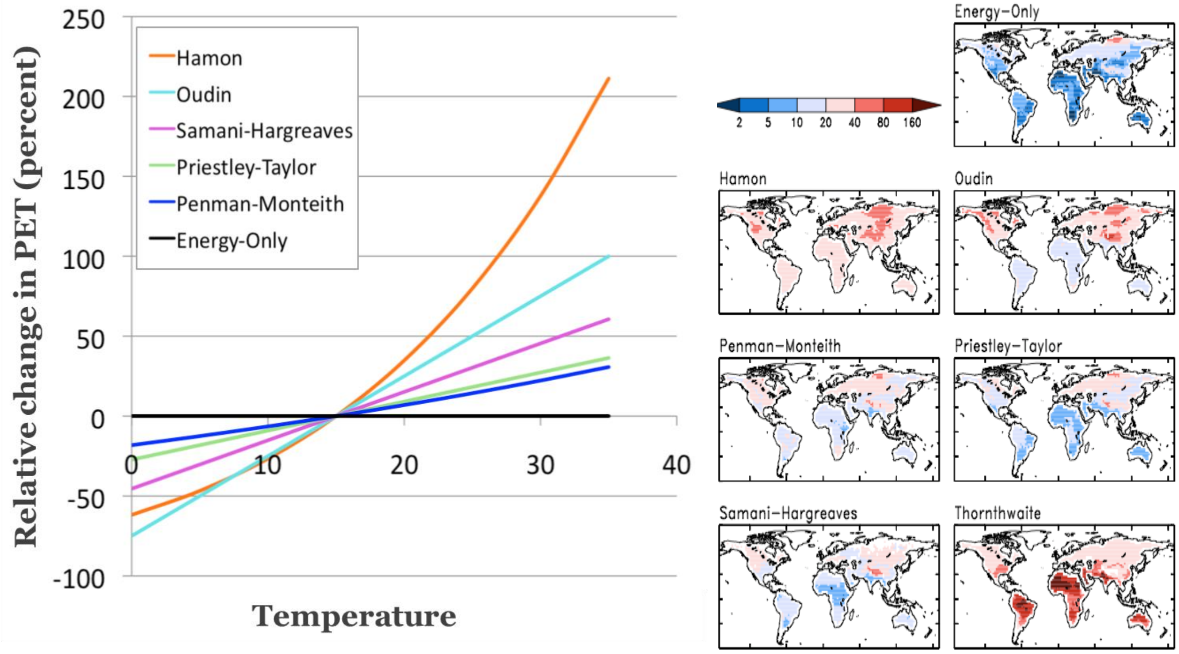

Figure 3. *The relative change in PET (by percent) and the differing method estimations of PET as applied to a multi-model ensemble of GCMs was presented by P C. Milly at the STAC workshop.*

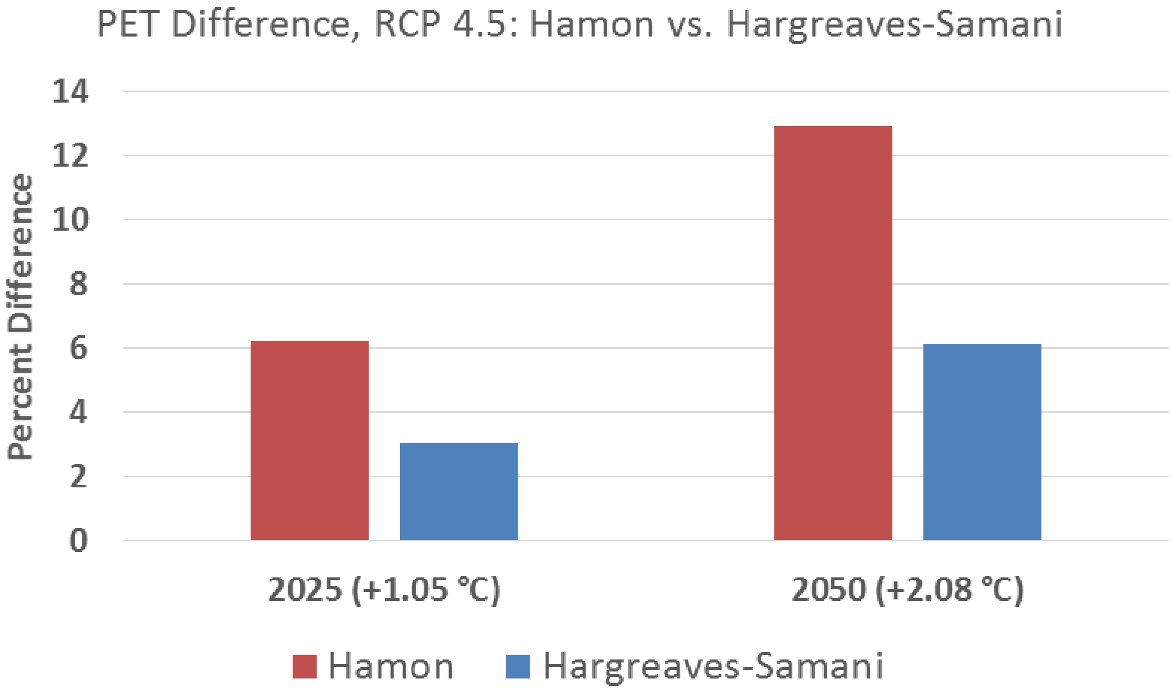

Figure 4. *The relative difference in PET produced by using either the Hamon or Hargreaves-Samani methods are shown here. In 2025 projections produced by the WSM, the Hamon method simulated an increase in PET that was 3.17% greater than that simulated with the Hargreaves-Samani method. This change was more pronounced in 2050 simulations where the Hamon method outpaced the PET rate of Hargreaves-Samani by 6.77%.*

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WSM Preliminary Climate Modeling Results

Initial simulations of altered precipitation, temperature, CO_2 concentrations, and potential evapotranspiration within the WSM were run in order to determine the individual variable and cumulative effects of all variables on flow, nutrient, and sediment loads delivered to the Chesapeake Bay. The percentage changes for each parameter and the combined impact of all variables are shown in the figures below. Sensitivities to changes in flow and loads based upon both the Hamon and Hargreaves-Samani PET methodology are also shown, but only the Hargreaves-Samani method is included in the fully integrated output. As can be seen throughout all plots (Figures 11.2.3A, 11.2.3B*)*, solely increasing precipitation increased flow and loads. Choosing to only increase temperature in the WSM caused an increase in evapotranspiration and a subsequent decrease in flow and loads. This effect was more pronounced when the Hamon method was used to calculate PET in comparison with the Hargreaves-Samani methodology. The increase in CO_2 concentrations produced an increase in flow and loads as there was a greater stomatal resistance to PET. Overall, there was a net increase in flow and loads when these variables were combined in the cumulative bars for projections in 2025 and 2050. All projected changes in flow and loads shown in these plots were based upon model runs completed for the Beta 3 version of the WSM. The table below summarizes the total projected percent changes in flow and loads for 2025 and 2050.

WSM Beta 3 Loads	**2025 – Observed Precipitation Trends, RCP 4.5 Temperature**	**2050 – RCP 4.5 Precipitation, RCP 4.5 Temperature**
Flow	2.6%	6.7%
Nitrogen	1.7%	4.6%
Phosphorus	1.8%	5.2%
Sediment	5.2%	15.5%

Table 2. *Relative change in estimated annual 2025 and 2050 flow and nitrogen, phosphorus, and sediment loads as compared to a base condition without estimated changes in hydrology from climate.*

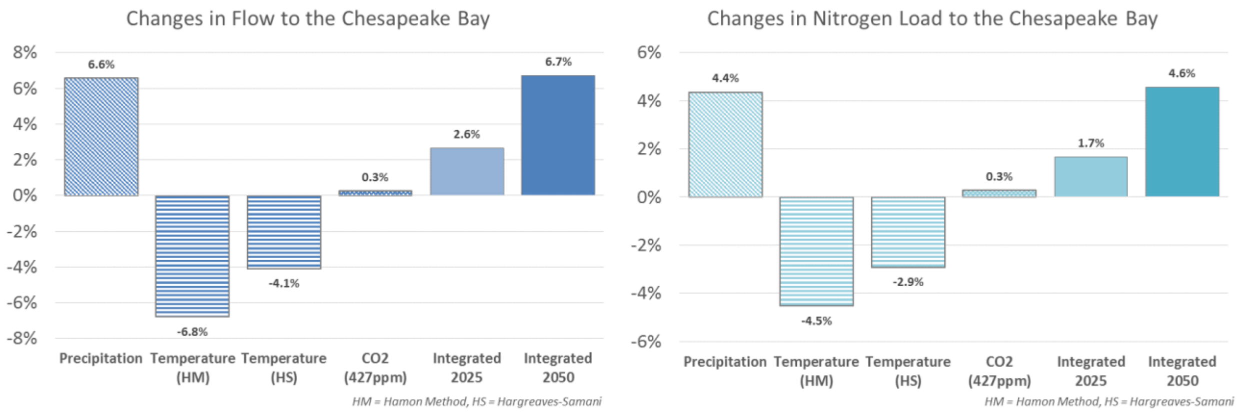
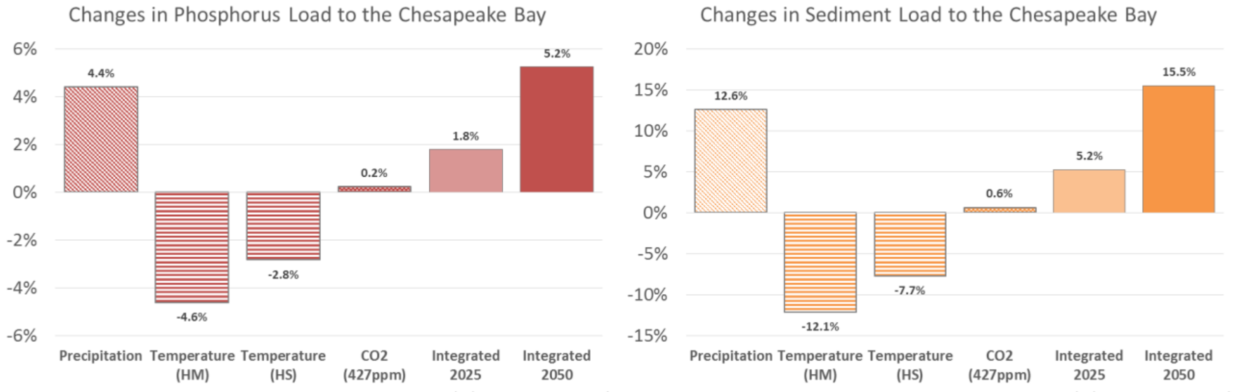


Figure 5. *The bar charts show the anticipated percent changes in annual flow (left) and nitrogen loads (right) delivered to the Chesapeake Bay under a scenario of climate change. Each bar represents the changes in delivery of each factor for an altered variable (e.g. "Precipitation" where only the volume and intensity of precipitation was altered) or a combination of all altered variables (rightmost two bars).*



HM = Hamon Method, HS = Hargreaves-Samani

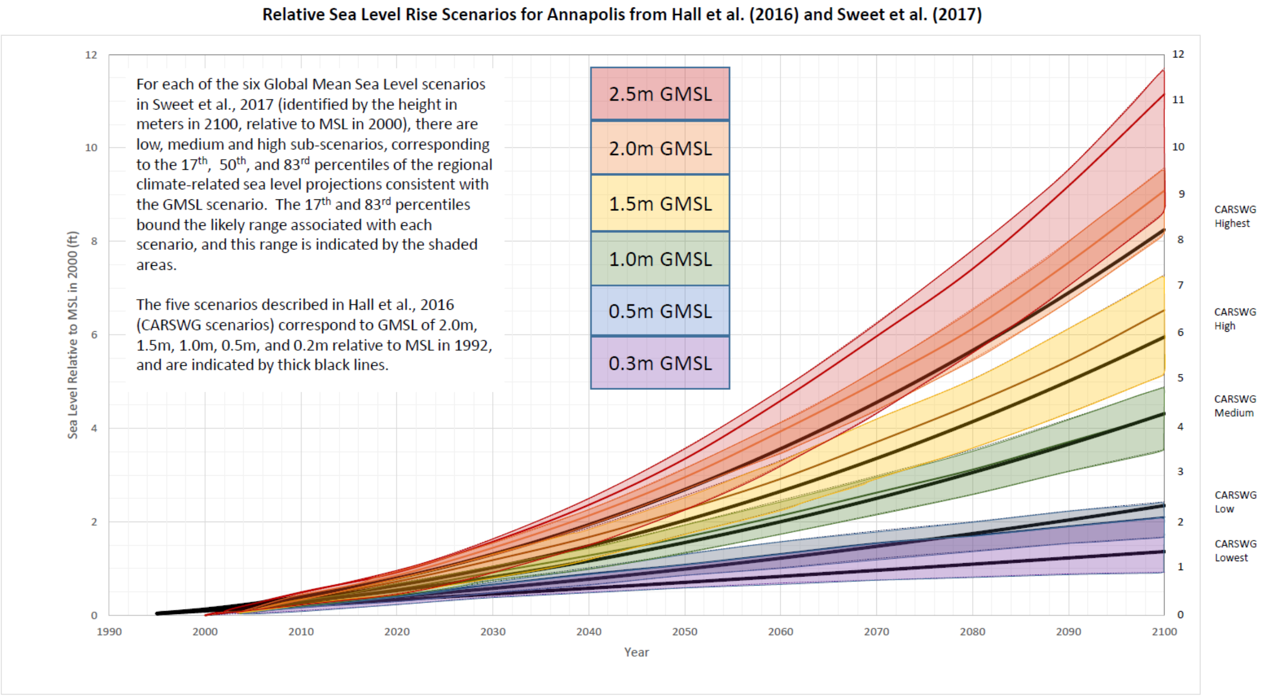
HM = Hamon Method, HS = Hargreaves-Samani

Figure 6. *The bar charts show the anticipated percent changes in annual phosphorus loads (left) and sediment loads (right) delivered to the Chesapeake Bay under a scenario of climate change. Each bar represents the changes in delivery of each factor for an altered variable (e.g. "Precipitation" where only the volume and intensity of precipitation was altered) or a combination of all altered variables (rightmost two bars).*

Water Quality Sediment Transport Model (WQSTM) Climate Assessment Methodology

Relative Sea Level Rise

The guidance provided for increasing levels of regional sea level rise (SLR) based upon global tide gauge rates and regional land subsidence rates came from the Climate Resiliency Workgroup. Specifically, the CRWG initially recommended that a range SLR projections for 2025 (0.2 - 0.4 m) and 2050 (0.3 - 0.8 m) as compared to the calibration period of 1991-2000 be applied in the WQSTM. Approximate medians of these ranges (0.3 m for 2025 and 0.5 m for 2050) were used for initial simulations of these changes. Refinements to these projections, were approved by the Climate Resiliency Workgroup on June 19, 2017 to a revise the lower bound estimate of SLR changes for 2025 to approximately 0.17 m. The CRWG recommended the lower bound projection of .17 m be used, based on relative sea level rise data from Sewells Point, VA, the closet tide gauge to the mouth of the Bay for which the sea level rise inputs are entered into the WQSTM. See Figures 7., 8 and 9 for data used in the CRWG's anlayis. See Appendix B. for more detail on Sewells, Pt. sea level rise data analysis.



For each of the six Global Mean Sea Level scenarios in Sweet et al., 2017 (identified by the height in meters in 2100, relative to MSL in 2000), there are low, medium and high sub-scenarios, corresponding to the 17th, 50th, and 83rd percentiles of the regional climate-related sea level projections consistent with the GMSL scenario. The 17th and 83rd percentiles bound the likely range associated with each scenario, and this range is indicated by the shaded areas.

The five scenarios described in Hall et al., 2016 (CARSWG scenarios) correspond to GMSL of 2.0m, 1.5m, 1.0m, 0.5m, and 0.2m relative to MSL in 1992, and are indicated by thick black lines.

Figure 7. Relative Sea level rise scenarios for Annapolis from Hall et.al (2016) and Sweet et al. (2017).

Site	Background RSL rate (mm/yr)	Background 1995-2025 RSL Estimate (mm)	1995-2025 GMSL rate (mm/yr)	1995-2025 SLR Estimate (cm)
BALTIMORE	1.4	42.0	3.0	13.2
LEWES	1.7	51.9	3.0	14.2
ANNAPOLIS	1.7	49.8	3.0	14.0
WASHINGTON DC	1.4	40.5	3.0	13.1
PORTSMOUTH	2.3	68.4	3.0	15.8
SOLOMON'S ISLAND	1.9	57.0	3.0	14.7
GLOUCESTER POINT	2.0	61.2	3.0	15.1
KIPTOPEKE BEACH	1.8	53.1	3.0	14.3
CAMBRIDGE II	1.7	52.2	3.0	14.2

CHESAPEAKE BAY BR. TUN.	2.2	67.2	3.0	15.7
SEWELLS POINT	2.5	74.4	3.0	16.4

Figure 9.

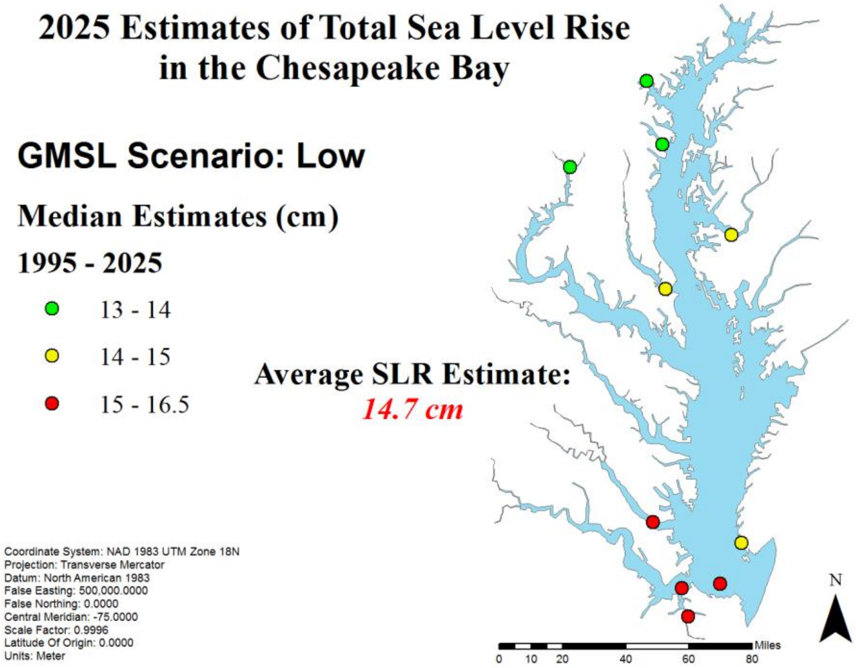


Figure 8 and 9. Summary of regional sea-level rise background data and projections (NOAA Technical Report, Sweet et.al, 2017).

Temperature Change

The simulation of temperature changes utilized changes in air temperature determined through an average of 6 global climate models, averaged between 2040 and 2060 (Figure 1). Future temperature changes for 2025 and 2050 WQSTM climate scenarios will be derived from the changes calculated in the Watershed Model, using Anne Arundel county’s temperature deltas as a proxy for changes in air temperature over the entirety of the Chesapeake Bay (Figure 2). The changes vary monthly and while the Bay temperatures are not altered directly through inputs, water temperatures also increase via fluxes of warmer air temperatures.

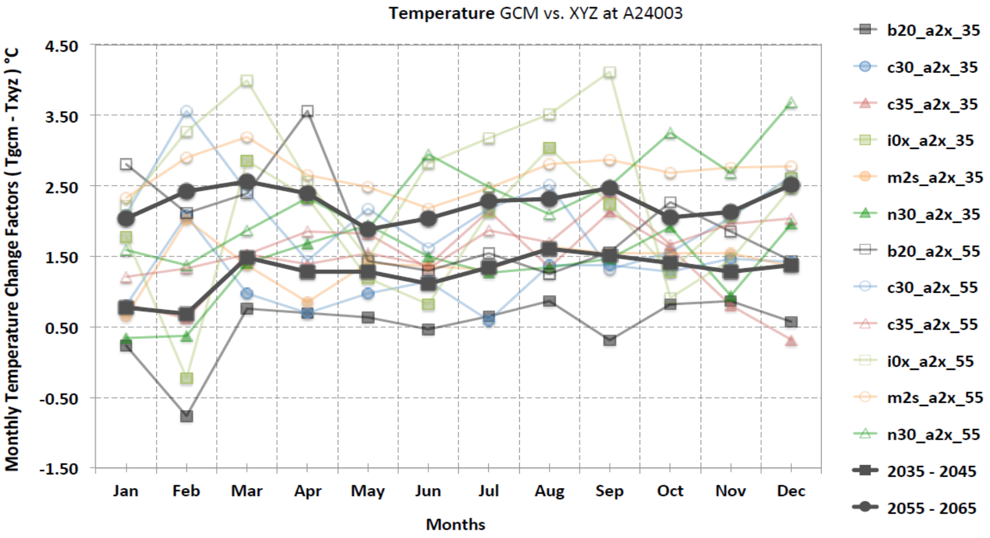


Figure 8. Simulation of temperature changes utilized changes in air temperature determined through an average of 6 global climate models, averaged between 2040 and 2060.

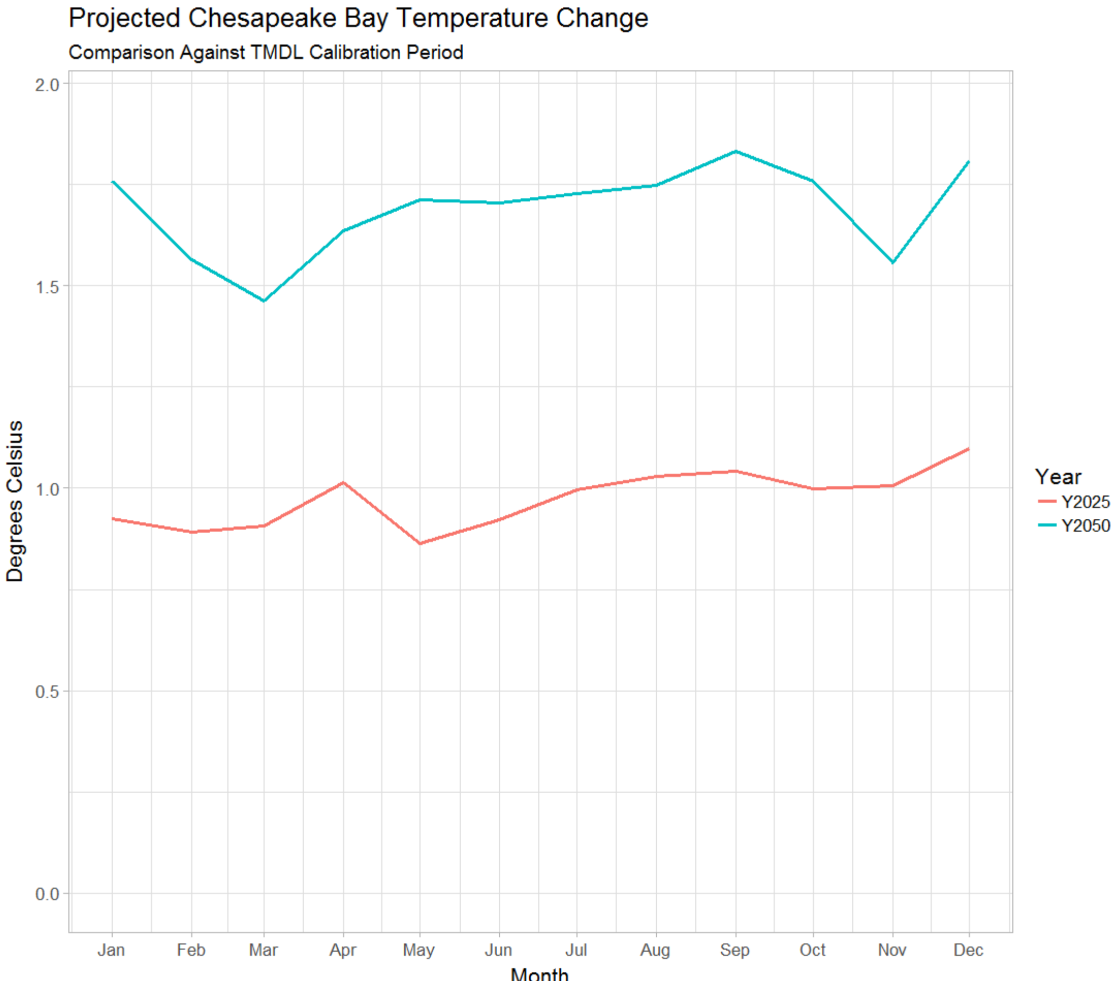


Figure 10. Projected Chesapeake Bay Temperature Change.

- Salinity values were also modified at the open boundary of the WQSTM, based on values provided by Hong and Shen, 2012.
    - Hong and Shen, 2012: “Given a sea-level rise of 0.3 m, the salt content of the Bay will increase [by] about 0.5 [PSU]”
    - Richard Tian noted that we changed the open boundary condition at the Bay Mouth to increase salinity by 0.4 PSU.
- Changes in flows and nutrient loads delivered from the Watershed Model are based upon climate scenario runs that correspond to the years of the WQSTM simulations. A factor of 1.2 was applied to streamflow temperatures entering the Bay based on Morril et al, 2014, to account for larger increases in stream temperatures due to air temperatures as compared to the warming in estuarine environments resultant from increased air temperatures.
    - Will future scenarios incorporate changes in stream temperatures based on watershed model inputs alone?
- *Adjustment of water temperature at the ocean boundary*. Monthly averaged observed surface water and bottom water temperatures at the Bay mouth were compared to observed air temperatures at the Patuxent Naval Air Station over the period 1985-2000 (Figure 9A). The monthly change in air temperatures derived from an average ensemble of GCMs were used to estimate changes in water temperatures (Figure 9B). These changes in the values of water temperatures were then applied to adjust the bi-weekly observed water temperature at the Bay mouth ocean boundary for warming scenarios (Figure 9C)
    - The changes of air and water temperatures among months were nonlinear, showing hysteresis in the rising and falling limbs, consistent with observations made by Lee and Cho, 2015.
    - In winter: $DW_T > SW_T > A_T$. In summer: $A_T > SW_T > DW_T$

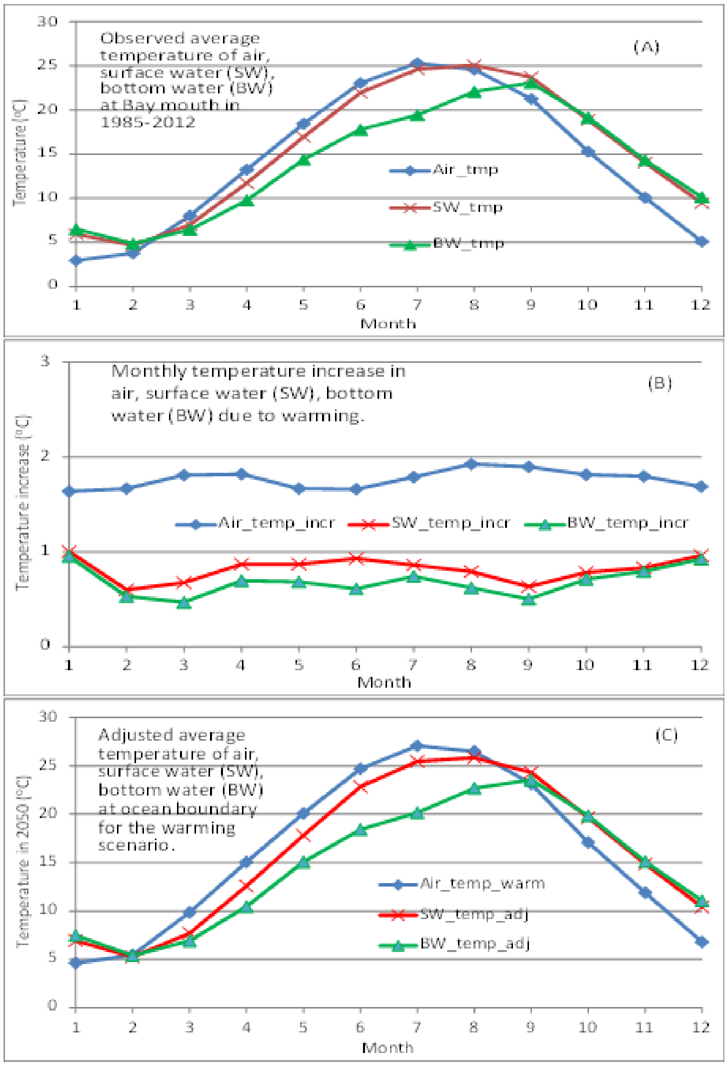


Figure 11.

Wetland Loss Methodology

There are two available data products that could be used to establish a baseline of current wetland area in the Chesapeake Bay (USDOI's National Wetland Inventory (NWI) and NOAA's Coastal Change Analysis Program (CCAP)); and two readily available modeling tools/methodologies that can be used to assess future wetland change (gain/loss) due to sea level rise in the Chesapeake Bay. Marsh change modeling runs have been conducted in the Chesapeake by the National Wildlife Foundation (2008) and the Maryland Department of Natural Resources (2012) using the Sea Level Affecting Marsh Model and by NOAA's Office for Coastal Management using the Digital Coast Sea Level Rise Marsh Impacts and Migration Tool.

NWF ran SLAMM v5 using a 30-meter Digital Elevation Model (DEM); Maryland DNR ran SLAMM v6.01 using a 10-meter DEM; and the NOAA Marsh Tool uses a 10-meter DEM. The NWF and Maryland DNR SLAMM modeling preselected sea level rise projections for 2025, 2050 and 2100. The NOAA tool, allows analysis of marsh loss to sea level rise in one-foot (1,2,3,4,5) foot increments.

Many other marsh studies have been conducted in the Chesapeake Bay at more localized or smaller regional scales; however, these studies do not support immediate data need for a current acreage number and projection of future area under varying sea level rise scenarios. Although SLAMM data is available, there are limitations to using modeling outputs to project future marsh loss. SLAMM modeling does not take into account current shoreline "hardening" (seawalls) or future land use changes, which could impact a marsh's ability to migrate inland. In these cases, SLAMM could over estimate future marsh gain on the upland side.

Recent published papers on wetland loss methodologies indicate that assessing loss/gain is a complicated process. For example, Matt Kirwan, VIMS, published a study in Nature Climate Change that argues that models, such as SLAMM, substantially overestimate marsh loss due to sea-level rise compared to dynamic models that account for biophysical feedback processes. E. Lentz et. al , also in Natural Climate Change asserts that inundation models can over predict lands likely to submerge. Despite the limitations these data sets and models, they represent the best available information at this time.

The Climate Resiliency Workgroup issued the following recommendations for assessing marsh loss in the WQSTM:

- Use a multi-model approach, tied to the CRWG's recommended range of sea level rise projections for 2025 and 2050, to gain estimates of current wetland area and projected wetland loss/gain. Use these estimates to inform watershed loads in the CBWQSTM modeling effort.
- To estimate project wetland gain/loss, analyze data results available through the National Wildlife Foundation, Sea Level Affecting Marsh Model v.5 of the Chesapeake Bay (2008) and data available through NOAA's Office for Coastal Management Sea Level Rise Marsh Impacts and Migration Tool.
- In interpreting the data available through these two products, assess whether the sea level rise projections used for the studies were consistent with the 2025 and 2050 SLR projections (as recommended by the CRWG); or, in the case of the NOAA Marsh Tool, whether data runs could be acquired for a different SLR scenario.
- The USGS/CBP GIS Team, which is working to compile the land use/land cover data set for the Midpoint Assessment, should work with the EPA/CBP Modeling Team to ensure there is consistency among the wetland classifications included in the marsh loss modeling outputs (NWF SLAMM (2008) and the NOAA Marsh Tool) to allow for side by side comparison of results.

Estimates of wetland loss were incorporated into the WQSTM by Carl Cerco with the use of NWF SLAMM v5 modeling and GIS mapping performed at the Bay Program.

<u>Citations</u>

Chesapeake Bay Program, 2016. Climate Resiliency Workgroup. *Recommendations on Incorporating Climate-Related Data Inputs and Assessments: Selection of Sea Level Rise Scenarios and Tidal Marsh Change Models.* August, 2016.

Johnson, Z., M. Bennett, L. Linker, S. Julius, R. Najjar, M. Mitchell, D. Montali, R. Dixon,

2016. *The Development of Climate Projections for Use in Chesapeake Bay Program Assessments*.

Glick, Patty, et al.. 2008. Sea-Level Rise and Coastal Habitats in the Chesapeake Bay Region, Technical Report. National Wildlife Federation, Washington, DC.

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Kirwin, Matt, S. Temmerman, E. Skeehan, G. Guntenspergen and S. Fagherazzi. 2016. Overestimation of marsh vulnerability to sea level rise. Nature Climate Change, volume 6. 253-260.

Lentz, Erika, E.R. Thieler, N.Plant, S. Stippa, R. Horton and D. Gesch. 2016. Evaluation of dynamic coastal response to sea level rise modifies inundation likelihood. Nature Climate Change, DOI 10.1038/NClimate2957.

WQSTM Preliminary Climate Modeling Results[3]

Influence of Estimated 2025 (0.3 m) and 2050 (0.5m) Sea Level Rise on Tidal Wetland Attenuation

There is little change in estimated total tidal wetland area for 2025 (0.3 m) and 2050 (0.5 m) which equates to negligible changes in tidal wetland attenuation. Long range (2100) conditions estimate tidal wetland changes to be on the order of a 40% loss in the Chesapeake which could reduce tidal wetland attenuation on the order of about 10 million pounds nitrogen and 0.6 million pounds phosphorus.

Influence of Estimated 2050 Estuarine Temperature Increases on Bottom DO

The influence of a 2050 estimated temperature increase on Chesapeake hypoxia is small, with an estimated increase in Chesapeake hypoxia ranging from 0.008 to – 0.06 mg/l. With the increased temperatures from watershed discharge, ocean inflow and estuarine warming the hypoxia increases are due to the increase in vertical stratification due to the increased thermocline, reduced oxygen saturation levels, and increased respiration. By extension, estimated 2025 temperature increases will also have slight influence on water quality standard achievement.

Influence of Estimated 2050 Sea Level Rise (0.5 m) on Bottom DO

The influence of a 2050 estimated sea level rise on Chesapeake hypoxia is also relatively small. The estimated change from the base hydrology (1991 to 2000) condition in Chesapeake hypoxia due to 2050 estimated sea level rise conditions ranges from 0.3 mg/l to -0.4 mg/l. Hypoxia decreases in the mid-Bay hypoxia are due to increased ventilation of deep Chesapeake waters by well oxygenated ocean waters, and also because of changes in vertical stratification.

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[3] Section to be updated with latest modeling results as they become available so that peer review materials include the latest modeling run details.

Appendix A: Recommended Watershed and Water Quality Sediment Transport Model (2025 Model Inputs)

Variable	**Input**	**Modeling Run Completed**	**Planned Uncertainty Analysis Component**
CO2	427 ppm	Watershed Model	No
Potential Evapotranspiration	Hargreaves-Samani	Watershed Model	Yes
	Hamon	Watershed Model	Yes
Temperature	RCP 2.6 Ensemble Median		Yes
	RCP 4.5 Ensemble Median	Watershed Model, WQSTM	Yes
	RCP 8.5 Ensemble Median		Yes
Precipitation	Historical Trend (+3.1%) with no Δ Intensity	Watershed Model	Yes
	Historical Trend (+3.1%) with Δ Intensity	Watershed Model	Yes
Sea Level Rise	0.17 meters		Yes
	0.3 meters	WQSTM	Yes
Wetland Loss	NWF SLAMM Model Runs (2008)	WQSTM	Yes
	NOAA SLR Viewer (Marsh Migration)		Yes

Appendix B: Recommended Watershed and Water Quality Sediment Transport Model (2050 Model Inputs)

Variable	Input	Modeling Run Completed	Planned Uncertainty Analysis Component
CO2	487ppm	Watershed Model	No
Potential Evap.	Hargreaves-Samani	Watershed Model	Yes
	Hamon	Watershed Model	Yes
Temperature	Six GCM Analysis: 2040 and 2060	WQSTM (prior methodology but not recommended by CRWG	No
	RCP 2.6 Ensemble Median		Yes
	RCP 4.5 Ensemble Median	Watershed Model	Yes
	RCP 8.5 Ensemble Median		Yes
Precipitation	RCP 2.6 Ensemble Median		
	RCP 4.5 Ensemble Median		Yes
	RCP 8.5 Ensemble Median		Yes
Sea Level Rise	.3 meters	WQSTM	
	0.5 meters	WQSTM	Yes
	0.8 meters		Yes
Wetland Loss	NWF SLAMM Model Runs (2008)	WQSTM	Yes
	NOAA SLR Viewer (Marsh Migration)		Yes

Appendix C. Sewell's Point Tide Gauge: Historic Data an Projections

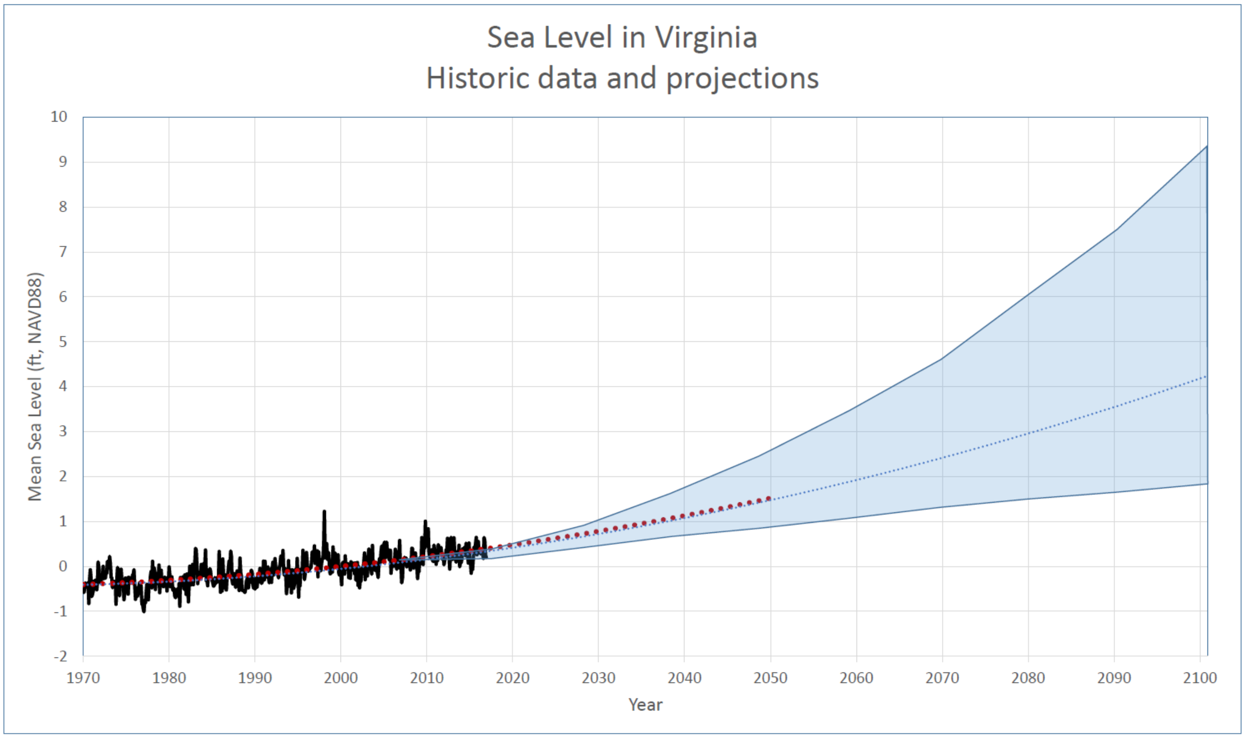

Figure legend:
Black line = observed monthly mean sea levels from 1970 through 2016 at the Sewell's Point tide gauge (referenced to NAVD88)
Red dotted line = exponential trend line fitted to observed values and projected 40 years into the future
Blue cone = range of projections for future sea levels based on global climate models adjusted to include subsidence in southeastern Virginia

Notes:
All the values in this figure are referenced to the elevation benchmark North American Vertical Datum of 1988 (NAVD88) now commonly used for FEMA Flood Insurance Rate Maps, FEMA Elevation Certificates, and many local land surveys. We use this datum because official tidal datums are based on water level observations between 1982 and 2001, and those values no longer represent the reality of water levels in the region. The current tidal datums are subject to revision at some point in the future.
The Sewell's Point water level observations are available from https://tidesandcurrents.noaa.gov/
The forecast of mean sea level for the next 40 years is based on analysis of the water observations over the past 40 years using an exponential trend analysis.
The range of model projections for future sea level through 2100 is based on the analysis reported in NOAA Technical Report NOS CO-OPS 083 titled "Global and regional sea level rise scenarios for the United States" published in January 2017. Available at:
https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf
The values used in this analysis are found in Table 5 on page 23 of that report. The values in that table are for Global Mean Sea Level rise scenarios (in meters) based on the most recent analyses found in the scientific literature.
After conversion to feet, the GMSL values were adjusted for subsidence using the 3.1mm/yr average

regional value computed by the National Geodetic Survey (2013) and reported in USGS Circular 1392 available at: https://pubs.usgs.gov/circ/1392/

There are 6 different sea level rise scenarios developed in the NOAA report. We show only the range between the "low" and the "extreme" scenarios on this figure. Decadal values for all six scenarios (adjusted for subsidence and converted to feet and the NAVD88 datum) are reported in the table below.

Sewell's Point mean sea level in feet relative to NAVD88										
climate change scenario	**year**									
	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
low	0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9
intermed-low	0.1	0.4	0.6	0.9	1.2	1.4	1.7	2.0	2.3	2.5
intermediate	0.1	0.4	0.7	1.1	1.5	2.0	2.5	3.0	3.6	4.2
intermed-hi	0.2	0.4	0.8	1.3	1.8	2.5	3.2	4.0	4.7	5.8
high	0.2	0.5	0.9	1.5	2.2	3.0	3.9	5.0	6.4	7.5
extreme	0.1	0.5	1.0	1.6	2.5	3.4	4.5	5.9	7.4	9.1

Sewell's Point RMSL scenarios (meters)			Sewell's Pt GMSL scenarios adjusted to MSL and NAVD88 with average 3.1mm/yr subsidence rate							
	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
low	0.028	0.089	0.150	0.221	0.282	0.343	0.404	0.465	0.526	0.577
intermediate-lo	0.038	0.109	0.190	0.271	0.362	0.443	0.534	0.615	0.696	0.777
intermediate	0.038	0.129	0.220	0.341	0.462	0.603	0.754	0.925	1.096	1.277
intermediate-hi	0.048	0.129	0.250	0.391	0.562	0.753	0.974	1.215	1.446	1.777
high	0.048	0.139	0.270	0.451	0.662	0.923	1.184	1.515	1.946	2.277
extreme	0.038	0.139	0.300	0.501	0.752	1.053	1.384	1.815	2.246	2.777
	2025 =	0.174		2050 =	0.462					