Chesapeake Bay Program
Climate Change Modeling 2.0

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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at http://www.chesapeake.org/stac.

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Executive Summary

The Chesapeake Bay Total Maximum Daily Load (TMDL) places limits on nitrogen, phosphorus, and sediment to meet water quality standards for dissolved oxygen, chlorophyll, and clarity. The TMDL calculations were based on climate conditions representative of the 1990s; however, since that time climate change has already resulted in increased rainfall, temperature, and sea level. The current understanding of the Bay ecosystem's response to climate forcing suggests that increased rainfall results in higher nutrient and sediment loads, while increased Bay temperatures exacerbate hypoxia by lowering the solubility of oxygen and increasing oxygen consumption by respiration and remineralization. On the other hand, these impacts can be partially offset as higher temperatures in the watershed decrease nutrient delivery to the Bay through enhanced evapotranspiration and denitrification, and increased sea level results in increasing modeled oxygen levels. Consideration of these feedbacks in the Bay ecosystem is essential for quantifying how climate change will impact the ability of the TMDLs to achieve the Chesapeake Bay's water quality standards and allow for more informed management decisions in the face of uncertainties inherent in any future projections.

As part of the US EPA's Chesapeake Bay Program's (CBP) 2017 Midpoint Assessment of the Chesapeake Bay TMDL, the CBP evaluated the impact of climate change between 1995 and 2025 on attainment of dissolved oxygen and water clarity water quality standards in the Bay. In May and September of 2017, preliminary estimates of the impact of climate change showed that minimal additional reductions, beyond that of the Bay TMDL, would be required. Later that year, an updated analysis including a revised estimate of 2025 sea level rise and altered assumptions of temperature change on the ocean boundary suggested that a much greater level of reductions, an additional 9.1 million pounds of nitrogen (4.6 percent of the total allowable load) and 0.49 million pounds of phosphorus (3.4 percent), would be needed to meet water quality standards. Recognizing the large difference in the two estimates, the CBP's Principals' Staff Committee (PSC) revised the Midpoint Assessment climate change strategy in December 2017, calling for additional in-depth climate change impact analyses to take place in 2019, with the refined projections to be used in a reconsideration of how to account for climate change effects in 2021.

The Chesapeake Bay Program Climate Change Modeling 2.0 workshop was held in late 2018 to give guidance and expert advice on the models and the assessment framework used to assess the effect of climate change on the TMDL. Scientists and managers developed recommendations that could be implemented to support assignment of any additional load reductions in 2021 and made recommendations on longer-term modeling goals for the partnership. Although a full workshop report is only now being published, several recommendations on near-term model revisions have already been implemented and have supported policy decisions by the PSC. The longer-term model revisions recommended here will be useful in guiding the partnership regarding future projections of climate change impacts on the attainment of the Bay TMDL and water quality standards in the Chesapeake Bay.

Major recommendations

Many consensus recommendations emerged from the breakout sessions and are captured in detail in the main report. The main recommendations are summarized as follows:

In the near term (by 2021):

1. Introduce the estimation of uncertainty into the decision process.
2. Closely examine all climate-related sensitivities in the watershed and estuarine models and characterize the relative importance of these effects on dissolved oxygen. Prioritize:
   a. Improving the watershed model's response to flow and sediment change, including nutrient speciation changes.
   b. Estimating the effect of climate change on Best Management Practices (BMPs).
   c. Evaluating the effect of sea-level rise on estuarine hypoxia with multiple model comparisons.
   d. Adjusting the estuarine model's simulation of temperature dependent phytoplankton dynamics.
3. With the knowledge gained from sensitivity analyses of recommendation #2, prioritize improvements and enhanced quantification of uncertainties in model inputs:
   a. Use General Circulation Models (GCMs) rather than trend extrapolation for projections beyond 2025, incorporating seasonal changes
   b. Re-evaluate estuarine model forcing, particularly the magnitude of sea-level rise, open boundary conditions (specifically temperature), and the influence of wind.
4. Compare multiple existing estuarine model simulations, including the CBP's Water Quality and Sediment Transport Model, from 1985 through recent wet years.

In the longer term (by 2025):

1. Create a more sophisticated evaluation framework that incorporates various sources of uncertainty:
   a. To model future climate beyond 2025, rely entirely on projections based on multiple General Circulation Models (GCMs) rather than extrapolation of past trends. This will allow for better incorporation of seasonal and spatial variability in climate projections.
   b. For projections of conditions beyond 2050, evaluate multiple Representative Concentration Pathways (RCPs; IPCC 5th Assessment) or Shared Socioeconomic Pathways (SSPs; IPCC 6th Assessment).
   c. Recognize and quantify multiple sources of uncertainty for use in modeling and decision-making.
2. Continue development of climate-related watershed model capabilities with particular attention to BMP effectiveness.
3. Develop a new estuarine model with:
   a. An unstructured grid that extends onto the coastal shelf.
   b. Updated biogeochemistry, particularly appropriate for a future warmer climate.
   c. A simulation of wetting, drying, and waves.

Introduction

The Chesapeake Bay Total Maximum Daily Load (TMDL) (USEPA 2010) specifies the average annual nitrogen, phosphorus, and sediment limits required to meet water quality standards for dissolved oxygen, chlorophyll, and clarity. The averaging period for load estimation, representing a typical climate decade, was chosen to be 1991-2000. Although climate change was acknowledged in the 2010 TMDL, it was not explicitly included. A preliminary analysis included as an appendix in the TMDL documentation involving the Susquehanna basin showed that small decreases in nitrogen and phosphorus load, and small increases in sediment load might be expected by 2025 (USEPA 2010 appendix E).

The effect of climate change was more formally incorporated into the Midpoint Assessment of the TMDL, conducted in 2017 and 2018. Recommendations from the STAC Workshop, *Development of Standardized Climate Projections for Use in Chesapeake Bay Program Assessments* (Johnson, et al, 2016) were used in the creation of climate input data sets for the CBP models. In December 2016, the Chesapeake Bay Program (CBP) partnership agreed to the assessment procedures for determining projected 2025 climate impacts on the watershed streamflow and pollutant loads (nitrogen, phosphorus, and sediment) and estuarine water quality. The Chesapeake Bay Program Phase 6 Watershed Model (P6WM) and estuarine Water Quality Sediment Transport Model (WQSTM) 2025 climate change modeling results were presented to a joint meeting of the Modeling Workgroup and the Water Quality Goal Implementation Team in early December 2017. At that time, the CBP modeling team estimated that relative to the proposed Phase III Watershed Implementation Plan (WIP) planning targets without simulated climate change influence, basin-wide loads would need to be decreased by 9.1 million pounds of nitrogen (4.6 percent) and 0.49 million pounds of phosphorus (3.4 percent) to counteract the influence of climate change on dissolved oxygen water quality standards. The climate change presentation begins on slide 292 of the combined presentation from the December 2017 joint meeting.

The reductions estimated in December 2017 required a substantially greater level of effort from the partners than implied by preliminary work presented in May and September 2017. The CBP's Principals' Staff Committee (PSC) was struck by how rather small changes in assumptions on climate change affected the estimates. As a result, the PSC arrived at a revised climate strategy. The climate-related requirement in the Phase III Watershed Implementation Plans was reduced to the inclusion of a narrative strategy. Numerical climate-related nutrient reduction targets would be incorporated into the 2022-2033 milestones pending an update to the CBP modeling system and assessment framework. The PSC directed the CBP to better understand the science and develop revised estimates of pollutant load changes with specific attention to BMP responses. A date of 2021 was set to consider the results of updated methods, techniques, and studies and revisit existing estimated loads due to climate change to determine if any updates to those load estimates are needed for the 2022-2023 milestones. The partnership would do preliminary work in 2018 to prepare for a year of adjustments to the modeling system in 2019. Technical review and approval would occur in 2020 to set the stage for a decision on climate change in 2021. The plan and timeline are shown in Figure 1.

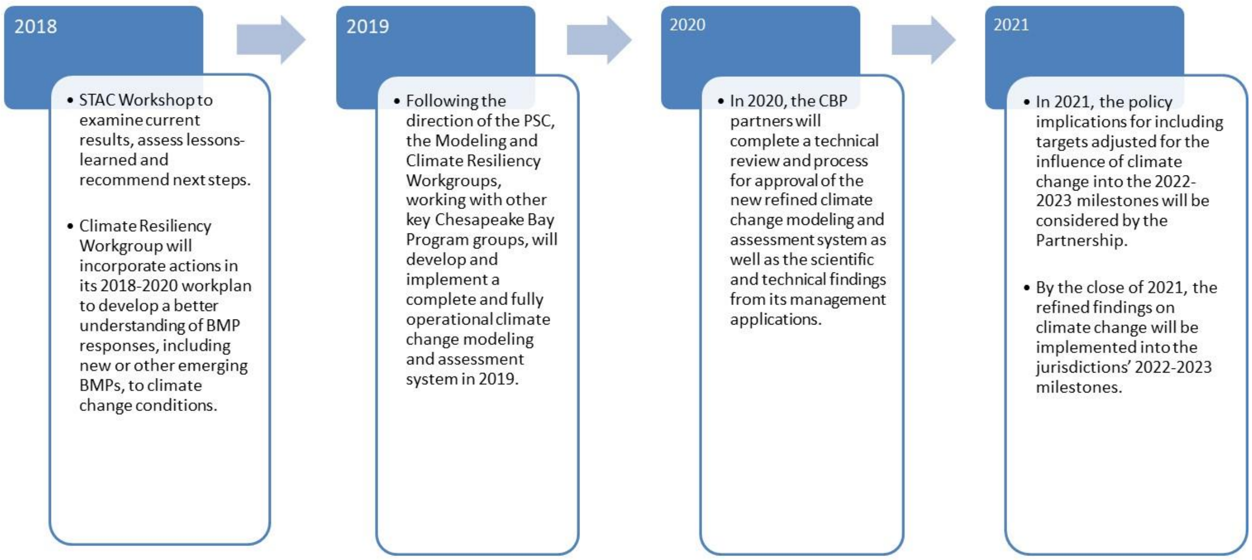

Figure 1: Multi-year climate change work plan

The Chesapeake Bay Program Climate Change Modeling 2.0 workshop was organized for late 2018 to give input on watershed modeling, estuarine modeling, and the overall climate change assessment framework to be incorporated into the work of the CBP's Modeling and Climate Resiliency Workgroups. The two-day workshop brought together watershed managers and experts in climate change, estuarine, and watershed sciences to undertake a detailed and focused examination of the current results of the CBP's Midpoint Assessment climate change modeling efforts, assess lessons learned, and recommend next steps. In addition, guidance was sought in formulating a longer-term plan of study, including field sampling and data analysis, monitoring and modeling that will improve understanding of long-term climate change impacts, vulnerability, and risk management in the Chesapeake watershed and estuary, which could be considered in the conceptual framework in the next phase of CBP model development.

Although a full workshop report has not until now been published, draft recommendations from breakout groups were produced shortly after the September 2018 workshop, presented to STAC separately for the watershed, estuarine, and framework groups, and used in the model revisions. The CBP modeling team worked with interested workshop participants to implement many of the recommendations in the climate analysis. Additionally, the CBP efforts were informed by a STAC workshop on *Monitoring and Assessing Impacts of Changes in Weather Patterns and Extreme Events on BMP Siting and Design* (Johnson, et al. 2018) which provided guidance on important climate-related effects to include in models. A STAC peer review of the existing CBP climate change assessment framework (Herrmann, et al. 2018) gave clarity to the areas of analysis that were appropriately addressed and those that needed additional effort. STAC reviews of the Phase 6 Watershed Model (Easton, et al. 2017) and the Water Quality Sediment Transport Model (Brady, et al. 2018) provided climate change recommendations as well. The Modeling Workgroup, following guidance from its members and STAC, produced revised modeling estimates in October 2019. The Principals' Staff Committee approved the adjustments to the planning targets to account for climate change in December 2020. Full documentation of the modeling decisions and the partnership process is available on the Chesapeake Assessment and Scenario Tool (CAST, Chesapeake Bay Program 2017) model documentation page.

Presentations

A series of presentations provided the scientific and management background for the participants prior to the breakout sessions. Links to all presentations can be found on the STAC workshop page. They are also linked individually through the presentation titles in this document.

Welcome – Lee Currey, Maryland Department of the Environment

The CBP uses the Phase 6 modeling suite of tools to provide analyses that support decision making as part of the Chesapeake Bay TMDL 2017 Midpoint Assessment. The suite of Chesapeake Bay Program Partnership models includes watershed, estuarine, land use change, and atmospheric deposition models. Initial results of the climate change analysis indicate that significant reductions of nitrogen and phosphorus will need to be made to counteract the effects of climate change on dissolved oxygen in the Bay and meet state water quality standards. The workshop is motivated in part by the varying climate estimates presented to the PSC in 2017 and also by decisions and timelines for a Partnership decision on incorporating climate change in the TMDL midpoint assessment. Workshop participants' expertise is needed in the short term to meet these near-term goals and to lay out strategies to address climate change in the long term. Participants were urged to focus on the science rather than the policy questions.

Global Perspectives on the Effects of Climate Change on Coastal Eutrophication – Don Boesch, UMCES

Climate change assessments for eutrophication issues have been performed and published for the Baltic Sea and the Gulf of Mexico. The Baltic Sea is expected to see decreases in oxygen brought about by increases in temperature and nutrient loading resulting from increased runoff by 2100. Similarly, the Gulf of Mexico is expected to see more hypoxia on the Louisiana Shelf which would require nutrient load reductions beyond those in the Gulf Hypoxia Action Plan to offset.

There is a wealth of global literature on climate change effects with some commonalities, but each region has its own idiosyncratic issues. Participants were encouraged to focus on the "big things" that we need to get right in the Chesapeake and to seek solutions that limit climate change as well as nutrient loads. The early findings that trend in hypoxia in the Chesapeake is inversely related to the amount of sea-level rise has increased the interest in accurate measurements and realistic projections of sea level. Recent improved analyses of sea-level rise were presented.

Introduction and Purpose of Workshop – Mark Bennett, USGS

A change in the CBP's climate assessment, caused by a change in the primary driving assumptions, led the PSC to postpone the climate decision until additional analysis could be performed. In the initial 2017 assessment, an increase in rainfall led to an increase in loading, which raised hypoxia in conjunction with an increase in the Bay temperature. However, these effects were almost exactly offset by sea-level rise which decreased hypoxia. For the final 2017 assessment, the calculated amount of sea-level rise was decreased relative to previous estimates, and the ocean temperature assumptions were altered, leading to a substantially greater reduction in loads to counteract the effects of climate change. Separate breakout groups will focus on watershed, estuarine, and the climate analysis framework to inform the climate reanalysis taking place in 2019.

Overview of Climate Impact Assessment Framework and Implementation – Gary Shenk, USGS-CBPO

The CBP climate assessment as of December 2017 included decisions about how to create future rainfall and meteorology climate scenarios for use in the models, sensitivities of those models to the climate inputs, and the method to calculate the impact on nutrient planning targets. Each breakout group was given specific parts of the climate assessment to address.

As recommended by the previous STAC climate change workshop (Johnson, et al. 2016), precipitation for 2025 is modeled by applying long-term trends in observed annual precipitation to the 1991-2000 observed rainfall. All temperature and precipitation forcing data for 2050 are generated using relative changes in GCMs. The analysis framework breakout group was to examine these assumptions along with the method of applying expected changes in dissolved oxygen relative to climate change to the TMDL nutrient loading targets.

The watershed breakout group examined the applicability of the Phase 6 watershed model to simulate the effects of climate change on watershed loads. The hydrologic and sediment load sensitivity is simulated directly with Hydrologic Simulation Program – Fortran (HSPF). Nitrogen change is assumed to be proportional to hydrology with no change in concentration. Phosphorus will change relative to stormflow and sediment washoff.

The estuarine group assessed the ability of the estuarine WQSTM to realistically simulate the effects of climate change and the model inputs used in the sensitivity experiments. Specifically, the estuarine group was asked to consider sea-level rise, surface temperature, ocean boundary conditions, and the response of the WQSTM to all inputs including changes in watershed loads.

Findings of the Phase 6 Watershed Model – Gopal Bhatt, Penn State and Lewis Linker, EPA-CBPO

Following the recommendations of Johnson et al. 2016 under the guidance of the Modeling and Climate Resiliency Workgroups, the CBPO modeling team employed the Phase 6 Watershed Model to estimate the effect of climate change on the delivery of flow, nutrients, and sediment to the Chesapeake Bay. An overall increase in annual precipitation of 3.1% between 1995 and 2025 based on long-term trends was in general agreement with estimated increases from GCMs for RCP4.5. By 2050, the increase relative to 1995 is expected to be 6.28%, based on evaluation the median of multiple GCMs. Temperature increase is expected to average 1.12°C by 2025 and 2.03°C by 2050, also using RCP4.5. Rainfall was added preferentially to the highest historical rainfall events rather than spread evenly over all events. Change in potential evapotranspiration (PET) was estimated using the Hargreaves-Samani method which was demonstrated to be more appropriately reactive to changes in temperature.

By 2025, flow and nitrogen were modeled to have similar increases of 2.3% and 2.4%, respectively. Sediment and phosphorus were likewise similar in their increases of 3.3% and 3.1%, respectively. By 2050, the estimates had increased to 6.0% for flow, 8.3% for nitrogen, 15.3% for phosphorus, and 16.2% for sediment. The greater increase in nitrogen relative to flow was due to an increase in simulated scour of organic nitrogen.

Preliminary Estimates of Future Climate Change Influence on Water Quality in the Chesapeake Bay Using CH3D-ICM – Richard Tian, UMCES, Carl Cerco, Attain, and Lewis Linker, EPA-CBPO

The CBP's estuarine Water Quality and Sediment Transport Model (WQSTM), otherwise known as CH3D-ICM, was run with updated inputs to produce initial estimates of the effect of climate change on dissolved oxygen concentrations. Sea-level rise relative to 1995 was set at 0.17 meters for 2025 and 0.5m for 2050, based on the recommendation of the Climate Resiliency Workgroup. Air temperature was set to an increase of 1.05°C for 2025 and 1.85°C for 2050. Temperature and salinity were adjusted accordingly at the open boundary.

Looking strictly at hypoxia defined as water with less than 1 mg/l oxygen, sea-level rise reduced hypoxia significantly and more than made up for increased watershed loads. However, the increased temperature increased hypoxia and was the dominant effect. Of the various temperature effects, the effect on saturation was greater than the effect on biological rates, which in turn was greater than the effect on stratification.

Management Actions in Response to Climate Change – Tony Buda, USDA-ARS; Jon Butcher, Tetra Tech; Curtis Dell, USDA-ARS; and Adel Shirmohammadi, UMD

It is anticipated that management strategies will need to be modified to deal with climate change. Panelists gave short presentations leading to a discussion of climate effects on land management. Future management actions will need to deal with the increased frequency and severity of large events. Tony Buda illustrated the importance of large events using phosphorus loads from a small research watershed in Pennsylvania. A single storm, Tropical Storm Lee, accounted for 21% of the decadal phosphorus loads from that watershed. Jon Butcher pointed out that urban BMPs could be sized to expected future climate, but that there would be significant cost associated with more robust design. He also referenced work pointing to the potential for decreased effectiveness in agricultural conservation practices. Curt Dell anticipated increased use of winter cover crops and double cropping with warmer winter temperatures. He also saw the need for more irrigation and a likely increase in the diversity of crops grown. Adel Shirmohammadi related results of a modeling study that identified critical source areas on the landscape and how they are expected to expand under climate change. Programs that target BMPs to critical source areas are expected to be effective at meeting TMDL limits, particularly in the face of climate change.

More research is needed before we have full knowledge of the anticipated effects of climate change on management practices, but we can start to adapt our modeling suite to what information is available. Research outside of the Chesapeake Bay region should be used to make up for the lack of local studies. Models will need to operate at a finer scale and should first address seasonality, crop uptake, and irrigation to be most effective at incorporating the effects of climate change. As the simulation of management practices is refined in the models, it will become necessary to work on incentives for adopting BMPs that are sited appropriately and effective in a changing climate.

Questions for breakout groups

Using the foundational information in the morning presentations and participating in plenary discussion, workshop participants were invited to breakout groups to formulate recommendations for the Chesapeake Bay Program. The following initial list of questions was provided by the steering committee. Breakout groups developed additional and alternative questions as described under the individual breakout sessions.

- How do the responses of the CBP Phase 6 Watershed Model (P6WM) and Water Quality Sediment Transport Model (WQSTM) to future climate forcing compare to other modeling efforts and frameworks?
- What additional or different climate change approaches and methods should be incorporated into the P6WM and WQSTM?
- How can CBP modeling efforts account for potential impacts of larger landscape-level changes (e.g., changes in land use or agricultural systems) on nutrients and sediments loads?
- What ranges of inputs should be used for the WQSTM for water column temperature and ocean boundary changes?
- How does the relative rate of increasing precipitation, temperature, and sea-level rise influence Chesapeake water quality in 2030, 2035, 2040, and other future years? What are the trends of climate change impacts going forward beyond 2025?
- What new and/or refined methods and modeling techniques could be used to better assess projected impacts on watershed loads and estuarine impacts for a range of future scenarios?
- What improvements could be made to the methodology used to develop jurisdiction-specific nutrient pollutant loads due to 2025 climate change conditions and beyond?
- What are the remaining research gaps and highest priority information needs (e.g., data, research, modeling methods and techniques, programmatic efforts)?

Results of the Three Breakout Group Discussions

Discussions within breakout groups began on the afternoon of the first day and continued through the morning of the second day. Breakout group leaders were charged with organizing the group and choosing members responsible for facilitating the discussion, collecting notes, reaching consensus on priority recommendations, and drafting the recommendations for the workshop report. Leaders typically also filled some or all of those roles.

In the afternoon of the second and final day of the workshop, breakout group leaders presented a short list of recommendations that represented the consensus high-priority recommendations from their group. The recommendations were discussed in plenary and received additional input from a group of water quality managers who were asked for feedback. These results of these discussions were considered in the final recommendations.

Watershed Model Breakout Group

Specific questions for the watershed group

1. How do the responses to future climate forcing in the present application of the CBP Phase 6 Watershed Model (P6WM) compare with other modeling efforts and frameworks? Which assumptions and processes (regarding, for example, temperature, precipitation, soil moisture, evapotranspiration, plant growth, etc.) are particularly sensitive with regard to delivery of fresh water, nutrients and sediments to tidal waters? Are there more defensible assumptions or formulations that could be implemented by 2019?
2. Although the P6WM simulation of climate changes through 2025 showed only small changes in TN and TP delivery to the estuary they indicated greater increases for more soluble and bioavailable forms that exacerbate estuarine hypoxia. Are these projections of nutrient speciation reliable and appropriate?
3. For the period extending at least to 2050, how should CBP modeling and assessment efforts account for potential impacts of landscape-level changes and practices, e.g., urban and agricultural land use, forest composition and dynamics, agricultural cropping systems, irrigation, storm-water management, etc., on nutrients and sediments loads? Specifically, how can the sensitivity of and improvements in BMPs in response to climate change be incorporated in the modeling framework?
4. From the perspective of watershed processes, how can the uncertainty in model projections best be quantified and the degree of confidence communicated effectively to decision makers, both for projections through 2025 and, in the longer term, through 2050?
5. What are the most critical needs for information, synthesis, and research?

The watershed breakout group discussed near-term and long-term changes that could be made to the simulation of the effects of climate change in the Chesapeake Bay Program's Phase 6 and future watershed models.

Watershed Model Discussion and Recommendations

The P6WM has an explicit simulation of the effects of climate change on hydrology and sediment using the Hydrologic Simulation Program – Fortran (HSPF). Since spatially variable stormwater runoff and sediment washoff are used in the P6WM to predict phosphorus load, these relationships can be used to estimate the changes in phosphorus loads associated with climate change. Nitrogen loads, however, are not directly related to climate variables in the P6WM, so additional methods must be built into the Watershed Model to simulate the effect of climate on nitrogen loads. The method of simulation related to climate change was described in plenary and again in the watershed breakout. The watershed group came to an agreement on the four general recommendations to improve modeling of the climate effects on nutrient delivery in the Chesapeake Bay watershed: Improve the nutrient response to flow and sediment change; improve the response of nutrient speciation to climate change; incorporate the effects of climate change into BMP effectiveness estimates; and introduce the estimation of uncertainty into the decision process.

Improve the nutrient response to flow and sediment change

Currently, the P6WM simulates a change in nitrogen that is proportional to the change in flow due to climate effects. This response to changes in flow is based on prior CBP modeling and published reports on the effects of climate change. Phosphorus load changes are based on climate-induced changes in surface runoff and sediment washoff for agricultural and natural landscapes. There is currently no phosphorus loading effect of climate change simulated in developed areas. The changes in nitrogen and phosphorus are applied separately to each land use and segment. The workshop participants suggested that the CBP investigate the following improvements to the nutrient response in the P6WM. They felt that these goals were all attainable in the short term by 2019, but that there should also be a more in-depth and long-term effort.

Spatially vary the relationship between nitrogen and flow. The assumed proportional relationship between change in flow and change in nitrogen output to a stream is supported at the large scale, but there may be significant differences between land use types and between geographic settings. It is suggested that the CBP undertake an additional literature review to investigate these different responses. Published small-scale modeling efforts may be particularly useful. The CBP should also investigate using the existing P6WM responsiveness to groundwater recharge and available water capacity.

Developed area sensitivity to Phosphorus. The lack of a response of developed area phosphorus loads to climate change is not supportable, especially if climate change causes altered sediment loading from developed areas. As with nitrogen, it is suggested that the CBP address this through a literature review concentrating on published small-scale modeling efforts.

Investigate potential changes to wastewater overflows. The current modeling for climate change does not consider the effect of climate on the frequency or severity of wastewater overflows. In combined sewer systems, overflows could be assessed through the existing combined sewer overflow model at the CBP. Sanitary sewer overflows would also be affected and should be investigated through literature reviews and by examining local and state records across the jurisdictions, potentially leading to revised data input and flow-driven deliveries for each watershed.

Change the nitrogen and phosphorus speciation methods

The nitrogen speciation in the P6WM is determined by an observed positive correlation between total nitrogen load per acre and ratio of nitrate to total nitrogen at the more than 100 CBP nontidal network monitoring stations where the USGS calculates nitrogen loads (https://cbrim.er.usgs.gov/). The nitrogen speciation relationship is applied to all combinations of land use and land segment individually. As nitrogen loads are modified by climate change, the relationship between total nitrogen and nitrate is applied to the new loads and as a result, the nitrate fraction increases under climate change in the model. The species fractions of phosphorus loading from land are not modified for climate change scenarios. Climate runs are simulated in the HSPF riverine module for large rivers and species fractions of both nitrogen and phosphorus are modified by the simulation through biogeochemical processes.

The workshop participants suggested that the observed relationship between nitrate fraction and total nitrogen was likely due to spatial differences in land use rather than climate differences and therefore it is not appropriate to apply the ratio in climate scenarios. A better approach for the 2019 analysis for nitrogen would be to keep the species fractions constant through climate runs as is currently done for phosphorus. Another suggestion was to look at observed surface runoff and baseflow speciation and apply modeled changes in surface and baseflow components of runoff in response to climate to re-estimate nitrogen species fractions.

In the longer term, the CBP should revisit the question of changing nitrogen and phosphorus speciation as a reaction to climate change. Specifically, the CBP should investigate the complex concentration-discharge relationships in the observed record and should include analysis of changes in the proportion of species with discharge. In addition to the CBP nontidal network, there are other existing data sets such as the Maryland Department of Natural Resources storm sampling network, the International Stormwater BMP Database, and other Municipal Separate Storm Sewer System (MS4) databases that could be useful in separating the effects of climate, land use, geology, and BMPs on nutrient speciation. Small-scale studies may exist that could be used in the upcoming STAC climate change synthesis for a section on speciation. Fine-scale models could be used to generate knowledge that could be generalized for the watershed. For example, increased temperatures could result in a change in animal and plant species density, phenology, and activity that would in turn alter stream chemistry.

Incorporate the effects of climate change into the BMP effectiveness estimates

Many participants in the watershed breakout identified the need to understand the effects of climate change on BMP effectiveness estimates as a top priority; however, it was also understood that the recommendations were long-term rather than for the 2019 assessment. In a previous STAC report (Johnson, et al 2018), the CBP was urged to support the development of tools to support the design of BMPs with the consideration of climate change. The protocol for CBP BMP expert panels (Chesapeake Bay Program 2015) requires the consideration of variability due to climate; however, the complete reports rarely address climate change.

A successful consideration of the climate effects on BMPs would need updated intensity-duration-frequency (IDF) rainfall curves and then a simulation or analysis of the effects that these changes in IDF curves would have on BMP performance. For BMPs that incorporate "green" components, the effect of changes in temperature and soil moisture on plant growth should also be considered. The effects of failure of the BMP in extreme conditions and the frequency of failure should be included. The CBP should recommend that states update their stormwater regulations similarly to updated regulations in Wisconsin, California, Massachusetts, and Canada. Many BMPs have an intended effect of pollutant reduction and co-benefits that may occur downstream or within the management practice itself. These co-benefits may also be sensitive to climate change.

It is clear from the prior STAC report (Johnson, et al., 2018) and the BMP expert panel protocol that the CBP understands the need to incorporate climate considerations in BMP effectiveness estimates, but that the resources have been limited. The CBP should update the BMP panel protocol to emphasize climate change effects on the BMP and be prepared to support the efforts of the BMP panels appropriately. The CBP could request that the Chesapeake Bay Trust develop a Request for Proposals for BMP response to climate change. The CBP could request that the upcoming STAC synthesis on climate change assess the tools currently in existence to address this problem as a means of organizing some of the research that needs to be done.

Consider uncertainty in the decision-making process

The incorporation of uncertainty estimation in the CBP decision making process is a frequent recommendation from STAC to the CBP (e.g. Stephenson, et al 2018). However, the difficulty in completing an uncertainty quantification and the complexity of the decision-making process often confound efforts. Climate change presents an ideal opportunity for a 'trial run' of decision making under uncertainty. An uncertainty quantification considering different global climate models and downscaling techniques has already been presented to the CBP partnership (see, for example the presentation to the Modeling Workgroup from July, 2018). The decision-making process may be tractable as well in that it is limited to one issue with lower stakes than the full planning target-setting efforts of 2017.

The participants in the workshop recommended that by 2019, the effects of climate change could be presented as probabilities or risks. The additional reductions required to offset the effects of climate change could be reported as a probability distribution from which statistics could be determined. For example, it could be reported there is a 50% chance that the effect is equivalent to at least X million pounds of nitrogen and a 90% chance that the effect is equivalent to at least Y million pounds of nitrogen. Alternatively, a reduction of 9 million pounds of nitrogen may result in an increase in probability of meeting water quality standards from A% to B%. In the longer term, the participants recommended that the CBP fully integrate uncertainty into models and decisions and that the CBP should consider techniques like robust decision making or least regrets analysis.

Estuarine Model Breakout Group

Specific Questions for the Estuarine Model Breakout Group

1. How do the estuarine water quality responses to future climate forcing (specifically including temperature increases, sea-level rise, and changes in inputs of freshwater, nutrients, and sediment from the watershed) in the present application of the CBP Water Quality and Sediment Transport Model (WQSTM) compare with those of other comparable modeling efforts and frameworks? What causes differences and how can these be tested? Which assumptions regarding both forcing (e.g., temperature, sea-level rise, watershed inputs) and processes (e.g., hydrodynamics and biological processes) are particularly consequential for the simulated distribution, timing and severity of hypoxia? Are there more defensible assumptions or formulations that could be implemented by 2019?

2. How should the next generation of the WQSTM and other estuarine models evolve to produce reliable estimates of climate change-related risks to water quality and other Bay restoration goals for the period extending at least to 2050? How might climate change modify the estuary in ways that would require reformulation of the structure and assumptions of the modeling approaches (through, for example, changes in ocean boundary conditions, winds, and solar radiation; retreat of shorelines and wetlands; and loss or invasions of species that have large influence on ecosystem processes)?

3. From the perspective of estuarine responses, how can the uncertainty in model projections best be quantified and the degree of confidence communicated effectively to decision makers, both for climate impact assessment through 2025 and, in the longer term, through 2050.

4. What are the most critical needs for information, synthesis and research?

Near-term recommendations for the estuarine model

Resolve the effect of sea-level rise

The estuarine breakout group discussed the existing discrepancies between the results of the multiple ongoing climate change modeling studies currently being implemented in the Bay. Specifically, Irby et al. (2018), based on the Regional Ocean Modeling System (ROMS), find that sea-level rise between 1995 and 2050 is likely to reduce Chesapeake Bay hypoxia. This result is also supported by similar scenario tests performed with the CBP's WQSTM estuarine model. However, another different Chesapeake Bay implementation of ROMS (later published as Ni et al., 2019) found that sea-level rise will exacerbate hypoxia. Since estuarine circulation and stratification are both expected to increase with sea-level rise, but likely have opposite impacts on oxygen, this is a complex problem that needs further study. The estuarine breakout group agreed that better understanding this discrepancy between model results of the impact of sea-level rise on hypoxia should be the highest short-term priority for the CBP.

Re-examine biogeochemical model parameterizations to realistically account for temperature dependence

Increase phytoplankton growth at high temperatures. The estuarine model currently includes phytoplankton growth curves that flatten or decrease with increased temperatures, rather than increasing as would be expected from the classic Eppley relationship (Eppley, 1972). Part of the rationale for this parameterization is that the spring diatom group is generally less abundant in summer. To force this to occur in the model, the spring diatom group is parameterized with a growth rate that slightly decreases at higher temperatures. However, this is inconsistent with the understanding that phytoplankton generally tend to grow faster in warmer temperatures. Over decadal time scales as water temperatures continue to warm, we would expect new types of phytoplankton to outcompete and grow faster than the current phytoplankton in the Bay. As a result, the breakout group recommends that the estuarine model should incorporate a phytoplankton temperature-growth curve that increases exponentially at high temperatures. This is not likely to alter the existing calibration since this effect will be most influential during very warm conditions that have seldom occurred in the past but will likely occur more often in future decades.

Include a temperature dependent mortality or grazing rate in the model. Not only will phytoplankton grow faster at warmer temperatures, but phytoplankton will also likely be grazed at faster rates, and this needs to be accounted for in the model as well. In fact, the temperature dependence of grazing parameterizations should typically be greater than that of phytoplankton growth.

Re-evaluate model forcing

Re-examine the outer boundary conditions. It is not clear from open ocean warming studies whether the Mid-Atlantic Bight is increasing or decreasing in salinity (Saba et al., 2015). The breakout group thus recommends that tests should be performed with both conditions (increasing salinity at the boundary and decreasing salinity at the boundary) in order to determine the impact of such changes on the estuary.
Investigate downscaled future wind products. Downscaled GCM wind products, such as those obtained via Multivariate Adaptive Constructed Analogs, are now available for the Chesapeake Bay region. These changes in future wind forcing are expected to be small, but it is not clear what the impact of these wind changes will be on hypoxia. The breakout group thus recommends some simple tests should be performed to quantitatively examine the importance of future changes in winds as a major cause of future change in hypoxia. These tests should be conducted with multiple GCMs, since different GCMs appear to project different future changes in wind speed and direction.

Focus on relevant metrics

To date, the CBP Modeling Workgroup has largely focused their estuarine climate change studies on the impact of climate change on hypoxic volume, however the Water Quality Standards are focused on spatial and temporal distributions of oxygen *concentrations*, as well as water clarity, and chlorophyll concentrations. Thus, to determine the impact of future climate change on our attainment of these critical water quality standards, the impact of climate change on these metrics should be examined, rather than focusing primarily on hypoxic volumes.

Medium-term recommendation for the estuarine model

Conduct a multiple model comparison

The estuarine breakout group agreed that it is essential that a rigorous multiple model comparison and skill assessment be performed over the historical period of 1985-2018. This is unlikely to be performed in time for the CBP's reevaluation of climate change effects on the TMDL but should be a goal in the next several years. Rigorous model comparison would increase confidence in the CBP's estuarine modeling system, and directions for future change, much as the shallow water modeling comparison effort did several years ago. In particular, the models should be compared for the recent years, especially given recent unusually wet conditions. To facilitate this comparison, the breakout group recommended that the CBP should extend the coupled P6WM-WQSTM simulations at least through 2018, so that model results in more recent years can be compared with other state-of-the-art model results.

Longer-term recommendations for the estuarine model

Develop a new estuarine model

Although the current estuarine model has been adequate for addressing the CBP's needs over the past several decades, the estuarine breakout group agreed that to address many of the climate change issues that CBP managers feel are critically important, a more state-of-the-art "next generation" estuarine model is now required. The critical components of this next generation model are summarized below, which will ensure that the CBP's modeling system can adequately address climate change related policy questions.

1. **Use an unstructured grid model.** The Chesapeake Bay is a large multi-scale system that requires a model that can resolve processes at multiple spatial scales. Small tributaries and regions of strong bathymetric change could fail to be successfully simulated with a grid scale that is appropriate only to the main stem of the Bay. The estuarine breakout group agreed that an unstructured grid model is required to resolve small-scale processes where such resolution is required and allow for lower resolution to save computation time/cost where it is not. Note that this was also a strong recommendation of STAC's CBP Modeling in 2025 and Beyond workshop (Hood et al., 2019).
2. **Simulate wetting and drying.** Because sea-level rise and recurrent flooding are already having critical impacts on many parts of the Chesapeake Bay system, a model is required that includes episodic wetting and drying of grid cells and can thus adequately simulates coastal flooding and changing coastlines. The existing model is structured as if there is a hard and fixed barrier surrounding the Bay's tidal waters, and thus sea-level rise results in an increase in estuarine depth, but no corresponding increase in area or coastal flooding. Accurate simulations of the effects of sea-level rise cannot be attained with such a simplified system.
3. **Develop a spectral wave model.** The breakout group agreed that a spectral wave model is required as part of this "next generation" model, in order to ensure that shoreline erosion and sediment transport will be accurately represented as these will also likely be changing in the future.
4. **Extend the open boundary onto the coastal shelf**. One of the most significant issues with the current estuarine model, and perhaps one of the most straightforward to correct, is the location of the outer boundary. Currently the WQSTM grid ends at the Chesapeake Bay mouth, however the breakout group agreed that the outer boundary of a future model grid must be moved farther offshore onto the Mid-Atlantic Bight shelf, as is the case with all other Chesapeake Bay modeling systems (e.g. Irby et al., 2016, Da et al., 2018, Hong and Shen, 2012, Testa et al., 2014, Lanerolle et al., 2011, Ye et al., 2018, Cai et al., 2020, Cai et al., 2021). We note that this was also a recommendation of the STAC WQSTM Review Panel (Brady et al, 2018). The breakout group

further recommended that the model solutions be relaxed (nudged) to observations where and when they exist at the Bay mouth.

5. **Improve biogeochemical model parameterizations**. Re-examine all temperature and salinity dependent parameterizations, including changing stoichiometric relationships. Add additional parameters that may be important for climate change, such as acidification which may be critical for oyster simulations, zooplankton as a linkage to higher trophic levels, and potentially Harmful Algal Bloom (HAB) species. The wetland and SAV models should be improved with new research. The system should be used to investigate the impacts of climate change on higher trophic levels, including invasive species.
6. **Improve model forcing.** The realism of atmospheric forcing for the estuarine model should be revisited. Many reanalysis products with realistic spatial and temporal variability now exist, and may be far superior to what is currently used by the WQSTM. These could, for example, include more low-pressure systems, which might have a significant effect on oxygen dynamics. Potential impacts of future tidal range changes should also be investigated.

Overall CBP framework of climate analysis breakout group

Specific questions for the Framework group

1. What improvements to the current framework used by the CBP to determine the nutrient load reductions needed compensate for the effects of climate change in the Chesapeake TMDL could reasonably be implemented by 2019? Answers should consider both the deliberations on (a) the watershed and estuarine components of the current model framework and (b) the methods employed to estimate additional load reductions based on modeled changes in attainment of dissolved oxygen criteria.
2. How should the uncertainties inherent in (a) the P6WM and WQSTM, (b) the assumptions regarding changed conditions, and (c) load reduction estimation, inform the degree of confidence placed by decision-makers in potential adjustments made in the TMDL to compensate for climate change through 2025?
3. Beyond 2025, in consideration of the likely host of changes in the watershed and estuary both as a result of, and in response to, climate change, how might the present CBP model framework be adapted to guide Chesapeake Bay restoration goals at least to 2050? Should alternative modeling approaches be employed and how might they inform a management-responsive model framework?
4. As extrapolation of past trends becomes increasingly unreliable into the future, what regional or global models (or ensembles) of climate and other (e.g. sea-level, shoreline and wetland changes, acidification, etc.) drivers should be considered to provide a longer-term perspective for achieving Chesapeake Bay restoration goals, including but not limited to water quality attainment? Which greenhouse gas concentration pathway scenarios should be used? How should projections be represented, e.g. by central tendency, confidence intervals or ranges?
5. How could the CBP climate change assessment framework be structured to support iterative risk management, explicitly recognizing uncertainties and that they narrow over time, but taking reasonable and prudent actions to limit climate change and adapt to unavoidable changes in sufficient time?
6. Which of the information and research needs identified for the watershed and estuary are most critical from a management perspective? How could these needs be met? What should be the scope and focus of the proposed STAC climate change synthesis?
7. What societal responses to climate change (e.g., greenhouse gas emission reduction requirements, rapid transition to renewable energy, increased demand for biofuels, food supplies, transportation, flood and water management) might pose risks or opportunities for water quality attainment and how might these be included in the assessment framework?

Group discussion

The charge to Breakout Group 3 was to recommend improvements to the overarching CBP framework of climate change impact analysis and its incorporation in the Total Maximum Daily Load (TMDL). The discussion was structured around seven guiding questions above. Broadly, the questions addressed improvements to the approach used by the CBP to assess and compensate for climate change impacts by 2025 for incorporation within the TMDL, and the formulation of a plan of analysis and study to improve understanding of longer-term climate change impacts and management responses in the Chesapeake watershed and estuary. The latter included the evolution of the conceptual framework for the next phase of CBP model development that extends the horizon to 2050 and beyond.

In considering these questions the discussions noted that the CBP undertook an extensive and commendable effort to incorporate climate change considerations into the challenge of reducing loads of nutrient pollutants sufficient to achieve water quality objectives. The applied computational procedure used the established watershed and estuarine water quality models on which CBP management decisions rely, and adjusted them by a single set of changes in key climatic factors estimated to occur between 1995 and 2025. These changes were modeled by extrapolation of recent trends (in the case of precipitation and sea-level rise) or from the projections (in the case of air temperature) by an ensemble of General Circulation Models (GCMs) that assume a certain future change in atmospheric concentration of carbon dioxide and other greenhouse gases. The CBP models were then used to estimate the changes in low dissolved oxygen (hypoxia) in the deep waters in the Bay and the nutrient reductions needed for criteria attainment compared to the prior scenario that was based upon 1995 climate and sea level. It was then estimated that additional nitrogen load reductions of 9.1 million pounds per year beyond the current TMDL, assuming a certain allocation of responsibility among the jurisdictions, would be required to achieve the water quality requirements.

Figure 2 outlines the computational procedure that was used to produce the estimate of 9.1 million pounds of additional basin-wide nitrogen. A major concern regarding this procedure is that future climate inputs and watershed and estuarine responses were treated deterministically, producing extremely overconfident results. This concern has been voiced previously by the expert panel that conducted STAC-sponsored review of the Climate Change Assessment Framework (Herrmann et al., 2018).

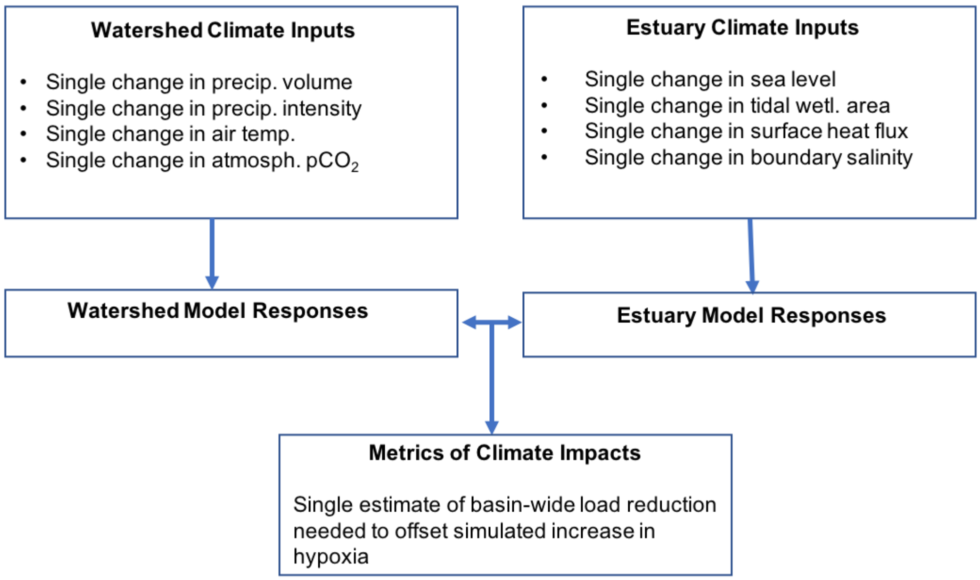

Figure 2: Generalized schema of the computational procedure used by the Chesapeake Bay Program to assess climate change effects on the Total Maximum Daily Loads (TMDL).

The challenges of characterizing the watershed and estuarine responses to the changing climate were discussed by Breakout Groups 1 and 2, which focused on the watershed and estuarine modeling, while the discussions in Breakout Group 3 were centered around future climate conditions and a need to develop a comprehensive computational strategy that could be suitable for explicit and systematic incorporation of uncertainties inherent in any projections of the future. The following are recommendations based on the Group 3 discussion, organized around the 2025 and longer-term assessments. Following the recommendations, an illustration is given of a comprehensive strategy for planning an informative ensemble of climate simulations that might be used to expand on the deterministic computation summarized in
Figure 2.

General Recommendations

Produce actionable science

Models and assessments regarding climate change effects on water quality should be framed to provide actionable information leading to effective responses and solutions. For example, beyond estimation of changes in nutrient loads delivered from the watershed, modeling and assessment should indicate how best management practices (BMPs) could be adapted to mitigate these effects. Now and into the future, we are in a new era of integrated management in which we will be mitigating and adapting to climate change at the same time we work to improve and maintain water quality. Actions taken to mitigate and adapt to climate change offer some opportunities, as well as some risks, for achieving water quality and other Chesapeake Bay ecosystem objectives.

Estimate the uncertainty of projections

The uncertainties associated with projecting climate change impacts should be clearly and properly characterized, together with the recognition that climate change impacts will present an evolving, moving target throughout the coming century. Estimated nutrient reduction targets should not be presented as single numbers, but the probabilities around an estimate of central tendency, or in the case of long-term changes based on GCM models, "stress-testing" to determine the likelihood of meeting the TMDL targets under a range of plausible future climatic conditions. This idea is further developed in the section below on a computational strategy for uncertainty quantification (see section *Illustration of the Utility of an Ensemble Computational Strategy*). The CBP response to climate change should be framed as an iterative risk management problem. Targets based on estimates of central tendency or other approaches should be characterized as such. Where uncertainties are high, the level of confidence in the direction of the trend should be communicated.

Characterize the importance of various climate drivers

When presenting and communicating the proposed nutrient reduction targets to the partnership, the CBP should characterize the sensitivity of the targets to different drivers (e.g., changes in temperature, sea-level, precipitation, and runoff). Because the relative confidence in the projected changes varies, with higher confidence in temperature than runoff, for example, decision makers can better grasp the risks and long-term challenges if informed about the sensitivities to different drivers. Going forward, scientists should work to better define those changes and sensitivities that are least understood.

Use GCMs rather than trend extrapolation for long-range projections

Additional analyses of the responses of nutrient loading or hypoxia to interannual climate variability could demonstrate possible responses to climate change in the future and improve modeling skill. However, while the near-term (present to 2025) assessment might rely on appropriate extrapolations of environmental trends (e.g., precipitation or sea level) computed over the recent past, it must be recognized that extrapolation is a far less reliable predictor over longer time horizons (post-2025), when state shifts and changes in the rate of greenhouse gas emissions will play an important role. These longer-term assessments must rely on projections based on widely accepted General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs).

Recommendations for 2025 projections

Assess BMP performance under climate change

Providing estimates of the nutrient load reductions needed to offset the effects of climate change on water quality attainment is necessary, but insufficient. Ultimately, to be useful these estimates should be accompanied with assessments of the sensitivity of water quality BMPs to changes in precipitation, air temperature and other climate drivers. There is a need for improved understanding of the resilience of different water quality BMPs to climate change, including beneficial changes in design and siting.

Communicate the assumptions of trend extrapolation

It should be clearly communicated that changes in temperature and precipitation through 2025 largely reflect the internal variability of climate (e.g., decadal oscillations) as well as long term climate change.

Incorporate seasonal changes

As currently implemented, the “delta method” used to create meteorological time series representing future climate change does not capture the fact that changes are not uniform over the seasons. A single multiplier is used to adjust precipitation in each month of the year. Differential changes across the seasons could have major effects on watershed and estuarine processes. As part of the 2025 assessment, the methods used to create climate change scenarios should be revised to incorporate seasonal variability.

Improve modeled shoreline processes

As currently implemented, the estuarine model does not adequately represent processes and feedbacks associated with Bay shoreline wetting and drying, nor the losses and gains of tidal wetlands associated with shoreline transgression. The effects of shoreline transgression on wetlands and other shoreline habitats could have significant effect on Bay water quality. As part of the 2025 assessment, an effort should be made to improve the representation of shoreline processes in the estuarine model.

Re-examine all assumptions regarding climate change

As the approach for projecting the effects of climate change on hypoxia by 2025 is refined, all of the assumptions regarding changing conditions should be carefully reexamined based on recommendations of the breakout groups specifically addressing the watershed and Bay water quality models. For example, the Principals’ Staff Committee was particularly concerned about sensitivity to the assumption about sea-level rise that had been changed from 0.30 to 0.17 meters, the latter based on the linear trend projection of relative sea level at the Sewells Point tide gauge station. It is well documented that sea level is rising at an accelerating rate, calling into question the appropriateness of a linear extrapolation. Extrapolations based on fitting nonlinear, quadratic equations to tide gauge data yield projected sea-level rise of 0.23 m by 2025 at Sewells Point (www.vims.edu/research/products/slrc/). These more defensible empirical projections closely agree with locally adjusted sea-level rise estimates of 0.24 to 0.27 cm between 1995 and 2025, based on a model widely used for relative sea-level rise projections in Maryland, New Jersey, California, Washington, and Oregon (Kopp et al. 2017).

Include simulation of climate effects in Chesapeake Assessment and Scenario Tool (CAST)

The current version of CAST does not have the capability for assessing how future changes in climatic drivers could affect nutrient loading to the Bay. CAST could be a useful tool for assessing climate change effects and for increasing the transparency of CBP's 2025 climate change assessment if this capability were provided. In addition to future changes in long term average climate, effort should be made to include CAST capabilities for assessing the impacts of changes in the frequency and/or magnitude of extreme events.

Recommendations for 2025-2050 projections

Use model projections rather than trend extrapolation

The current CBP analysis of climate change impacts in 2035 and 2045 includes a hybrid approach that uses trend extrapolation and GCM projections to estimate future changes in temperature and precipitation. This breakout group recommends that instead, an appropriately designed approach based on an ensemble of Chesapeake simulations should be developed for the 2035/45 assessment (e.g., see section *Illustration of the Utility of an Ensemble Computational Strategy*). That is, an ensemble of climate simulations of the Chesapeake system should be forced with a likely range of projected temperature and precipitation futures based on considering multiple GCMs rather than just central measures of temperature and precipitation futures derived from GCM models or ensembles. For sea-level rise the quadratic projection agrees reasonably well with projections of widely used models, as discussed above, until mid-century. Later in the century, sea-level rise is likely to accelerate at a greater rate, depending on the RCP tracked, therefore, probabilistic projections available for specific RCPs should be used for post-2050 projections (Kopp et al. 2017).

Evaluate multiple RCPs

Projections of climate change effects on Bay water quality attainment beyond 2050 should use multiple RCPs, as the climate consequences will be heavily influenced by the degree of success in reducing emissions by that time.

Maintain spatial differences in climate projections

The Chesapeake Bay watershed is large and contains a range of hydro-climatic and physiographic settings. The effects of climate change will vary regionally and in different watershed settings, e.g., north to south. Any future efforts for understanding and responding to climate change impacts should reflect this variability and seek to develop a more spatially explicit understanding of where in the watershed climate change impacts will be most severe. This understanding will inform where actions to offset the effects of climate change should be focused.

Use uncertainty estimates in the decision process

The development and negotiation of future nutrient reduction targets to address climate change should incorporate the uncertainty associated with the simulated nutrient reduction estimates, together with available information about the sensitivity of the estimates to different drivers (e.g., temperature, sea-level rise, and precipitation). This information could be acquired from an ensemble modeling approach designed to capture the key sensitivities and uncertainties associated with future climate change and the response of the watershed and estuary. See section below on a computational strategy for uncertainty quantification.

Develop an improved suite of mechanistic models

There is a need for an improved suite of modeling tools that provide flexible capabilities for exploratory analysis to evaluate a wide range of climate, socioeconomic, and management response scenarios on the Chesapeake Bay restoration goals. A key aspect is coupling of the watershed and estuarine models to provide a transparent mechanistic tool linking changes in climate, watershed loads to the Bay, estuarine responses, and key CBP management metrics and water quality standards (e.g., dissolved oxygen or additional nutrient reductions). To the extent possible, the modeling suite should be able to incorporate, as desired, finer resolution simulations to address more local questions, such as flood risk. At the same time, the framework should also be computationally efficient, capable of processing a large number of simulations to learn about system behavior and characterize uncertainty. The modeling suite should also be developed as a "community" model, allowing third party developers to access and modify the code to explore various aspects of risk, resilience, and co-benefits of management responses. The modeling system as described here would be useful not only in a regulatory context, but also in assessing and communicating in an open and transparent way about uncertainty, risk, and increasing resilience to a range of future conditions and events.

Stay informed about similar efforts world-wide

The CBP should make a concerted effort to keep abreast of efforts to assess and manage climate change impacts in other coastal regions of the world. While the Chesapeake Bay has differences from those regions, there are many common processes and issues (e.g., hypoxia), and the CBP can learn from the experience of others. Examples include the Baltic Sea, Tampa Bay, the northern Gulf of Mexico and the Fourth (2018) California State Climate Change Assessment.

Re-evaluate goals relative to climate change

In the long term, particularly if global efforts to limit climate change have limited success, it may be necessary to reconsider the current CBP water quality goals and whether they are achievable. If not, an appropriate response may be to plan for change rather than to maintain existing goals which are not realistically achievable.

Create a climate research strategy

A sustained long-term research, monitoring, and assessment program focused on detecting and managing the impacts of climate change on the Bay would provide important information to guide the CBP response to climate change. To better coordinate this effort and illustrate its value to Stakeholders, the CBP should consider developing, supporting, and periodically updating a Strategic Research Framework that identifies ongoing activities and priority knowledge gaps.

Illustration of the Utility of an Ensemble Computational Strategy

Characterizing uncertainty is extremely challenging, and no universally agreed-upon recipe exists. Specific approaches and the level of detail must be selected based on the task at hand and the available computing resources. The following is a strategy that could be used to plan, in the near-term, an ensemble of climate simulations that will inform the degree of confidence in the attainment of TMDLs under future climate. Because the primary goal here is to illustrate the utility of the overall strategy, the specific details used in the examples below were selected to make the illustration easy to follow and will need to be reevaluated and adjusted during the actual implementation.

The deterministic computational procedure that was used to produce the estimate of 9.1 million pounds of additional basin-wide nitrogen reductions needed to offset climate change to meet water quality criteria mandated by the TMDL is outlined in Figure 2. In Figure 3, we illustrate how the above deterministic computation could be expanded to incorporate a limited number of key uncertainties in climate inputs using factorial experimental design (Shardt, 2015). The strategy outlined here is conceptually similar to the approach taken by Al Aamery et al. (2016). As in the deterministic computation, the additional nitrogen load reductions are used as a metric of climate impact or "response variable".

We start by identifying climate characteristics or "factors" to which the response is most sensitive, and which are most uncertain to the best of our knowledge: (1) projected change in air temperature and precipitation volume, (2) projected change in precipitation intensity, and (3) future sea-level rise. We bracket the uncertainties in the selected factors by allowing a finite number of settings or "levels" for each factor. Specifically, given the prior knowledge that the RCP emission scenarios do not start to diverge until about 2040 but there is a large spread between GCMs, it is reasonable to bracket the uncertainty in future air temperature and precipitation volume by selecting a single RCP but four GCMs, which are representative of the extremes of the future climate. A scatter plot of future changes in air temperature and precipitation volume for 31 GCM was presented at the workshop; this information could be used to select the four "extreme" models. Thus, choice of climate model (C) is defined as the first factor and is allowed to assume four levels: (1) "cold and dry"; (2) "cold and wet"; (3) "hot and dry"; and (4) "hot and wet". The second factor is precipitation intensity (phosphorus), with two levels: (1) "precipitation change is uniform across the baseline probability distribution of precipitation events" (i.e., the intensity does not change in the future) and (2) "precipitation change is greater towards the upper tail of the baseline probability distribution of events" (i.e. the intensity changes in the future). The third factor is the sea-level rise (S), with two levels: (1) "high-end projection for SLR" and (2) "conservative projection for SLR" (for example, 30 cm and 17 cm for 2025).

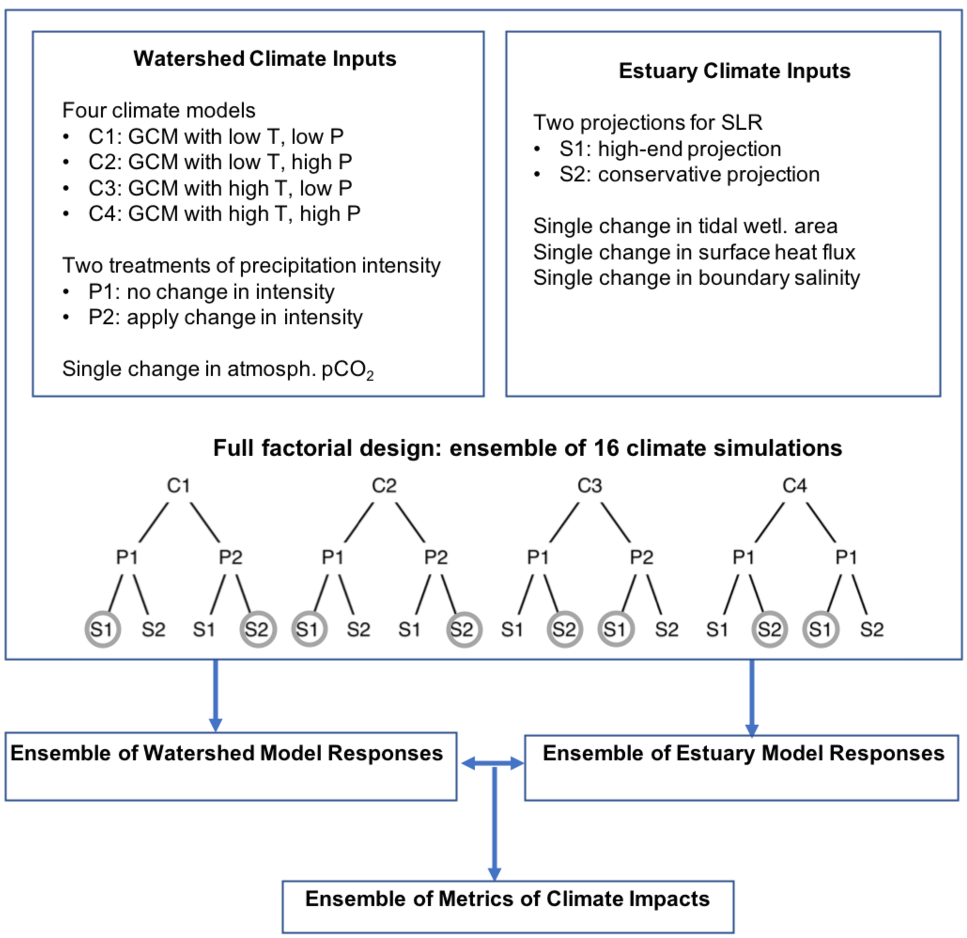

Figure 3: A schematic of an ensemble simulation of additional nitrogen load reductions. The procedure explicitly includes uncertainty in air temperature, precipitation volume, precipitation intensity, and sea-level rise. The eight highlighted ensemble members provide an example of a balanced partial factorial design.

With the above setup, the full factorial design consists of 16 possible combinations of factors and levels or "experimental treatments" (Figure 3). However, a useful amount of information can be inferred from a smaller ensemble of model simulation, with the condition that the partial ensemble is unbiased. For example, the following is a balanced 8-member ensemble: C1P1S1, C1P2S2, C2P1S1, C2P2S2, C3P1S2, C3P2S2, C4P1S2, C4P2S1, where each climate model is used twice, each precipitation intensity treatment is used 4 times, and each SLR treatment is used 4 times (see highlighted ensemble members in Figure 2). This ensemble will provide a first order estimate of how uncertain the climate change TMDL effects are and, if needed, help plan additional simulations to investigate the most consequential climate factors.

To illustrate the above points, consider hypothetical results of the partial factorial experiment outlined in Figure 3. The simulated additional nitrogen reductions are summarized in a bar plot in Figure 4a. The placement of the ensemble members on the x-axis is sorted in the increasing order of simulated nitrogen reductions, which are given on the y-axis. In this hypothetical example, the distribution of the results appears approximately bimodal, with the "high-end SLR" simulations clustering around 3 million pounds and the "conservative SLR" simulations clustering around 9 million pounds. Such pattern suggests that the simulated load reductions are extremely sensitive to the SLR factor, and thus, additional SLR simulations must be conducted.

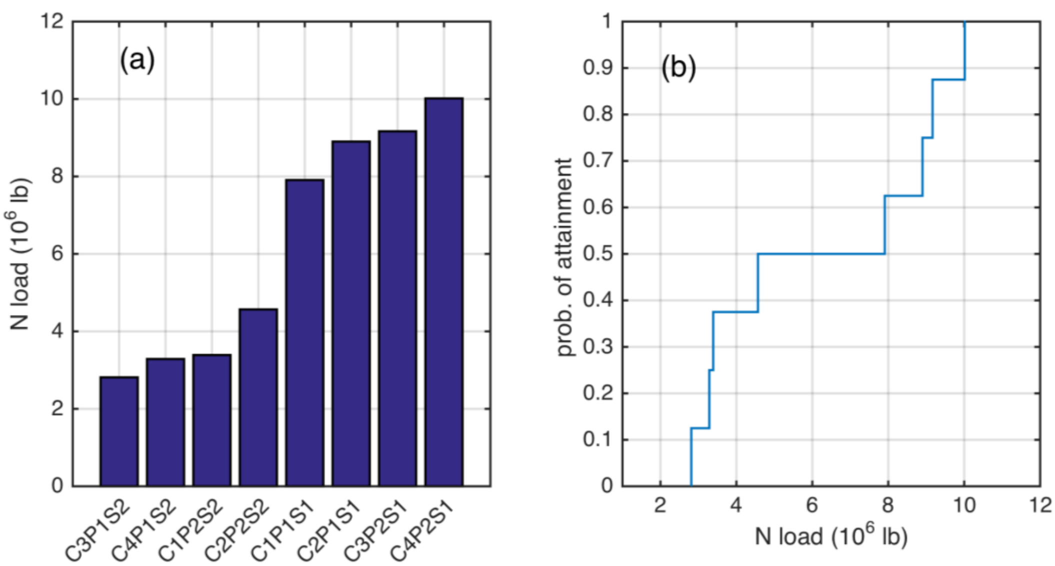

Figure 4: A hypothetical ensemble of results following the experimental design illustrated in Figure 2: (a) a bar plot showing simulated nitrogen load reductions required to maintain water quality standards for the eight-member ensemble; (b) the empirical cumulative distribution of the simulated nitrogen load reductions shown in (a).

The empirical cumulative probability distribution of the ensemble output provides a means of informing the decision-making process when it is time to negotiate the specific load targets to address future climate impacts. Because the additional load reduction values for each ensemble member are calculated such as to ensure the attainment of water quality standards, the cumulative probabilities (Figure 4b) may be interpreted as the level of confidence that a given load reduction will ensure the attainment of the TMDL-mandated water quality standards. For example, reducing nitrogen loads by an additional 7 million pounds gives only 50% confidence that the water quality standards will be achieved. On the other hand, two million pounds more will increase confidence to 80%. Confidence estimates in this example are generated assuming equal probability for each ensemble member. The method could be refined using likelihoods for each member.

We note that while the uncertainties in watershed and estuarine responses were not addressed in the illustrations above, they are of major concern and could potentially be treated in similar factorial manner. For example, given the known sensitivity of the watershed model to the PET parameterization, the ensemble approach can be repeated using different PET parameterizations, to which the watershed model has already been calibrated, as was presented at the workshop.

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Appendix A: Workshop Agenda

Scientific and Technical Advisory Committee Workshop
Chesapeake Bay Program Climate Change Modeling 2.0
September 24-25, 2018
Crowne Plaza Hotel, Annapolis MD Arundel C Ballroom
Workshop Webpage:
http://www.chesapeake.org/stac/workshop.php?activity_id=289

Workshop Motivation and Goals

- The motivation for the workshop stems from the decision of the Chesapeake Bay Program (CBP) Principals' Staff Committee to develop a framework for addressing climate change impacts in jurisdictions Phase III Watershed Implementation Plans (WIPs). The CBP Partnership recognizes that further work is needed to have jurisdictions account for additional nutrient and sediment pollutant loads, due to anticipated 2025 climate change conditions, in their 2-year milestones beginning in 2022.

- The goal of the workshop is to develop recommendations for new and/or refined methods and modeling techniques to be completed and fully operational by 2019, to assess the potential impacts of 2025 and longer-term climate change on watershed loads and estuarine processes, to characterize and manage the risk of climate change impacts to CBP goals.

- In addition, guidance is sought in formulating a long-term plan of study, including field sampling and data analysis, monitoring and modeling that will improve understanding of long-term climate change impacts, vulnerability and risk management in the Chesapeake watershed and estuary, which could be considered in the conceptual framework in the next phase of CBP model development.

Day 1: Monday, September 24

8:30 Sign-In for Attendees *Coffee and light breakfast provided for attendees

9:00 Welcome – Lee Currey, MDE

9:20 Plenary: Global Perspectives on the Effects of Climate Change on Coastal Eutrophication
– Don Boesch, UMCES
A state-of-the art overview of efforts to model the effects of climate change on hypoxia and ecosystem conditions will be presented. What are the "big things" that we need to get right?

9:50 Introduction and Purpose of Workshop – Mark Bennett, USGS

10:00 Overview of Climate Impact Assessment Framework and Implementation
– Gary Shenk, USGS-CBPO
Short description of the models and analysis methods used in the climate change impact assessment completed by the CBPO in 2017. Linkages between models and key sensitivities to climate inputs.

10:30 Findings of the Phase 6 Watershed Model – Gopal Bhatt, Penn State

Key findings of the Phase 6 Watershed Model under the estimated 2025 climate change conditions and details of the simulation method relative to climate will be presented. In addition, the influence of the relative rates of increasing precipitation and temperature on watershed on flow and loads to the tidal Chesapeake in 2035, 2045, and 2055 will be estimated.

10:50 Findings of the WQSTM – Richard Tian, UMCES and Carl Cerco, Attain

Key findings of the CBP Water Quality and Sediment Transport Model (WQSTM) under the estimated climate change conditions and details of the simulation method relative to climate will be presented. The influence of the relative rates of increasing precipitation and temperature on watershed flow and loads to the tidal Chesapeake in 2035, 2045, and 2055 will be estimated.

11:10 DISCUSSION / Q&A (Moderator - Lew Linker, EPA-CBPO)

What additional or different climate change approaches and methods should be incorporated into the Phase 6 Watershed Model for the 2019 Climate Change Assessment?

What additional or different climate change approaches and methods should be incorporated into the WQSTM for the 2019 Climate Change Assessment?

What additional or different climate change approaches and methods should be incorporated into potential next generation CBP watershed and estuarine models for climate change assessment?

12:00 Break *Boxed lunch provided for attendees

12:30 Round Table: Management Actions in Response to Climate Change

– Tony Buda, USDA-ARS; Jon Butcher, Tetra Tech; and Curtis Dell, USDA-ARS; Adel Shirmohammadi, UMD

Anticipating longer growing seasons, crop rotation changes, and changes in BMP efficiencies, the panel will consider important features in the simulation of watershed loads under climate change conditions that are currently unaddressed in the current CBP climate change assessment framework.

What management approaches that address climate change in developed land, agricultural land, and undeveloped (natural) land should be included in future CBP modeling?

1:30 Instructions for Break-out Groups

Group 1: Simulation of Climate Change Processes and land management in the Phase 6 Watershed Model Influencing Chesapeake Water Quality
Group 2: Simulation of Climate Change Processes in the WQSTM Influencing Chesapeake Water Quality
Group 3: Assessment of the overall CBP framework of climate change analysis

Breakout Session I

Each breakout will have two chairs who will lead and facilitate discussion, and a recorder. The goal of the afternoon is for each breakout to produce 2 items:

1. List of draft recommendations, with focus on the top consensus priorities
2. Longer list of thoughts and notes from discussion, for inclusion in workshop report

1:45 Breakout Round-Robins
Group members should come prepared to share their reactions to the morning's larger group discussion in regard to their breakout topic and in consideration of the breakout questions. Discuss resource and data needs, advantages, and disadvantages.

2:45 Break (15 mins)

3:00 Focused Breakout Discussion
Discuss alternative development strategies in detail. The goal of the focused breakout session is for the breakout members to fully understand the questions and proposed solutions.

4:30 Cross-Pollination
Breakout Group 3 will divide in half and meet with Groups 1 and 2. This time will be used to share ideas heard this afternoon and get input from other participants to help refine recommendations and inform prioritization.

5:30 Recess & Happy Hour
Evening Homework! Adjourn to the bar and learn something new from someone in another breakout group

Day 2: Tuesday, September 25

8:00 *Coffee and light breakfast provided for attendees

Breakout Session II

Prioritizing Breakout Recommendations
Breakout groups will reach consensus on draft recommendations from the previous day for presentation to the wider group. As time allows, groups can begin to work on longer descriptions of the draft recommendations.

10:30 Break (30 mins)

11:00 Plenary Presentation of Breakout Proposals (20 mins per group)
All participants will reconvene and chairs for each breakout group will briefly present the group recommendations

12:00 Break *Boxed lunch provided for attendees

12:45 Compiling Recommendations & Cross-Cutters Response

Facilitated discussion of final recommendations presented before lunch focused on compatibility between proposed components with a view toward formulating a realistic and unified vision for future CBP modeling. 'Cross-cutters' will present their perspectives on the consensus recommendations and their major takeaways.

1:45 Looking Ahead: STAC Science Synthesis
Engage participants in a discussion on potential topics for a 'deeper dive' synthesis effort through STAC, based on findings and recommendations of the workshop.

2:30 Wrap-up Discussion – Looking Ahead for the CBP Climate Change Assessment Framework

What new and/or refined methods and modeling techniques could be used to better assess projected impacts on watershed loads and estuarine impacts for a range of future scenarios in 2019? In a future 2025 assessment?

What improvements could be made to the methodology used to develop jurisdiction- specific nutrient pollutant loads due to 2025 climate change conditions and beyond?

What are the remaining research gaps and highest priority information needs for the 2019 CBP Climate Change Assessment (e.g., data, research, modeling methods and techniques, programmatic efforts)? For climate change assessments in 2025 with the next generation of the CBP models and assessment methods?

3:00 Adjourn

Appendix B –Workshop Participants

Bill Ball	CRC
Brian Benham	VT/STAC Chair
Mark Bennett	USGS
Karl Berger	MWCOG
Gopal Bhatt	PSU/CBPO
Karl Blankenship	Bay Journal
Donald Boesch	UMCES
Anthony Buda	USDA-ARS
Jon Butcher	Tetra Tech
Carl Cerco	Attain, inc.
Blake Clark	UMCES HPL
Victoria Coles	UMCES HPL
Lee Currey	MDE
James Davis-Martin	VA DEQ
Curtis Dell	USDA-ARS
Rachel Dixon	CRC/STAC Coordinator
Scott Doney	UVA
Jen Dopkowski	NOAA-CBPO
Jordan Fischbach	RAND
Chris Forest	PSU
Marjy Friedrichs	VIMS
Norm Goulet	NVRC
Annabelle Harvey	CRC/STAC Staff
Maria Herrmann	PSU/STAC
Kyle Hinson	VIMS
Raleigh Hood	UMCES HPL
Thomas Johnson	EPA/STAC
Zoe Johnson	USNA
Daniel Kaufman	CRC
Ming Li	UMCES
Lew Linker	EPA/CBPO
Andy Miller	UMBC/STAC
Hassan Mirsajadi	DNREC
Dave Montali	Tetra Tech
George Onyullo	DOEE
Ray Najjar	PSU
Wenfei Ni	UMCES HPL
Rob Nicholas	PSU
Andrew Ross	Princeton-GFDL
Kevin Sellner	Hood
Gary Shenk	USGS/CBPO
Adel Shirmohammadi	UMD
Charlie Stock	Princeton-GFDL
Richard Tian	UMCES/CBPO
Lauren Townley	NY DEC

Cuiyin Wu	CRC
Guido Yactayo	MDE
Joseph Zhang	VIMS
Qian Zhang	UMCES/CBPO