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

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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 www.chesapeake.org/stac.

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Executive Summary

A workshop entitled *Development of Climate Projections for Use in Chesapeake Bay Program Assessments* was organized to help the Chesapeake Bay Program (CBP) assess the applicability of available climate data, downscaling techniques, projections and scenarios to establish an approach for climate analysis in CBP models and assessments. The goal of this workshop was to assist the CBP with the selection process and formulate recommendations for future application of climate projections in assessments to be undertaken by the Partnership, including modeling efforts to support the 2017 Midpoint Assessment, as well as other programmatic climate change impact assessments. The workshop was well attended by climate change scientists as well as CBP decision-makers and technical managers. A key finding of the workshop was that substantial scientific understanding currently exists, supporting the need to plan and act on the ongoing, continuous – but heretofore unrecognized – influence of climate change on Chesapeake restoration efforts, despite uncertainties.

The workshop centered entirely on technical aspects related to climate science, research, data and information needs; matters of CBP policy were not addressed. Nevertheless, the workshop was partly motivated by existing policies, such as the 2010 Total Maximum Daily Load (TMDL), that call for an assessment of the impacts of a changing climate on Chesapeake Bay water quality and living resources. The 2014 Chesapeake Bay Agreement also includes 29 individual management strategies, covering a wide range of watershed restoration goals that can only be sustained over the long term by addressing climate change impacts.

There was consensus at the workshop that the climate change assessment approach should, to the extent practicable, be made available for application at the regional, state, and local levels. Although some localities have established climate projections for planning purposes (e.g., sea-level rise (SLR)), a standardized set of projections and assessment methodology has yet to be developed for the watershed as a whole. Projections for sea-level, precipitation, air temperature, water temperature, salinity, and potential evapotranspiration, among others, are needed as inputs to a variety of hydrological and ecological models, including local TMDL models, to assess potential future climate impacts on natural and human systems.

The CBP will have to choose among the general circulation models (GCMs), emission scenarios, downscaling techniques, and historical observation data to establish a framework for climate analysis in the suite of CBP models. Participants recognized constraints on the CBP, however, that require them to focus on the year 2025 for short range climate change assessments and planning in the 2017 Midpoint Assessment. Nevertheless, participants urged the CBP to examine another period of future scenarios centered on 2050, at the far edge of the planning horizon, for scoping scenarios. This is because the results of management actions that are in place by 2025 may not be felt for decades, due in part to the lag times associated with groundwater flow. Meeting the 2017 Midpoint Assessment decision requires the attendant constraint of selecting a climate change modeling approach that can be applied within the next six months using the models and other assessment tools at hand.

Workshop consensus was that all aspects of climate and land use change that influence watershed and Bay should be addressed in the 2017 Midpoint Assessment, as changes in processes will determine the effectiveness of management actions. Relevant changes include: 1) air temperature; 2) precipitation; 3) sea-level; 4) wind speed and direction; 5) humidity; and 6) atmospheric deposition of nitrogen. These changes in the climate system are expected to alter key variables and processes within the Chesapeake Bay and its watershed, including evapotranspiration, soil moisture, streamflow, water temperature, salinity, estuarine circulation, and key water quality variables (e.g., water clarity, chlorophyll, and dissolved oxygen). These climate changes should be examined in concurrence with land use changes that will interact with and potentially exacerbate climate change impacts. To the extent practicable, the effect of all of these changes on key living resources such as wetlands, submerged aquatic vegetation (SAV), and oysters should also be assessed.

Workshop participants recommended the use of historical (~100 years) trends to project precipitation to 2025 for purposes of the Midpoint Assessment, as opposed to utilizing an ensemble of future projections from GCMs. Shorter term climate change projections using GCMs have large uncertainties because climate models are structured to look further out and at much larger scales. Participants in the workshop shared varied perspectives on the topic of uncertainty and climate projections. One recurring perspective was that uncertainty in some climate change projections is high, particularly for precipitation volumes and intensities across the Chesapeake watershed. There are inherent limitations in projecting precipitation, particularly its intensity, from existing regional statistical and dynamical downscaling of GCMs because they don't take adequate account of mesoscale processes that are important in water dynamics. Furthermore, extrapolating short term trends in precipitation is particularly risky. There are strong cyclic variations associated with climate models that impact shorter term precipitation trends and make longer term projections difficult.

Participants recommended that for long-term assessments (2050 and beyond) the CBP use an ensemble or multiple global climate model approach, selecting model outputs that bound the range of key climate variables (e.g., temperature, precipitation) for the Chesapeake Bay region. The use of multiple scenarios covering a range of projected emissions (representative concentration pathways (RCP) 4.5 and 8.5, as currently being utilized for Fourth National Climate Assessment) was recommended along with the inclusion of the 2 °C emissions reduction pathway (RCP 2.6). Lastly, participants advised the CBP to use an existing system to access GCM downscaled scenario data (such as ‘LASSO’ described in more detail in Section II) in lieu of conducting a tailored statistical climate downscaling process for the Chesapeake Bay watershed.

Multiple tools are already available to assess the impacts of climate change on the Chesapeake Bay watershed and its living resources. The Chesapeake Bay Watershed Model (CBWM), the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM), and living resource models such as models of SAV, tidal wetlands, and oysters, will be used to examine the impact of climate change on water quality and estuarine ecosystems during the 2017 Midpoint Assessment. Over time however, other assessment tools could be added to examine the impact of climate change as it relates to additional 2014 Chesapeake Agreement Goals and Outcomes.

Key Scientific Findings

1. There is sufficient scientific understanding to provide insights into the decisions faced by the CBP over the short and long term to anticipate and manage for unavoidable climate change.
2. There is strong confidence in continued warming trends, recognizing that there is inter-annual variability.
3. There is less confidence that the watershed will experience an increase in the intensity of precipitation; there may be more variability, with a significant trend annually, but not in all seasons.
4. There is wider agreement on the seasonal precipitation changes (wetter winters and springs, potentially drier summers) than overall annual precipitation changes, although it is likely that both will occur.
5. Projected trends in discharge are likely to differ from those in precipitation. Timing of rainfall, antecedence, and evapotranspiration are contributing factors to the differences in observed discharge and precipitation trends for the Chesapeake Bay.
6. There are inherent limitations in projecting precipitation, particularly its intensity, from existing regional statistical and dynamical downscaling of GCMs because they don't take adequate account of mesoscale processes that are important in water dynamics.
7. Extrapolating short term trends in precipitation is particularly risky. There are strong cyclic variations associated with climate models that impact shorter term precipitation trends and make their use in longer term projections difficult.
8. Climate models are structured to look further out and at much larger scales than current management goals (i.e., 2025 Chesapeake Bay Agreement goals and outcomes). By 2025, the end of the policy horizon, anthropogenic drivers within GCMs are just beginning to act in ways that clearly differentiate the anthropogenic impacts from the other cyclical drivers of climate.
9. For the purposes of the Midpoint Assessment modeling approach, projections for 2025 should be considered in terms of a 30-year projection from 1995 (mid-point of 1991 to 2000

Chesapeake Bay TMDL simulation period) through 2025, and the analysis of climate trends should be based on long term historical trends. Climate models and analyses of short-term (<50 years) data are not suitable for short-range projections because they include decadal-scale weather cycles which lead to large uncertainties in short-term trends.

Recommendations

The workshop culminated with the following specific recommendations related to the selection, use, and application of climate projections and forecasts for the 2017 Midpoint Assessment.

1. The Partnership should seek agreement on the use of consistent climate scenarios for regional projections of Chesapeake Bay condition and the benefits of an integrated source of climate change projection simulation data that all seven jurisdictions could draw from.
2. For the 2017 Midpoint Assessment, use historical (~100 years) trends to project precipitation to 2025 as opposed to utilizing an ensemble of future projections from GCMs. Shorter term climate change projections using GCMs have large uncertainties because climate models are structured to look further out and at much larger scales.
3. The Partnership should carefully consider the representation of evapotranspiration in Watershed Model calibration and scenarios because the calculation method for evapotranspiration has a strong influence on the strength and direction of future water balance change.
4. Looking forward, the 2050 timeframe is more appropriate for selecting and incorporating a suite of global climate scenarios and simulations to provide long-term projections for the management community, and an ongoing adaptive process to incorporate climate change into decision-making as implementation moves forward.
5. Beyond the 2017 Midpoint Assessment, it is recommended that the CBP use 2050 projections for best management practice (BMP) design, efficiencies, effectiveness, selection, and performance – given that many of the BMPs implemented now could be in use beyond 2050.
6. For any 2050 assessment, use an ensemble or multiple global climate model approach, selecting model outputs that bound the range of key climate variables (e.g., temperature, precipitation) for the Chesapeake Bay region. Use multiple scenarios covering a range of projected emissions (RCP 4.5 and 8.5 are a reasonable range to select and are currently being utilized for Fourth National Climate Assessment). Include the 2 °C emissions reduction pathway (RCP 2.6) as well as more "business as usual" assumptions.
7. Select an existing system to access GCM downscaled scenario data (such as ‘LASSO’ described in more detail in Section II) in lieu of conducting a tailored statistical climate downscaling process for the Chesapeake Bay watershed.

Introduction

The 2014 Chesapeake Bay Agreement includes 29 individual strategies to be developed and implemented by six Goal Implementation Teams (GITs). Most, if not all, of these strategies will include a suite of actions necessary to address climate change impacts. In addition, the 2010 Total Maximum Daily Load (TMDL) documentation and the 2009 Executive Order call for an assessment of the impacts of a changing climate on Chesapeake Bay water quality and living resources that will be addressed during the upcoming 2017 Midpoint Assessment.

The Chesapeake Bay Watershed Model (CBWM), the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM), and living resource models, such as models of underwater grasses, tidal wetlands, and oysters, will be used to examine the impact of climate change on water quality and estuarine ecosystems. Other assessment tools will be utilized to examine the impact of climate change on other goals and outcomes. Although some localities have established climate projections for planning purposes (e.g., sea-level rise), a standardized set of projections has yet to be developed for the Watershed. Such projections for sea-level rise, precipitation, air temperature, and potential evapotranspiration, among others, are needed as inputs to a variety of hydrological and ecological models to assess potential future climate impacts on natural and human systems.

The 2014 Intergovernmental Panel on Climate Change (IPCC) report relied on the Coupled Model Intercomparison Project, featuring approximately 30 global general circulation models (GCMs), each with multiple emission scenarios. Additionally, there are multiple downscaling techniques that are available to move from these global-scale models to an appropriate scale for the Chesapeake Bay and its watershed. Extrapolation of decades of historical observations of temperatures, precipitation intensity, precipitation volume, sea-level rise, and estuarine salt intrusion have also been used to assess future scenarios as a result of climate change (IPCC-TGICA 2007).

The Chesapeake Bay Program (CBP) will have to choose among the GCMs, scenarios, downscaling techniques, and historical observation data to establish an approach for climate analysis in the CBP models. The goal of this workshop was to assist the CBP with the selection process and formulate recommendations for future application of climate projections in assessments to be undertaken by the Partnership, including modeling efforts to support the 2017 Midpoint Assessment, as well as other programmatic climate change impact assessments.

On March 7-8, 2016, the Scientific and Technical Advisory Committee (STAC) of the CBP conducted a workshop entitled “The Development of Climate Projections for Use in Chesapeake Bay Program Assessments.” Over the course of the workshop, approximately 50 attendees participated and actively engaged in discussion sessions. The goal of the workshop was to conduct a review of GCMs, scenarios, downscaling techniques, and historical observation data for the purposes of helping the CBP assess the applicability of available climate data and establish a framework for climate analysis in the CBP models. The workshop agenda (Appendix A) was centered on answering the following questions:

1. What climate change variables are of most concern to the CBP partners in the consideration of the 2017 Midpoint Assessment decisions and for longer term climate change management decisions?
2. What are the approaches that can be taken to select climate change scenarios for CBP assessments?
3. What characteristics of those climate variables need to be specified, such as the temporal and spatial resolution, in order to provide the most utility at the regional, state, and local levels?
4. What climate change scenarios meet CBP decision-making needs for the 2017 Midpoint Assessment as well as for longer term climate change management decisions and programmatic assessments?

The body of the following report addresses the four above questions in separate dedicated sections. Within the text, links to workshop presentations and other references are provided; all workshop presentations and other associated materials can be found at http://www.chesapeake.org/stac/workshop.php?activity_id=258.

Section I: Climate Change Data and Projection Needs for Chesapeake Bay Assessments

The 2010 Chesapeake Bay TMDL is the largest, most complex TMDL in the country, covering a 166,000 km^2 area across seven jurisdictions. The Bay TMDL allocates loadings of nitrogen, phosphorus, and sediment to sources and areas of the watershed contributing those pollutants to remove impairments for aquatic life in the Bay's tidal tributaries and embayments. A successful TMDL relies on good water quality standards. In the Chesapeake, the water quality standards were based on what living resources require to persist and thrive. The Chesapeake TMDL has water quality standards of dissolved oxygen (DO) in four separate habitats (deep channel, deep water, open water, and migratory fish regions), a chlorophyll standard (both narrative and numeric) and a water clarity/submerged aquatic vegetation (SAV) standard to ensure healthy shallow water regions of the Bay.

Throughout the workshop, the following three climate variables external to the Bay-watershed system emerged as being of most concern to long-term management of the Chesapeake Bay and its watershed:

(1) **Air temperature** (Najjar, workshop presentation): This variable has a profound effect on the functioning of the Bay and its watershed through impacts on evapotranspiration (which influences soil moisture and streamflow), water temperature, and indirectly on streamflow, biogeochemical rates (such as nitrification and denitrification), habitat suitability (e.g., for seagrasses and fish), and oxygen solubility, among others.
(2) **Precipitation** (Najjar, workshop presentation): The delivery of freshwater, nutrients, and sediment to the Bay is mainly driven by the amount and intensity of precipitation in the watershed. Thus, Bay circulation and water quality strongly respond to changes in watershed precipitation.
(3) **Sea-level** (Ezer, workshop presentation): Tidal wetlands, which are a major feature of the Bay's living resources, are strongly influenced by sea-level. Bay circulation and salinity are also affected by sea-level.

Other climate variables may be important to consider as well, such as wind speed and direction, humidity, and downwelling solar and longwave radiation, which variably influence evapotranspiration, water temperature, and estuarine circulation. The atmospheric CO_2 concentration also has importance beyond its influence on the climate, as an increase in CO_2 leads to ocean acidification.

Addressing the challenge of climate change impacts on Chesapeake water quality standards will be difficult; the Clean Water Act requires that water quality standards must be met regardless of potential impacts. In 2017, the CBP partnership will decide if, when, and how to incorporate climate change considerations into the Phase III Watershed Implementation Plans (WIPs). Among the Bay Program partners, discussions have begun on how future changes in precipitation volume and intensity could change stormwater and other management practices (DeMooy, workshop presentation; Johnson workshop presentation), or how sea-level rise impacts communities and tidal wetlands (Ezer, workshop presentation).

The CBP partners are developing the tools to quantify the effects of climate change on watershed flows and 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 on key living resources.

Section II: Approaches for Selecting Climate Scenarios and Projections

From a high-level perspective of framing the need for and selection of climate change scenarios, two paradigms exist: the first and most dominant assumes a need to predict using physically-based computer models to support planning efforts; the second emphasizes the need to understand regional and sectoral climate-related vulnerabilities and how to manage in light of large uncertainties associated with climate change and its possible impacts. Both approaches are used as a basis to select climate change scenarios, but the first requires accurate predictions in order to support adaptation planning while the second supports adaptation planning that focuses on robust solutions to cover a range of potential climate change outcomes (Weaver, workshop presentation).

Climate scenarios are developed using a GCM driven by emissions scenarios. The most recent emissions scenarios developed by the IPCC employ representative concentration pathways (RCPs). RCPs are an expression of future radiative forcing, or the change in net downwelling infrared radiation at the Earth's surface by the year 2100 caused by changes in atmospheric constituents, such as carbon dioxide. The four principal scenarios – RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 – range from a low emissions scenario in which greenhouse gas concentrations reach a maximum in 2040 and decline to levels slightly above current levels by 2100 (RCP 2.6), to a high emissions scenario in which greenhouse gas concentrations continuously increase, reaching values roughly a factor of three higher than current values (RCP 8.5). Choosing climate change scenarios requires selecting the emissions scenarios, the specific GCMs that run those emission scenarios, and, in some cases particular realizations of those GCMs (a realization being a specific run of the GCM with a very slightly altered initial state) (Morefield, workshop presentation).

Currently, there are more than 35 GCMs. Climate scenario data from these GCMs can be used directly or can be downscaled using several different methods. Downscaling generally refers to the manipulation of a coarser resolution dataset to create data with finer resolution. The two general approaches for downscaling are statistical and dynamical. There is no consensus on a single best downscaling approach.

In statistical downscaling, empirical relationships between large-scale and local-scale variables like temperature and precipitation are developed based on historical observations via a variety of methods. The technique is based on the principle that both the large-scale climate state and local physiographic features act together to determine local climate. The major advantage of statistical downscaling is the relative computational efficiency compared to dynamical downscaling. They are also flexible and effective at removing errors in historical simulated values. This provides a good match between the average (multi-decadal) statistics of observed and statistically downscaled climate at the spatial scale, and over the historical period of the observational data used to train the statistical model. A shortcoming of this approach is the assumption that the statistical relationships between coarse- and fine-resolution variables created using historical data will also hold in the future under a changing climate. This assumption may be valid for lesser amounts of change, but could lead to errors, particularly in precipitation extremes with larger amounts of climate change. A number of databases provide statistically downscaled projections for a range of higher and lower future scenarios for the contiguous United States. Examples include the Multivariate Adaptive Constructed Analogs (MACA) (Abatzoglou and Brown 2012) and monthly Bias-Corrected and Statistically Downscaled (BCSD) projections (Reclamation 2013).

Dynamical downscaling uses outputs from GCMs to establish boundary conditions for finer resolution simulations using Regional Climate Models (RCMs) within a limited area of the globe (e.g., the Northwest or Southeast U.S.). Several advantages of dynamical downscaling are internal consistency among different variables based on physical principles, the ability to investigate the specific physical processes and system dynamics that lead to the simulated changes, and higher resolution data (typically on the order of 10-50 km horizontal grid mesh). RCMs are subject to the same types of uncertainty as global models, such as not fully resolving physical processes that occur at even smaller scales. They also have additional uncertainty related to how often their boundary conditions are updated and where they are defined. These uncertainties can have a large effect on the precipitation simulated by the models at the local to regional scale. RCM simulations for the U.S. are available from several sources, the most common and comprehensive being the North American Regional Climate Change Assessment Program (NARCCAP).

There are a number of readily available sources climate change planning scenarios (e.g., U.S. Climate Resilience Toolkit, USGS Geo Data Portal). There are fewer tools available, however, that can be used to guide users through the process of selecting scenarios for specific assessments. One tool presented at the workshop is “Locating and Selecting Scenarios Online” (LASSO). LASSO pulls from all publicly available climate model outputs to provide data visualizations that illuminate the characteristics of the different scenarios. These visualizations support scenario selections tailored to the decision context and sensitivities of the system or species being assessed (Morefield, workshop presentation).

Participants at the workshop advocated the use of a multiple model/multiple scenario approach to represent different emission scenarios (RCPs). The recommended RCPs include RCP 2.6, which assumes that global annual greenhouse gas emissions peak by about 2020 consistent with the United Nations Framework Convention on Climate Change, 2015 Paris Agreement. RCP 2.6 could constrain the increase of global mean surface temperature to less than 2 ^{o}C and this could be used to define a minimum baseline for CBP adaptation. However, there are also good reasons to assume that world-wide emissions consistent with RCP 2.6 will be difficult to achieve and therefore RCP 4.5, which assumes a moderate growth in emissions peaking by about 2040, should also be considered in addition to RCP 8.5, which assumes a high growth in CO_2 equivalent emissions that continue to rise throughout the 21st century.

The application of new approaches to ensemble modeling was also encouraged including the LASSO tool (Morefield, workshop presentation) and other approaches in order to keep the number of climate change scenarios at a feasible operational level (Buda, workshop presentation; Muhling, workshop presentation).

Section III: Characteristics and Format for Climate Scenarios and Projections

For each modeling effort to be undertaken by the CBP in order to determine future climate change impacts on the Bay, its watershed, and the associated living resources, there is a need to: define specific data needs (e.g., historical observations/trends, future projections, climate variables); determine data requirements (e.g., range of scenarios vs. sole variable); establish spatial extent (e.g., geographic relevance); and select temporal scale (e.g., seasonal, inter-annual, decadal and beyond).

Workshop presenters provided an overview of the data needs and format for temporal and spatial drivers to complete both watershed scale physical and biological and ecological climate change assessments. Presentations made on key Chesapeake living resources assessments of SAV (Zimmerman), oysters (Mann), tidal wetlands (Mitchell), and ecosystems (Townsend), highlighted some important considerations regarding the application of climate data to Chesapeake Bay assessments, while other speakers provided feedback on decision points and the process for selecting specific climate change indicators for more generalized local, state, and regional assessments (Muhling, DeMooy, Johnson, Ezer, Buda). Take-away points from the presentations and discussion that followed are:

- **Geographic relevance**: When looking at the Bay as a whole, there is a danger of glossing over regional differences (e.g., Eastern shore of Virginia vs. Norfolk) because changes in some resources (such as tidal marshes) may be location-specific on a relatively small scale (Mitchell).
- **Climate variability**: It is critical to examine the role of climate variability and not just long-term change. Synoptic climate patterns (such as the Bermuda High) and variations in climate modes that operate on interannual (El Niño/Southern Oscillation (ENSO)) and decadal (Pacific Decadal Oscillation (PDO)) scales influence the climate of the Chesapeake region (Townsend).
- **Non-climate related drivers**: Impacts from climate change are likely to interact synergistically with those from changes in land use and other human factors. For example, it is not just increasing atmospheric CO_2 that is driving pH change, but also changes in estuarine photosynthesis and respiration resulting from enhanced nutrient loads from the watershed. It is difficult to tease out which complex climate drivers vs. non-climate drivers dominate the observed impacts and to predict the impact of these drivers into the future (Mann). While air temperature and precipitation are key drivers to

understand, both local estuarine and watershed dynamics are also important for predicting estuarine conditions (Muhling).

- **Secondary climate drivers**: For SAV, turbidity may have a bigger impact in the Bay than nutrient loading, so there is a need for more data and information on storm incidence (Zimmerman). Other climate drivers to consider include wind speed and direction. Given their significance, we should examine how to include these components beyond the midpoint assessment timeframe of 2025.
- **Varying timescales, non-linearity and feedback loops**: Biologic response occurs over varying timescales and species and organisms evolve together over time; changes in one will effect changes in another (Mann).
- **Sea-level rise parameters**: For sea-level rise, assessments can make use of both past (historic) measurements and future estimates. In terms of geographic scale, projections on global sea-level rise are too large for practical local and regional planning and there is a need to consider the linear rate of change as well as the acceleration. Projections based on statistics of past sea-level data may be useful in the short term but do not take into account potential long-term changes (Ezer).
- **Seasonal, hourly and daily data**: Several speakers (Buda, DeMooy, Johnson, Bhatt) spoke of the need for climate variables at hourly and/or daily resolution to serve as useful input for modeling climate change impacts.
- **Importance of locally relevant climate indicators**: Both DeMooy and Johnson spoke on the importance of selecting climate change indicators that matter to decision-makers. Delaware and the District of Columbia (DC) have undertaken projects to generate downscaled climate projections that are locally relevant. For both jurisdictions, climate scenarios for RCP 4.5 and 8.5 were derived and a suite of climate indicators were referenced to individual long-term weather stations. Delaware selected temperature and precipitation indicators and DC selected the same but also added in extreme events.

Despite the general availability of climate change data and information and a fairly concerted effort by researchers within the watershed to gain a better understanding of climate trends and impacts, many questions remain to be answered: how will the water balance change with climate change; will streamflow increase or decrease?; how will the frequency of floods and low flows change?; how will climate change affect extremes?

Section IV: Selecting Climate Change Scenarios for the 2017 Midpoint Assessment and Beyond

The Chesapeake Bay Program has identified the need to develop a 2025 climate change scenario to support the 2017 Midpoint Assessment. A constant ten-year average hydrology was used to establish the 2010 Chesapeake TMDL. The hydrologic period for TMDL modeling purposes is the period that represents the long-term average hydrologic conditions for the waterbody. This is important so that the Bay models can simulate local long-term average conditions for each area of the Bay watershed and tidal waters to ensure that no single area is modeled with a particularly high or low loading, an unrepresentative mix of point and nonpoint sources, or extremely high or low river flow. The selection of the representative hydrologic averaging period that ensured a balance between high and low river flows across the Bay watershed was the 1991-2000 hydrology (USEPA 2010).

The use of a constant ten-year average hydrology ensured stationarity and prevented assessment of climate change because of the fixed and unchanging temperatures and hydrology. The application of a 2025 year scenario allows for the adjustment of the ten-year hydrology to reflect climate change effects. In essence, the 2025 scenario is actually a 30 year projection of climate change from a base of 1995, the mid-point of the 1991-2000 hydrology. The use of a 2025 future period is due to the third and last phase of the WIPs, which are designed to complete the implementation of management practices in order to achieve tidal water quality standards, cover the period of 2018 to 2025. Altogether, the 2025 scenario will provide the CBP partnership the tool to decide when, and how to incorporate climate change considerations into the Phase III WIPs.

Workshop presentations by Linker (workshop presentation) and Bhatt (workshop presentation), described aspects of the 2025 scenario. Bhatt described an extrapolation of observed precipitation data from 1984 to 2014, which developed spatially and temporally detailed (seasonal) data for the Chesapeake Bay and watershed and suggested that shortcomings of relying solely on the recent three decades of precipitation could be overcome by constraining the volume of extrapolated precipitation to that of the long term precipitation record. That record, described by Rice (workshop presentation) in her presentation of long-term historical precipitation and flows from the 1920s to present, would provide for long-term trends that would be isolated by decadal climate oscillations such as the North Atlantic Oscillation (NAO) and other similar phenomena. Rice also stated that trends in long-term precipitation do not often match long-term trends in discharge due to a variety of factors including timing of rainfall, antecedent moisture conditions, and evapotranspiration, among others. Other workshop presentations, including Najjar (workshop presentation) and Ezer (workshop presentation) discussed aspects of historical trends for the watershed and sea-level rise, respectively.

Workshop participants recommended the use of recent regional sea-level rise (RSLR) projections such as described by Ezer (workshop presentation), which incorporates glacial rebound, groundwater withdrawals, Chesapeake bolide impact crater, and Gulf Stream influence. A recent effort in Maryland to project RSLR based on regional expert consensus can be found here: http://www.umces.edu/sites/default/files/pdfs/SeaLevelRiseProjections.pdf, which found a mean estimate for 2050 relative SLR (over 2000) of 0.4 m (0.2-0.7 m). This is consistent with the 0.5

m used in the dissolved oxygen scenario modeling, which represents a baseline change from 1995 (mid-point of the 1991-2000 average hydrology used in the Chesapeake TMDL). However, as in all climate projections, this will depend on the emissions pathway.

Overall, workshop participants supported the approach of a 2025 scenario, but recognized that the detailed extrapolation of trends based on 1984-2014 trends were insufficient. Furthermore, there is a need for trends to be augmented and constrained by additional long-term information from other sources such as the observed precipitation and discharge trend record described by Rice (workshop presentation). Relying solely on the extrapolation of recent trends in precipitation fails to account for strong cyclic variations associated with ENSO, the PDO, the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation, and other climate modes.

For long-term climate change management decisions and programmatic assessments, the selection of a 2050 scenario was recommended. Muhling (workshop presentation), Weaver (workshop presentation), and other presenters indicated that a 2050 scenario would be within an envelope where strong anthropogenic influence on climate would have traction allowing ensembles of climate models to be used. At the same time, the 2050 scenario would be useful as an engineering design point for capital projects with a design life of several decades, such as large stormwater facilities and other water resource structures. The 2050 scenario would also accommodate the time needed for some management actions to be fully effective, due to, for example, the lag times associated with groundwater flow. Participants recommended using an ensemble approach for 2050 utilizing downscaled climate variables from a number of GCMs that would be considered representative of the region.

Although the use of downscaled information from GCM's was recommended for 2050 scenario assessments, it was not recommended for 2025 scenario development. A more simplistic approach of using historical extrapolations was recommended for 2025 scenario development. This recommendation reflects the ability of climate models to capture anthropogenic impacts on the climate over larger spatial and temporal scales, which makes them more applicable for 2050 and beyond scenarios. By 2025, the anthropogenic drivers have not yet started to act in a way that differentiates the anthropogenic impact from the other cyclical drivers of climate.

There is strong confidence in continued warming trends, recognizing that there is year to year variability, but less confidence in projections of precipitation volume and intensity. The approach used for representing evapotranspiration in the projections is also a large part of the uncertainty (Milly, workshop presentation). The interaction of changing precipitation amounts, timing of rainfall, and evapotranspiration result in streamflow projections that are characterized by uncertainty with large consequences for nutrient and sediment loading.

Findings

A summarized list of findings based on presentations and discussions that occurred among workshop participants is as follows:

1. There is sufficient scientific understanding to provide insights into the future on what the CBP should be doing over the short and long term to anticipate and manage for unavoidable climate change.
2. There is strong confidence in continued warming trends, recognizing that there is interannual variability.
3. There is less confidence that the watershed will experience an increase in the intensity of precipitation; there may be more variability, with a significant trend annually, but not in all seasons.
4. There is wider agreement on the seasonal precipitation changes (wetter winters and springs, potentially drier summers) than overall annual precipitation changes, although it is likely that both will occur.
5. Projected trends in discharge are likely to differ from those in precipitation. Timing of rainfall, antecedence, and evapotranspiration are contributing factors to the differences in observed discharge and precipitation trends for the Chesapeake Bay.
6. There are inherent limitations in projecting precipitation, particularly its intensity, from existing regional statistical and dynamical downscaling of GCMs because they don't take adequate account of mesoscale processes that are important in water dynamics.
7. Extrapolating short term trends in precipitation is particularly risky. There are strong cyclic variations associated with climate models that impact shorter term precipitation trends and make their use in long-term projections difficult.
8. Climate models are structured to look further out and at much larger scales than current management goals (i.e., 2025 restoration goals). By 2025, the end of the policy horizon, anthropogenic drivers within GCMs are just beginning to act in ways that clearly differentiate the anthropogenic impacts from the other cyclical drivers of climate.
9. For the purposes of the Midpoint Assessment modeling approach, projections for 2025 should be considered in terms of a 30-year projection from 1995 (mid-point of 1991 to 2000 Chesapeake Bay TMDL simulation period) through 2025 and the analysis of climate trends should be based on long term historical trends. Climate models and analyses of shorter-term (<50 years) data are not suitable for short-range projections because they include decadal-scale weather cycles which lead to large uncertainties in short-term trends.

Recommendations

The workshop culminated with the following specific recommendations related to the selection, use and application of climate projections and forecasts for the 2017 Midpoint Assessment:

1. The Partnership should seek agreement on the use of consistent climate scenarios for regional projections of Chesapeake Bay condition and the benefits of an integrated source of climate change projection simulation data that all seven jurisdictions could draw from.
2. For the 2017 Midpoint Assessment, use historical (~100 years) trends to project precipitation to 2025 as opposed to utilizing an ensemble of future projections from GCMs. Shorter term climate change projections using GCMs have large uncertainties because climate models are structured to look further out and at much larger scales.
3. The Program should carefully consider the representation of evapotranspiration in watershed model calibration and scenarios because the calculation method for evapotranspiration has a strong influence on the strength and direction of future water balance change.
4. Looking forward, the 2050 timeframe is more appropriate for selecting and incorporating a suite of global climate scenarios and simulations to provide long-term projections for the management community, and an ongoing adaptive process to incorporate climate change into decision-making as implementation moves forward.
5. Beyond the 2017 Midpoint Assessment, it is recommended that the CBP use 2050 projections for best management practice (BMP) design, efficiencies, effectiveness, selection, and performance – given that many of the BMPs implemented now could be in the ground beyond 2050.
6. For any 2050 assessment, use an ensemble or multiple global climate model approach, selecting model outputs that bound the range of key climate variables (e.g., temperature, precipitation) for the Chesapeake Bay region. Use multiple scenarios covering a range of projected emissions (RCP 4.5 and 8.5 are a reasonable range to select and are currently being utilized for Fourth National Climate Assessment). Include the 2 °C emissions reduction pathway (RCP 2.6) as well as more "business as usual" assumptions.
7. Select an existing system to access GCM downscaled scenario data (such as ‘LASSO’ described in more detail in Section II) in lieu of conducting a tailored statistical climate downscaling process for the Chesapeake Bay watershed.

Conclusion

Workshop consensus was that all aspects of climate change that influence Chesapeake Bay watershed should be addressed in the 2017 Midpoint Assessment, including changes in: 1) air temperature, 2) precipitation, 3) sea-level, 4) wind speed and direction, 5) humidity, and 6) atmospheric deposition of nitrogen. These changes in the climate system are expected to alter key variables and processes within the Chesapeake Bay and its watershed, including evapotranspiration, soil moisture, streamflow, water temperature, salinity, estuarine circulation, and key water quality variables (e.g., water clarity, chlorophyll, and dissolved oxygen). These climate factors should be looked at in coincidence with land use changes that will interact with and potentially exacerbate climate change impacts. To the extent practicable, the effect of all of these changes on key living resources such as wetlands, SAV, oysters, and other living resources should be assessed.

There was consensus at the workshop that the climate change assessment should, to the extent practicable, be available for application at the regional, state, and local levels. Although some localities have established climate projections for planning purposes (e.g., sea-level rise), a standardized set of projections has yet to be developed for the watershed. Projections for sea-level, precipitation, air temperature, water temperature, salinity, and potential evapotranspiration, among others, are needed as inputs to a variety of hydrological and ecological models, including local TMDL models, to assess potential future climate impacts on natural and human systems.

Drawing from the findings and recommendations presented at the workshop and summarized in this document, the CBP, with input from CBP's Modeling and Climate Resiliency Workgroups, should develop the proposed climate change assessment framework for the 2017 Midpoint Assessment. To initiate this process, workshop participants identified three near term key actions:

1. Convene a group of climate researchers to reach agreement on several key points, including but not limited to:
    a. Determination of a baseline
    b. Key variables to consider (temperature, precipitation, sea-level rise)
    c. Suite of GCMs to apply for Midpoint Assessment Needs; and living resources (SAV, Oysters, and Fish) assessment needs
    d. Downscaling techniques and Potential Evapotranspiration (PET) models to apply
    e. Range of scenarios to run
    f. Process to evaluate above modeling outputs
2. Convene a group of sea-level rise researchers and resource experts to reach agreement on sea-level rise estimates to apply; how to best approach simulating effect of sea-level rise on living resources (SAV, Oysters, Fish) and wetlands, and the range of sea-level rise scenarios to run.
3. The Climate Resiliency Workgroup should provide guiding principles to the jurisdictions to consider while developing their Phase III WIPs.

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Appendix A: Workshop Agenda

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

Scientific and Technical Advisory Committee (STAC) Workshop

March 7-8 2016
Westin Annapolis, 100 Westgate Circle, Annapolis MD 21401

Workshop Goals

The 2014 Chesapeake Bay Agreement includes 29 individual strategies to be developed and implemented by six Goal Implementation Teams (GITs). Most, if not all, of these strategies will include a suite of actions necessary to address climate change impacts. In addition, the 2010 TMDL documentation and the 2009 Executive Order call for an assessment of the impacts of a changing climate on the Chesapeake Bay water quality and living resources that will be addressed during the upcoming 2017 Midpoint Assessment.

The Chesapeake Bay Watershed Model, the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM), and living resource models, such as models of underwater grasses, tidal wetlands, and oysters, will be used to examine the impact of climate change on water quality and estuarine ecosystems. Other assessment tools will be utilized to examine the impact of climate change on other goals and outcomes. Although some localities have established climate projections for planning purposes (e.g., sea-level rise), a standardized set of projections has yet to be developed for the watershed. Such projections for sea-level rise, precipitation, air temperature, storm intensity, and potential evapotranspiration, among others, are needed as inputs to a variety of hydrological and ecological models to assess potential future climate impacts on natural and human systems.

The 2014 Intergovernmental Panel on Climate Change (IPCC) report relied on a Coupled Model Intercomparison Project featuring approximately 30 global general circulation models (GCMs), each with multiple emission scenarios. Additionally, there are multiple downscaling techniques that are available to move from these global-scale models to an appropriate scale for the Chesapeake Bay and its watershed. Extrapolation of decades of historical observations of temperatures, precipitation intensity, precipitation volume, sea level rise, and estuarine salt intrusion have also been successfully used for future scenarios of climate change.

The Chesapeake Bay Program (CBP) will have to choose among the GCMs, scenarios, downscaling techniques, and historical observation data to establish a framework for climate analysis in the CBP models. The goal of workshop is to assist the CBP with the selection process by addressing the following questions:

1. What climate change variables are of most concern to the CBP partners in the consideration of the 2017 Midpoint Assessment decisions and for longer term climate change management decisions?

2. What are the approaches that can be taken to select climate change scenarios for CBP assessments?

3. What characteristics of those climate variables need to be specified, e.g., temporal, spatial, and other relevant characteristics? In what format are scenarios needed to provide the most utility at the regional, state, and local levels?

4. What climate change scenarios meet CBP decision-making needs for the 2017 Midpoint Assessment as well as for longer term climate change management decisions and programmatic assessments?

Day 1: Monday, March 7

8:30 Registration, light breakfast (provided)

9:00 Welcome Address – Rich Batiuk, U.S. EPA Chesapeake Bay Program

9:10 Introduction and Purpose of Workshop – Mark Bennett, USGS

Session I: Introduction and Background

9:25 Climate Change Impacts of Most Concern for Chesapeake Bay Agreement Goal and Outcome Attainment – Zoe Johnson, NOAA/CBPO

9:45 Use of Climate Change Scenarios for Supporting Decision Making – Chris Weaver, U.S. EPA

10:15 Climate Change in the US with an Emphasis on the Northeast: Past, Present, and Future – Ray Najjar, Penn State
A presentation on how climate has changed in the Northeast region, how it is expected to change in the future and how extrapolation of past trends can be used for short range 10-15 year projections of climate change.

10:45 Sea-level Rise for the Chesapeake Bay Area: Causes, Trends, and Future Projections – Tal Ezer, Center for Coastal and Physical Oceanography, ODU
The various aspects that contribute to local sea level rise in the region and the impact on flooding will be reviewed. These include global sea level rise, land subsidence, and response to oceanic and atmospheric dynamic, such as potential climatic changes in the Gulf Stream. The difficulty of estimating future sea level rise will be discussed.

11:15 DISCUSSION (Moderator: Lew Linker, EPA/CBPO)
What are the approaches that can be taken to develop climate change scenarios for Chesapeake Bay Program decision-making? What are the important climate drivers and time periods for assessment of climate change impacts for the 2017 Midpoint Assessment as well as for longer term climate change management decisions?

12:00 LUNCH (provided)

Session II: Case-Study Examples of Climate Trend Assessments, Data, and Scenario Needs for CBP Climate Assessments of the Watershed and Estuary

Overview: This session will provide short, concise presentations on climate change information needs for past and ongoing CBP assessments in the watershed and tidal estuary. Each presenter will provide an overview of data needs and format for temporal and spatial climate drivers to complete the assessment.

1:00 Historical Flow Trends – Karen Rice, USGS
Trends in precipitation and flow in different Chesapeake watersheds will be examined.

1:20 Evapotranspiration – Chris Milly, USGS
The presentation will examine the challenges in the simulation of climate-model-implied growth in potential evapotranspiration.

1:40 Assessing the Hydrologic and Water Quality Impacts of Climate Change in Small Agricultural Basins of the Upper Chesapeake Bay Watershed – Anthony Buda, USDA-ARS
This presentation will examine projected trends in statistically downscaled climate data for a representative agricultural basin of the Upper Chesapeake Bay watershed and outline a proposed approach for assessing the impacts of these trends on watershed hydrology and water quality using the Soil and Water Assessment Tool.

2:00 Patuxent River Case Study (Urban Storm Water) – Susan Julius, U.S. EPA
A study of the application of a scenario selection process in an urban watershed and the findings of that study will be discussed.

2:20 Approaches to the Simulation of Climate Change with the CBP Watershed and Estuarine Model – Gopal Bhatt, PSU; Ping Wang, VIMS; and Guido Yactayo, UMCES
Initial scenarios generated by the Watershed Model based on an extrapolation of observed precipitation based trends and projected to the years 2025 and 2050 will be

presented and estimates of the influence sea-level rise and temperature increases have on Bay water quality will be discussed.

2:40 **2017 Midpoint Assessment Management Needs – Lewis Linker, U.S. EPA Chesapeake Bay Program and Carl Cerco, USACE-ERDC**
Initial work done to support an assessment of how climate change in 2025 and 2050 could influence achieving Chesapeake water quality standards will be presented, including simulations of the influence of changes in watershed loads, sea level rise, estuarine temperature increases, and tidal marsh loss.

3:00 **Break**

3:15 **DISCUSSION (Moderator: Ray Najjar, PSU)**
What specific climate data are needed for ongoing or planned assessments? In what format are climate data needed: temporal scale (e.g., 2025, 2050, 2100); spatial scale (e.g., field scale, watershed scale, regional scale); and what variables (e.g., min, max daily temp, extreme precipitation events vs. mean annual changes).

4:30 **Adjourn Day One**

Day 2: Tuesday, March 8

8:00 **Registration, light breakfast (provided)**

8:30 **Welcome, Summary of Day 1, and Comments from Workshop Participants**

Session III: Case-Study Examples of Climate Trend Assessments, Data, and Scenario Needs for CBP Climate Assessments of Ecosystems

Overview: This session will provide short, concise presentations on climate change information needs for past and ongoing CBP assessments in key ecosystems. Each presenter will provide an overview of data needs and format for temporal and spatial climate drivers to complete the assessment.

8:45 **Downscaling Climate Models for Ecological Forecasting In Northeast U.S. Estuaries – Barbara Muhling, Princeton/NOAA GFDL**
Statistical downscaling is commonly used to convert global climate model outputs to a regional scale. The results of recent downscaling experiments for the Chesapeake Bay and Susquehanna watershed will be discussed, along with consideration of variability among downscaling methods.

9:15 **Impacts of Climate Change on Chesapeake Oysters – Roger Mann and Ryan Carnegie, VIMS**
Oysters provide ecosystem services in the Chesapeake Bay as benthic pelagic couplers, as structural complexity (reefs) in the benthos, and as central components in the bay

alkalinity budget. All are subject to change in response to projected climate change: (1) What is the impact of climate driven changes in temperature and/or salinity on oysters, oyster diseases and the oyster-disease interaction; (2) what is the impact of changing water chemistry on oysters in both the larval and adult life history stages; (3) what is the impact of (1) and (2) combined on oyster population dynamics and the role of oysters as an alkalinity bank; and (4) can we proactively manage any of it?

9:45 *Zostera* & SAV Response to Projected Temperature and CO_2 Concentrations – Victoria Hill & Dick Zimmerman, ODU

10:05 Climate Change and Ecological Forecasting in the Chesapeake Bay – Howard Townsend, NOAA

10:25 Loss of Coastal Marshes to Sea-level Rise – Molly Mitchell, VIMS
Molly Mitchell, of the VIMS Center for Coastal Resources Management will describe a survey and analysis of wetland loss due to sea level rise in the Chesapeake as well as data and modeling needs for assessing climate change impacts on tidal wetlands.

10:55 Break

Session IV: Climate Scenarios, Projections, and Realizations - What Do We Have and What Do We Need?

Overview: This session will focus on approaches to selecting climate change scenarios for the Chesapeake Bay Program that fit the needs of local, state, and regional partners and stakeholders. One key focus of this session is to identify approaches for streamlining scenario selection while maintaining analytic consistency and rigor across the Program.

11:05 State Perspectives on Climate Change Scenario Selection – Kate Johnson, DC and Jennifer DeMooy, DE
Both Delaware and the District have used statistical downscaling for climate change impact assessments. Why they chose the particular downscaling approach used and how the downscaled projection will be applied in their respective states will be described.

11:35 A Climate Scenario Selection Tool – Phil Morefield, U.S. EPA

12:05 DISCUSSION (Moderator: Susan Julius, EPA)
What climate change scenarios meet Chesapeake Bay Program decision-making needs for the 2017 Midpoint Assessment as well as for longer term climate change management decisions? In what format are realizations needed that will provide the most utility at the regional, state, and local levels? Is there a need for consistency among climate change scenarios across the watershed and state and local jurisdictions?

12:30 LUNCH (provided)

1:30 WRAP UP DISCUSSION (Moderator: Rich Batiuk, U.S. EPA Chesapeake Bay Program)

There are many physical, biological, and ecological changes that will take place in a Chesapeake Bay influenced by climate change. In order to better evaluate future behavior of the entire system of watershed, airshed, estuary, and ecosystem under a variety of adaptive climate change management strategies, what are the most important climate data and information needs? This includes considerations of what, when, where, and how to sample the watershed, estuary, and ecosystem as well as how to best synthesize research, observations, and model analysis in order to improve understanding of how the system is changing and adaptive management approaches. Also, what laboratory and field studies should be undertaken to better understand past trends and project future impacts.

In addition to the short and long-term CBP science priorities, we need to consider what steps are needed to make the best use of the current state of our understanding to evaluate management decisions that must be made in the next year as a part of the 2017 Midpoint Assessment. In particular, what are the most important improvements that should be made to the suite of models (watershed and Bay) in order to better predict how climate change will modulate the transport and fate of nutrients and sediment to tidal waters and how that will affect the achievement of the TMDL goals in the Bay?

2:30 Adjourn

Appendix B: Workshop Participants

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Appendix C: Presentation Summaries

Session 1: Introduction and Background

Climate Change Impacts of Most Concern for Chesapeake Bay Agreement Goal and Outcome Attainment – Zoe Johnson, NOAA/CBPO

Recognizing the need to gain a better understanding of the likely impacts as well as potential management solutions for the watershed, a new goal was added to the 2014 *Chesapeake Bay Watershed Agreement*, committing the Chesapeake Bay Program partnership to take action to "increase the resiliency of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure and communities, to withstand adverse impacts from changing environmental and climate conditions." This new goal builds on the 2010 TMDL documentation and the 2009 Presidential Executive Order 13508, which also call for an assessment of the impacts of a changing climate on the Chesapeake Bay water quality and living resources.

Chesapeake Bay Program (CBP) partners are currently working on several fronts to formulate plans, conduct modeling and other assessments, and align existing monitoring programs to gain a better understanding of the trends and likely impacts of a changing climate. Modeling and monitoring efforts will be used to ultimately inform the development of specific adaptation strategies and targeted restoration and protection activities, as well as evaluate progress towards reducing the impact of climate change over time.

In December 2015, the CBP Scientific and Technical Advisory Committee (STAC) undertook a planning exercise to help inform the program's prioritization of climate change impacts of most concern with respect to the Chesapeake Bay Agreement. During the facilitated exercise, STAC members were asked to: 1) explore and discuss aspects of climate change, which may impact the achievement of individual goals and outcomes (e g., restore x acres of wetlands by year xxxx); 2) assign a qualitative (low, medium, high) factor of risk in terms of the influence of future climate impact on "goal/outcome attainment"; and 3) to identify research needs to fill critical information gaps. Results of the first phase of this planning exercise are presented in Figure 1.

Figure 1. Goal Attainment: *Qualitative Factor of Risk*

Goal	**Outcome**	**Qualitative Factor of Risk**	**Primary Climate Drivers**
Water Quality	2025 WIP Outcome	Medium	SLR, T, P, EE
	WQ Attainment	High (over long-term)	SLR, T, P, EE
Healthy Watersheds	Healthy Waters	Varied response	T, P, EE

Vital Habitats	Black Duck	High	SLR
	Brook Trout	High	T, P
	Wetlands	Medium (non-tidal)/High (tidal)	SLR, P
	Stream Health	High	T, P
	SAV	HIgh	SLR, T, EE
	Forest Buffer	Medium	SLR, P, EE
	Urban Tree Canopy	Medium	T, P
Land Conservation	Protected Lands	Low - Medium	SLR
	Public Access	Low - Medium	SLR
Sustainable Fisheries	Blue Crab	Medium	T
	Oyster Restoration	Medium	T, OA
	Fish Habitat	High	SLR, T, P, EE
	Forage Fish	High	SLR, T, P

Building from the STAC analysis, the CBP will be using a suite of model applications, including the Chesapeake Bay Watershed Model, the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM), and a number of living resource models to examine the impact of climate change on the Chesapeake Bay watershed and its ecosystems. Other assessment tools will be utilized to examine the impact of climate change on other goals and outcomes. Specific climate change projections or scenarios to guide programmatic assessments have yet to be developed. Projections for sea-level rise, precipitation, air temperature, storm intensity, and potential evapotranspiration, among others, are needed as inputs to a variety of hydrological and ecological models to assess potential future climate impacts on natural and human systems.

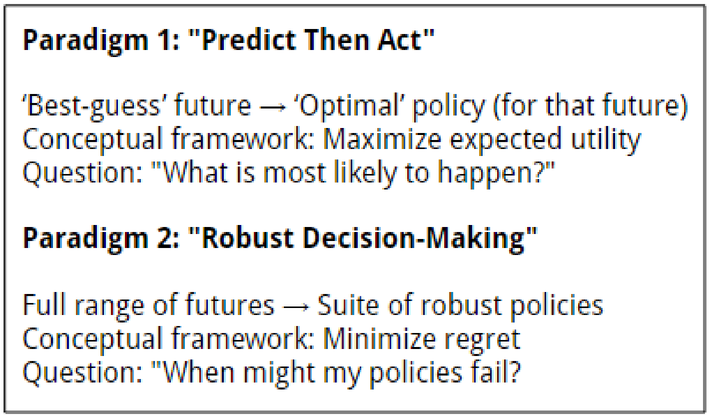
At the very basic level, for each modeling effort to be undertaken, there is a need to define specific data needs (e.g., historical observations/trends, future projections, climate variables); determine data requirements (e.g., range of scenarios vs. sole variable); establish spatial extent (e.g., geographic relevance); and select temporal scale (e.g., seasonal, inter-annual, decadal and beyond).

The Use of Climate Change Scenarios for Supporting Decision-Making **– Chris Weaver, U.S. EPA**

Climate change presents numerous unique challenges to effective, science-based decision support. In particular, while the methods, practices, and tools of health and ecological risk assessment have provided the foundation for EPA’s ability to leverage the best-available science to meet its mission to protect human health and the environment, the character of the climate change problem is proving difficult to accommodate within traditional risk assessment frameworks.

One major challenge is the presence of deep uncertainty about future climate changes, and its associated impacts. This uncertainty results from lack of predictability of future climate change due to natural year-to-year and decade-to-decade variability in the climate system; potentially large and poorly understood feedbacks (e.g., carbon cycle feedbacks); the uncertain trajectory of key anthropogenic drivers, especially greenhouse gas emissions; and uncertainty about how human systems will respond and adapt. These limits on climate system predictability are felt most strongly at precisely the space and time scales most relevant for environmental management, such as the regional and local scales of watersheds and communities, or for short-term extremes such as heavy rainfall events. What this means in practical terms is that, not only is the past no longer a reliable guide to the future, but it will often be difficult to describe expected future climate change and impacts with well-characterized probability distributions around ‘most likely’ future conditions.

Rather than dependence on highly imperfect predictions of future climate conditions and impacts of greatest relevance for watershed management, use of scenarios within ‘bottom-up’ or ‘robust’ decision frameworks (Paradigm 2) can help overcome these uncertainty-based challenges, as well as help address intrinsic barriers (cognitive, behavioral, institutional) to good decision making.



Paradigm 1: "Predict Then Act"

‘Best-guess’ future → ‘Optimal’ policy (for that future)
Conceptual framework: Maximize expected utility
Question: "What is most likely to happen?"

Paradigm 2: "Robust Decision-Making"

Full range of futures → Suite of robust policies
Conceptual framework: Minimize regret
Question: "When might my policies fail?

The choice of initial set of scenarios will need to reflect the shift in decision framework

- Choose initial scenarios that most clearly bound the decision-relevant climate changes, in the face of multiple uncertainties, rather than produce a contingent probability distribution around a ‘most likely’ future value. This is a natural consequence of focusing on societal risk, where a disproportionate fraction of total risk will often be associated with low-probability outcomes (‘tail risks’).
- Choose initial scenarios that most clearly distinguish between futures in which your policies succeed and those in which they fail. These will most often be composed of variables with (a) highest impact on management endpoints and (b) highest levels of uncertainty.

Climate Change in the Northeast US: Past, Present, and Future – Raymond Najjar, The Pennsylvania State University

The climate of the Northeast United States (US), including the Mid-Atlantic Region that the Chesapeake Bay and its watershed lie in, has undergone change over the past century or so. Observational trends were summarized by Kunkel et al. (2013a,b) and are reported here. Although interannual variability is substantial, annual mean temperature and precipitation in the Northeast US have undergone significant long term increases of about 2 °F and 10%, respectively. Extreme precipitation has increased as well. Like the rise in global mean temperature, there is high confidence that the primary cause in the temperature increase of the Northeast US is an increase in greenhouse gases (Kunkel et al. 2013a), a conclusion drawn in part from simulations of regional climate with and without increases in greenhouse gas concentrations. On the other hand, it appears that natural climate variability has dominated the observed precipitation increase, as climate models do not consistently simulate a precipitation increase when greenhouse gas increases are included in them. Furthermore, there are significant statistical linkages between Mid-Atlantic precipitation and climate modes, particularly El Niño/Southern Oscillation and the Pacific Decadal Oscillation, on decadal time scales (Schulte et al. 2016).

Climate model projections in the Northeast US indicate substantial changes (Kunkel et al. 2013a, b). The average warming among 15 climate models by 2035 is nearly 3 °F and is essentially independent of emissions scenario due to the long lifetime of CO_2 in the atmosphere and the large thermal inertia of the climate system (mainly the ocean). By 2055 the average warming is sensitive to the emissions scenario, with 2085 projections of nearly 5 °F and 8 °F warming under the B1 and A2 scenarios, respectively (which are bracketed by the RCP 2.6 and 8.5 scenarios discussed in the body of this report). There is high confidence that the historical warming trend will continue into the future as not a single climate model projects cooling. About 80% of global climate models project increased precipitation in the Northeast US into the 21st century; the average increase by 2085 is about 5%, with a modest sensitivity to the emissions scenario. There is a greater increase and a greater consensus for precipitation in the winter and spring (~15% average increase among the models by mid-21st century), and a suggestion that summer precipitation may decline slightly. Finally, climate models consistently project an increase in the intensity of precipitation in the Northeast US as greenhouse concentrations continue to increase. By the mid-21st century, the mean increase in precipitation intensity (defined as the number of days per year with precipitation above 1 inch) is typically between 10 and 20% throughout the Chesapeake Bay watershed.

In summary, the Chesapeake Bay watershed has become warmer and wetter, and precipitation has become more intense. These trends can be expected to continue throughout the 21st century, but natural variability is likely to create cycles in precipitation that will periodically enhance and weaken its long-term increase.

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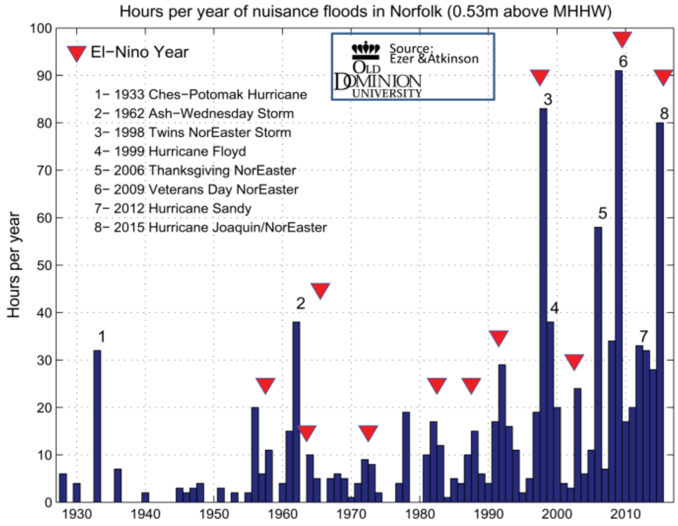
***Sea-level Rise for the Chesapeake Bay Area: Causes, Trends, and Future Projections* – Tal Ezer, Center for Coastal and Physical Oceanography, ODU**

The sea level rise (SLR) around the Chesapeake Bay (CB) is one of the highest of all U.S. coasts and the rates are accelerating. Local SLR rates over the past 10-30 years are ~4-6 mm/year, which are higher than the global mean SLR rates of ~1.7 mm/year over the past century or even higher than the ~3.2 mm/year over the past 20 years as seen from satellite altimeter data. There are also variations within the CB, with rates that are higher in the south part of the bay and slightly lower in the north and along the eastern shore of Virginia. This SLR results in acceleration in the frequency and periods of flooding (see Figure below).



Relative SLR in CB is primarily the result of three processes: 1) global SLR due to warming ocean temperatures and melting land ice, 2) local land subsidence, and 3) changes in ocean and atmospheric dynamics. The CB's coasts are experiencing subsidence due to recent human activities such as groundwater extraction and long-term Glacial Isostatic Adjustment (GIA) since the end of the ice age. Climatic changes and weakening in the Gulf Stream appear to result in increased coastal sea-level and flooding. Remote influence from climate patterns such as El-Nino and the North Atlantic Oscillation (NAO) can also impact the region, but they are difficult to predict.

Projections of future SLR in the region need to take all these factors into account by combining data and models. For relatively short-term projections of 10-20 years or so, statistical projections based on analysis of linear and non-linear past trends may be useful, but for longer projections, say 50-100 years, climate models that take into account future greenhouse emission scenarios and increasing melting of ice sheets are needed.

ODU's Climate Change and Sea Level Rise Initiative (http://www.odu.edu//research/initiatives/ccslri) and the Center for SLR (http://www.centerforsealevelrise.org/) address those issues; recent research papers from these activities are listed below (PDFs available at http://www.ccpo.odu.edu/~tezer/Pub.html).

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Session II: Case Study Examples of Climate Trend Assessments, Data, and Scenario Needs for CBP Climate Assessments of the Watershed and Estuary

Historical Flow Trends – Karen Rice, USGS

Analysis of Long-Term Hydrologic Records in the Chesapeake Bay Watershed

Karen C. Rice[1,2] and Douglas L. Moyer[1]
[1]U.S. Geological Survey, Virginia Water Science Center
[2]University of Virginia

Hydrologic data were analyzed to determine the relations between long-term precipitation and long-term discharge trends in the Chesapeake Bay (CB) watershed. Previous research on runoff from 1930 through 2010 indicates that some flow metrics, for example, the mean one-day maximum runoff, show differences in their trends between northern and southern watersheds (Rice and Hirsch 2012). The north-south dividing line is approximately the Pennsylvania—Maryland border (Rice and Hirsch 2012). The amount, frequency, and intensity of precipitation have increased in the eastern United States (U.S.), however, the observed increases have been greater in the northeast than the southeast (Karl and Knight, 1998; U.S. Climate Assessment, 2014). The 165,759-square kilometer (km^2) CB watershed spans the north-to-south gradient in precipitation increases.

Daily mean discharge data were obtained for 27 U.S. Geological Survey (USGS) gaging stations in and near the CB watershed for calendar years 1927 through 2014. The watersheds have diverse land use and span areas from 303 to 62,419 km^2. PRISM (http://www.prism.oregonstate.edu/historical/) precipitation data (Daly et al. 2008) were downloaded and spatially and temporally averaged to obtain mean monthly data specific to each of the 27 watersheds from 1927 through 2014. The objectives of the talk presented at the CB Scientific and Technical Advisory Committee workshop were to: (1) determine if and how the changes in precipitation are being manifested as changes in discharge; (2) identify any spatial differences in the precipitation—discharge relations; and (3) compare these evaluations of the historical record (1927-2014) to the period specific to the CB Program's Watershed Model (1985-2014).

Annual distributions of daily mean discharge and monthly total precipitation for each watershed were analyzed; values of precipitation and discharge corresponding to each decile (0th, 10th, 20th,…100th) were assembled for each year; linear regressions were fitted for the whole period for each decile, and slopes and p-values (at the $\alpha \leq 0.05$ level) were recorded. The spatial patterns in significant increasing (≤ 0.05) precipitation and discharge trends in the deciles differed between the northern and southern watersheds. Among the northern watersheds, the number of sites with significant increasing precipitation was highest for the 60th, 70th, and 80th deciles, whereas the number of sites with significant increasing discharge was highest for the 0th through 60th deciles. Among the southern watersheds, significant increasing trends in precipitation occurred only in the 50th, 60th, and 70th deciles. In contrast, significant increasing trends in discharge occurred in the 0th through 20th deciles and in the 50th through 90th deciles. In general, the linkage between precipitation and discharge was less in the southern watersheds as compared with those in the north. Also in the south, trends in precipitation had lower slopes; there were fewer significant precipitation and discharge trends, and the significance of the trends decreased; and, among the deciles, there were fewer significant trends (Rice and others, 2016). The disconnect between precipitation and discharge trends might be explained by the basic hydrology of watersheds, whereby lag times, travel times, land use, snow pack and timing of snowmelt, antecedent conditions, and evapotranspiration all influence the nature of the manifestation of the precipitation on discharge. There were far more significant increasing trends for the historical record (1927-2014) of discharge than for the period specific to the Watershed Model (1985-2014) across all deciles. The discrepancy in the number of significant increasing trends between the two periods can be attributed to the quantitative power of a linear trend test, which is highly sensitive to the number of observations.

The presentation can be summarized into three simplified points: (1) trends in discharge deciles do not mirror those of precipitation; (2) discharge response to precipitation in the northern watersheds differs with that of the southern watersheds; and (3) for discharge, the shorter recent record (1985-2014) has far fewer significant trends than the historical record (1927-2014).

Acknowledgments:
We appreciate the efforts of Jason A. Lynch, U.S. Environmental Protection Agency, for downloading, compiling, and modeling the PRISM data for each watershed.

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***Evapotranspiration* – Chris Milly, USGS**

This presentation provided an overview of the challenges in the simulation of climate model implied growth in potential evapotranspiration (PET). To estimate historical Susquehanna River basin (SRB) runoff, the use of the median across many climate models is more accurate than the use of most individual models or small collections thereof. Similarly, a many-model ensemble was more skillful than any single model in reproducing global pattern of 20th century streamflow trends. A large number of climate models is needed to obtain a stable estimate of future SRB runoff change. Variation in past estimates of SRB runoff change is significantly affected by at least two factors: 1) use of different climate models and 2) the use of different hydrologic models, especially PET formulations.

Offline estimates of runoff change based on empirical PET estimates are generally biased low relative to runoff changes in climate models themselves. Use of a more process-based approach to PET in "offline" hydrologic modeling of climate change requires surface radiation. Climate models produce their own runoff, and this is a useful source of climate-change information.

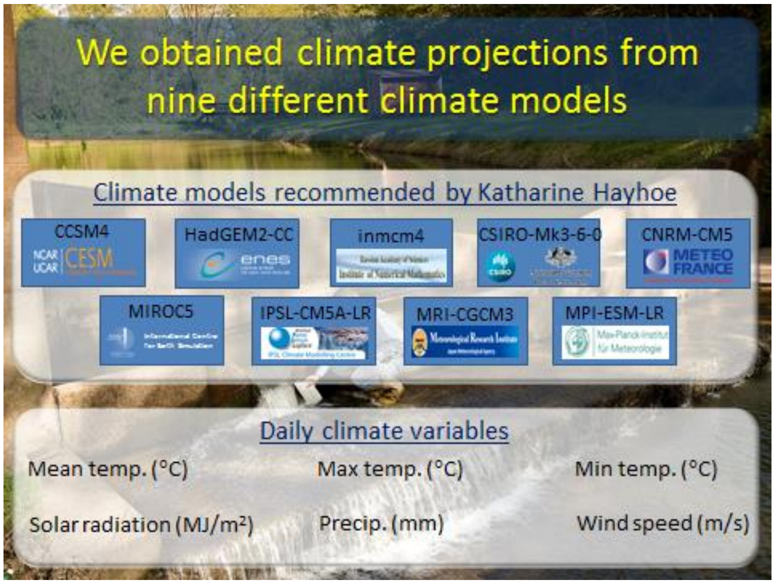
Assessing the Hydrologic and Water Quality Impacts of Climate Change in Small Agricultural Basins of the Upper Chesapeake Bay Watershed – Anthony Buda, USDA-ARS

Contributers: Anthony R. Buda, Al Rotz, Ray Bryant, Peter Kleinman,
Gordon Folmar, Sarah Goslee, and Tamie Veith (USDA Agricultural Research Service); Anne Stoner and Katharine Hayhoe (Texas Tech University); and Amy Collick (University of Maryland Eastern Shore)

Changes in climate and shifting weather patterns are expected to pose numerous challenges to agriculture in the Chesapeake Bay watershed this century. Chief among these challenges is maintaining an acceptable balance between agricultural production and water quality protection. In this presentation, we examine projected trends in future climate for representative agricultural basins of the Upper Chesapeake Bay watershed and outline a proposed approach for assessing the impacts of these trends on watershed hydrology and water quality using the Soil and Water Assessment Tool (SWAT). The project focuses on four agricultural watersheds comprising the Upper Chesapeake Bay Long-term Agroecosystem Research (LTAR) location. These watersheds span the physiography of the Upper Chesapeake Bay basin, and include Conewago Creek (Appalachian Piedmont), Mahantango Creek (Appalachian Valley and Ridge; shale), Spring Creek (Appalachian Valley and Ridge; karst), and Anderson Creek (Allegheny Plateau). For each watershed, we obtained statistically downscaled climate projections from nine different global climate models (see Figure 1 for a list of the models; see Stoner et al. 2013 for details on the downscaling approach) for two greenhouse gas emission scenarios, including business as usual (RCP 8.5) and stabilization (RCP 4.5).

Assuming a business as usual emissions pathway, preliminary downscaled climate change projections for the Mahantango Creek watershed suggest that mean annual temperatures in the middle of this century (2045 to 2064) will be 3.5°C warmer than the twenty-year period from 1971 to 1990, with an accompanying 12.7% increase in mean annual precipitation over the same time frame. Along with changes in average climatic conditions, weather extremes also will become more likely, with hotter maximum daily temperatures, an increased frequency of daily rains greater than one inch, and longer strings of consecutive dry days all anticipated as the climate warms. In order to assess the impacts of these projected climate changes on watershed hydrology and water quality, we will use the variable source area hydrology version of SWAT (TopoSWAT) to simulate watershed performance in each of the Upper Chesapeake LTAR basins for 20th century climate, as well as for early- (2015 to 2034), mid- (2045 to 2064), and late (2081 to 2100) 21st century. In addition to assessing climate impacts on agricultural watersheds, we also will examine the effects of changing agricultural management practices in SWAT using Pennsylvania’s Watershed Implementation Plan (WIP) as a reasonable proxy for early 21st century land management in each basin.

Ultimately, we anticipate that long-term watershed simulations will provide average and extreme event estimates of water quantity and nutrient and sediment export under current and projected future climate in the Upper Chesapeake Bay region. Additionally, the array of management strategies evaluated with the models will provide farmers and watershed managers with necessary guidance on how best to maintain water supply and reduce nutrient and sediment losses under various climatic conditions expected this century.



We obtained climate projections from nine different climate models

Climate models recommended by Katharine Hayhoe

CCSM4
HadGEM2-CC
inmcm4
CSIRO-Mk3-6-0
CNRM-CM5
MIROC5
IPSL-CM5A-LR
MRI-CGCM3
MPI-ESM-LR

Daily climate variables

Mean temp. (°C)
Max temp. (°C)
Min temp. (°C)
Solar radiation (MJ/m²)
Precip. (mm)
Wind speed (m/s)

Figure 1: Nine climate models from which statistically downscaled climate data were obtained.

Reference

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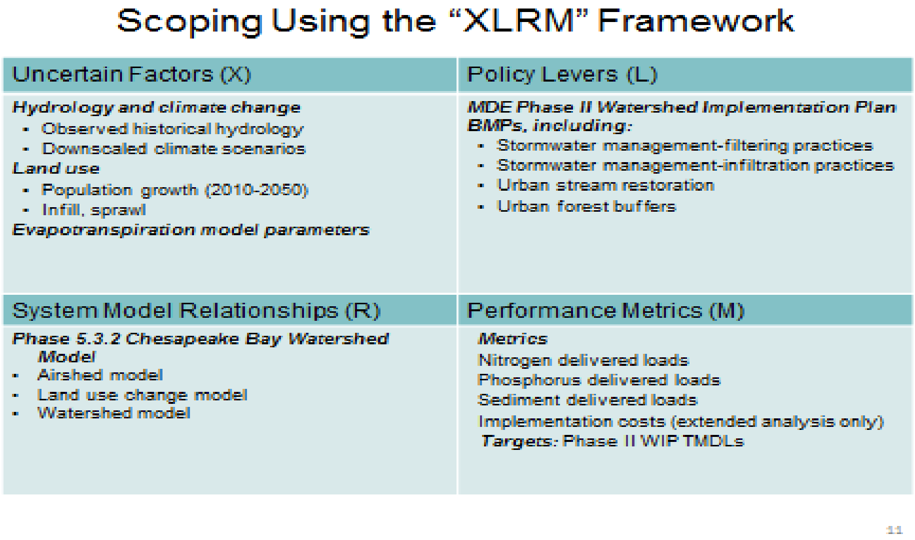
***Patuxent River Case Study (Urban Storm Water)* – Susan Julius, U.S. EPA**

Contributors: Susan Julius[1], Thomas Johnson[1], Jordan R. Fischbach[2], Robert J. Lempert[2]
[1]U.S. EPA
[2]Rand Corporation

Robust Decision-Making (RDM) explicitly recognizes and incorporates uncertainty into evaluation of alternative management decisions with the goal of identifying those strategies that are robust across the widest range of potential futures. This presentation discusses results of a pilot study focused on the Patuxent River in the Chesapeake Bay to test RDM's usefulness for considering climate change and other key uncertainties in urban stormwater planning.

We examined the contribution of stormwater pollutants from the Patuxent to the Total Maximum Daily Load (TMDL) for the Chesapeake Bay under multiple scenarios of land use, climate, and pollutant removal efficiencies for different suites of best management practices (BMPs). The stormwater practices used in this analysis were from the Maryland's Phase II Watershed Implementation Plan. The projections of plausible future hydrology and land use conditions were done using the Chesapeake Bay Program's Phase 5.3.2 model together with scenario inputs developed and provided by CBP partners. Twelve land use scenarios with different population projections and development patterns were used, along with 18 climate change scenarios, several future time periods, and alternative assumptions about BMP performance standards and efficiencies associated with different suites of stormwater BMPs (see Scoping Framework below). The goal of the case study was to support the Chesapeake Bay Program in providing climate-related decision support for water quality management, and more generally help EPA assess the effectiveness of RDM to support water quality management.



Scoping Using the "XLRM" Framework

Uncertain Factors (X)	Policy Levers (L)
Hydrology and climate change • Observed historical hydrology • Downscaled climate scenarios ***Land use*** • Population growth (2010-2050) • Infill, sprawl ***Evapotranspiration model parameters***	***MDE Phase II Watershed Implementation Plan BMPs, including:*** • Stormwater management-filtering practices • Stormwater management-infiltration practices • Urban stream restoration • Urban forest buffers
System Model Relationships (R)	**Performance Metrics (M)**
Phase 5.3.2 Chesapeake Bay Watershed Model • Airshed model • Land use change model • Watershed model	*Metrics* Nitrogen delivered loads Phosphorus delivered loads Sediment delivered loads Implementation costs (extended analysis only) *Targets:* Phase II WIP TMDLs

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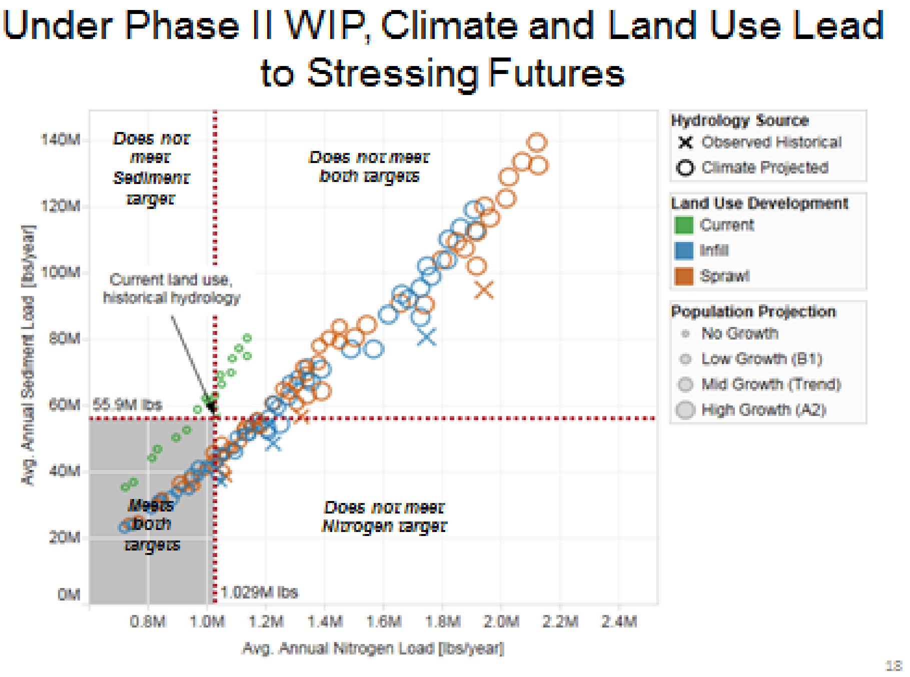
Our initial vulnerability analysis showed that under historic climate and no change in current land uses, Maryland's Phase II WIP for the Patuxent meets new water quality TMDL targets for nitrogen, phosphorous, and sediment. In addition, when compared with current management, the Phase II WIP increases the number of plausible futures in which TMDL targets are met, especially cases where all three targets are exceeded with current management.

More often than not, however, the Phase II WIP does not meet TMDL targets when a changing climate and future changes in population or development patterns are considered. Specifically, scenario discovery demonstrates that water quality targets for nitrogen are most often not met when precipitation increases over the historical average (or declines by only a small amount), impervious land cover increases, or both. Similar patterns were observed for phosphorus and sediment targets (see Figure below of Phase II Sediment and Nitrogen loads under different combinations of climate and land use changes).

In the future, cost-effective options could be considered to hedge against future changes in climate and land use. For example, greater investment in BMP types such as wetlands or urban filtering practices may be considered that appear to provide cost-effective pollutant load reduction for impervious areas when compared with other approaches.



However, a preliminary analysis suggests that in some plausible stressing futures, very few BMP types considered could meet existing water quality targets at reasonable cost. This may mean that additional options have to be developed and employed in the basin, including changes to land use practices, to help avoid future impervious area growth. Also, developing “signposts” to monitor to detect changes from the desired trajectory of control for pollutants could be used to trigger additional BMP investments or new policy options. In general, monitoring BMPs, testing current and potential new BMPs, adaptively managing as new data and information are gathered, and revisiting targets where necessary are good practices in light of the significant climate change uncertainties.

Approaches to the Simulation of Climate Change with the CBP Watershed and Estuarine Model – **Gopal Bhatt, PSU; Ping Wang, VIMS; and Guido Yactayo, UMCES**

A collection of six General Circulation Models were used as inputs to estimate anticipated changes in temperature throughout the watershed in the year 2050. Anticipated changes in precipitation were adjusted by utilizing regressions derived from a 30 year historical record of watershed precipitation events to extrapolate forward in time. Potential Evapotranspiration was modified by Hamon's method (1961) and increasing CO_2 concentrations were used to effect changes in stomatal resistance. These inputs resulted in large variations of watershed loadings in comparison with loads generated from a calibration run of the Chesapeake Bay Program's Phase 5.3.2 Watershed Model, suggesting that significant management actions would need to be taken to account for steeply increasing nutrient and sediment loads anticipated for future climate scenarios.

2017 Midpoint Assessment Management Needs – Lewis Linker, U.S. EPA Chesapeake Bay Program and Carl Cerco, **USACE-ERDC**

Linker outlined the motivations and schedule demands that the Chesapeake Bay Program has placed upon its decisions to integrate factors of altered climate in the Phase III Watershed Implementation Plans (WIPs). The support systems in place to determine relative changes in hypoxia and living resource conditions using the Bay Program's Water Quality and Sediment Transport Model (WQSTM) were also explained. Changes in water quality standards due to impacts of changing temperature, sea-level, watershed loads, and tidal wetland attenuation were discussed. Overall, there was generally little impact with regards to water quality standards from these factors, although further exploration of these issues is necessary to better evaluate targeted management responses to factors such as tidal marsh loss, stormwater management, or others.

Session III: Case-Study Examples of Climate Trend Assessments, Data, and Scenario Needs for CBP Climate Assessments of Ecosystems

Downscaling Climate Models for Ecological Forecasting In Northeast U.S. Estuaries – **Barbara Muhling, Princeton/NOAA GFDL**

Contributors: Barbara Muhling[1,2], Carlos Gaitan[2,3], Desiree Tommasi[1,2] Charles Stock[2], Vincent Saba[2,4]
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1: Princeton University Program in Atmospheric and Oceanic Sciences
2: NOAA Geophysical Fluid Dynamics Laboratory
3: University of Oklahoma
4: NOAA Northeast Fisheries Science Center

The objective of this project is to apply a range of statistical downscaling techniques to northeast U.S. estuarine and nearshore environments, and to use these to project future habitat for diadromous fishes and habitats. We are particularly interested in the contribution of the downscaling method to overall uncertainty. Results presented here described the preliminary application of these statistical techniques to the Chesapeake Bay and Susquehanna River watershed.

Analyses of historical *in situ* observations showed that estuarine dynamics could be approximated using only the atmospheric variables available from general circulation models (air temperature, precipitation). An estuarine water temperature model was built using a non-linear lagged air temperature relationship, and verified using >25 years of *in situ* measurements. A water balance model using Hamon evapotranspiration was then applied to the Susquehanna River watershed, which supplies ~50% of freshwater inflow to Chesapeake Bay. Historical monthly river discharge (1970-2006) was well correlated with model predictions (R^2=0.8), with good bias characteristics once a correction for wind-induced snow under-catch was incorporated. Air temperature over Chesapeake Bay, and air temperature and precipitation over the Susquehanna watershed, were then downscaled using five different statistical techniques: bias correction quantile mapping, change factor quantile mapping, equidistant quantile mapping, cumulative distribution function transform, and a modified delta method. Projections from the IPSL-CM5A-LR general circulation model (GCM) under RCP8.5 were selected for the initial test case. Results showed that future modeled estuarine water temperatures from the downscaled methods were cooler in spring, but warmer in summer than the GCM, with substantial (~2°C) model spread at high temperatures. Similarly, the downscaled methods projected lower future catchment precipitation and higher air temperatures than the GCM, resulting in lower calculated Susquehanna River streamflow through 2100. Streamflow showed a slight negative trend between the present day and 2100, but may have been biased by the use of a highly temperature-dependent evapotranspiration metric. Overall, results suggested that use of different statistical downscaling methods may have the greatest influence on projections once air temperatures substantially exceed present day values, due to different ways of dealing with extrapolation within each method. Ongoing work will apply downscaled projections to new and existing models of distribution, recruitment and phenology for diadromous fishes and habitats.

Impacts of Climate Change on Chesapeake Oysters – Roger Mann and Ryan Carnegie, Virginia Institute of Marine Science

Oysters (*Crassostrea virginica*) provide ecosystem services in the Chesapeake Bay as benthic pelagic couplers, as structural complexity (reefs) in the benthos, and as a central component in the bay alkalinity budget. All such services are subject to modification in response to projected climate change. *C. virginica* occupies a remarkable latitudinal range from the Yucatan in the south (annual temperature range 23.4 – 29.3°C) to Prince Edward Island in the north (annual range -1.1 – 18.3ºC); it is also found in a wide range of salinity from 5ppt in the upper Chesapeake Bay to full seawater salinity in coastal embayments of the Atlantic coastline. Projected climate driven temperature and salinity changes in the Chesapeake Bay are within these ranges. The impact of resident oyster diseases (the non-native MSX and the native *Perkinsus marinus*) is increased at higher temperature and salinity, and remains a long term point of concern in bay oyster populations. Recent observations suggest that *P. marinus* is evolving in response to competition with the introduced MSX, and the oyster is responding to both of these changing disease challenges. Over the past decade the date of 50th percentile of oyster recruitment has occurred increasingly earlier in the year, a movement in excess of 30 days in the Piankatank and Great Wicomico Rivers, and slightly less so in the James River. In the Piankatank and Great Wicomico Rivers the changing period of recruitment has resulted in a larger mean size in Young of the Year (YOY) recruits in the fall months. Larger overwintering YOY proffer the option of increased survival at the year one class, and gradually increasing rates population expansion. In turn, increased production bodes well for shell accretion in reef habitats and accumulation of carbonate as a component of the Bay-wide alkalinity bank. The balance between recruitment, growth and mortality of live oysters, and the fate of shell as a substrate is not a static equilibrium, but more appropriately described as a moving baseline. What remains unresolved is (a) the question as to which of the complex climate drivers versus non climate drivers dominate the observed changes, and (b) our ability to predict where this movement will end.

***Climate Change and Ecological Forecasting in the Chesapeake Bay* – Howard Townsend, NOAA**

Beyond water quality, the Chesapeake Bay Program has a range of climate-related management needs focused on habitats and living resources. To address these needs requires an understanding of the effects of climate change at an ocean scale and estuarine scale. In the North Atlantic, climate change is predicted to result in: 1) increased sea surface temperature and surface salinity, 2) change in precipitation (resulting in salinity changes) and pH, as well as 3) changes in peaks and timing of primary productivity. This wide-sweeping range of changes at the ocean-scale becomes even more complex as we consider what might occur in the estuarine environment with its multi-faceted habitats and variety of important living marine resources. Given the wide array of changes and the complexity of the estuarine environment, assessing the impacts of climate change on Chesapeake Bay habitats and living resources is a formidable task. Working with partners, NOAA scientists have begun to make some initial attempts to assess some of these climate impacts in the bay at an ecosystem-level down the level of pathogens. This presentation highlighted some of these efforts, which although they are preliminary efforts, they are important first steps.

Loss of Coastal Marshes to Sea-level Rise – **Molly Mitchell, VIMS**

Marshes contribute to habitat and water quality in the Chesapeake Bay. Their importance to Bay functions has led to concerns about their persistence. In many areas, marshes are eroding, appear to be disappearing through ponding in their interior or are being replaced with shoreline stabilization structures. We undertook a study to examine the changes in marsh extent and community over the past 40 years to better understand the effects of human pressure and sea-level rise on marsh coverage.

Approximately 40 years ago, a tidal marsh inventory of the York River marshes established the historic marsh communities and their distributions. This inventory was re-done in 2010 to examine shifts in community composition, distribution and the extent of invasive species. Loss of marsh was apparent throughout the mainstem of the York River, however, there was some marsh gain near the turbidity maximum and where forested hummocks on marsh islands have become inundated. Shifts in marsh community composition between historic and current surveys were apparent although the type of shifts seen differed along the length of the river and between the north and south shores. One significant change in marsh community has been the introduction of Reedgrass (Phragmites australis) along the length of the York River. Indications of marsh flooding (possibly due to sea-level rise) can be seen in the York River system where areas which historically had significant high marsh communities appear to have converted almost entirely to low marsh. Indications of salinity shifts can also be seen where historically freshwater marshes now support brackish mixed communities.

Session IV: Climate Scenarios, Projections and Realizations

State Perspectives on Climate Change Scenario Selection – **Kate Johnson, DC and Jennifer DeMooy, DE**

Delaware Climate Projections: Methods and Findings

Jennifer de Mooy (Delaware Division of Energy and Climate) presented a short summary of how the state of Delaware had downscaled climate projections developed in 2012. The state's interest in having state-specific projections was driven in part by its coastal location and vulnerability to storm surge, sea-level rise, and flooding.

Delaware contracted with Katharine Hayhoe, Anne Stoner, and Rodica Gelca from ATMOS Research & Consulting to produce downscaled projections for temperature and precipitation indicators. The Hayhoe proposal was selected for its use of both CMIP3 and CMIP5 models in the analysis (CMIP5 models being new at the time). Dr. Hayhoe's downscaling methodology –

Statistical Asynchronous Regional Regression Model (ARRM) – has been widely used in a number of state, regional, and national assessments.

Delaware State Climatologist Daniel J. Leathers worked closely with Dr. Hayhoe's team to provide quality-controlled data from 14 Delaware weather stations. Local data is used in the AARM statistical downscaling analysis. Dr. Leathers also conducted a review of historic trends in temperature and precipitation, based on weather data from 1895 through 2012.

The projections analysis uses two scenarios: a higher and lower scenario corresponding with RCP 8.5 (higher) and RCP 4.5 (lower), for a time frame through 2100. Over 160 climate indicators were chosen for temperature, precipitation, and secondary indicators - relative humidity, heat index, and potential evapotranspiration. These can generally be grouped by averages and extremes. Averages include annual and seasonal averages, or percentage change; extremes include number of days > or < certain thresholds (e.g. days with maximum temperature >95˚F).

The methodology and findings of the climate projections analysis conducted for Delaware can be found in the Delaware Climate Change Impact Assessment: http://www.dnrec.delaware.gov/energy/Pages/The-Delaware-Climate-Impact-Assessment.aspx

To make the large volume of detailed data available to researchers and practitioners, the state of Delaware has recently launched the Delaware Climate Projections Portal. Through the Portal, projection data can be viewed or downloaded for any of the 14 weather stations for 55 climate indicators and for any selection of years up to 2100. The Portal is still in beta-testing stage, but can be accessed here: http://climate.udel.edu/declimateprojections/ . Please contact Jennifer de Mooy with any questions. (Jennifer.Demooy@state.de.us)

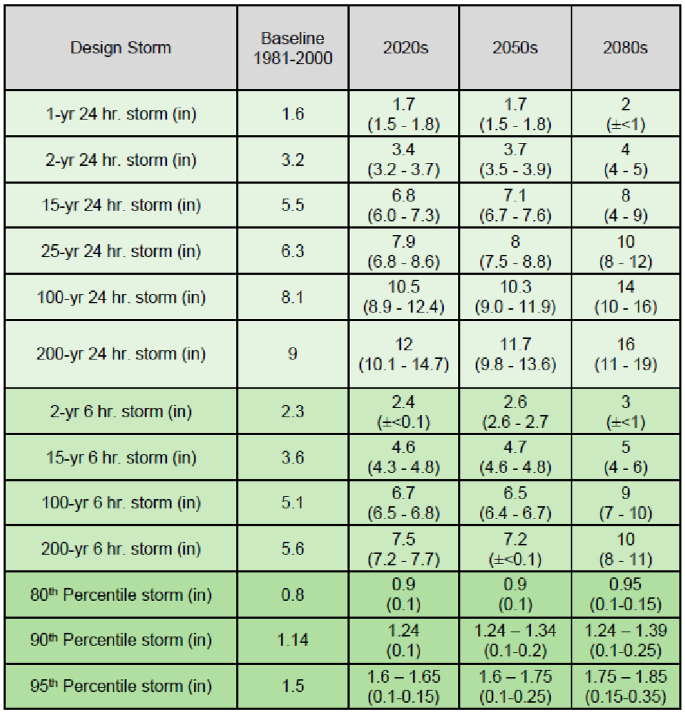
Climate Change Projections for Washington, D.C.

Kate Johnson, with the Department of Energy and Environment (DOEE), presented an overview of recently developed Climate Change Projections for Washington, DC. A recent study, conducted Katharine Hayhoe and, Anne Stoner from ATMOS Research & Consulting, used downscaling: a process of incorporating local data into global climate models in order to translate the results to the local level. Nine global climate models were used along with high and low emissions scenarios with local data from 3 weather stations. Daily temperature, precipitation, and humidity projections for 1960- 2100 were produced for the study. Climate projections were averaged over 20-year periods: Baseline (1981- 2000); 2020s (2015- 2034); 2050s (2045- 2064); and 2080s (2075- 2094). Climate indicators were then developed for the following temperature and precipitation variables:

Precipitation (Extreme Events)	**Precipitation (Extreme Events) cont.**
# of days/year with rainfall at or above 1 in	80th Percentile storm (in)
# of days/year with rainfall at or above 2 in	90th Percentile storm (in)
1-yr 24 hr storm (in)	95th Percentile storm (in)
2-yr 24 hr storm (in)	**Temperature (Average Temperature)**
15-yr 24 hr storm (in)	Summer Maximum Temperature (daytime)
25-yr 24 hr storm (in)	Summer Minimum Temperature (nighttime)
100-yr 24 hr storm (in)	**Extreme Events**
200-yr 24 hr storm (in)	# of heat waves per year
2-yr 6 hr storm (in)	Avg heat wave duration (in days)
15-yr 6 hr storm (in)	# of days/yr with heat index at or above 95 F
100-yr 6 hr storm (in)	# of days/yr with ambient temp at or above 95 F
200-yr 6 hr storm (in)	Increase in frequency of the 2012 heat wave

The modeling also derived extreme heat events (expressed in days over 95°F heat index) and looked at heat wave length and frequency. Heat waves, defined as 3 consecutive days when the heat index is above 95°F, are projected to be more frequent and last longer. Results of modeling for precipitation projections for DC indicate that observed trends in measures of extreme precipitation are expected to continue to increase. Charts show the number of days per year with more than 1" (top) and 2" (bottom) of precipitation in 24h. By the 2080s, the number of days per year with more than 2" of rain are expected to more than double from 2 days to 4.5 days under the higher scenario.

The project also included an analysis of "design storm" events. Changes in rainfall volumes have a significant impact on infrastructure. Design storms are the selected events that engineers use to design drainage infrastructure, bridges, culverts, etc. Input from DC Water, DDOT and DDOE's Stormwater Management Division informed the selection of events that are used as standards for stormwater, wastewater, and transportation infrastructure. The chart below shows how rainfall volumes are projected to increase across the relevant design storm events, especially for the more extreme (100 and 200 year) events.



Design Storm	Baseline 1981-2000	2020s	2050s	2080s
1-yr 24 hr. storm (in)	1.6	1.7 (1.5 - 1.8)	1.7 (1.5 - 1.8)	2 (±<1)
2-yr 24 hr. storm (in)	3.2	3.4 (3.2 - 3.7)	3.7 (3.5 - 3.9)	4 (4 - 5)
15-yr 24 hr. storm (in)	5.5	6.8 (6.0 - 7.3)	7.1 (6.7 - 7.6)	8 (4 - 9)
25-yr 24 hr. storm (in)	6.3	7.9 (6.8 - 8.6)	8 (7.5 - 8.8)	10 (8 - 12)
100-yr 24 hr. storm (in)	8.1	10.5 (8.9 - 12.4)	10.3 (9.0 - 11.9)	14 (10 - 16)
200-yr 24 hr. storm (in)	9	12 (10.1 - 14.7)	11.7 (9.8 - 13.6)	16 (11 - 19)
2-yr 6 hr. storm (in)	2.3	2.4 (±<0.1)	2.6 (2.6 - 2.7	3 (±<1)
15-yr 6 hr. storm (in)	3.6	4.6 (4.3 - 4.8)	4.7 (4.6 - 4.8)	5 (4 - 6)
100-yr 6 hr. storm (in)	5.1	6.7 (6.5 - 6.8)	6.5 (6.4 - 6.7)	9 (7 - 10)
200-yr 6 hr. storm (in)	5.6	7.5 (7.2 - 7.7)	7.2 (±<0.1)	10 (8 - 11)
80th Percentile storm (in)	0.8	0.9 (0.1)	0.9 (0.1)	0.95 (0.1-0.15)
90th Percentile storm (in)	1.14	1.24 (0.1)	1.24 – 1.34 (0.1-0.2)	1.24 – 1.39 (0.1-0.25)
95th Percentile storm (in)	1.5	1.6 – 1.65 (0.1-0.15)	1.6 – 1.75 (0.1-0.25)	1.75 – 1.85 (0.15-0.35)

Johnson discussed how changes in design storm events presents both implications and opportunities for further Modelling Drainage infrastructure is generally designed to handle rainfall from a 15-year event. Historically, that meant 5.5” of rain. In the future, a storm with the same frequency will bring rainfall of: 6.8” in the 2020s; 7.1” inches in the 2050s; and 8” inches in the 2080s. The result, without upgrades, could mean more frequent flooding and CSO discharges.

The Technical Report for the District of Columbia’s climate change projections can be found at: http://doee.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/Attachment%201%20.ARC_.Report_07-10-2015.pdf

A Climate Scenario Selection Tool – Phil Morefield, U.S. EPA

There are numerous archives of climate model output freely available. The size, complexity and diversity of data contained in these archives complicates the tasks of acquiring, processing and then analyzing these model outputs. In addition, most of these archives provide little, if any, guidance that helps answer the commonly asked question: “*Which climate projection(s) should I use*?”

A new Web tool under development at EPA will assist interested users in the process of identifying and processing climate model output. The LASSO project (**L**ocating **A**nd **S**electing **S**cenarios **O**nline) has two primary goals. First, to produce a simple, intuitive tool that provides access to climate model output, with some ability to process that information into meaningful statistics (e.g., seasonal climate deltas). Second, to provide a capability to visualize and explore climate model output in a way that helps illuminate those climate realizations that might be most useful to a particular user. The LASSO tool will present various *strategies* for selecting a specific set of climate projections that generally reflect model uncertainty and risk tolerance in the context of the user's particular needs.