

# Climate Change and the Chesapeake Bay: *State-of-the-Science Review and Recommendations*

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*A Report from the Chesapeake Bay Program Science and Technical Advisory Committee (STAC)*

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## Executive Summary

The U.S. EPA's Chesapeake Bay Program asked the Scientific and Technical Advisory Committee (STAC) to review current understanding of the impact of climate change on the tidal Chesapeake Bay and to identify critical knowledge gaps and research priorities. This report addresses that charge and provides the foundation for actions to accelerate the incorporation of climate change considerations into key resource management decisions.

Our literature review reveals an abundance of evidence from laboratory, field and numerical modeling studies that documents a high sensitivity of physical, chemical, and biological processes in the Bay to climate related forcings of atmospheric CO<sub>2</sub> concentration, sea level, temperature, precipitation (through streamflow), and storm frequency and intensity. Trends of warming and sea level increases over the 20<sup>th</sup> Century are well established in the Bay. Scenarios for CO<sub>2</sub> emissions indicate that by the end of this century the Bay region may experience significant changes in climate forcings with respect to historic conditions, including: CO<sub>2</sub> concentrations will be 50 to 160% higher, relative sea level will be 0.7-1.6 m higher, and water temperature will be 2-6° C higher. Also likely, though less certain, are increases in precipitation amount (particularly in the winter and spring), precipitation intensity, intensity of tropical and extratropical cyclones (though their frequency may decrease), and sea-level variability. The greatest uncertainty is associated with changes in annual streamflow, though there is some confidence that winter and spring flows will increase.

The high sensitivity of the Chesapeake Bay to climate suggests that the functioning of the Bay by the end of this century will be very different from what has been observed over the last century. These changes will be superimposed, exacerbated, and ameliorated by concurrent changes in human activities, notably urbanization, agriculture, resource management, and ecological restoration. Given the uncertainty in precipitation and streamflow forecasts, the direction of some changes is not known. However, some consequences appear relatively likely, including (1) the mean and variance of sea level will increase, increasing the likelihood of coastal flooding and submergence of estuarine wetlands; (2) salinity variability will increase on many time scales as a result of increases in precipitation intensity, drought, and storminess; (3) warming and higher CO<sub>2</sub> will select for harmful algae, such as dinoflagellates; (4) warming and greater winter-spring streamflow will increase hypoxia; (5) warming will reduce the prevalence of eelgrass, the dominant submerged aquatic vegetation in the Bay; (6) increases in CO<sub>2</sub> could mitigate some of the negative impacts of climate change on wetlands and eelgrass; (7) warming will alter interactions among trophic levels, and ultimately favor subtropical fish and shellfish species in the Bay. In addition, climate change will bring about cultural, social and economic responses, which currently are poorly understood, that will affect policies and programs to address climate change.

It is important to recognize that the scenarios considered here are not destiny for the Bay. The magnitude and, in some cases, the direction of impacts associated with climate change depend on the magnitude of CO<sub>2</sub> emissions over the next century. The scenarios considered in this study are based on particular combinations of assumptions about population, economic activity, and fossil fuel use. Lower emissions scenarios will produce less change in the Bay and reduce impacts on sensitive systems. There is still time to make choices that lead to lower

emissions outcomes and reduced impacts. However, it is also clear that all scenarios point to significant changes, and current trends point to higher emissions and higher relative impacts. Consequently, climate change is more than a future threat to the Chesapeake Bay, and the Bay Program and its partners can and should take action to assess the implications of changing climatic conditions and ensure that resource protection and restoration strategies will be effective under future conditions. This conclusion supports several general recommendations for the Bay Program and its partners. They can and should take immediate action to:

1. Understand the implications of climate change for important management decisions and, when possible, the consequences of management decisions for climate change (i.e., CO<sub>2</sub> emissions).
2. Identify and change policies or management actions that directly or indirectly increase CO<sub>2</sub> emissions or exacerbate vulnerability to climate change.
3. Ensure that monitoring systems can reliably detect signs of climate change and differentiate these signals from restoration or degradation.
4. Take immediate action to develop new approaches to ensure that restoration strategies and policies will be effective under changing climatic conditions.
5. Take a leadership role in the development of a comprehensive, Bay-wide Climate Change Action Plan to serve as a roadmap for mitigating the drivers and preparing for the consequences of climate change.

This report provides a foundation of information to support these recommendations. The report begins with Section I, a summary of knowledge gaps and their implications for the Bay Program. This is followed by Section II, a detailed review of scientific literature and research. Each section is organized around four interrelated issues: (1) physical drivers of change, (2) environmental monitoring, (3) impacts on restoration strategies, and (4) adaptive responses to climate change.

# Section I: Knowledge gaps and research priorities

## 1. Introduction

The Earth's climate is changing due to human activities. Global temperatures have risen by over 0.5° C in the last century, and models suggest far-reaching changes in climate during the next century [IPCC, 2007]. The United Nation's Intergovernmental Panel on Climate Change (IPCC) has repeatedly evaluated the consequences of these changes and found the potential for severe impacts on human health, ecosystems, water resources, and agricultural systems. The Chesapeake Bay research community has begun to consider the causes and consequences of climate change. As detailed in Section II of this report, it is likely that higher CO<sub>2</sub> concentrations, rising sea level, increasing temperatures, and changes in precipitation and storminess regimes will have far-reaching consequences for the Chesapeake Bay ecosystem and the Chesapeake Bay Program's goals for the restoration of water quality and living resources (as described in the *Chesapeake 2000* agreement).

This review focuses on four research themes that are directly relevant to the Chesapeake Bay Program:

- Climatic drivers of change
- Monitoring changing conditions
- Impacts of changing climate on restoration strategies and Bay Program goals
- Development of resilient and adaptive management strategies

These themes are interrelated; however, they are not fungible. Effort allocated to one issue cannot substitute for attention to the others. Similarly, priorities set in one area should not take precedent over priorities in other areas. They are all equally important elements required to understand and address climate change in the Chesapeake Bay. Effective action requires adequate consideration of each area, and, conversely, inattention to any category undermines the value of work in all of them. Section I of this report provides a set of conclusions, observations, and recommendations based on an extensive review of scientific research presented in Section II. The report also presents three types of prospective research questions associated with each theme:

- One **critical question** associated with each research area. Immediate efforts to address this question are critical to the success of the Bay Program
  - Two-to-four additional **important questions** presented after each critical question. These questions represent the next tier of issues, and they are important concerns with near-term implications.
    - Several additional **relevant technical questions** are presented throughout Section II. These questions reflect gaps in current scientific understanding and opportunities for productive lines of future research.

## 2. Climate drivers of change in the Chesapeake Bay

Climate variability and climate change create challenges for the restoration of water quality and living resources in the Chesapeake Bay. Understanding of spatial and temporal dynamics associated with physical drivers is essential for developing effective responses to these challenges. Researchers have identified a variety of physical changes through analysis of historic observations and climate system modeling, including past and projected changes in atmospheric CO<sub>2</sub> concentration, sea level, temperature, precipitation, streamflow, and storms (Section II.2). Trends and scenarios for sea level and temperature are relatively well constrained. However, the greatest uncertainty is associated scenarios for precipitation—perhaps the most important variable required to understand the future of the Chesapeake Bay. Spatial and temporal changes in precipitation patterns have far-reaching implications for the Bay through direct and indirect impacts on watershed hydrology (Section II.2.4) and essential biogeochemical processes (Sections II.3 and II.5.1). These impacts would likely be exacerbated by higher air temperature and concurrent stressors such as land cover change. **It is essential to pursue a more comprehensive and sophisticated understanding of potential changes in regional precipitation and the implications of potentially unprecedented combinations of temperature and precipitation.**

### **CRITICAL QUESTION:**

How will climate change alter regional precipitation patterns, and what are the most important aspects of precipitation change for ecosystem and watershed processes?

*Important questions about the climatic drivers of change:*

- What is the relationship between river flow and regional air temperature? How might this relationship change under future climatic conditions?
- Can existing watershed models (e.g., the CBP Phase V model) accurately simulate run-off and river flow regimes under plausible future combinations of precipitation and temperature?
- How will climate-driven changes interact with concurrent changes such as land use/land cover change, invasive species, and social and economic processes to alter the physical environment (e.g., the timing and magnitude of storm water run-off)?

## 3. Monitoring change

Environmental monitoring is an essential component of the Chesapeake Bay Program. Computer models and simulations are used to develop environmental policy and regulation, but the ultimate success (or failure) of the Program is based on real world conditions. Climate change adds to the already critical need for monitoring and creates new challenges. Chesapeake Bay monitoring systems must be designed to detect long-term trends *and* allow managers to differentiate changes driven by climate from those associated with restoration action or other sources of degradation. These distinctions are essential to understanding the efficacy of management actions and attributing the causes of change in ecosystem health and water quality. **It is essential that the Bay Program evaluate the consequences of climate change for existing monitoring systems and ensure that sampling designs provide adequate statistical power to detect trends and differentiate sources of improvement or degradation.**

**CRITICAL QUESTION:**

How should a Bay-wide monitoring system be designed, deployed, and operated to detect and differentiate climate-driven changes from the other sources of change?

*Important monitoring questions:*

- Can the existing monitoring system provide the statistical power needed to reliably detect trends in climatic variables associated with key management decisions, including peak water temperatures, summer wind regimes, and the frequency and severity of drought conditions?
- Which environmental measures provide the most sensitive indicators of climate change?
- Which environmental indicators are relatively insensitive to climatic change?
- How can information about the relative sensitivity of physical, chemical, and biological indicators be conveyed to policymakers, managers, and other stakeholders and used to inform resource management?

#### 4. Impacts on Chesapeake Bay Program restoration strategies

Understanding the physical drivers of change and consideration for the effectiveness of environmental monitoring ultimately creates the foundation for the most important questions facing the Bay Program: What are the implications of climate change for the Bay Program's efforts to restore water quality and living resources? Three of the Bay Program's most important strategies include:

- Bay-wide water quality regulation (e.g., Total Maximum Daily Load, TMDL)
- State tributary strategies designed to achieve the goals of the *Chesapeake 2000* agreement
- Activities to protect and restore living resources, such as submerged aquatic vegetation, oysters, and fisheries.

These strategies are central to the success of the Bay Program. They are all known to be sensitive to climate. Climate change is likely to undermine key assumptions used in current approaches to developing and deploying these strategies. For example, calculations used to estimate TMDLs are based on a carefully selected subset of historic meteorological observations. Trends in variables such as temperature or precipitation violate assumptions used in these calculations and undermine confidence in the results. There is no scientific basis for the lack of consideration for current and future trends in key climatic variables. **It is essential for the Bay Program to develop methods for calculating TMDLs that explicitly incorporate information about changing climatic conditions.**

State partners have developed restoration and resource protection plans called tributary strategies. These documents describe a combination of approaches needed to restore Bay water quality. The performance of individual management practices is central to the design of tributary strategies, and our understanding about their performance is based on observations under historic climatic conditions. For example, the ability of retention ponds to capture sediment and remove nutrients varies as a function of precipitation volume and intensity among other climatic factors. It is increasingly likely that practices based on historic precipitation regimes may not meet performance goals under future conditions. Similar considerations are relevant to the majority of



the 58 individual Best Management Practices used in state tributary strategies. **It is important for the Bay Program and its partners to assess the consequences of climate change for the efficacy of management practices.**

Similar considerations also apply to efforts to address living resources. Restoration efforts rely on understanding historic relationships between climatic conditions and ecological processes. However, changes in climate are likely to jeopardize these relationships. For example, planting of submerged aquatic vegetation (SAV) is a major emphasis for the Bay Program. However, some SAV species are known to be highly sensitive to peak summer temperatures and flow regimes (Section II.5.2). Climate change is likely to alter both of these variables and the likelihood of restoration success. Fortunately, it is possible to identify these climatic assumptions and take action to develop more sustainable restoration plans. For example, experience in other ecosystems has shown that it is possible to identify resilient sites where cool local waters offset rising regional temperatures and help sustain restored populations. **The Bay Program and its partners should assess the vulnerability of living resource restoration efforts to climate change and require projects to take specific steps to increase the likelihood of success under changing conditions.**

Each of these cases illustrates that climate change can have direct implications for key strategies used by the Bay Program. It is time for the Bay Program to consider these impacts in more detail, and, most importantly, take action to explicitly incorporate information about changing climatic conditions into analyses and decision making.

#### **CRITICAL QUESTIONS:**

- How can climate change be considered in the development of a Bay-wide regulation?
- How will state tributary strategies perform under changing climatic conditions?
- How will living resource restoration strategies perform under changing climatic conditions?

#### *Important climate change impact research questions:*

- How will climate change alter the cost or feasibility of achieving water quality and living resource restoration goals?
- What are the implications of sea-level rise for tidal wetland loss, shoreline and near-shore erosion, inundation of low-lying coastal communities, and the performance of shoreline hardening strategies?
- What are the implications of climate change for non-indigenous species, diseases, pathogens, and pest species?

## **5. Adaptive responses to changing climatic conditions**

Understanding the impact of climate change on Bay Program priorities provides the foundation for changes in management practice to prepare for and respond to changing conditions. The climate change science community calls such responses “adaptation.” This is a long-standing area of scientific research; however, interest is increasing as resource managers notice the early signs of climate change and recognize that additional impacts are likely and quite possibly inevitable.

Researchers distinguish between resilient and adaptive responses to climate change impacts. *Resilient* responses help increase the capacity of a human or ecological system to

respond to disturbance and accommodate changing conditions. Resilient responses typically do not require making assumptions or forecasts about future conditions, but rather they seek to identify opportunities to make decisions more robust to a range of future conditions. *Adaptive* responses go further by basing management on current observations and anticipated future conditions. Adaptive approaches are particularly appropriate for decisions associated with rising sea levels and temperatures where trends are clear and projections are consistent (Sections II.2.2 and II.2.5). In these situations, it would be irresponsible to base decisions with long-term consequences on historic observations alone. Moreover, it would be inefficient to simply plan for a very broad range of future conditions (i.e., “super-sized” infrastructure). It is possible to anticipate future conditions and design accordingly. As with any adaptive approach, effective and efficient action requires close coupling of management and monitoring to understand, prepare for, and respond to changing conditions. **The Bay Program and its partners can and should take action to increase the resilience of its activities to uncertain precipitation regimes and adapt to rising temperatures and sea levels.**

### **CRITICAL QUESTION:**

How can restoration strategies be designed, deployed, and monitored to ensure that they are resilient and adaptive to changing climatic conditions?

*Important climate adaptation questions:*

- How can water quality regulation be formulated to be more resilient to climatic fluctuations and anticipate changing climatic conditions?
- How can ecological restoration strategies be adapted to anticipate rising sea levels and changing temperature regimes?
- How should management practices be altered to increase their resilience to future precipitation regimes?
- How can coastal landowners make resilient and, when possible, adaptive decisions about their responses to rising sea levels?

## **6. Next steps**

Climate change is more than a future threat to the Chesapeake Bay. The Bay Program and its partners are making far-reaching decisions with implications decades into the future. In this context, climate change is an immediate consideration for efforts to protect and restore water quality and living resources. **It is essential that the Bay Program and its partners take immediate action to understand the consequences of changing climatic conditions and make the consideration for climate change an integral part of decision making.**

### **6.1 Understanding the consequences of climate change**

The Bay Program and its partners can and should take immediate action to address these issues through its existing authorities, responsibilities, and resources. The first, and perhaps most important step, is to explicitly recognize that climate change should be considered in a wide-range of resource management decisions: water quality regulation, tributary strategies, living resource restoration, and many others. These decisions are typically based on historic

climatic observations, and they are likely to be highly sensitive to climate change. **The Bay Program and its partners can and should immediately require all major resource management decisions to include an assessment that considers the consequences of changing conditions for the cost and efficacy of the action and explicitly considers management options that would increase resilience or facilitate adaptation to changing conditions.**

## 6.2 Understanding ecosystem processes

The Bay Program is confronted with significant uncertainties associated with the implications of climate change for key ecosystem processes. Some of the most pressing issues include:

- The implications of climate change for precipitation and evapotranspiration, particularly the representation of these processes in the Phase V watershed model (Sections II.2.3 and II.2.4).
- The impact of climate change on non-point source loadings (Sections II.3.1 and II.3.2).
- The role of food web dynamics in mediating the response of estuarine ecosystems to changing conditions (Section II.5).
- The consequences of climate change for specific targets, such as harmful algal blooms, the biogeography of disease, and fisheries productivity (Sections II.5.1.4 and II.5.4)

Efforts to address these issues will require acceleration and reorientation of existing lines of research. In some cases, it may create new motivations to address long-standing ecological issues, such as Bay food web dynamics. **The Bay Program and its partners can and should provide direct support and, where possible, encourage research sponsors to provide targeted resources for climate change-related research on key ecosystem processes.**

## 6.3 Research coordination and leadership

The current body of knowledge reflects a history where research efforts have generally been broad in scope and, with notable exceptions, lacking in depth and duration. This pattern results from decades of sporadic funding opportunities, the lack of institutional commitments, and the absence of widely-recognized research priorities. **There is no institutional focal point for climate change research and development activities relevant to the Chesapeake Bay.**

This situation contrasts with a number of regions with strong, long-standing relationships between climate science, public policy, and ecosystem restoration. For example, the Climate Impacts Group (CIG) at the University of Washington is an award-winning interdisciplinary research group that works to understand natural climate variability and global change to increase the resilience of the Pacific Northwest to fluctuations in climate. The CIG has contributed demonstrably to a foundation of knowledge that supports some of the most progressive public policy in the nation with regard to climate change (e.g., King County, Washington's 2007 Climate Plan). The Chesapeake Bay would benefit directly from a similar organization. **The Bay Program and its partners should take the lead in establishing an organization that links climate science, policy, and management throughout the watershed as quickly as possible.**

## 6.4 Climate Change Action Plan

An assessment of climatic assumptions and sensitivities provides immediate opportunities for improvements to internal Bay Program decision making processes. This is necessary but not sufficient to address the scope of the problem. It is equally important for the Bay Program to take a leadership role in addressing climate change across the watershed. One mechanism for achieving this is the development of a multi-jurisdictional, Bay-focused Climate Change Action Plan. This Plan would build on and complement state-level Climate Action Plans with a specific emphasis on impacts and adaptation opportunities relevant to the protection and restoration of the Chesapeake Bay. The plan should include a detailed roadmap for research and management to help the Bay Program achieve its mission under changing climatic conditions. The Bay-wide Climate Change Action Plan would also provide a focal point for identifying and coordinating policies, regulations, and strategies that contribute directly or indirectly to the drivers of climate change. **The Bay Program and its partners should take immediate action to promote and support the development of a Bay-wide Climate Change Action Plan.**

## Section II: Research review

### 1. Introduction

The goal of this section is to provide an up-to-date review of research relevant to climate change impacts on the Chesapeake Bay. This review does not cover the full depth of current understanding, but, to the degree possible, we have attempted to survey the breadth of relevant work. The section follows a logical progression from changes in physical conditions through their impacts on water quality and living resources to our current understanding about opportunities for adaptive management actions.

We limit the scope of our review to climate change impacts and adaptive management strategies, excluding mitigation activities such as the regulation of climate change drivers, most notably greenhouse gas emissions. We strongly believe that greenhouse gas mitigation is an essential component to solving climate-change related problems in the Chesapeake Bay and other estuaries. The magnitude and, in some cases, the direction of impacts associated with climate change depend on the magnitude of CO<sub>2</sub> emissions over the next century. The scenarios considered in this study are based on particular combinations of assumptions about population, economic activity, and fossil fuel use. Lower emissions scenarios will produce less change in the Bay and reduce impacts on sensitive systems. There is still time to make choices that lead to lower emissions outcomes and reduced impacts. However, it is also clear that all scenarios point to significant changes, and current trends point to higher emissions and higher relative impacts. The Bay Program may play a role in reducing emissions, particularly where its interests overlap with land use, agriculture, transportation, and infrastructure. Consideration for these issues is important but beyond the scope of this study. These issues require and deserve an independent investigation. We also limit the scope of the review to the tidal Chesapeake Bay, excluding terrestrial and freshwater impacts other than those that subsequently affect tidal areas of the basin. A number of recent reviews consider terrestrial impacts in and around the Chesapeake watershed [*Abler et al.*, 2002; *Iverson et al.*, 2008; *Moore et al.*, 1997; *Ollinger et al.*, 2008; *Paradis et al.*, 2008; *Rodenhouse et al.*, 2008; *Rogers and McCarty*, 2000; *Wolfe et al.*, 2008]

It is important to note that many of the activities and products described in the following sections are associated with a series of important research efforts including:

- Mid-Atlantic Regional Assessment (MARA), 1998-2000, funded by the Environmental Protection Agency
- Consortium for Atlantic Regional Assessment (CARA), 2003-2006, funded by the Environmental Protection Agency
- Northeast Climate Impacts Assessment (NECIA), ongoing, funded by the Union of Concerned Scientists
- Coastal Hypoxia Research Program (CHRP), ongoing, funded by the National Oceanic and Atmospheric Administration.

We also note that this report builds directly on a number of important earlier reviews, including those discussing the impact of climate change on ecosystems, coastal areas and marine resources of the mid-Atlantic region [*Moore et al.*, 1997; *Moss et al.*, 2002; *Najjar et al.*, 2000;

Rogers and McCarty, 2000; Wood et al., 2002], the United States [Field and Boesch, 2000; Scavia et al., 2002], and the World [Kennedy et al., 2002].

## 2. Climatic and hydrologic processes affecting the Bay

Estuaries, which have interfaces with the land, atmosphere and open ocean, can be influenced by climate change in a variety of ways (Figure 1): (1) the direct effect of changing atmospheric composition on the chemistry of the estuary; (2) changing water temperature; (3) changes in freshwater inflow quantity and quality that result from changes in the climate of the watershed (mainly precipitation and temperature); and (4) changes in forcing from the open ocean, including sea-level rise. This section discusses observed trends and future projections of atmospheric CO<sub>2</sub>, temperature, precipitation, streamflow and sea level in the Bay region. Changes in the quality of freshwater inputs are discussed in Section II.3.

### 2.1 Atmospheric composition

Being a well mixed gas in the atmosphere, regional and global projections of atmospheric CO<sub>2</sub> are essentially identical. Projections for global mean atmospheric CO<sub>2</sub> concentration over the next 100 years vary widely, mainly because of the uncertainty in future CO<sub>2</sub> emissions (Figure 2), but also because of unknown feedbacks between climate and the carbon cycle and differences in the representation of Earth system processes in simulation models. Because of the relatively short equilibration time of CO<sub>2</sub> at the air-sea interface (about 1 year), surface water CO<sub>2</sub> changes are expected to closely track atmospheric CO<sub>2</sub> changes. The most relevant consequence of this will likely be a decrease in pH and carbonate ion concentration, [CO<sub>3</sub><sup>2-</sup>], which are determined from the chemical equilibria of the carbonate system. Interest in CO<sub>3</sub><sup>2-</sup> stems from the fact that CaCO<sub>3</sub>-secreting organisms, like many shellfish, require [CO<sub>3</sub><sup>2-</sup>] to be above a certain level, typically the saturation concentration. Orr et al. [2005] showed that average [CO<sub>3</sub><sup>2-</sup>] and pH decreases of about 10% and 0.1, respectively, have already taken place throughout the surface ocean due to the invasion of anthropogenic CO<sub>2</sub>. Under a greenhouse gas scenario similar to the Intergovernmental Panel on Climate Change's SRES A2 storyline (Figure 2, Box 1), these changes increase to 45% and 0.5, respectively, by 2100. We are not aware of similar studies in estuaries, where salinity, alkalinity, dissolved inorganic carbon (which influence the sensitivity of pH and [CO<sub>3</sub><sup>2-</sup>] to CO<sub>2</sub>) may differ dramatically from their counterparts in seawater.

### 2.2 Water temperature

Figure 3 shows 20<sup>th</sup> century surface water temperature variability measured at two piers in the Chesapeake Bay, one located near the mouth of the York River, located 45 km from the mouth of the Chesapeake Bay [Austin, 2002], and the other located near the mouth of the Patuxent River, which empties into the central portion of the main stem of the Chesapeake Bay [Secor and Wingate, 2008]. Highly variability is superimposed on a long-term warming; the 1990s were about 1° C warmer than the 1960s, implying a warming trend of about 0.3° C per decade. Figure 3 also shows an estimate of surface water temperature averaged over the

mainstem Bay based on data from the Chesapeake Bay Water Quality Monitoring Program, which sampled the water column at least monthly at several dozen stations throughout the mainstem Bay since 1984. The correspondence between the pier and the Bay average data during the period of overlap indicates that the longer time series measured at the piers reflect mean Bay temperature quite well.

*Austin* [2002] noted a correspondence of the York River surface water temperature with the North Atlantic Oscillation (NAO) index, particularly when the data were averaged over several years (correlations of annually averaged quantities were much lower). He also determined that the beginning of spring, as defined by the time when water temperature first reaches 15° C (a critical temperature for when many Bay species spawn or migrate), occurred roughly three weeks earlier in the 1990s than in the 1960s. Analyzing the same York River water temperature time series, *Wood et al.* [2002] found significant warming trends existed in seven of the twelve calendar months falling within the spring, summer, and winter seasons. *Preston* [2004] analyzed surface ( $\leq 1$  m) and subsurface ( $\geq 15$  m) temperature data from the Chesapeake Bay Water Quality Monitoring Program (1984-2002), as well as historical data archived by the Chesapeake Biological Institute (from 1949). The annual water temperature anomalies were found to be positively and significantly ( $p < 0.05$ , Bonferroni adjusted  $t$ -test) correlated with regional air temperature as well as Northern Hemisphere mean air temperature, suggesting large-scale controls on Bay water temperature, consistent with *Austin's* [2002] connection of Bay temperature with the NAO and *Cronin et al.'s* [2003] finding of a strong correspondence between temperature anomalies in the Bay and on the continental shelf at monthly to interannual time scales since the 1980s. *Cronin et al.* [2003] also documented several rapid shifts of Chesapeake Bay spring temperature of  $\sim 2$ - $4^\circ$  C during the past two millennia. Mean spring water temperature was found to be 1.6 and 2.5° C higher during the 20<sup>th</sup> century than during 1720-1850.

An important finding from the temperature studies is that there is a high correlation between water temperature in the Bay and regional atmospheric and oceanic temperature at time scales ranging from monthly to decadal. Thus, it seems likely that the regional temperature projections made from climate models can be applied directly to the Bay. This is fortunate because climate models, even nested regional climate models, are currently not able to resolve the Bay itself.

Two recent studies have analyzed the output of global climate models (GCMs) in the Chesapeake Bay region. As part of CARA, *Najjar et al.* [2008] analyzed the output of seven GCMs over three major mid-Atlantic estuaries (Chesapeake Bay, Delaware Bay and the Hudson River Estuary). Projections were found to differ greatly among the models (Figure 4), but historically the multi-model average generally performed better than individual models. The multi-model average was able to track the observed 20<sup>th</sup> century warming of the northern watersheds (Hudson, Delaware, and Susquehanna), but not the weak cooling observed in the southern portion of the Chesapeake watershed [e.g., *Allard and Keim*, 2007]. The multi-model average also simulated the long-term annual average temperature well, but overestimated the annual temperature range (summer minus winter) and interannual variability. Model-averaged projections for the six scenarios shown in Figure 2 range from 3 to 6° C warming by 2070-2099 (Figure 5a). When the best-performing models are used, the projected warming decreases to 2-5° C (Figure 5c). As part of NECIA, *Hayhoe et al.* [2007] conducted an analysis of nine global climate models for the Northeast U.S. (Pennsylvania to Maine), which includes the northern half of the Bay watershed (essentially the Susquehanna River Basin). They also found that the multi-

model average captures the observed long-term increase in annual-mean regional air temperature over the 20<sup>th</sup> century, including the acceleration during the last 30 years. Projected temperature changes are similar to those of *Najjar et al.* [2008].

Changes in temperature extremes are as important as annual mean temperature changes, as noted below for submerged aquatic vegetation (Section II.5.2). *Meehl et al.* [2007] analyzed the output of nine global climate models for changes in heat waves, defined as “the longest period in the year of at least five consecutive days with maximum temperature at least 5° C higher than the climatology of the same calendar day.” Under the A1B scenario, heat waves along the east coast of North America, including the Mid-Atlantic, are projected to increase by more than 2 standard deviations by the end of the 21<sup>st</sup> century.

## 2.3 Precipitation

Though precipitation falling directly on Chesapeake Bay has a very small influence on the Bay’s overall water balance, precipitation falling on the Bay watershed is extremely important in regulating streamflow to the Bay, which is a dominant driver of Bay circulation, biogeochemistry, and ecology. Several studies have documented 20<sup>th</sup>-century increases of precipitation in the United States, including the Northeast, particularly in extreme wet events [*Groisman et al.*, 2001; *Groisman et al.*, 2004]. Climate models have, in general, not been able to simulate this long-term change in precipitation in the Northeast U.S. [*Hayhoe et al.*, 2007; *Najjar et al.*, 2008]. Climate models are able to capture long-term means of annual, winter, and summer precipitation over the Chesapeake Bay watershed, though there is a tendency to predict too much precipitation in spring and too little in fall [*Najjar et al.*, 2008]. *Hayhoe et al.* [2007] and *Najjar et al.* [2008] show similar results regarding GCM precipitation predictions under enhanced greenhouse gas levels: (1) multi-model averages of more annual precipitation (Figure 5c and 5d), (2) a wide spread among models of annual precipitation change (Figure 4), and (3) greater consensus among the models in winter and spring, when precipitation is projected to increase (Figure 4). For example, over the Chesapeake Bay watershed, precipitation projections range from -17% to +19% (multi-model mean of 3%) for 2070-2099 with respect to 1971-2000 under the A2 scenario [*Najjar et al.*, 2008]; in winter, the model range is -5% to +16% (multi-model mean of 8%). The wide spread in modeled precipitation changes reflects the fact that the Mid-Atlantic region lies at the boundary between subtropical precipitation decreases and subpolar precipitation increases; consensus increases for the winter results as this boundary moves south [*Meehl et al.*, 2007].

An important characteristic of precipitation is its intensity, particularly for watershed export of sediment, phosphorus, and (to a lesser extent) nitrogen to estuaries (Section II.3.1 and II.3.2). Defining this as the annual mean precipitation divided by the number of days with rain, *Meehl et al.* [2007] showed that many models predict significant increases of precipitation intensity, particularly at middle and high latitudes, including the Mid-Atlantic region. Under the A1B scenario, Mid-Atlantic precipitation intensity is expected to increase by 1 standard deviation by the end of the 21<sup>st</sup> century. The increase in precipitation intensity was found to be a result of the increase in annual precipitation as well as the number of dry days, a finding consistent with changes in storm frequency and intensity (Section II.2.6).

## 2.4 Streamflow



Streamflow reaching Chesapeake Bay is governed by how much precipitation falls on its watershed, but also by evapotranspiration loss to the atmosphere, and by watershed storage changes. Over interannual timescales, storage changes are believed to be small, and thus streamflow is simply equal to the excess of precipitation over evapotranspiration averaged over the watershed. Averaged over many years, streamflow to the Bay is about 40% of precipitation over its watershed [*Sankarasubramanian and Vogel, 2003*]. Much of the interannual variability in streamflow to the Bay is driven by precipitation, with a relatively small role for evapotranspiration. For example, *Najjar [1999]* found that 89% of the variability of annual-average Susquehanna River flow (which is half of the total freshwater flow to the Bay) is explained by watershed precipitation. *Austin [2002]* examined the 1957-2000 record of annual streamflow into the Chesapeake Bay and found substantial interannual variability (a range of more than 2.5) as well as decadal variability characterized by dry conditions during the 1960s, wet conditions during the 1970s, and relatively normal conditions since then. No obvious long-term trend was noted, though the Northeast has been characterized as a region of increasing streamflow, particularly in extreme wet events [*Groisman et al., 2001; Groisman et al., 2004*].

A longer-term perspective on flow into the Chesapeake Bay was provided by *Saenger et al. [2006]*, who used salinity proxy data and streamflow-salinity relationships to infer variability in Susquehanna River flow throughout the Holocene. Their analysis suggests that average streamflow 6000-7000 years ago was 72% lower than it has been during the past 1500 years. Large decadal and centennial variability during the last 1500 years was also inferred.

Previous hydrological modeling studies found widely varying streamflow projections in the Northeast U.S. (Table 1), even when forced by the same climate models [*Neff et al., 2000; Wolock and McCabe, 1999*]. This is a puzzling result, especially given that hydrological models generally are able to accurately hindcast the historical streamflow record in the Mid-Atlantic Region [e.g., *Hayhoe et al., 2007; Najjar, 1999; Swaney et al., 1996; Wolock et al., 1996*]. However, most of the past variability is due to changes in precipitation. The discrepancy in future projections most likely arises because models predict different evapotranspiration responses (and therefore streamflow responses) to temperature change. This divergence is probably due to the lack of an observational record of *substantial* temperature change with which to constrain hydrological models. For example, the standard deviation of annual air temperature over the Chesapeake Bay Watershed is 0.5° C [*Najjar et al., 2008*], which is small compared with the multi-model mean projected 100-year warming (Figure 5). Other confounding influences on streamflow, which are generally not considered in future projections, include vegetation changes, the direct influence of CO<sub>2</sub> on evapotranspiration, and land use change (predominantly urbanization, agriculture, and forestry).

The seasonality of streamflow into the Chesapeake Bay is extremely important because it helps to regulate the timing of the spring bloom (Section II.5.1.1). Hydrological model simulations by *Hayhoe et al. [2007]* in the U.S. Northeast predict greater wintertime flows (due to snow melt) and depressed summer flows (due to increased evapotranspiration). They also predict an advance of the spring streamflow peak of nearly 2 weeks. A statistical approach by *Schoen et al. [2007]* combined with climate model output suggests that the 7Q10 will decrease substantially in the future. Early water balance studies of the Susquehanna River Basin also suggest greater winter flows but there is less agreement on summer flows and timing of the spring freshet [*Najjar, 1999; Neff et al., 2000*]. January-May average flow of the Susquehanna has been used to predict summertime circulations parameters [*Hagy, 2002*] and dissolved oxygen levels [*Hagy et al., 2004*]. Historically, there is a strong correlation between January-May flow

and precipitation in the Susquehanna River Basin such that fractional flow increases are equal to fractional precipitation increases [Najjar, 2008]. Given the consensus among models regarding spring and winter precipitation increases, it seems fairly likely that January-May flow of the Susquehanna River will increase in the future.

Due to the greater number of precipitation-free days as well as the greater evapotranspiration (resulting from higher temperatures), drought is expected to increase in the future. Defining drought as a 10%-or-more deficit of monthly soil moisture relative to the climatological mean, Hayhoe *et al.* [2007] simulated increases in droughts of different durations over the Northeast U.S. For example, the number of short-term (1-3 months) droughts was projected to increase 24-79% (B1 & A1F1 scenarios) by 2070-2099 with respect to 1961-1990. Medium (3-6 months) and long (> 6 months) droughts had even larger fractional increases. This has implications for the functioning of terrestrial ecosystems (particularly wetlands) in the Bay watershed. Greater drought frequency also is likely to mean a greater frequency of saltwater intrusion events into the Bay.

## 2.5 Sea level

Tide gauge measurements reveal a steady increase in sea level throughout the Chesapeake Bay during the 20<sup>th</sup> Century (Figure 5). Global-mean sea surface height increased at a rate of  $1.8 \pm 0.3 \text{ mm yr}^{-1}$  over the second half of the 20<sup>th</sup> Century [Church *et al.*, 2004], and there is evidence that this rate is increasing [Church and White, 2006]. Sea-level rise during the second half of the 20<sup>th</sup> Century has been monitored accurately at six sites in the Chesapeake Bay and ranges from 2.7 to 4.5  $\text{mm yr}^{-1}$ , with an average of 3.5  $\text{mm yr}^{-1}$  [Zervas, 2001]. The enhanced rate of sea-level rise in the Bay most likely reflects geological processes associated with the retreating ice sheet to the north of the Bay during the end of the last glacial period [Davis and Mitrovica, 1996]; the presence of the glacier caused the land to bulge in front of it (in the Bay region), and the subsequent retreat resulted in sinking of the land. Water withdrawals from underground aquifers have also been alleged to cause significant subsidence, but hard evidence is lacking. Rahmstorf [2007] noted that rates of historic sea-level rise calculated with climate models tend to be too low, most likely because ice sheet dynamics are poorly understood. He developed a semi-empirical approach that predicts global sea-level increases of 700 to 1000 mm by 2100 for a range of scenarios spanning B1 to A1FI (Figure 2d). Allowing for errors in the climate projections and in the semi-empirical sea-level rise model, the projected range increases to 500 to 1400 mm. If we add a Chesapeake Bay local component of 2  $\text{mm yr}^{-1}$  to this, we obtain sea-level increases of approximately 700 to 1600 mm by 2100.

Future increases in mean sea-level are likely to be accompanied by increases in sea-level variability. As noted below (Section II.4.1), the tidal range is likely to increase as a result of increases in mean sea level in the Bay. Further, increases in extreme wave heights are likely to accompany the expected increases in intense storms, both tropical and extratropical, discussed next.

## 2.6 Storms

Tropical cyclones and extratropical winter cyclones can have dramatic and long-lasting effects on estuaries. For example, 50% of all the sediment deposited in the Northern Chesapeake Bay between 1900 and the mid-1970s was due Tropical Storm Agnes (June 1972) and the

extratropical cyclone associated with the Great Flood of (March) 1936 [Hirschberg and Schubel, 1979]. In October 2003, the winds associated with Hurricane Isabel produced a maximum storm surge of 2.7 m in the Chesapeake Bay and also mixed the estuary, resulting in biogeochemical and ecological changes that were felt into the following spring [Roman *et al.*, 2005].

Trenberth *et al.* [2007] summarized recent studies on tropical cyclone trends, noting a significant upward trend globally in their destructiveness (due to intensity and lifetime decreases) since the 1970s, which is correlated with sea surface temperature. Christensen *et al.* [2007] and Meehl *et al.* [2007] summarized future projections in tropical cyclones, concluding that it is likely that peak wind intensities will increase.

Past and future trends in tropical and extratropical cyclones are fairly clear at the hemispheric scale but not at the regional scale. There is good evidence that, for the middle latitudes (which include Chesapeake Bay and its watershed), winter extratropical storm frequency decreased and intensity increased over the second half of the 20<sup>th</sup> century [McCabe *et al.*, 2001; Paciorek *et al.*, 2002]. However, an analysis of U. S. East Coast extratropical winter storms shows no significant trend in frequency and a marginally significant ( $\alpha = 0.10$ ) decline in intensity [Hirsch *et al.*, 2001]. Lambert and Fyfe [2006] show remarkable consistency among GCMs in the future projections of winter extratropical cyclone activity. For the A1B scenario (see Figure 2), the multi-model means over the Northern Hemisphere are a 7% decrease in frequency of all extratropical winter cyclones and 19% increase in intense extratropical winter cyclones, comparing the 2081-2100 period to the 1961-2000 period. Christensen *et al.* [2007] summarize a number of future climate modeling studies and conclude that it is future decreases in the total number of extratropical cyclones and increases in intensity are likely. We are not aware of any studies that focus on cyclone changes in Chesapeake Bay region. In a study focused on North America, Teng *et al.* [2007] suggest that cyclone frequency in the Northeast U.S. will decrease, though they note that regional projections should be used with caution.

## 2.7 Climatic and hydrologic processes summary

The uncertainty in future climate forcing of the Chesapeake Bay region varies dramatically among the proximate important forcing agents (atmospheric CO<sub>2</sub>, water temperature, sea level and streamflow). Much greater certainty exists for projected trends in atmospheric CO<sub>2</sub>, water temperature and sea level (all increasing) than for streamflow and storminess. The uncertainty in streamflow projections stems from uncertain precipitation predictions and hydrological model uncertainty. However, it seems likely that winter and spring streamflow will increase. Further, heat waves and precipitation intensity are likely to increase, which will likely result in greater extremes (high and low) of streamflow.

### **Summary of questions for Section 2—Climatic processes:**

- What are the projected changes in pH and carbonate ion concentration in Chesapeake Bay?
- How can we reduce the range of future precipitation projections and assign reliable uncertainty estimates to these projections?
- Why do climate models fail to capture the historic increase in precipitation in the Chesapeake Bay watershed?
- Why is the historic rate of warming in the lower Chesapeake watershed substantially lower than that in the upper portion of the watershed?

### 3. Fluxes of nutrients and sediment from the watershed

Most of the nutrient inputs to Chesapeake Bay come from non-point sources such as agriculture and atmospheric deposition. The fluxes of sediments and nutrients from the landscape are profoundly affected by climate, and so it is reasonable to expect that climate change will influence non-point source (NPS) pollution. A limited body of research has begun to examine the implications of climate change for NPS pollution of nutrients and sediment in the Chesapeake Bay watershed. We first consider sediments and phosphorus; most NPS phosphorus pollution is particle bound, so the controls on sources and fluxes of both sediment and phosphorus are similar [Howarth *et al.*, 1995; Howarth *et al.*, 2002; Moore *et al.*, 1997; Sharpley *et al.*, 1994; Sharpley *et al.*, 1995]. We then consider nitrogen, which moves through the landscape primarily in dissolved forms and thus has sources and fluxes that are quite different from those of phosphorus and sediment [Carpenter *et al.*, 1998; Howarth *et al.*, 1996; Howarth *et al.*, 2002]. We consider the role of atmospheric deposition—particularly atmospheric deposition onto forests—in more detail because of the large uncertainties involved, as well as the likely climatic sensitivity. We then discuss the role of wetlands as a nitrogen sink in the landscape, and how climate may influence this. We end Section 3 with a brief discussion of the climatic influence on point sources of nutrient pollution.

#### 3.1 Non-point pollution by sediments and phosphorus

One major control on NPS sediment and phosphorus pollution is the rate of erosion, which is influenced by the interaction of land-use patterns and climate [Meade, 1988; Moore *et al.*, 1997]. Erosion rates from forest ecosystems are quite low, whereas erosion from agricultural lands, impervious surfaces, and construction sites can be very high [Swaney *et al.*, 1996]. Meade [1988] estimated that the conversion of forests to agricultural lands in the eastern U.S. between 1700 and 1900 probably increased erosion rates by 10-fold or more. Erosion occurs when water flows over these surfaces, and that in turn occurs when soils are saturated with water or during major precipitation or snowmelt events. Erosion is less in forests than in disturbed landscapes because the forest vegetation keeps the soil intact and because evapotranspiration rates are higher, lessening the amount of surface water runoff.

Annual sediment loading to the Chesapeake Bay is a non-linear function of annual streamflow (Figure 7). This indicates an increase in total suspended sediment concentration as flow increases, likely resulting from enhanced erosion and resuspension of sediments in the streambed. Thus, we can expect erosion from disturbed lands to increase if climate change were to result in increased stream discharge, though note the large uncertainty in future flow projections in the mid-Atlantic region (Section II.2.4, Table 1). However, even if the mean discharge were to remain unchanged, erosion could increase if the precipitation intensity were to increase, a projection that appears to be more certain (Section II.2.3). To date, there has been little if any testing of how various climate change scenarios may affect erosion in the watersheds of the Chesapeake Bay.

Phosphorus pollution from NPS is a function of the amount of phosphorus associated with eroded soils in addition to the rate of erosion. Agricultural soils are elevated in phosphorus compared to forest soils because of the addition of inorganic fertilizers and manure [Carpenter *et al.*, 1998; Sharpley *et al.*, 1994; Sharpley *et al.*, 1995]. With the increasing concentration of

animal agriculture in the US since the 1950s, the addition of phosphorus from animal wastes now exceeds any potential uptake by crops in many areas, including much of the Chesapeake Bay watershed [Howarth *et al.*, 2002; Kellogg and Lander, 1999]. Not only can erosion of these P-rich agricultural soils be a major source of phosphorus pollution, but the problem remains as agricultural lands are converted into suburban landscapes; phosphorus losses can be particularly great from erosion at construction sites when the soils are former agricultural soils, and even storm water retention ponds and wetlands can be major sources of NPS phosphorus pollution if the systems are constructed with P-rich soils [Davis, 2007].

### 3.2 Non-point pollution by nitrogen

Nitrogen NPS pollution is controlled by an interaction of nitrogen inputs to the landscape and climate. For many large watersheds and regions in the temperate zone—including the major tributary rivers of the Chesapeake Bay—the average export flux of nitrogen per area of watershed is 20 to 25% of the net anthropogenic nitrogen inputs (NANI) to the watershed or region, where NANI is defined as the use of synthetic nitrogen fertilizer, nitrogen fixation associated with agro-ecosystems, atmospheric deposition of oxidized forms of nitrogen (NO<sub>y</sub>), and the net input of nitrogen in foods and feeds for humans and for animal agriculture [Boyer *et al.*, 2002; Boyer and Howarth, 2008; Howarth *et al.*, 1996]. However, the percentage of NANI that is exported out of a watershed in rivers is related to climate. For the Mississippi River, McIsaac *et al.* [2001] demonstrated that the large annual variation in nitrate export could be explained by a simple model that considers NANI and discharge; the model allows more storage of NANI in the watershed during dry years and greater export of the stored NANI in years when discharge was higher. Similarly, Boynton and Kemp [2000] showed that years with high runoff resulted in enhanced nutrient export from the Chesapeake Watershed. Castro *et al.* [2003] modeled nitrogen fluxes to the major estuaries of the United States, including Chesapeake Bay, as a function of NANI, land use, and climate. Their models suggested that land use is a very important factor in determining export of NANI, with greater export from urban and suburban landscapes and much lower export from forests, and that land use and climate may interact strongly.

In addition to climate influencing nitrogen fluxes through the wet-dry cycles described above, Howarth *et al.* [2006] suggested climate may also influence the sinks of nitrogen in the landscape, and that average climate over many years may therefore affect the percentage of NANI exported downstream to estuaries. They compared this average percentage export of NANI across 16 major river basins in the northeastern US that vary significantly in climate, with higher precipitation and freshwater discharge and lower temperatures in the more northerly watersheds (Figure 8). In the watersheds where precipitation and river discharge is greater, the percentage of NANI that flows downriver to coastal ecosystems is up to 40-45%, while in drier regions only 10-20% is exported over long-term periods [Howarth *et al.*, 2006]. There may also be a relationship to temperature, with greater percentage exports where the climate is cooler, but the relationship is not as strong as for precipitation and discharge and is not statistically significant [Howarth *et al.*, 2006]. Howarth *et al.* [2006] attributed the influence of climate on nitrogen export to act through sinks of nitrogen in the landscape, with less denitrification in the wetter watersheds due to lower water residence times in wetlands and low-order streams. Several models suggest that denitrification is the greatest sink for nitrogen in these northeastern watersheds [van Breemen *et al.*, 2002].

*Schaefer and Alber* [2007] expanded on the analysis of *Howarth et al.* [2006] by analyzing data both from the 16 northeastern watersheds and from the major watersheds in the southeastern United States. This larger data set showed a significant influence of temperature, with low percentage export of NANI at high temperatures and a greater percentage export of NANI at low temperatures ( $r^2 = 0.76$ ,  $p < 0.0001$ ). *Schaefer and Alber* [2007] attribute the temperature effect on export to act through denitrification, with warmth favoring higher rates. However, temperature was not a significant factor in explaining percentage export of NANI within the southeastern watersheds, just as it was not within the northeastern watersheds. The significant correlation with temperature observed by *Schaefer and Alber* [2007] is driven by the large temperature difference between the northeastern and southeastern regions. Other controlling factors such as soil types may be at play across this larger data set. For example, the soils in the southeast are much older than those in the northeast, where glaciation is much more recent, and the older soils may be more sorptive of nitrate (*Howarth et al.*, manuscript in preparation).

A better understanding of the influence of climate on the percentage export of NANI is critical to predicting the effects of climate change on nitrogen inputs to Chesapeake Bay. As discussed above, climate change will lead to both higher temperatures and greater precipitation and discharge in the watersheds of the Chesapeake. *Howarth et al.* [2006] conclude that the wetter environment will lead to greater nitrogen fluxes from the landscape, while *Schaefer and Alber* [2007] suggest the temperature influence will be more important, and that higher temperatures lead to lower nitrogen fluxes.

Evaluating the influence of precipitation and discharge, *Howarth et al.* [2006] developed a simple predictive equation that uses average precipitation or discharge and NANI to explain the mean flux of nitrogen in rivers in the Northeast U.S. with reasonably high precision ( $r^2 = 0.87$  to  $0.90$ ). They used the NANI and precipitation equation to predict possible climate change consequences on nitrogen fluxes for the Susquehanna River basin; the Susquehanna is the single largest source of nitrogen to the Chesapeake Bay. Given the climate change predictions for increased precipitation presented by *Najjar et al.* [2000], and assuming no change in NANI or land use, *Howarth et al.* [2006] predicted an increase in nitrogen flux down the Susquehanna River of 17% by 2030 and 65% by 2095 (associated with precipitation increases of 4% and 15%, respectively). More updated precipitation projections for the Susquehanna River Basin [e.g., Figure 4; *Hayhoe et al.*, 2007; *Najjar et al.*, 2008] would yield similar results.

If temperature is the major factor controlling the percentage export of NANI, as *Schaefer and Alber* [2007] conclude, a warming of 3° C would decrease the nitrogen flux down the Susquehanna by about 20%, a trend opposite that predicted by *Howarth et al.* [2006]. Note, however, that while *Schaefer and Alber* [2007] focused on the negative correlation between temperature and fraction of NANI exported by rivers, they reported a similarly strong positive correlation between the fraction of NANI export and discharge ( $r^2$  of 0.76 and 0.74, respectively with  $p$  values for both  $< 0.0001$ ). Evaluating the controls on percentage NANI export from the landscape—including climatic variables such as temperature, precipitation, and discharge, but also variables such as soil types and depth, topography, and vegetation type—should be a high research priority.

Process-based simulation models of biogeochemical cycling in watersheds offer one approach for assessing the impact of climate change on riverine N export to coastal waters. Many such models exist and could potentially be used. Note, however, that these models all make explicit assumptions about the relationship between climate and nitrogen flux. Their

predictions are only as good as are the underlying assumptions. The current level of uncertainty about the importance of underlying mechanisms that relate nitrogen flux to climatic controls inherently limits the usefulness of simulation models. Another weakness of process-based models is that they treat organic forms of nitrogen poorly. Much of the flux of nitrogen in rivers occurs as inorganic nitrogen, and it is commonly assumed that human activity largely affects these inorganic nitrogen fluxes and that organic fluxes remain relatively constant [Howarth *et al.*, 2002]. However, Brookshire *et al.* [2007] have recently demonstrated that increased atmospheric deposition can increase the export of organic nitrogen from forests.

The only process-model-based climate change study of N export we are aware of in the watersheds of Chesapeake Bay is that of Johnson and Kittle [2007], who simulated the response of annual nitrogen loading in the Western Branch of the Patuxent River, Maryland to changes in annual mean air temperature and precipitation (Figure 9). Their sensitivity analysis was conducted through iterative runs of an HSPF watershed model using a new extension to the widely-used BASINS water quality modeling system called the Climate Assessment Tool. Their work predicts that N export decreases by about 3% for a temperature increase of 1° C, and increases by 5% for a precipitation increase of 5% (Figure 9). The temperature and precipitation sensitivity of N export is smaller than that of discharge (14% ° C<sup>-1</sup> and 2.4% %<sup>-1</sup>, respectively, not shown), indicating that stream N levels in the model increase under warming and decrease under higher precipitation.

### 3.3 Atmospheric deposition of nitrogen

As noted above, the nutrient load to Chesapeake Bay is dominated by non-point sources. Agricultural sources are reasonably well known, but significant uncertainty remains about the magnitude of inputs from atmospheric deposition. Depositional inputs occur both onto the landscape with subsequent export to the Bay and directly onto the surface of the Bay, and include both wet deposition and deposition as dry gases and particles. The dry deposition remains difficult to characterize, although progress in our understanding is being made. The dry deposition of many abundant nitrogen pollutant gases (such as NO, NO<sub>2</sub>, HONO, and NH<sub>3</sub>) is not measured in any of the national deposition monitoring programs (NADP, CASTnet, or AIRMon). The most recent runs of the CMAQ model (an emission-based model of atmospheric deposition that includes real time meteorology and atmospheric chemistry, and estimates deposition at the scale of a 12-km grid) suggest that 30% of the total deposition in the watershed of the Chesapeake Bay is simply not measured in current monitoring efforts [Denis, 2007].

Another major uncertainty is the proportion of deposition onto the landscape that is exported. Many forests retain most deposited nitrogen and export only a small amount, but this can vary with climate and with the nitrogen status of the forest [Aber *et al.*, 2003; Castro *et al.*, 2007]. Some nitrogen-saturated forests in western Maryland export more nitrogen than they receive in wet deposition during wet years and retain a much higher percentage of nitrogen inputs in dry years [Castro *et al.*, 2007]. Forests make up 58% of the Chesapeake Bay Basin [Sprague *et al.*, 2006], and small differences in the amount of nitrogen exported from them can make a large difference in the overall nitrogen budget of Chesapeake Bay. The export of deposition from other land types is far greater, but also quite uncertain [Howarth *et al.*, 2002]. As estimates of deposition have been revised in recent years, estimates from the Chesapeake Bay Program's model of the overall importance of atmospheric deposition have risen steadily, from less than 20% in 2002 to 32% currently [Shenk, 2007]. Other studies estimate the nitrogen inputs

to Chesapeake Bay as contributing from 14% to 64% of the total nitrogen load [Castro *et al.*, 2003; Howarth, 2006].

Climate change may alter both the pattern of nitrogen deposition (due to changes in reaction kinetics, precipitation, and wind patterns) and the retention of nitrogen once it is deposited. Some of the factors that control the retention versus export of nitrogen from the landscape were discussed briefly above (Section II.3.2). Another way in which climate change could influence this partitioning is through impacts on growth and productivity of forests, which have been shown to strongly influence the retention of deposited nitrogen [Aber *et al.*, 1998]. The impact of these changes may be mediated by forest disturbances, such as gypsy moth outbreaks [Eshleman *et al.*, 2000], which may also be sensitive to climatic variation and change [Gray, 2004].

Climate change eventually will lead to major changes in the species composition of forests, and these changes too are likely to influence nutrient export. Modeling studies have suggested that habitat for some tree species within the Chesapeake Bay watershed will increase, such as red maple, sweetgum, and loblolly pine, while other currently plentiful species are expected to decline, such as black cherry, American beech, and other oaks [Iverson and Prasad, 1998; Iverson *et al.*, 2005]. These changes in species composition could have significant effects upon nutrient retention and exports from forest ecosystems. Many studies have shown that tree species composition, and the resulting litter quality, are important factors in controlling variation in N cycling in temperate forest soils [Lawrence *et al.*, 2000; Lovett *et al.*, 2002; Zak *et al.*, 1989]. Greater abundances of sugar maple (*Acer saccharum*) and striped maple (*A. pensylvanicum*), for example, were associated with greater net nitrate production in soils relative to coniferous trees [Venterea *et al.*, 2003], making stands dominated by maple species more susceptible to losses of nitrate to surface waters.

### 3.4 Freshwater wetlands

Freshwater wetlands represent critical areas of aquatic ecosystem function, serving as nursery areas, sources of dissolved organic carbon, critical habitat areas, and stabilizers of global levels of available nitrogen, atmospheric sulfur, carbon dioxide, and methane [Mitsch and Gosselink, 2000]. Additionally, they are the ecotone and interface between human activities in uplands and the streams and rivers of the Chesapeake Bay watershed. Because they lie at the interface between terrestrial and aquatic systems, they are especially vulnerable to changes in soil moisture regime. Changes in water sources (ground and surface), as well as changes in evapotranspiration, will impact wetlands. Most wetland processes are dependent on catchment-level hydrology [Gitay *et al.*, 2001]. Potential impacts range from extirpation to enhancement, and include alterations in community structure and changes in ecological function [Burkett and Kusler, 2000]. There is evidence that wetlands that depend primarily on precipitation for their water supply may be more vulnerable to climate change than those that depend on regional groundwater systems [Winter, 2000]. The number and complexity of factors that influence wetland occurrence and type makes it difficult to predict the fate of wetlands directly from knowledge of temperature and precipitation changes alone. Needed are predictions of change in hydrology that will be induced by both climate and land cover change. For example, the hydrologic impacts from changes in rainfall patterns will depend on the amount and location of impervious surfaces in the watershed.



While all wetland types serve valuable roles in their watershed, headwater wetland/stream systems may contribute a disproportionate share to watershed functioning and the larger drainage areas and regional watersheds into which they drain. *Brinson* [1993] described how headwater streams tend to set the biogeochemical state of downstream river networks. These low order headwater streams account for 60-75% of the nation's total stream and river lengths, making their riparian communities of extreme importance for overall water quality [*Leopold et al.*, 1964]. *Lowrance et al.* [1997] emphasized the importance of riparian ecosystems along 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> order streams for nutrient abatement, pollution reduction of overland flow, and other ecosystem level processes in the Chesapeake Bay Watershed. In these systems, the connectivity of the floodplain to the adjacent stream is especially important to the functioning of both communities and, in turn, all associated downstream systems. Natural patterns of channel and floodplain connectivity sustain resident biota and ecosystem processes like organic matter accumulation, decomposition, and nutrient cycling [*Bayley*, 1995; *Sheldon et al.*, 2002]. This lateral and longitudinal connectivity is extremely important for the maintenance of viable populations of aquatic organisms in headwater streams. The loss of stream connectivity to the floodplain can lead to the isolation of populations, failed recruitment, and even local extinctions [*Bunn and Arthington*, 2002].

It must be noted that climate-induced impacts to wetlands will be layered onto an already compromised state of the resource. An assessment of wetland condition in the Upper Juniata River Watershed, PA [*Wardrop et al.*, 2007b] reported that over 68% of the total wetland area was in medium or low condition, correlated with increasing agricultural and urban land use in the watershed. Two regional assessments of wetland condition indicate that the ability of wetlands in both the Upper Juniata and Nanticoke River watersheds to perform valuable functions, such as removal of inorganic nitrogen and retention of inorganic particulates, is already significantly reduced [*Wardrop et al.*, 2007a; *Whigham et al.*, 2007], with the majority of wetlands functioning below reference standard levels. These impacts are expressed primarily by modification of supporting hydrology [*Brooks et al.*, 2004]. Climate-induced hydrologic regime changes may simply stress these systems further, resulting in their decreased capacity to serve important ecotone functions.

### **3.5 Point source pollution**

Growing populations are likely to interact with changes in climate to alter discharge from point sources of pollution, such as water treatment plants, industrial facilities, and urban storm water systems. Although theoretical relationships suggest the potential for significant impacts, there has been little work done in the Chesapeake Bay Watershed. A screening assessment of the potential impact of climate change on combined sewer overflow (CSO) in the Great Lakes and New England found that many CSO systems are designed primarily based on analysis of historical precipitation regimes [*U. S. Environmental Protection Agency*, 2008b]. Design capacity of CSO systems was found to be linearly proportional to anticipated precipitation intensity; as a consequence, significant increases in precipitation intensity (Section II.2.3) will likely undermine design assumptions and increase the frequency of overflow events. A similar analysis for publicly-owned treatment works (POTWs) found that the operations of POTWs are sensitive to both the volume of incoming effluent and the hydrologic condition of receiving waters (e.g., a water body's 7Q10 low flow) [*U. S. Environmental Protection Agency*, 2008a].

Climate change could therefore have a significant effect on both National Pollutant Discharge Elimination System (NPDES) permitting and POTW financing.

### 3.6 Summary of watershed biogeochemistry

Climate change is likely to alter the biogeochemistry of the Bay watershed in ways that will significantly impact the Bay, but the direction of change is not well constrained given the uncertainty in flow projections (Section II.2.4). Also, the lack of a mechanistic understanding of nutrient cycling on the watershed scale hampers the ability to predict the impact of climate change. It seems likely that nutrient and sediment loading during winter and spring will increase because flow will likely increase during this time, but it is not clear how temperature effects will play out. Given no change in the annual flow regime, it seems likely that P and sediment loading will increase as a result of the increased intensity of rain events (even though they are less frequent), but a quantitative relationship between particle loading and precipitation intensity still remains to be established. Nitrogen fluxes seem likely to increase over the relatively short term (if precipitation and discharge do indeed increase), although this prediction is quite uncertain. Over a longer time period, changes in the community structure of the landscape and in land use may dominate the change in flux. Increased variability in precipitation and discharge will lead to greater variability in the fluxes of both nitrogen and phosphorus, with very large inputs during wet periods and far less during dry periods.

#### **Summary of questions for Section 3—Fluxes of nutrients and sediment from the watershed:**

- What is the actual rate of nitrogen deposition in the Chesapeake Bay watershed, particularly for nitrogen gases such as NO, NO<sub>2</sub>, HONO, and NH<sub>3</sub>, and particularly near emission sources? How will climate change influence nitrogen deposition?
- What controls the retention vs. export of nitrogen once it is deposited onto the landscape, and how does this partitioning differ for forests and developed land?
- How will climate change affect the retention vs. export of deposited nitrogen in forests and developed land?
- What is the relationship between sediment-bound loading and precipitation intensity?

## 4. Bay physical response

The implications of climate change will be determined in large part through interactions with key physical processes. It is important to recognize that physical processes will not just “pass through” climatic changes [Meir *et al.*, 2006]. Rather, they will mediate change through dynamics that amplify or buffer rates and magnitudes of change. Such processes are nearly ubiquitous; however, this section is limited to three critical and relatively well-understood phenomena: circulation, salinity, and suspended sediment.

### 4.1 Circulation

There are no direct measurements of estuarine circulation in the Chesapeake Bay that document the influence of climate variability, nor are there modeling studies that attempt to quantify the potential impact of future climate change on Bay circulation. Rather, measurements of temperature and salinity have been used to quantify stratification and infer circulation patterns and rates of mixing. The Chesapeake Bay (especially its central portion) evolves from a relatively well-mixed water column in winter to strongly stratified conditions during the summer. The spring freshet results in fresher, less dense surface water overriding deeper saltier waters. As summer approaches, warming surface waters and low wind conditions reinforce stratification. *Hagy* [2002] analyzed mainstem Bay salinity and temperature data to show that the April-September average stratification in the mid-Bay is strongly and positively correlated to the January-May average Susquehanna river flow. Given the likely increase in this flow in the future (Section II.2.4), it appears that summer-time stratification increases are likely as well. It is less likely that warming will enhance this stratification significantly because the time scale of climate change is expected to be long enough that the Bay as a whole will warm. *Hagy's* [2002] diagnostic box modeling of the circulation showed that the summer-averaged landward advection below the pycnocline into the middle Bay increases with the January-May average Susquehanna river flow, but the relationship between river flow and vertical mixing is more complex.

The only numerical modeling study to consider the impact of climate change on Chesapeake Bay circulation is the recent study by *Zhong et al.* [2008], which suggests that the tidal range near Baltimore, Maryland, which is in the upper portion of the Chesapeake Bay, will increase by 15-20% if sea-level increases by 1 m. *Zhong et al.* [2008] argue that this amplitude increase is caused by friction reduction and the Bay being closer to its resonant period. A study in Delaware Bay also found an increase in the tidal range with sea level [*Walters*, 1992]. No other estuarine circulation impacts of sea-level rise have been modeled, to our knowledge. However, increases in tidal range are likely to be accompanied by increases in mixing and shoreline inundation.

## 4.2 Salinity

Salinity variations throughout the Bay have been shown to be strongly tied to streamflow [e.g., *Schubel and Pritchard*, 1986], and simple models are able to accurately predict monthly-average salinity throughout the mainstem Bay from the flow of the Susquehanna River [*Gibson and Najjar*, 2000]. *Gibson and Najjar* [2000] estimated that a change in annual streamflow of 10% would result in a change in annual mean salinity (of opposite sign) of about 1, 4, and 7% in the lower, middle, and upper mainstem Bay, respectively. Maximum change in salt concentration is in the central Bay, approximately -0.6 for a 10% flow increase. With projected flow changes by the end of the 21<sup>st</sup> century of -40 to +30% (Table 1), annual mean salinity in the central Bay could change by as much as 2 in either direction.

Salinity variability is likely to change in response to climate change. Given the projected increases in January-May flow of the Susquehanna River (Section II.2.4), we can expect a decrease in mean salinity during the winter and spring; summer and fall projections are much more uncertain. Saltwater intrusion events with durations greater than 1 month are likely to increase because of the projected increases in drought frequency (Section II.2.4).

Only one study has attempted to quantify salinity variations due to sea-level rise in the Chesapeake Bay. After accounting for streamflow variations, *Hilton et al.* [2008] found

significant trends in about half of the volume of the mainstem Chesapeake Bay between 1949 and 2006, during which average sea level in the Bay rose by about 0.2 m. The mean salinity change in these regions was about 0.8, at least half of which could be explained by sea-level rise, according to hydrodynamic model simulations. Given a salinity sensitivity to sea level of about  $0.4 \div 0.2 \text{ m} = 2 \text{ m}^{-1}$ , a sea-level rise of 0.7 to 1.6 m by 2100 (Section II.2.5) would increase salinity by 1.4 to 3.2.

### 4.3 Suspended sediment

Excess sediment contributes substantially to the Bay's poor water quality [Langland *et al.*, 2003], the majority of this sediment is non-volatile [Cercio *et al.*, 2004], and this non-volatile component is mainly delivered by rivers [Smith *et al.*, 2003]. In 2003, The Chesapeake Bay Program (CBP), proposed to reduce land-based sediment loading by 18% by 2010 in order to achieve the water clarity needed for underwater grasses to survive [Chesapeake Bay Program, 2003]. A least squares fit to the data in Figure 7 yields a sediment load of  $110 \text{ kg s}^{-1}$  for the mean streamflow of  $2500 \text{ m}^3 \text{ s}^{-1}$  during 1990-2004. Using projected flow changes by the end of the 21<sup>st</sup> century of -40 to +30% (Table 1), we estimate that the mean sediment load could increase to  $210 \text{ kg s}^{-1}$ , almost a doubling, or decrease to  $19 \text{ kg s}^{-1}$ , less than a fifth of the current load. Thus climate change has the potential to either undo efforts to meet water clarity goals or make it much easier to reach them. As noted above, more intense precipitation in fewer events will probably increase sediment loading, but the sensitivity is unknown.

In addition to natural and anthropogenic processes in watersheds that influence suspended sediment concentrations in rivers, estuarine suspended sediment is controlled by a variety of processes: the amount of streamflow entering the estuary, shoreline erosion, *in situ* biological production and decomposition, the re-suspension of particulate matter through currents (driven by winds, tides and buoyancy forces), the redistribution by advection and mixing within the estuary, and the rate of sedimentation. Many of these controls are also sensitive to climate, but quantitative relationships that link climate change to changes in sediment fluxes are lacking.

### 4.4 Bay physics summary

Despite all of the research on the physical oceanography of Chesapeake Bay, little is known about its seasonal and interannual characteristics, the time scales most relevant for climate change. Summertime stratification and landward advection below the pycnocline are likely to increase in response to increases in winter-spring streamflow, but other circulation responses to climate, such as those due to changes in winds and sea level, are poorly known because of the uncertainty in the climate change itself as well as the lack of research on estuarine physics to climate. Salinity will likely increase in response to sea-level rise and warming alone (due to increased evapotranspiration and thus decreased streamflow), but the lack of consensus in annual precipitation changes makes the overall direction of salinity change highly uncertain. Increases in salinity variability are possible on the seasonal time scale (if summers do not get wetter) and are likely on the interannual time scale (due to droughts). The relationship of sediment loading to flow is well constrained on annual time scales (Figure 7) but not for extreme events. The connection between other sediment sources and climate is poorly known. Predictive

modeling of extreme temperature events, which are important for submerged aquatic vegetation (Section II.5.2) and likely other organisms, is also lacking.

#### **Summary of questions for Section 4—Bay physical response**

- How does Bay circulation respond on seasonal and interannual time scales to changes in freshwater forcing and sea level?
- What is the sensitivity of Bay salinity to sea-level rise? Can model predictions be tested through existing Bay monitoring systems?
- How will sea-level rise influence shoreline erosion and suspended sediment levels in the Bay?
- Can historically parameterized hydrological models adequately represent and predict the loading of suspended sediment (and other NPS components) under future climatic conditions?
- What factors cause extreme warm events in Chesapeake Bay?

## **5. Living resources**

One of the most important goals of the Bay Program partnership is the restoration of living resources and associated ecosystems. Climate is a fundamental driver and organizing factor in ecological processes, and, consequently, climatic conditions will create complex and multi-faceted responses. It is impossible to crisply bound the scope of these implications for living resources within the Bay, and here we attempt to highlight examples of interactions with key elements and processes. The following sections describe a substantial, but obviously incomplete body of knowledge ranging from the most fundamental biogeochemical processes to the top of the food chain.

### **5.1 Food webs, plankton, and biogeochemical processes**

Water quality and ecosystem dynamics in the Bay are underpinned by a foundation of processes associated with complex food webs, plankton, and biogeochemical cycles. Many of these processes are likely to be highly sensitive to anticipated climate changes. This section focuses on a selected set of critical issues, including the linkage of nutrient inputs from the watershed to plankton productivity, the direct effects of rising CO<sub>2</sub> concentrations, and the direct impact of temperature. We use this review as a basis for deriving implications for key management end-points including chlorophyll *a* concentrations, harmful algal blooms, and dissolved oxygen concentrations.

#### **5.1.1 Nutrient cycling and plankton productivity**

Over 1450 phytoplankton taxa have been identified in the Chesapeake Bay and its tidal estuaries [Marshall *et al.*, 2004], including a variety of chlorophytes, dinoflagellates, cyanobacteria, euglenophytes, chrysophytes, xanthophytes, coccolithophorids, cryptophytes, prasinophytes, raphidophytes, prymnesiophytes, and dictyochophytes. Within this spectrum, however, the phytoplankton community is typically dominated by diatoms throughout the year

[Adolf *et al.*, 2006]. Compositional changes in the flora have been recorded since 1850 [Cooper and Brush, 1991] and species diversity appears to have increased over the last 20 years [Marshall *et al.*, 2004] as has chlorophyll *a* [Kemp *et al.*, 2005], effects largely attributed to eutrophication. A history of microbial community characteristics is less well documented. As microbes appear to differentially respond to climate change variables, the interactive effects of eutrophication and climate change may be difficult to distinguish [Fulweiler *et al.*, 2007].

Phytoplankton production and species composition in the Chesapeake Bay generally follow predictable seasonal patterns dictated primarily by annual river flow, light, and temperature [Malone *et al.*, 1996; Marshall and Nesius, 1996]. Meteorology, through river discharge, governs spring bloom timing and extent [Harding Jr., 1994]. During the relatively low-light, cold, and turbulent winter/early-spring period, centric diatoms dominate the flora [Sellner, 1987]. Stratification due to the strong two-layer flow and spring riverine nutrient delivery promote the annual spring bloom because large, chain-forming diatoms are maintained in the surface mixed layer where light and nutrients (delivered by the spring freshet) are plentiful [Miller and Harding, 2007]. As nutrients are exhausted from the surface waters and not replenished due to decreased mixing with bottom waters and decreased freshwater flow, a substantial fraction of the spring diatom bloom sinks (mostly as intact cells) through the pycnocline. Thereafter, surface summer productivity is supported by nutrient supply from below the pycnocline resulting from temporary destratification (storms) and pycnocline tilting (see below) [Kemp *et al.*, 1992; Malone, 1992]. During the warm stable summer months, the algal community shifts to a mixture of picoplankton (principally cyanobacteria), small centric diatoms, and flagellates [Malone *et al.*, 1986; Sellner, 1987]; aperiodic dinoflagellate blooms are also frequent. At this time, primary productivity, microzooplankton grazing, zooplankton production, and fish production are high (Section II.5.4.3). Turnover times are rapid so biomass levels are often low. Because grazing is high in the summer and the phytoplankton community is dominated by small algal cells, fewer cells sink and a large fraction of this production is recycled in the water column contributing to the microbial food web [Malone *et al.*, 1991]; only a small fraction settles out and is available for food chains that support growth of fish. Further, many dinoflagellates that bloom in the Chesapeake Bay during summer and fall exert toxic or otherwise harmful effects, including *Pfiesteria* spp. and *Karlodinium veneficum* [Place *et al.*, 2008], *Prorocentrum minimum* [Tango *et al.*, 2005], *Dinophysis acuminata* [Marshall *et al.*, 2004], *Cochlodinium heterolobatum* [Ho and Zubkoff, 1979], *C. polykrikoides* [Mulholland *et al.*, 2008b], and *Alexandrium monilatum* [Vogelbein, 2008]. These populations are remineralized in the water column following lysis, and thus do not fuel high oxygen demand in the benthos from sedimentation and subsequent microbial breakdown in surficial sediments [Sellner *et al.*, 1992].

The projected winter-spring precipitation increases for the Bay watershed (Figure 4, Section II.2.3) will likely increase nutrient loading either with the spring freshet, if the precipitation is predominantly snow, or with runoff from individual rainfall events if warming causes the winter-spring precipitation to be dominated by rain. This will likely lead to higher estuarine nutrient concentrations and supported planktonic production and possibly change the timing of productivity due to changes in the timing of nutrient delivery.

Alternatively, the summer period, depicted as more drought-likely (see above), could be typified by sporadic, high intensity storms and discharge events. If storms are over land, resulting discharge could result in buoyant, nutrient-rich plumes into the tributaries and Bay leading to increases in short-term stratification and increased preponderance of algal blooms, as

identified by *Loftus et al.* [1972]. The plumes can select for motile dinoflagellates and surface blooms, including some of the problematic taxa identified above. The plumes provide temporary stratification as well as elevated nutrient concentrations in the short-term at a time when pre-storm nutrient concentrations are low and primary producers most productive [see above; *Malone et al.*, 1991].

In contrast to impacts from overland storm passage, should the intense storms pass over the bay and tributaries, mixing of the water column would likely occur, yielding optimal conditions for diatom growth, not unlike conditions and floral response observed in the fall overturn of the mesohaline bay [*Sellner*, 1987]. The annual sequence resulting from climate change might therefore be a sequence with a larger-than-average spring diatom bloom, followed by small cells during the summer drought, interspersed with aperiodic dinoflagellate blooms or diatom maxima from storm passage.

Wind direction may also modify surface production during the summer when annual productivity is at its maximum. Should these summer/fall storm events be accompanied by dramatic shifts in wind direction from the normally dominant west direction to northerly or southerly along the axis of the bay, frequent pycnocline tilting could occur, pumping sub-pycnocline, post-spring regenerated nutrients into surface water to support shoreline blooms of diatoms and dinoflagellates [*Malone et al.*, 1986; *Sellner and Brownlee*, 1990; *Weiss et al.*, 1997], the latter substrate for microbial production, not fish. Further, wind speed and direction are important determinants of upwelling and downwelling along the coast so the timing of high flow events with respect to the dominant oceanic wind regime will influence the impact of the plume on the coastal ocean [*Filippino et al.*, 2008].

### 5.1.2 CO<sub>2</sub> effects on phytoplankton

CO<sub>2</sub> can directly stimulate growth of phytoplankton without carbon concentrating mechanisms (CCMs). CO<sub>2</sub> is the preferred form of carbon for the principle carbon-fixing enzyme, ribulose-1,5-bisphosphate carboxylase-oxygenase (Rubisco); however, most of the dissolved inorganic carbon in equilibrated seawater is bicarbonate ion (HCO<sub>3</sub><sup>-</sup>). As a consequence, most cells have various CCMs in order to concentrate CO<sub>2</sub> near active Rubisco sites. Species without CCMs are likely to benefit directly from increases in CO<sub>2</sub>. Further, there are different forms of Rubisco with different affinities for CO<sub>2</sub>. Many of the bloom-forming microalgae are dinoflagellates, which appear to have a form of Rubisco that has a low affinity for CO<sub>2</sub> compared with the Rubisco found in most other microalgae [*Ratti et al.*, 2007; *Whitney and Yellowlees*, 1995]. Increases in the partial pressure of CO<sub>2</sub> in water (*p*CO<sub>2</sub>) predicted from carbon cycle models (Section II.2.1, Figure 2b) might alleviate carbon limitation of Rubisco and allow higher growth rates of these dinoflagellates, thereby increasing the number of harmful algal blooms throughout the system.

Evidence for CO<sub>2</sub> limitation of productivity and growth can be seen during bloom conditions, when rates of phytoplankton consumption of CO<sub>2</sub> exceed atmospheric re-supply [*Loftus et al.*, 1979]. Accompanied by an increase in pH, this change could lead to species selection because some taxa are able to better cope with both elevated pH and low *p*CO<sub>2</sub> (e.g., *Prorocentrum minimum*, *Microcystis aeruginosa*) [*Hansen*, 2002; *Seitzinger*, 1991]. However, we know little about the range of tolerances of most algal species and how they will respond as part of an ecosystem. Further, we know little about how other taxa might respond to changes in *p*CO<sub>2</sub> (or temperature or the combined effects), and how these responses would affect

competitive interactions. *Riebesell et al.* [1993] demonstrated that diatom growth can be limited by CO<sub>2</sub>, similar to reports of enhanced diatom growth under elevated CO<sub>2</sub> [*Tortell et al.*, 2002]. In other work, CO<sub>2</sub> stimulated cyanobacterial growth and N<sub>2</sub> fixation for a variety of diazotrophic taxa [*Fu et al.*, 2008a; *Hutchins et al.*, 2007; *Levitan et al.*, 2007]. N<sub>2</sub> fixation and diazotrophic organisms have now been demonstrated to fix substantial new N in the Chesapeake Bay plume and surrounding coastal waters [*Mulholland et al.*, 2007; *Mulholland et al.*, 2008a], suggesting that increasing CO<sub>2</sub> could impact biogeochemical cycles substantially. In addition to diazotrophic cyanobacteria, *Synechococcus* growth as well as growth of the raphidophyte *Heterosigma akashiwo* were stimulated under both high CO<sub>2</sub> and high temperature scenarios [*Fu et al.*, 2008a; *Fu et al.*, 2008b], whereas *P. minimum* was less affected [*Fu et al.*, 2008b].

Secondary effects of higher CO<sub>2</sub> and enhanced phytoplankton production might be enhanced carbohydrate production and release: as CO<sub>2</sub> enhances photosynthetic carbon fixation by some phytoplankton, increases in carbohydrate release may also occur, which might stimulate bacterial production or promote aggregation and settling of material [*Riebesell*, 2004]. This, in turn, favors heterotrophic production through elevated water column and benthic metabolism (largely microbial), further expanding the current dissolved oxygen problems of the deeper Bay.

### 5.1.3 Temperature effects on plankton

In addition to CO<sub>2</sub> effects, temperature is important in regulating the growth of phytoplankton. In general, higher growth rates are achieved at higher temperatures within a given species' temperature range, but more subtle impacts are likely as well. For example, temperature affects species succession, with small phytoplankton becoming dominant as temperatures increase [*Sommer et al.*, 2007]. There also appears to be asynchronous changes in the timing of seasonal events such as spring phytoplankton blooms [e.g., *Wiltshire and Manly*, 2004] and the response of associated grazers. The result is a decoupling of historic relationships between grazers and their food [*Edwards and Richardson*, 2004]. In particular, high latitude systems now have earlier spring blooms and this affects grazers' ability to "keep up," thereby altering the particle rain to the benthos [*Edwards and Richardson*, 2004]. Further, combined effects of eutrophication and climate change are thought to have contributed to a system-wide shift from net denitrification to net N<sub>2</sub> fixation in the Narragansett estuary [*Fulweiler et al.*, 2007], with important implications for the nutrient inventories in estuaries and coastal systems.

In the Chesapeake Bay system, it appears that blooms of some potentially harmful taxa are occurring earlier and expanding their range [*Marshall*, 2008]. For example, there was an extensive *Cochlodinium polykrikoides* bloom in August, 2007 in the lower Chesapeake Bay system, toxic to juvenile fish and oysters [*Mulholland et al.*, 2008b]. The recent whelk kill associated with the first recorded bloom of toxin-producing *Alexandrium monilatum* [*Vogelbein*, 2008] in the York River further exemplifies potential range expansion for problematic harmful algal species. Should blooms of these organisms continue to expand their range or begin to impinge on larval recruitment seasons, the impacts to higher trophic levels could be profound.

Temperature increases are likely to affect the metabolic status of the Chesapeake Bay. In a synthesis of microbial rate measurements in the Chesapeake Bay, *Lomas et al.* [2002] found that planktonic respiration increases with temperature more rapidly than photosynthesis. Their results suggest that the Bay might become net heterotrophic on an annual time scale, reversing its current net autotrophic status [*Smith and Kemp*, 1995]. This is consistent with the concepts described above where we might expect increased heterotrophy from bacterial decomposition of



carbohydrates, whose production would be enhanced due to (1) higher levels of phytoplankton photosynthesis resulting from elevated CO<sub>2</sub> and (2) the lysis of dinoflagellate production in the water column, rather than the benthos [Sellner *et al.*, 1992].

#### 5.1.4 Harmful algal blooms and pathogens

The Chesapeake Bay and its tributaries, through spring-fall stratification and nutrient-rich conditions, is an ideal environment for bloom-forming dinoflagellates [see Margalef, 1978; Sellner *et al.*, 2001]. Further, for marine bloom-forming phytoplankton, it has been suggested that “warmer water temperatures can encourage a shift in species composition of algae toward the more toxic dinoflagellates” (quote from Haines *et al.* [2000] and attributed to Valiela [1984]), further supported by increases in toxic blooms in Asia associated with the warm phase of El Niño [Hallegraeff, 1993]. Further, there is paleontological information associating dinoflagellate dominance with warmer ocean surface waters [Dale, 2001; Mudie *et al.*, 2002].

Temperature-induced stratification may play a role in algal community structure as well. Peperzak [2003] has conducted several experiments with brackish bloom-forming and non-bloom forming taxa under simulated stratified conditions and a 4° C temperature increase. In these experiments, a cosmopolitan contributor to estuarine systems (*Skeletonema costatum*) was not perturbed by the shift to stratified conditions, suggesting that this common winter-spring taxon in the Bay would remain a key contributor to spring production. However, *P. minimum*, the spring co-dominant in the Chesapeake and occasional toxin producer [see Luckenbach *et al.*, 1993] and two raphidophytes (*Heterosigma* spp.) found in mid-Atlantic coastal bays, were stimulated by the increased stratification and temperature, suggesting an increase in the frequency of blooms under these climate change conditions [Fu *et al.*, 2008b]. This potential preference for bloom taxa associated with expected climate-induced changes in stratification (and temperature) is echoed in North Sea data: dinoflagellate maxima have occurred earlier in recent years, compared to those in the late 1950s, and this has been attributed to the shift to increasing stratification and temperature [Edwards and Richardson, 2004]. Similarly, Johns *et al.* [2003] suggest that increasing contributions of dinoflagellates near Georges Bank in the Gulf of Maine are likely the result of increasing stratification and stability in the area, due to progressive freshening.

Shifts in algal taxonomic composition from flow-induced stratification pose potential problems both in terms of altered food web structure and toxicity to trophic groups. Projected changes could increase production by dinoflagellates (noted above), a group associated with altered tropho-dynamics through several mechanisms. Several taxa can reduce zooplankton grazing and fecundity due to poor food quality [e.g., Harvey *et al.*, 1989] or the production of toxins or grazing-deterrent compounds [e.g., Adolf *et al.*, 2007]. Very high cell abundances can also reduce grazing pressure from co-occurring zooplankton populations [e.g., Sellner and Olson, 1985]. Pelagic bacterial production may increase as well due to lysis of dinoflagellates production largely in the water column and not the benthos [Sellner *et al.*, 1992]), favoring heterotrophic flagellates rather than copepods. The net result is an increase in the importance of the microbial food web rather than the classical food chain that supports fish production.

Additional impacts of an altered climate, specifically prolonged droughts [Hayhoe *et al.*, 2007], will also likely result in increased introduction of coastal populations of phytoplankton, including several harmful taxa. Droughts will lead to low flows and greater oceanic intrusion into the Bay, elevating salinity further north in the system as well as delivering unique taxa to the

region. This occurred during the spring and summer of 2002 following drought conditions in 1999-2002. With oceanic intrusion into the mid-Bay region, coastal populations of *Dinophysis acuminata* were delivered to the lower Potomac River estuary [Marshall *et al.*, 2004], resulting in fears for okadaic acid intoxication and diarrhetic shellfish poisoning for the oyster-consuming public. Climate-induced drought severity might, therefore, select for more frequent exposures to toxic algal bloom species, currently rare in the system.

The leafy chlorophyte *Enteromorpha*, a macroalga, is stimulated by elevated water temperatures [Lotze and Worm, 2002] and a similar taxon, *Ulva*, is characteristic of eutrophic estuaries including the Chesapeake and its tributaries. It is conceivable that warmer winters and springs might favor earlier growth of these two macroalgae and contribute to fouling of shorelines and submerged vegetation, clogging of commercial fish nets, and hypoxic conditions in sheltered bays, following storms and wind events. Further, the decay of these blooms has been associated with the onset of other harmful algal blooms in other areas, such as *Aureococcus anophagefferens* [Kana *et al.*, 2004].

Bacteria will also respond to temperature changes. Some true heterotrophic bacteria, like the *Vibrio* species, are associated with serious illnesses, such as gangrene and sepsis. Pathogenic species, such as *Vibrio vulnificus* and *V. cholerae*, have been identified in Chesapeake Bay waters (summarized in Rose *et al.* [2000]). *V. cholerae* and *V. parahaemolyticus* appear to be associated with elevated sea surface temperatures [Colwell, 1996; McLaughlin *et al.*, 2005]. Further, growth of a free-living strain of this bacterium has been shown to be stimulated by a coastal dinoflagellate bloom off of California [Mouriño-Pérez *et al.*, 2003], reaching levels three orders of magnitude higher than the known minimum infectious dose, indicating that climate change-induced increases in harmful algal blooms (see above) might conceivably increase threats to human health either directly or through fueling of pathogen growth with bloom-derived organic matter. Taxon-specific relationships between phytoplankton and bacteria need to be more fully explored.

Shellfish ingestion and concentration of pathogenic bacteria can also lead to outbreaks of gastroenteritis, and with *V. vulnificus*, death in some human consumers (see refs. in Rose *et al.* [2000]). Increasing temperatures in the Chesapeake Bay would favor these bacteria (references above), increasing the threat of this disease in the basin. Reports from the Center for Disease Control summarized from state monitoring indicate a recent local trend consistent with the high temperature selection for the genus<sup>1</sup>. In summer, 2005, water temperatures were 2-3° C higher than in the summers of 2003 and 2004; *Vibrio* outbreaks totaled 26 in Maryland for the warmer summer versus 0 and 2 outbreaks, respectively, for 2003 and 2004. Although a small data set, increasing incidences of this taxon with higher water temperatures locally is consistent with the prevalence of the bacterium in elevated temperature waters noted above and may foreshadow future conditions as climate change induced temperatures increase.

### 5.1.5 Dissolved oxygen

Dissolved oxygen levels have become a central issue as a measure of the health of the Chesapeake Bay. Although seasonal hypoxia is known to be a natural feature of the estuary, the size, frequency, and severity of hypoxic conditions is an indicator of human impacts on the Bay ecosystem. Hypoxia is caused by the combination of the sinking of the spring phytoplankton bloom, which fuels bottom respiration, and density stratification, which inhibits mixing that

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<sup>1</sup> [http://www.cdc.gov/foodborneoutbreaks/outbreak\\_data.htm](http://www.cdc.gov/foodborneoutbreaks/outbreak_data.htm)

would otherwise replenish the deeper waters with oxygen [Hagy *et al.*, 2004; Malone *et al.*, 1996]. During summer, plankton deposition (as zooplankton fecal pellets, larger diatoms, and other algal debris) continues at rates sufficient to maintain respiration and low-O<sub>2</sub> (< 2 mg l<sup>-1</sup>) conditions [e.g., Kemp *et al.*, 1999; Newell *et al.*, 2007]. The significant trend of increasing intensity, duration, and extent of hypoxic conditions since 1950 is related to increased nutrient loading from human activities in the watershed [Boesch *et al.*, 2001; Hagy *et al.*, 2004; Kemp *et al.*, 2005; Malone, 1992].

Climate change may also contribute to changes in the spatial and temporal distribution of hypoxic conditions. Hagy *et al.* [2004] found January-May average flow of the Susquehanna River to be a good predictor of the subsequent summertime volumes of low-oxygen water. Their functional fits to the data suggest that a 10% flow increase will increase the volume of anoxic water (< 0.2 mg l<sup>-1</sup>) by 10%, severely hypoxic water (< 1.0 mg l<sup>-1</sup>) by 6%, and mildly hypoxic water (< 2.0 mg l<sup>-1</sup>) by 3%. Najjar [2008] showed that January-May flow of the Susquehanna River is highly correlated with January-May watershed precipitation, and that fractional flow and precipitation changes are equal. Thus, the likely increases in winter-spring precipitation projected over the 21<sup>st</sup> century (Figure 4) could result in summertime oxygen declines. If nutrient loading increases with precipitation in the non-linear manner suggested by Howarth *et al.* [2006] (Section II.3.2), then plankton production and hypoxia will increase further.

Higher respiration and lower O<sub>2</sub> solubility associated with regionally increased summer temperatures would contribute to further reductions in bottom water O<sub>2</sub> concentrations [e.g., Sampou and Kemp, 1994]. The sensitivity of the oxygen saturation concentration to temperature ( $d[\text{O}_2]_{\text{sat}} / dT$ ) increases in magnitude as water cools (i.e., oxygen declines for a given temperature increase are greater at lower temperatures). The climatological temperature range in the mainstem Chesapeake Bay is approximately 2-27° C, with a corresponding range in  $d[\text{O}_2]_{\text{sat}} / dT$  of -0.34 to -0.13 mg l<sup>-1</sup> °C<sup>-1</sup> ( $S = 15$ ). Thus, for a projected warming of 2-5° C by 2100 (Figure 5b), the estimated decrease in O<sub>2</sub> concentration is 0.7-1.7 mg l<sup>-1</sup> during the coldest months and 0.3-0.7 mg l<sup>-1</sup> during the warmest months. The difference in oxygen concentration between severely hypoxic and anoxic waters is 0.8 mg l<sup>-1</sup>. At the temperature of sub-pycnocline waters in July (~20° C)  $d[\text{O}_2]_{\text{sat}} / dT$  is equal to -0.16 mg l<sup>-1</sup> °C<sup>-1</sup> and thus a warming of about 5° C will make waters that are currently hypoxic turn anoxic solely due to solubility effects.

Higher temperatures would also tend to accelerate rates of nutrient recycling, further stimulating phytoplankton production and potentially deposition [e.g., Kemp *et al.*, 2005]. This, coupled with the suggested shift towards greater heterotrophy with warming [Lomas *et al.*, 2002], would tend to drive oxygen concentrations ever lower. Simulation modeling studies for the northern Gulf of Mexico support these hypothesized responses of bottom water hypoxia to climate change scenarios [Justić *et al.*, 1996; 2003].

## 5.2 Submerged aquatic vegetation

Communities of seagrasses and related submerged aquatic vegetation (SAV) in the Chesapeake Bay are highly sensitive to changes in environmental conditions, including salinity and temperature. Historically, the Bay was inhabited by more than fifteen species of SAV. One of these plants, eelgrass (*Zostera marina*), is a globally dominant north-temperate seagrass. Although eelgrass has a moderate salinity tolerance range (~15-40), it is confined to the higher salinity regions of the lower Bay. The only other true seagrass in the Bay is widgeon grass

(*Ruppia maritima*), a highly adaptable euryhaline (salinity tolerance of 0-45) pioneer plant that inhabits coastal waters of the US from Maine to Texas [Kantrud, 1991]. All of the other SAV species in the Bay are freshwater plants (meaning that they evolved in purely freshwater habitats) [Stevenson and Confer, 1978], with modest salt tolerance (in general,  $S < 15$ ). At least half of these species, including the two seagrasses, remain present in the Bay today, although most are at abundance levels greatly reduced from historical levels [Moore et al., 2000]. Most of the Bay's SAV populations have similar annual cycles of abundance, with summer peaks and growing seasons that extend from spring through fall. The Bay's eelgrass population differs because it is near the southern limit of its geographic distribution. Consequently, eelgrass exhibits a bimodal seasonality in biomass and growth, with late-spring and mid-fall peaks and summer minima that reflect limited tolerance for high temperature [Wetzel and Penhale, 1983].

Availability of light is a primary factor regulating SAV abundance and spatial distribution, particularly in inherently turbid estuarine systems like the Chesapeake Bay [Kemp et al., 2005]. Minimum light requirements for survival of SAV are 10- to 20-fold higher than those of algae [e.g., Dennison et al., 1993]. A major decline in the Bay's SAV abundance, which began in the mid-1960s [Orth and Moore, 1983], appears to be largely attributable to widespread decreases in water clarity and increases in nutrient concentrations throughout the estuary [e.g., Kemp et al., 1983; Moore and Wetzel, 2000; Twilley et al., 1985]. Higher turbidity associated with increased runoff of nutrients and sediments has been shown to inhibit seagrass growth because of reduced light availability [e.g., Kemp et al., 2005; Quammen and Onuf, 1993; Twilley et al., 1985]. This sensitivity may be particularly problematic in the context of climate change given the possibility of significant increases in sediment loading resulting from greater and more episodic precipitation, as discussed in Sections II.2.3 and II.3.1.

SAV species exhibit widely varying sensitivity to temperature change, with optimal growth temperatures ranging from 22-25° C for eelgrass [e.g., Bintz et al., 2003] to 30-35° C for various freshwater plants growing in brackish habitats [Santamaría and van Vierssen, 1997]. Trends of increasing temperature in New England coastal waters appear to have rendered eelgrass stands more susceptible to light stress associated with nutrient enrichment and overgrowth by epiphytic algae [Bintz et al., 2003]. A recent massive eelgrass die-off in the Chesapeake Bay in the summer of 2005 appears to have been triggered by an extended hot period with daily peak water temperatures exceeding 33-35° C [Orth and Moore, 2008]. It appears that high temperatures and low water column mixing may contribute to internal oxygen deficiency in eelgrass plants, degradation of meristematic tissue, and mortality [Greve et al., 2003].

In broad terms, inter-annual variations in SAV distribution and abundance appear to correspond to fluctuations in freshwater flow. For example, in the Choptank River estuary, low flow tends to be associated with higher plant abundance [Stevenson et al., 1993]. Similarly, an inferred long-term (multi-decade) data record on seagrass growth and rainfall in the Mediterranean littoral zone revealed a strong inverse correlation, suggesting that freshwater had a negative impact on seagrass [Marba and Duarte, 1997]. For some seagrass, reduced salinity associated with high freshwater inputs to coastal waters would tend to cause osmotic stress for these halophytes [e.g., Fourqurean et al., 2003]. Conversely, the growth of other brackish water SAV may be stimulated by reductions in salinity [e.g., Stevenson et al., 1993].

Another example of SAV sensitivity to flow is the resurgence of widgeon grass in the Choptank River Estuary in 1985 after a four-year drought and a second explosive spread in 1993-1997 following a shorter (two-year) drought [Kemp et al., 2005]. One theory is that the period of

relatively clear waters and low nutrients associated with the 1980-1983 low flow conditions was sufficient for small beds in tertiary tributaries to flourish. These beds may have served as key seed sources for transport to the open Choptank where continued clear waters allowed rapid growth and dispersal of these pioneer plants and formation of large contiguous beds. By the time the second brief drought period occurred (1995-1996), the beds were sufficiently well established to exploit fully the improved water quality creating a second burst which peaked in 1997. Since this time, widgeon grass beds in the mesohaline Choptank appear to have been sufficiently established to maintain seed banks that allow this light-sensitive species to expand and contract with clear and turbid water associated, respectively, with low and high flow years. This may explain why correlations between Secchi depth and SAV cover are highly significant after 1996 but non-existent before this time.

In addition to temperature, salinity, and light, SAV is sensitive to CO<sub>2</sub> concentration. *Palacios and Zimmerman* [2007] showed that eelgrass biomass increased in response to elevated CO<sub>2</sub> levels under light-replete conditions during a year-long incubation. For an approximate doubling of CO<sub>2</sub> concentration above current levels, shoot biomass increased by 25%. However, there was no response under light-limiting conditions, a result that suggests that CO<sub>2</sub> increases could aid restoration efforts, but only if measures are also taken to maintain sufficient water clarity.

### 5.3 Estuarine wetlands

The Chesapeake Bay's shorelines are some of its most threatened resources, subject to the combined impacts of climate and land use change [*Maryland Department of Natural Resources*, 2000]. Coastal marshes and shoreline ecosystems provide important ecological functions, serving as nursery areas, sources of dissolved organic carbon, critical habitat areas, modifiers of local water quality, and stabilizers of global levels of available nitrogen, atmospheric sulfur, carbon dioxide, and methane [*Mitsch and Gosselink*, 2000]. Rising sea levels, changes in storm regimes, altered salinity regimes, CO<sub>2</sub> fertilization, and other climate-related factors will act along with continuing land use change and shoreline hardening to further stress already threatened coastal wetlands [*Rogers and McCarty*, 2000; *U.S. EPA*, 2002]. These ecosystems exist in a naturally changing environment, but the current and forecast rate of change are likely to overwhelm their inherent resilience [*Fisher et al.*, 2000].

Inundation by rising sea levels is one of the most direct threats faced by coastal and estuarine wetlands in the region. The amount of land inundated by a given sea-level rise is a complex function of elevation, shoreline geology, land use, wetland ecology, and the rate of sea-level rise. Current inundation estimates for Chesapeake Bay rely on elevation changes that bracket the projected sea-level rise range in the Bay of 0.7 to 1.6 m (Section II.2.5). *Titus and Richman* [2001], using Digital Elevation Models (DEMs) and shoreline data, estimate that about 2500 km<sup>2</sup> of land is below the 1.5-m elevation contour in Virginia and Maryland (essentially the shores of Chesapeake Bay). *Wu et al.* [2008] used DEMs with finer (30-m) horizontal resolution to estimate that 1700 km<sup>2</sup> of land in Virginia and Maryland lie below the 0.7-m contour, about half of which is wetlands.

The current forecasts for the rates of sea-level rise in the Chesapeake Bay are significantly greater than rates experienced for the last several centuries (Section II.2.5). At present it is not clear how much of the existing wetland complement in the Bay region will be able to either accrete vertically or migrate horizontally fast enough to keep pace with the

accelerated rate of change [Kearney *et al.*, 1988; Kearney *et al.*, 1994; Reed *et al.*, 2008; Stevenson *et al.*, 1985]. Extensive wetlands along the mainstem of the Bay, such as the Blackwater Wildlife Refuge in Maryland and the Guinea Marshes in Virginia, are already showing decreased areas of vegetative cover as a result of inundation and erosion. Extensive oxbow wetlands at the headwaters of the Bay's tidal tributaries are also undergoing changes in vegetative community composition that seem related to increased inundation frequency, a sign that the wetland is not keeping pace with rising sea level [Perry and Hershner, 1999].

Wetlands will also respond to elevated levels of atmospheric CO<sub>2</sub>, increasing temperatures, and changing salinity patterns. A *Scirpus olneyi* wetland sedge community of the Rhode River that was exposed to an approximate doubling of atmospheric CO<sub>2</sub> over a 17-year period revealed enhanced shoot density, shoot biomass, and rates of net CO<sub>2</sub> uptake (also known as net ecosystem exchange) compared to ambient exposures [Rasse *et al.*, 2005]. In contrast, *Spartina patens* showed no significant response to CO<sub>2</sub> [Erickson *et al.*, 2007]. Rasse *et al.* [2005] also clearly documented salinity stress on *S. olneyi*, with significant anti-correlations at the interannual time scale between salinity and the three growth measures referred to above. Elevated CO<sub>2</sub>-stimulation of plant growth has important implications for brackish marshes, many of which are dominated by C3 plant species such as *Scirpus olneyi*. Indeed, recent results from a Rhode River marsh [Megonigal, 2008] show that elevated CO<sub>2</sub> increases root biomass, which in turn raises elevation of the tidal marsh soil. The increase in elevation was ~3 mm yr<sup>-1</sup>, which is comparable to current rates of relative sea-level rise in the Chesapeake Bay. Thus, elevated CO<sub>2</sub> may stimulate marsh accretion and ameliorate marsh losses projected from accelerated sea-level rise. The combination of temperature increases and elevated CO<sub>2</sub> concentrations may produce different effects on marshes than elevated CO<sub>2</sub> alone, but we presently know little about these interactions.

The impact of rising sea level is compounded by on-going land use change and associated shoreline hardening. Recent Shoreline Situation Reports show a high percentage of hardened shoreline across the Bay region.<sup>2</sup> Increased shoreline hardening has limited the ability of marshes to migrate shoreward in response to sea-level rise. Detailed studies linking sea-level rise, land use change, and shoreline condition are very limited for the Chesapeake Bay. Dingerson [2005] used a combination of regression and fuzzy logic-based methods to provide shoreline development scenarios for a section of southern Virginia through 2025. This approach parallels techniques being used for Bay-wide land use and land cover scenarios. The study illustrated the potential for evaluating the consequences of development scenarios for shoreline condition, but the approach has yet to be used on larger areas and it is unclear which regions may be most vulnerable.

Inundation of coastal wetlands by rising sea levels may stress the systems in ways that enhance the potential for invasion of less desirable species, such as *Phragmites australis* (one of six species identified as causing, or having the potential to cause, significant degradation of the aquatic ecosystem of the Bay) [U. S. Environmental Protection Agency, 2008c]. Reported impacts include significant loss of plant diversity [Chambers *et al.*, 1999; Meyerson *et al.*, 2002; Warren *et al.*, 2001], changes in marsh hydrology with the development of *Phragmites* stands [see Marks *et al.*, 1994], and a reduction in insect, avian, and other animal assemblages [Chambers *et al.*, 1999; Osgood *et al.*, 2002]. Shifts within native plant communities are also probable, although difficult to predict with current experimental data [Dukes, 2007], and species

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<sup>2</sup> Information for Maryland and Virginia coastlines is available at: [http://www.crm.vims.edu/shoreline\\_situation\\_rpts.html](http://www.crm.vims.edu/shoreline_situation_rpts.html).

may show increased resilience to change under elevated CO<sub>2</sub> when they are exposed to adverse environmental conditions, as discussed above. Additionally, for many marsh systems to persist, a continued input of suspended sediment from inflowing streams and rivers is required to allow for soil accretion. Climate change might result in changed timing and overall delivery of sediment from upstream sources, but these consequences remain uncertain.

## 5.4 Fish and shellfish

Historic and contemporary climate variability can provide valuable models for understanding how climate change may operate through well-studied processes to influence fish and shellfish species as well as other components of the Chesapeake. This section will focus on temperature, salinity, plankton production, dissolved oxygen, and sea level because these variables are likely to be affected by climate change and affect the Chesapeake Bay estuarine ecosystem in ways that could alter the health, distribution, and abundance of ecologically and economically important fish and shellfish species.

### 5.4.1 Temperature impacts on fish and shellfish

The Chesapeake Bay currently lays at the boundary of subtropical and cold-temperate climate provinces and is regularly influenced by both continental and oceanic air masses. As warming progresses, it will differentially affect subtropical and cold-temperate species that utilize the Bay as a seasonal feeding ground or nursery area. Subtropical species will likely benefit from higher temperatures and some may increase their utilization of the Bay as a feeding ground, spawning ground, and nursery area [Austin, 2002; Wood, 2000]. Conversely, warming will limit the use of the Bay by some cold-temperate species. This is consistent with recent patterns of menhaden recruitment in Atlantic coast estuaries, which suggest the possibility of a northward shift in the major locations of Atlantic menhaden spawning away from the Chesapeake Bay [Houde, 2008]. Higher temperatures can decrease the areal extent of bioenergetically favorable Bay habitats for cold-temperate species during the growing season, because of direct effects of increased temperatures, and because higher temperatures both decrease dissolved oxygen content (discussed above, Section II.5.1.5) and increase metabolic costs (discussed below, Section II.5.4.4). Developing embryos of fishes are unable to temperature compensate and tend to have narrower temperature tolerances than other life stages. As a result, thermal tolerances of embryos may be particularly important in determining shifts in species distributions [Rombough, 1997].

Northward range expansions by subtropical species may either enhance or impair fisheries. Shrimps of the genus *Farfantepenaeus*, which now support important fisheries in North Carolina [Hettler, 1992], could increase and support viable fisheries in the Chesapeake Bay and elsewhere in the mid-Atlantic Bight. However, increasing temperatures, along with other climate-related changes in the Bay environment, may simultaneously facilitate the successful northward expansion of non-native species [Stachowicz *et al.*, 2002] and pathogens [Cook *et al.*, 1998]. In addition, physical or ecological factors other than temperature may preclude a smooth transition to a balanced ecosystem dominated by sub-tropical fishery species. For example, many Bay species depend on coastal and estuarine circulation patterns to distribute their planktonic egg and larval stages into suitable nursery areas [e.g., Epifanio and Garvine, 2001]. It is difficult to predict how coastal or Bay circulation patterns will change in the future

because they will be simultaneously influenced by freshwater inflow, sea level, surface wind fields, and coastal landforms (Section II.4.1). Altered current patterns may be especially important in affecting the rate of spread into the Chesapeake Bay by less mobile or coastal spawning subtropical shellfish and fish species. In addition, oligohaline-upper mesohaline species (such as the bivalves *Mytilopsis leucophaeata* or *Ischadium recurvum*) that live only in estuaries may spread northward slowly if they cannot tolerate the marine conditions that occur between estuaries.

Species that are at their southernmost range in the mid-Atlantic region may be eliminated from the Chesapeake Bay if water temperatures reach levels that are lethal or that inhibit successful reproduction. For example, the commercially important soft clam *Mya arenaria* in the Chesapeake Bay is near its southern distribution limit and may be extirpated if temperatures approach and remain near  $\sim 32^{\circ}\text{C}$  [Kennedy and Mihursky, 1971]. Non-fisheries species that currently have strong effects on the Chesapeake Bay food web may also be negatively affected by increasing temperatures. Lethal temperature for the lobate ctenophore, *Mnemiopsis leidyi*, collected from the Chesapeake Bay is approximately  $30^{\circ}\text{C}$  in laboratory experiments [Breitburg, 2002]. However, this ctenophore species extends through the tropics to South America, suggesting selective use of more oceanic waters and adaptation to warmer waters as possible responses to increasing water temperatures.

A persistent long-term rise in mean annual water temperatures is also likely to alter the seasonal distribution patterns of ecologically and economically important fish and shellfish species of the Chesapeake Bay. Warming will likely result in a shorter winter season and may allow for earlier spring immigration and later fall emigration of some coastal species; e.g., see Frank *et al.* [1990] for the St. Lawrence region. Spawning migrations of American shad (*Alosa sapidissima*) may be particularly sensitive to changes in seasonal patterns of water temperatures. American shad now migrate up the Columbia River (where they've been introduced) 38 days earlier than during the 1950s as water temperatures have increased as a result of reductions in spring flow by the Bonneville Dam [Quinn and Adams, 1996].

Higher water temperatures during winter may have positive effects on some species. Overwintering mortality of juvenile fishes can be an important factor contributing to year-class strength [Conover and Present, 1990]. For example, interannual variation in Atlantic croaker (*Micropogonias undulatus*) catches has been linked to winter temperatures with higher temperatures resulting in higher juvenile overwintering survival and stronger year classes [Hare and Able, 2007]. Severe winters are thought to have resulted in low catches of blue crab [e.g., Pearson, 1948] and recent studies highlight the importance of overwintering mortality to both juveniles [Bauer, 2006] and adults [Rome *et al.*, 2005] of this species in the Chesapeake Bay.

As with direct effects, indirect food web effects of increasing temperatures could either benefit or have deleterious effects on native fish and shellfish. Alterations in the timing of the winter-summer seasonal warming relative to seasonal patterns of day length could affect fishery production by changing the timing of the spring production bloom relative to the reproduction period of late-winter and spring spawning fishes. Such shifts could cause a mismatch (as described by Cushing [1975; 1990]) between the nutritional requirements of larval fishes and the abundance peak of their zooplankton prey. It is also possible that, for some species, warming trends could improve the match between prey availability and fish reproduction. In either case, the climate-induced changes in the frequency of matched prey abundance and larval feeding demand, as well as the ability of local populations to adapt to local prey conditions, are likely to



be important because early life history stage mortality rates establish the annual recruitment in many fish populations [Houde, 1987].

Warming may also alter the activity and abundance of predators that feed on fish eggs and larvae. There is strong evidence to suggest that an increase in winter water temperatures may be responsible for the decline in the winter flounder (*Pseudopleuronectes americanus*) population in Narragansett Bay, Rhode Island. Keller *et al.* [1999] and Keller and Klein-MacPhee [2000] have shown that winter flounder egg and larval mortality rates are higher in warmer rather than cooler water (3° C difference). These authors noted that in their mesocosm experiments, egg and larval predators were more active and more abundant in warm water and hatching winter flounder larvae were larger under colder conditions. Field sampling suggests that an important effect of increasing temperatures in Narragansett Bay has been an increase in the temporal overlap between the ctenophore *M. leidyi* and early life stages of summer-breeding fishes, such as flounder, that serve as its prey [Sullivan *et al.*, 2001]. In the Chesapeake Bay, *M. leidyi* peaks already coincide with reproduction by summer breeding fishes and shellfish. Nevertheless, the underlying mechanisms illustrated by the Narragansett Bay example could be important within the Chesapeake Bay food web as well.

The eastern oyster (*Crassostrea virginica*) has traditionally been an important fishery species for the Bay. As recently as 1987, the Chesapeake Bay was the largest oyster producer on the Atlantic and Gulf of Mexico coasts [Haven, 1987]. While overfishing has historically played an important role in demise of this fishery, two oyster pathogens, *Perkinsus marinus* (Dermo) and *Haplosporidium nelsoni* (MSX), have contributed to the long-term decline and have hindered the population's recovery despite considerable restoration efforts [Andrews, 1996]. Increasing winter temperatures appear to have already increased these diseases in oyster populations in Atlantic Coast estuaries [Burreson and Ragone Calvo, 1996; Cook *et al.*, 1998; Ford, 1996; Ford *et al.*, 1999; Paraso *et al.*, 1999]. The strong temperature dependence of Dermo, in particular, suggests that the Chesapeake region could experience increased oyster parasite stress in subtidal oysters as local water temperatures increase, but may simultaneously experience an extension in the northerly range of intertidal oysters [Malek, 2008]. Intertidal exposure during summer raises tissue temperatures to levels that are detrimental to *P. marinus* but within the physiological range of *C. virginica* [Malek, 2008; Milardo, 2001].

Fish parasites might also benefit from warmer climes, likely through production of one or more additional generations each year [Magnuson *et al.*, 1997; Marcogliese, 2001]. Increased temperatures leads to deterioration of body condition; e.g., lymphocytes decline, disease resistance decreases, and survivorship is reduced [references in Marcogliese, 2001]. Additionally, increasing temperature leads to faster development of planktonic and benthic invertebrates, enhancing parasite transmission [Chubb, 1982] as well as parasite diversity [Dobson and Carper, 1992]. These patterns may be dramatically altered under eutrophic conditions, with lake work suggesting increasing parasitism as eutrophic conditions increase but then decline with extreme eutrophication [Marcogliese, 2001]. Weisburg *et al.* [1986] have documented increases in the intermediate host *Limnodrilus* sp. for the fish redworm *Eustrongylides* sp. (pathogenic to avian definitive hosts) in warming eutrophic waters of the Bay; the fish infected include yellow perch (*Perca flavescens*) [Muzzall, 1999], which is common to the Bay. Warmer shelf waters might also lead to earlier arrivals and later departures of pelagic fishes [e.g., Frank *et al.*, 1990], favoring transmission of pelagic oriented parasites, as has been suggested for the St. Lawrence and Japan, increasing human illness from pathogen transfer via undercooked fish [Hubert *et al.*, 1989].

Winter survival of potential pathogens is also hinted at in recent observations in upper river basins. In the last four years, winter water temperatures have been substantially higher in the upper Shenandoah River area than the past, and each spring thereafter, major small mouth bass mortalities have been observed. Winter pathogen survival has been suggested as one explanation for these recurring events [*Chesapeake Bay Foundation*, 2007] and, if this hypothesis is correct, overwintering success and subsequent spring illnesses or mortalities may become increasingly common as regional water temperatures rise.

Warming might also influence pollutant impacts. For example, higher temperature induced-mercury methylation [*Booth and Zeller*, 2005] has been suggested as a possible mechanism to increase mercury uptake in fish and increase potential fetal impacts [*Bambrick and Kjellstrom*, 2004; from *McMichael et al.*, 2006]; fish tissue mercury concentrations are already a public health concern in Chesapeake jurisdictions.

#### 5.4.2 Salinity impacts on fish and shellfish

Changes in sea level, temperature, and precipitation are likely to create significant changes in estuarine salinity patterns (Section II.4.2). Unfortunately, the overall direction of salinity change is not clear due to the lack of consensus on annual precipitation projections (Figure 4). The most pronounced effects of altered salinity distributions on fishery species will likely result from changes in the distribution and abundance of predators, prey, and pathogens.

Salinity affects the eastern oyster in a variety of ways. First, the oyster has a physiological salinity range of 5 to 35. Second, pathogen prevalence is limited to salinities below about 12 [*Haven*, 1987]. Model and field surveys indicate that flow-related salinity fluctuations between 10 and 20 influence the range and infection rate of oysters by both pathogens [*Burreson and Ragone Calvo*, 1996; *Cook et al.*, 1998; *Ford*, 1996; *Paraso et al.*, 1999]. Third, spatfall success (recruitment) in the Bay oyster population has been shown to be positively affected by higher salinity [e.g., *Kimmel and Newell*, 2007]. Based on these three factors, salinity increases (which will very likely occur if precipitation remains unchanged), will have beneficial impacts on the eastern oyster.

Another example of complex species interactions that could be affected by climate change and could influence the state of Chesapeake Bay fisheries involves the two dominant gelatinous zooplankton species within the Bay, the ctenophore *M. leidyi* and the scyphomedusa *Chrysaora quinquecirrha* (the sea nettle) [*Purcell and Arai*, 2000]. Both of these species feed directly on fish eggs and larvae [*Cowan Jr. and Houde*, 1993; *Govoni and Olney*, 1991; *Monteleone and Duguay*, 2003] as well as on zooplankton that are important prey for adult forage fish and other fish species in early life stages [*Burrell and Van Engel*, 1976; *Cargo and Schultz*, 1966; *Feigenbaum and Kelly*, 1984; *Purcell*, 1992]. *M. leidyi* has a greater ability to deplete its prey than does *C. quinquecirrha*, and also feeds on oyster larvae. Interannual variability in salinity and flow strongly affect the timing of peak sea nettle abundances, with abundances peaking earlier in years of above-average salinity [*Breitburg and Fulford*, 2006]. Consequently, climate change may ultimately influence the timing and magnitude of direct effects of sea nettle consumption of ichthyoplankton and other zooplankton, as well the control sea nettles exert over their ctenophore, *M. leidyi*, prey.

#### 5.4.3 Plankton production impacts on fish and shellfish

Fisheries production in the Bay, as in most mid-latitude temperate systems, is strongly tied to the progression of annual production that is initiated by high early-spring streamflow (Section II.5.1.1) [e.g., *Cushing*, 1975; 1990; *Pope et al.*, 1994; *Silvert*, 1993]. The timing and magnitude of the spring zooplankton bloom is influenced by winter weather and spring streamflow [*Kimmel et al.*, 2006; *Wood*, 2000], and serves as food for young-of-the-year of spring spawning fishes and forage fish species that actively feed in the Bay in early spring. These small forage fishes are also directly influenced by salinity, dissolved oxygen, and zooplankton distributions and serve as important prey for larger fishes [*Brandt et al.*, 1992; *Jung and Houde*, 2003].

A change in the timing of the spring freshet could alter fishery production. For example, if the spring freshet should wane, or occur during higher temperatures after the seasonal transition from a diatom- to a flagellate and picoplankton-dominated assemblage, fishery production would likely be negatively affected [*Wood*, 2000]. An example of this occurred in 1989. Because the succession to a summertime phytoplankton community had already taken place when the freshet occurred, nutrients delivered by the delayed freshwater pulse promoted unusually strong production of picoplankton instead of a spring diatom bloom [*Malone et al.*, 1991]. Because many economically important Bay species (summer flounder, striped bass, Atlantic menhaden, etc.) depend on spring zooplankton (which are supported by the spring diatom bloom) during their early life history stages, a delay in the timing of the spring freshet would likely negatively affect fisheries production in the estuary. Fisheries operating outside the Bay would also be affected because many of these species spend much of their lives in the coastal ocean. Though there is a substantial uncertainty in the future projections of the timing of the spring bloom, there is an indication that the spring freshet will occur earlier and be stronger in the future (Section II.2.4); the implications of such a change for Chesapeake Bay fisheries are not clear.

#### 5.4.4 Dissolved oxygen impacts on fish and shellfish

Low dissolved oxygen affects growth, mortality, distributions and food web interactions of a wide range of organisms in the Chesapeake Bay [e.g., *Breitburg*, 2002; *Breitburg et al.*, 2003; *Kemp et al.*, 2005]. Seasonal hypoxia results in mortality of benthic animals in the deeper parts of the Bay, such that deep benthic macrofauna are essentially absent in the summer and depauperate during other times of the year [*Holland et al.*, 1987; *Sagasti et al.*, 2001]. Mortality of animals can also occur in shallow water environments with episodic advection of hypoxic or anoxic bottom water shoreward [*Breitburg*, 1990] and where warm, calm conditions result in diel hypoxic events in shallow waters [*Tyler and Targett*, 2007].

In addition to increasing mortality directly, hypoxia may have strong effects on the ecosystem and its fisheries through behavioral and physiological responses of organisms that alter trophic interactions over broad time and space scales [*Breitburg et al.*, 2001]. For example, increases in summer temperatures and increased anoxia or hypoxia may exclude species such as striped bass and Atlantic sturgeon (*Acipenser oxyrinchus*) from benthic feeding grounds and bioenergetically favorable cool deep-water environments [*Brandt and Kirsch*, 1993; *Coutant*, 1985; *Coutant and Benson*, 1990; *Niklitschek and Secor*, 2005; *Price et al.*, 1985; *Secor and Gunderson*, 1998]. Low dissolved oxygen can also alter trophic interactions that support fishery species by inhibiting production of ecologically important zooplankton grazers [*Roman et al.*, 1993], increasing some species' susceptibility to predation [*Breitburg et al.*, 1994; *Breitburg et*

*al.*, 1997], and providing predatory refuge to others [Sagasti *et al.*, 2001]. Repeated exposure of deeper subtidal oyster populations off Calvert Cliffs, MD to low-oxygen bottom water resulted in depressed growth rates relative to rates noted for oysters in shallower depths where exposure to low oxygen water was less frequent [Osman and Abbe, 1994].

Warming may increase the extent and severity of effects of hypoxia on macrofauna for two reasons. First, increased temperatures are predicted to increase the duration and severity of oxygen depletion in Chesapeake Bay waters as discussed above (Section II.5.1.5). As important, oxygen requirements of fishes tend to increase with increasing temperatures [Breitburg, 2002; Shimps *et al.*, 2005]. The combined effect of these two consequences of increasing temperature is likely to be a further reduction in the quality and spatial extent of suitable habitat in the Chesapeake Bay system for a wide range of aerobic organisms.

#### 5.4.5 Other impacts on fish and shellfish

Among the greatest concerns about climate change effects on fish and shellfish is the consequence of sea-level rise on tidal wetlands (Section II.5.3). Reductions in tidal marsh and submersed vegetation directly affect the Bay's fisheries because many fishes and crustaceans utilize these habitats as nursery areas and foraging grounds [e.g., Boesch and Turner, 1984; Fitz and Weigert, 1991; Fredette *et al.*, 1990; Kneib and Wagner, 1994]. Ecologically and economically important species that utilize these habitats include forage fishes such as mummichog (*Fundulus heteroclitus*), eastern mosquitofish (*Gambusia holbrooki*), and predatory nekton such as summer flounder, spotted seatrout (*Cynoscion nebulosus*), striped bass, and blue crabs (*Callinectes sapidus*). Because many of these species spend much of their life spans in the coastal Atlantic, significant loss or degradation of these habitats could also affect the larger-scale Northeast U.S. continental shelf large marine ecosystem.

Finally, increasing atmospheric CO<sub>2</sub> concentration can contribute to surface water acidification, with much of the scientific concern focused on the potential effects on calcification in corals [e.g., Kleypas *et al.*, 1999]. Coral reefs are absent in the Bay, but bivalves, as well as a number of other organisms such as foraminifera, rely on pH-sensitive processes to build calcium carbonate shells and other structures. Therefore CO<sub>2</sub> increases could dramatically alter calcification in these animals [Gazeau *et al.*, 2007]. Consistent with this pattern, Miller [2008] found that Chesapeake Bay oyster larvae reared in experimental aquaria under atmospheric CO<sub>2</sub> conditions that could be reached this century (560 ppm and 800 ppm, Figure 2b) grew and calcified more slowly than under ambient atmospheric conditions when temperature, salinity, light level, day/night cycle, and food quality/quantity were held constant.

### 5.5 Living resources summary

Bay living resources have shown a high sensitivity to environmental variables that are likely to change with climate. Current research suggests that climate-induced increases in winter and spring nutrient loading to the Bay will result in increasing phytoplankton production. Combined with higher temperatures that promote decreased oxygen solubility and greater heterotrophy, this increase in phytoplankton production will likely lead to more intense and more frequent episodes of hypoxia. Higher temperatures and CO<sub>2</sub> levels appear likely to select for increases in harmful algal blooms. The dominant submerged aquatic vegetation in the Bay (eelgrass) is likely to respond positively to the direct effects of higher atmospheric CO<sub>2</sub> levels,

but not if water clarity is unimproved or is further degraded by the likely increases in precipitation intensity, or if warming drives eelgrass out of its temperature range. Similar to SAV, estuarine wetlands will respond positively to higher CO<sub>2</sub> levels, but this may be by inundation due to sea-level rise. There is great uncertainty in the response of higher trophic levels in the Bay to climate change because of the accumulated uncertainty in projected changes in climate, watershed hydrology/biogeochemistry, lower trophic levels, and pathogens. What is clear is that the upper trophic levels exhibit a high sensitivity to environmental variables that are likely to change significantly in response to climate over this century.

### **Summary of questions for Section 5—Living resources**

- Which of the observed changes in the abundance or distribution of living resources in the Chesapeake Bay have been caused, at least in part, by climate change?
- Have increasing temperatures contributed to increases in the prevalence or effects of pathogens living in the Chesapeake Bay?
- How will food web dynamics mediate biotic responses to climatic change?
- How will host-pathogen systems (and other coupled biological systems) respond to changing conditions?
- What are the implications of climate change for ecosystem-based fisheries management plans?
- Will global and regional increases in atmospheric CO<sub>2</sub> concentrations lead to distinct phytoplankton speciation unlike the composition currently observed?
- Will increasing frequencies of extreme events (e.g., droughts, severe storms) select for a flora and bacterial community (including pathogens) more deleterious to current living resources and general public health?
- Will increasing water temperatures favor increased heterotrophy, elevated pathogenic bacteria levels, enhanced nutrient recycling, and through altered meteorology, increasing harmful algal blooms and anoxia?
- Which coastal areas and shorelines are more vulnerable to combinations of sea-level rise, shoreline hardening, and land use change?

## **6. Cultural, social and economic research**

### **6.1 Status of research**

Human activity will both drive and mediate the impact of climate change during the next century. The research community often describes the cultural, social, and economic foundation of climate change as its “human dimensions.” However, despite wide-spread recognition of the role of human activity in driving and responding to changing conditions, the social science of climate change is poorly researched and understood. The authors of this report considered omitting this section due to lack of information; however, the authors came to the consensus that this section provided an opportunity to underscore the importance of human activities for this issue and a chance to emphasize the relative lack of information.

### **6.2 Anthropological perspectives**

Climate change in the Chesapeake Bay region has the potential to create cultural and socio-economic impacts on a wide range of stakeholders, including commercial watermen, farmers, property owners, and municipal and county governments. To date, no systematic research has been undertaken to investigate how climate change will impact cultural and socio-economic processes, and vice versa across the Bay region. There is, however, research from other regions that provide insights on possible cultural and socio-economic impacts and effects of climate change for the Bay.

Early research has focused on the Arctic and low-lying islands. These studies have repeatedly identified a variety of potentially important cultural and socio-economic impacts. Maxwell [1997] points out, “*The impacts of future climate change are expected to be felt earliest and most keenly at Arctic latitudes.*” Not surprisingly, the government of Canada has begun researching the impacts of climate change in the Arctic [Government of Canada, 2004]. Canada’s 2004 report lists some general-level, potential environmental and socioeconomic impacts: “*The primary threat is from rising sea levels which are expected to bring damage to coastal infrastructure, increased risk of disease from insects and HABs, changes to renewable and subsistence resources, and loss of cultural resources and values*” (2004:19). Additionally, the changes in animal availability are altering the traditional seasonal diet of both the Cree and Inuit [Berkes et al., 1994]. Finally, Arctic fisheries are already experiencing both positive and negative impacts. Some traditional species such as rock cod are declining, the size of other species such as Arctic char appear to be increasing, while new fish species such as pink and Coho salmon have been seen for the first time [Ashford and Castleden, 2001].

The above studies are instructive for thinking about climate change impacts on livelihoods for the Chesapeake Bay. The hydrologic, biogeochemical, physical, and living resources impacts described above present a number of areas where the livelihoods of commercial watermen, farmers, and rural communities in general may be affected. Potential priorities for social science research include: the impact of coastal inundation on access to docks and waterfronts for commercial watermen; the implications of changes in precipitation for stream flow, salinity levels, and associated fisheries; the impact of possible increases in harmful algal blooms on fisheries and associated livelihoods; and the consequences of changes in temperature, rainfall patterns, and insects on farming practices. These priorities are direct extensions from a substantial body of scientific literature in other regions. It may be more difficult to anticipate the type and extent of cultural and socio-economic data needed to adequately measure the “human dimensions” of climate change across the Bay watershed. As with physical conditions, effective responses to climate change will require attention to the design and implementation of monitoring systems that can detect relevant changes in cultural, social, and economic activities.

In addition, rural development and changing land use patterns around the Chesapeake Bay create new socio-economic and political groups that will be affected by climate change. The research described above for traditional livelihood strategies does not offer much guidance on social science research directives when studying the impact on individuals and communities that do not depend directly on fishing or farming. A number of hypothetical examples can be used to produce a sense of the type of research issues that climate change will raise for these new populations. For example,

- How will shoreline property owners respond to climate factors that affect their property’s value and aesthetics?

- How will that response influence government decision making on the prioritizing and funding of climate change research and impact mitigation?
- How will areas placed in land conservation trusts be affected by climate change?
- How will biophysical outcomes of climate change affect new residents, tourists, and community efforts that promote heritage-based growth?

These examples questions are merely indicative of the types of new questions that the social sciences will need to investigate as part of any comprehensive research agenda on climate change for the region.

Finally, an important component of any social science research agenda on climate change will be the assessment of local knowledge and perceptions of climate change. These local knowledge assessments will be important complements to scientific research for at least three reasons. First, local knowledge may be able to identify impacts that are occurring long before these impacts are noticed by the scientific community, and local knowledge can be used to extend the reach of scientific inquiry into analysis of impacts on livelihoods, communities and land use practices. There are examples of this “local knowledge” research on climate change that can serve as methodological guidelines for studies of the Chesapeake [cf. *Vedwan*, 2006]. For example, the film *We are all Smith Islanders* (<http://chesapeakeclimate.org/index.cfm>) provides some first insights on local perceptions of climate change impacts on Bay communities. Second, local populations will have cultural perceptions of climate change that consist of frameworks of cultural knowledge and values. These frameworks can be conceptualized as existing cognitive models that individuals use, implicitly, to understand phenomena, including climate change. These cultural models may not match well with the models of climate change and impacts deployed by scientists and policymakers, thus raising the possibility that information produced by science and policy may not be effective in changing behaviors or alleviating impacts related to climate change goals. And third, any assessment of the cultural and socio-economic impacts of climate change for the Chesapeake Bay will need to place the discussion of local knowledge and cultural perceptions of climate change impacts within a broader political ecology context that incorporates approaches to understanding vulnerability, risk, uncertainty and resilience [*Lazrus*, 2007]. Affected stakeholders will have both individual and shared understandings of their vulnerability and risk to the impacts of climate change, as well as beliefs about what can be known and how well they (and the natural world) can “bounce back.” Of critical importance is that these perceptions of risk, uncertainty, and vulnerability may not be generated primarily by the biophysical impact, but rather by relations and understandings of the broader socio-political context of natural impact. This is one of the major social science “lessons learned” for disaster studies of the impacts of hurricane Katrina on New Orleans. Katrina was as much a cultural and socio-political event as a natural catastrophe and much of what is now relevant in the social science arena surrounding Katrina were factors that were present before the hurricane struck New Orleans.

### **6.3 Natural resource economics**

Considering the vast size of the Chesapeake Bay watershed and ecosystem, climate change impacts are likely to have important economic implications. These include issues such as flood control costs under altered precipitation regimes, agricultural losses and changes in non-point source loading from changes in storm-drought cycles, potential conflict over water

supplies, economic impacts on forestry operations, changes in seasonal energy use, declines in sensitive recreational fisheries, and changes in recreational opportunities (e.g., swimming, boating, etc.).

Approximately 25% of land in the Bay watershed is used for agricultural production. This industry provides grains, eggs, meat, milk, vegetables, and other agricultural products. Rising air temperatures and more extreme precipitation events, including both cycles of floods and droughts (e.g., conditions during Fall 2007) are likely to result in increased variation in farm production, such as intensification of agricultural boom-and-bust cycles. These changes have the potential to change the cost and availability of agricultural products and substantially change the basis for insurance and other forms of risk management<sup>3</sup>. Complex relationships between changes in climate and agricultural operations make outcomes difficult to predict. For example, confined livestock production costs (broilers and turkeys) may increase with higher summertime temperatures, but are likely to be offset by lower heating costs in winter. Consumer food costs may increase if such climate-related cost increases affect broader agricultural regions of the U.S. It will be important to create policies and programs that provide incentives and assistance for agricultural producers to prepare for changing climatic conditions. The design of these policies and programs can benefit from a foundation of applied research through institutions such as the Small Farms Program at Cornell University (including the study *Understanding Impacts of Climate Change on Agriculture*) and on-going efforts by a variety of coastal zone management programs (e.g., the 2007 Virginia Coastal Zone Partners Workshop focusing on the implications of global climate change).

As one of the largest and most productive estuaries in the world [*National Oceanic and Atmospheric Administration*, 1985; 1990], annual commercial fisheries landings data [*National Marine Fisheries Service*, 2001] reveal that Chesapeake Bay dockside value for the year 2000 totaled more than U.S. \$172 million, accounting for 5% of the value for all of the United States. Although these figures are significant, they *understate* the value of the Chesapeake Bay and its fisheries, because they do not account for the ecological and recreational services the Bay provides to the food web and fisheries of the North American Atlantic Coast. The Chesapeake Bay is an integral subsystem of the Northeast U.S. Continental Shelf Large Marine Ecosystem [*Sherman et al.*, 1996], serving as an important seasonal feeding ground and nursery area for ecologically and economically important coastal species that range from Florida to the Canadian Maritime Provinces. Examples include Atlantic menhaden (*Brevoortia tyrannus*), striped bass (*Morone saxatilis*), spot (*Leiostomus xanthurus*), summer flounder (*Paralichthys dentatus*), and the alosids, including American shad (*Alosa sapidissima*), alewife (*A. pseudoharengus*), and blueback herring (*A. aestivalis*). Considering both the economic and ecological importance of the Chesapeake Bay, it is important to undertake an initial assessment of the potential consequences of future climate changes for the ecosystem, fisheries, and associated cultural and socio-economic systems.

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<sup>3</sup> Insurance products and services based solely on historic observations will be particularly poorly prepared to address future risks, as past conditions will prove to be increasingly unreliable guides to future outcomes. Addressing this will require changes in practice for private firms and reform of regulatory processes (e.g., mechanisms to allow for the use of models and predictive information in rate setting). Many of the relevant issues are described in a 2005 publication *Climate Change Futures: Health, Ecological, and Economic Disruptions*, that was co-sponsored by the re-insurer Swiss Re and the United Nations Development Programme. A number of individual insurers have created a substantial foundation of information on climate change impacts and adaptive business strategies, perhaps most notably Swiss Re, Munich Re, and more recently AIG.



## 6.4 Adaptive responses

Efforts to understand climate impacts provide the foundation for the development of approaches for preparation and adaptation to changing conditions. Adaptation studies are necessarily interdisciplinary research efforts that require simultaneous consideration for social, economic, and environmental factors required to reduce the vulnerability of cultural and socio-economic systems to climate-related disruption. The goal is typically to identify opportunities to reduce vulnerability and increase likelihood of achieving societal goals under changing conditions. The EPA and NOAA have been the primary sponsors of this kind of research in the Mid-Atlantic. Both agencies have made substantial investments over the last decade; however, the results of this research appear to have had relatively little demonstrable impact on management practices.

The most prominent activities include the EPA's Mid-Atlantic Regional Assessment (MARA) and the follow-up Consortium for Atlantic Regional Assessment (CARA). Both of these activities involved teams from multiple institutions led by faculty at Penn State University. MARA provided a regional climate change impact study as part of the US National Assessment [Fisher *et al.*, 2000]. MARA emphasized stakeholder engagement and provided a broad-based evaluation of the implications of climate change for the region [Fisher, 2000]. CARA continued the emphasis on stakeholder-engagement with a greater emphasis on the development of resources for decision makers, including a collection of "Adaptation Tools and Strategies" available from the CARA website ([www.cara.psu.edu](http://www.cara.psu.edu)). These resources include links to primary literature and, in some cases, interactive web-based tools. In many ways, the CARA web-site reflects the "state-of-the-art" for regional assessment and decision support.

Unfortunately, CARA did not conduct a systematic evaluation of the value or effectiveness of these resources for specific decision makers. Consequently, it is difficult to understand or generalize about their value for any particular stakeholder group or issue. For example, it is not possible to know if these particular tools are addressing the "right issues" or provide value for targeted decision makers. This over-the-transom approach to knowledge transfer is common in the development of resources for adaptation. It is important to note that these limitations say as much or more about resource constraints and agency priorities as interests and capabilities of the research team and their many stakeholders. The value of individual decision support resources can be examined through a variety of program evaluation methods and many CARA participants have expressed their interest in this kind of work. However, funding from the original sponsors is no longer available and alternative resources have not materialized. One could reasonably conclude that a lack of agency follow through has substantially undermined the original investment in these programs.

Experience with programs such as MARA and CARA has clearly demonstrated that the demand for information about climate impacts and adaptation strategies is far greater than available resources can support. Consequently, it is essential to develop transparent and reproducible approaches to identify and prioritize the best candidates for research and development investments. Pyke *et al.* [2007a] developed a general method for evaluating and prioritizing opportunities for adaptation-related research and development associated with Chesapeake Bay water quality Best Management Practices and living resource restoration activities called for in tributary strategies. They screened an initial set of 150 practices and conducted more in-depth analysis on a sub-set of approximately 45 practices and activities.

They found that storm water management practices were among the strongest candidates for additional research to develop adaptive strategies based on a range of decision criteria and assumptions. This reflected the sensitivity of storm water management to changes in climate, understanding of both physical processes and management options, and the availability of specific opportunities for alternative action. Other practices, such as urban stream restoration and fishery management, were also identified as highly suitable, but they were found to be highly sensitive to specific prioritization criteria. *Pyke et al.* [2007a] concluded that it was not feasible to identify an optimal research and development portfolio for adaptation, but it was possible to collect meaningful information about the context and characteristics of potential candidates and provide a transparent, reproducible system for evaluating options. This type of work would benefit from interdisciplinary collaborations that help understand the cultural, social, and economic circumstances surrounding important impacts and adaptation strategies.

It is also possible to use this approach to identify and prioritize climate-sensitive or adaptive opportunities associated with individual land use or development projects. For example, *Pyke et al.* [2007b] considered the implications of climate change for elements of the built environment, particularly the impact of climate change on the performance of storm water management systems under future conditions. This information is useful to understand the efficacy of the ubiquitous Best Management Practices throughout their expected periods of performance. The study found that a large percentage of design decisions involved significant climatic assumptions or provided direct opportunities to make design choices that could reduce climatic vulnerability or enhance resilience (Figure 10). This suggests that the management practices being deployed today may not meet performance expectations under future conditions. This could significantly undermine efforts to protect and restore the Chesapeake Bay. Efforts to build on this work would benefit from interdisciplinary teams that bring together design, engineering, economic, and social research perspectives to develop, implement, and evaluate practical adaptation strategies associated with the design and operation of built environments.

#### **Summary of questions for Section 6—Social and economic research**

- How will climate change alter economic opportunities for individuals and the Bay region as a whole?
- How will climate change impact individual livelihoods and conditions facing sensitive groups, such as waterman or farmers?
- How much will it cost to adapt to changing conditions (i.e., achieve existing performance goals under future conditions)?
- How can we ensure that Bay monitoring systems are capturing and analyzing the most important pieces of information on the “human dimensions” of climate change?

## **7. Summary**

The scientific community has built and continues to expand a substantial foundation of understanding about the physical drivers of change in the Chesapeake Bay watershed and the implications of these changes for hydrologic processes and living resources. We conclude that the climate change-related research in or directly relevant to the Chesapeake Bay is uneven, fragmented, and certainly incomplete.

Support for this research has come from nearly every research sponsor active in the Bay. The largest fraction of specifically climate change-related work is associated with EPA and

NOAA programs, which have been able to provide important, if sporadic support, such as the two recent EPA-funded regional climate change impact assessments, MARA and CARA. These activities have directly or indirectly supported a substantial fraction of climate change research, notably including a number of research projects emphasizing interactions between resource managers, decision makers, and the scientific community. Outside of these large collaborative projects, many individual investigators and small teams have obtained funding to pursue climate change-related research from other state and federal programs, including notably NSF and NASA. Some of these projects have continued for over a decade, such as the long-running study of wetland plant communities under elevated CO<sub>2</sub> concentrations [Rasse *et al.*, 2005]. As one would probably expect from a region with such a concentration of research capabilities, there has also been a myriad of studies by individual investigators tackling small, climate change-related themes.

At this point in time, we conclude that the supply of timely and relevant climate-related information to support Chesapeake Bay management is limited by inadequate, inconsistent, and uncoordinated research funding. There are programs in place in other parts of the United States that demonstrate the benefits of sustained and directed efforts to provide scientific information to support key resource management and policy questions. The Bay Program partners can and should review these programs in detail and take immediate action to develop and implement a research coordination and research support program that will provide the information needed to address the key questions raised in this document. Without change, it appears unlikely that existing research support resources and agency priorities will provide timely incentives for key decisions facing the partnership.

This vision can be realized in a wide variety of ways, and the interface between climate change science, management, and policy is currently the subject of a National Research Council study (this is under the auspices of “decision support”). The Bay Program should seek opportunities to contribute to and learn from the NRC’s study. One widely-discussed option for the provision of effective decision support is the development of a responsive, collaborative, solutions-oriented applied research program that is guided by the needs of local and regional stakeholders. This type of research program might constitute a climate extension service for the Chesapeake Bay. The success of this kind of activity would be based on successful programs for issues such as soil conservation, wildlife management, and coastal zone management. In these cases, federal agencies have a long and successful track record of implementing programs that provide direct benefits to key constituencies and positive return-on-investment for society as a whole. These programs are often decentralized, embedding extension scientists within universities with a mandate to facilitate technology transfer. A similar approach could be devised for the Chesapeake Bay. Such a service does not necessarily entail the creation of entirely new institutions. Rather, it might be most effective if it was designed to stimulate the rigorous consideration of climate change *within* existing institutions.

Whatever form future climate change research and development in the Chesapeake Bay takes, it is clear that the time for action is now. Critical, climate-sensitive decisions loom on the near horizon and it is essential to put processes into motion to ensure that adequate scientific information is available when decisions need to be made. The consequences of delay are likely to include increasingly serious social, economic, and legal liabilities. Fortunately, this report represents a significant first step toward the consideration of climate change in Bay Program decision making. The Bay Program’s request for this information is a particularly positive sign

about recognition of the importance of the issue, and, hopefully, commitment to link scientific information with key management decisions.

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## Boxes, tables and figures

### **Box 1. Climate change scenarios.**

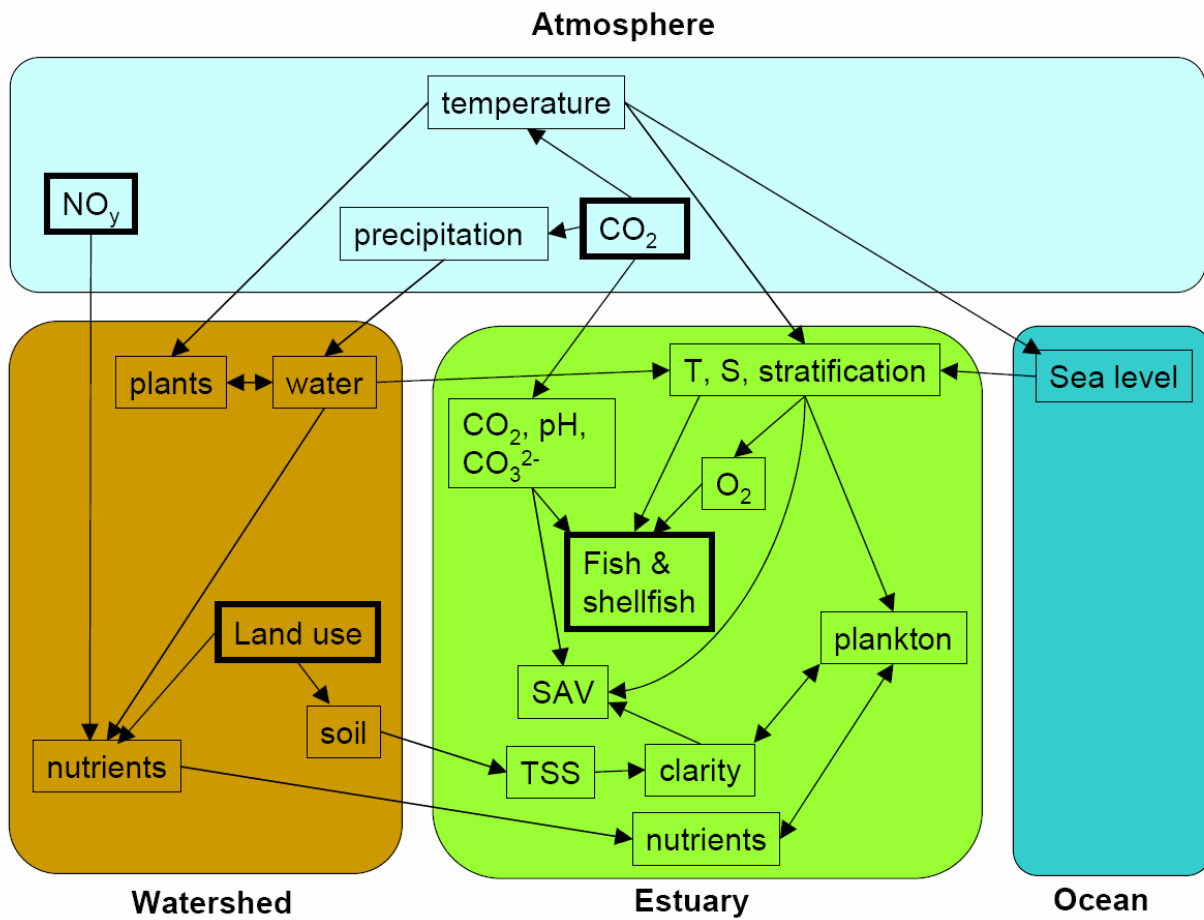
The United Nation's Intergovernmental Panel on Climate Change (IPCC) has developed a set of socio-economic scenarios as the basis for climate change modeling and policy analysis. The following verbatim descriptions from *Nakićenović and Swart* [2000] are the most widely used scenarios:

- **A1:** A future world of very rapid economic growth, global population that peaks in the mid-21<sup>st</sup> century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family has three groups that describe alternative directions of technological change in the energy system: fossil intensive (**A1FI**), non-fossil energy sources (**A1T**), or a balance across all sources (**A1B**) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).
- **A2:** A very heterogeneous world where the underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than other storylines.
- **B1:** A convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- **B2:** A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, and with intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is oriented toward environmental protection and social equity, it focuses on local and regional levels.

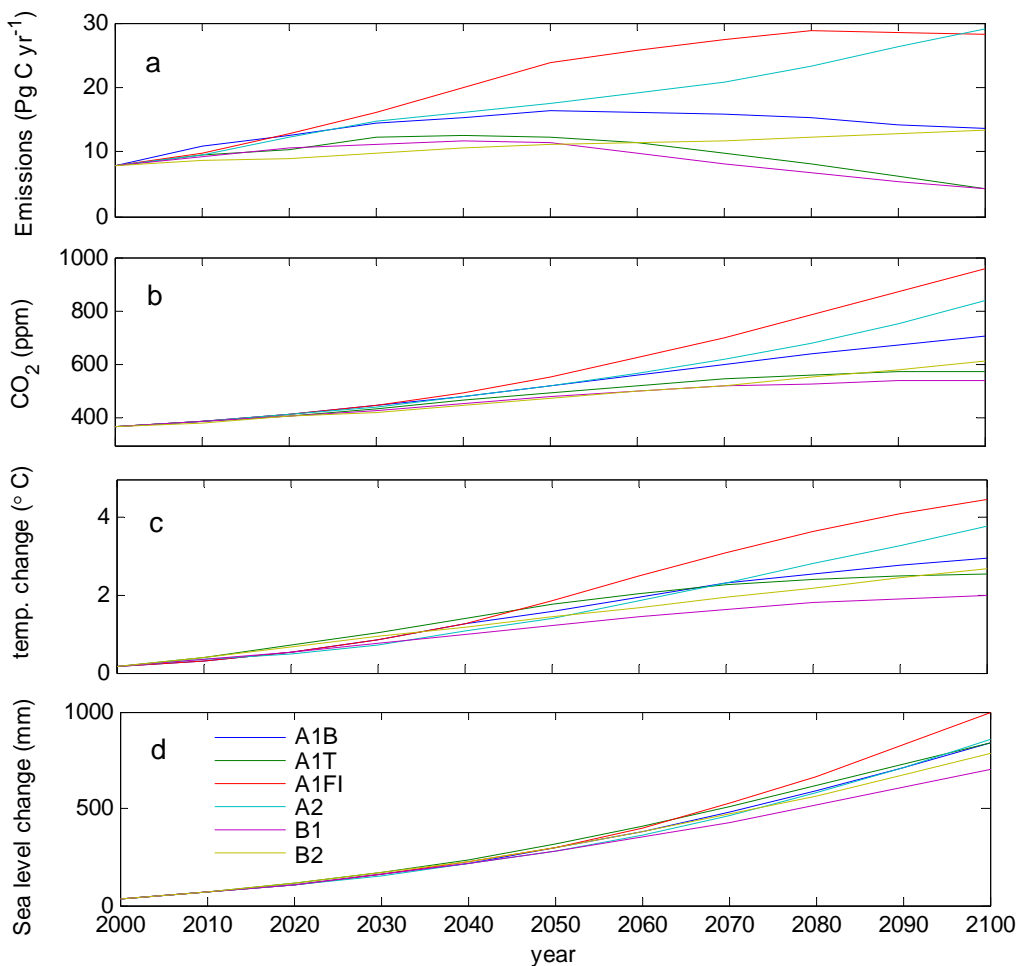
When considering future conditions in the Chesapeake Bay, it is important to note that there is no direct connection between these global storylines and regional conditions. This makes it important to carefully consider the implied relationship between global drivers and local and regional conditions (e.g., population size, technology choices, etc.). The U.S. EPA Global Change Research Program is currently developing tools to provide national and regional realizations of IPCC storylines for urban land cover through their *Integrated Climate and Land Use Scenarios* (ICLUS) project.

Table 1. Summary of modeling studies on the influence of climate change on streamflow in the mid-Atlantic region (reproduced from *Najjar et al.* [2008]).

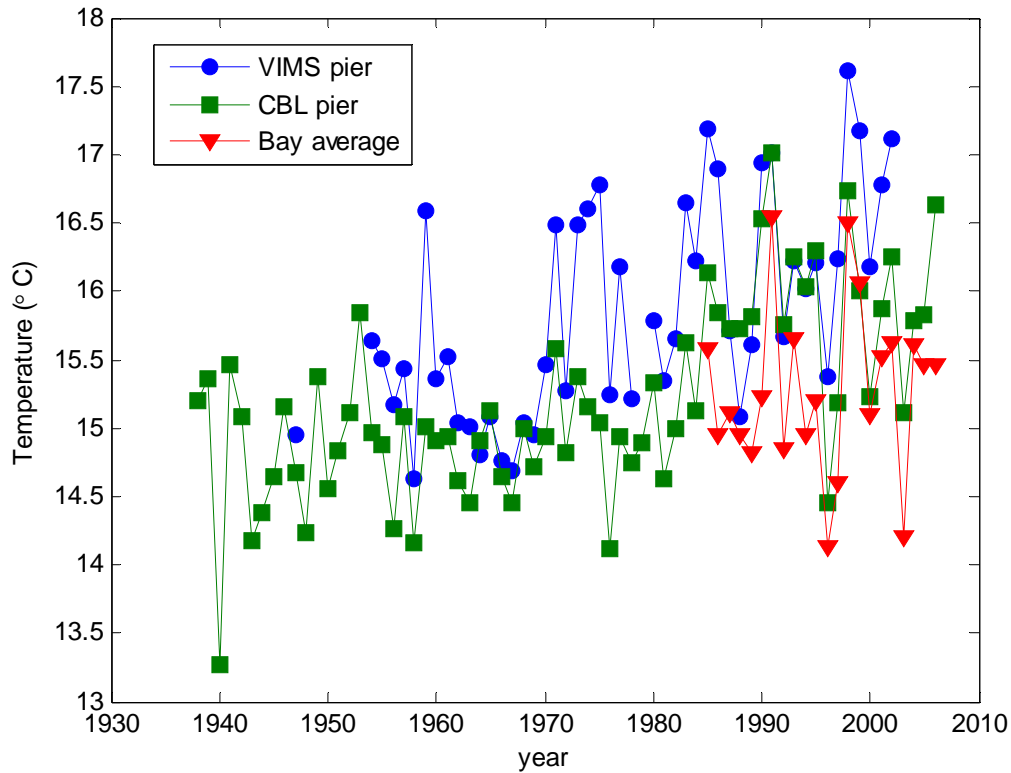
Reference	Region	CO <sub>2</sub> scenario	Time period	Number of GCMs	Annual streamflow change (%)
<i>McCabe and Ayers</i> [1989]	Delaware River Basin	doubling	--	3	-39 to 9
<i>Moore et al.</i> [1997]	Mid-Atlantic/New England	doubling	--	4	-32 to 6
<i>Najjar</i> [1999]	Susquehanna River Basin	doubling	--	2	24 ± 13
<i>Neff et al.</i> [2000]	Susquehanna River Basin	1% yr <sup>-1</sup> increase	1985-1994 to 2090-2099	2	-4 to 24
<i>Wolock and McCabe</i> [1999]	Mid-Atlantic	1% yr <sup>-1</sup> increase	1985-1994 to 2090-2099	2	-25 to 33
<i>Hayhoe et al.</i> [2007]	Pennsylvania and New Jersey	A1FI and B1	1961-1990 to 2070-2099	2	9 to 18



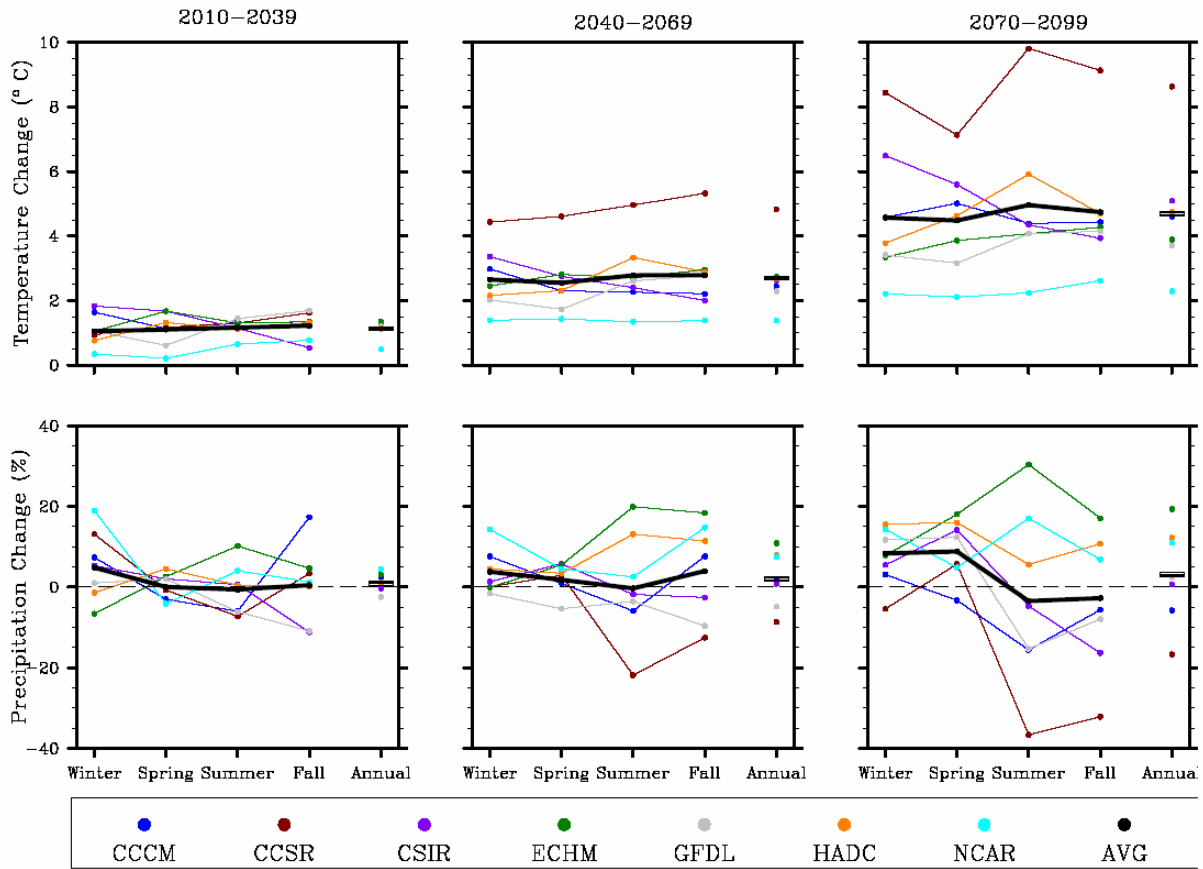
**Figure 1.** Schematic diagram illustrating some of the ways in which climate may influence an estuary. Boxes in bold (e.g., CO<sub>2</sub>) indicate quantities that humans can directly affect through emissions, land use, and fisheries.



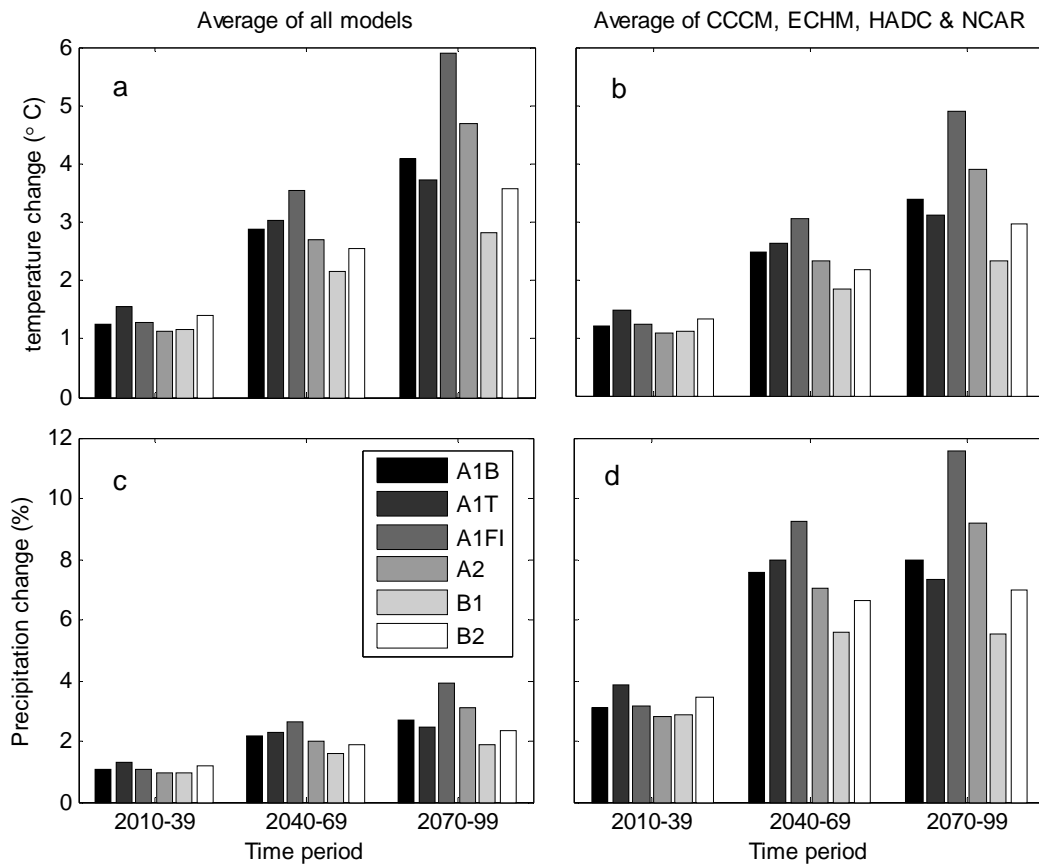
**Figure 2.** Global projections from the IPCC Third Assessment Report (TAR), except for panel (d). Six scenarios are shown, described in *Nakićenović and Swart* [2000]; also see Box 1. (a) CO<sub>2</sub> emissions; (b) modeled levels of carbon dioxide according to the Bern carbon cycle model; (c) global mean surface air temperature change with respect to 1990 from the average of nine TAR models. Data for these figures was taken from Appendix II of *Houghton et al.* [2001]. (d) Global mean sea-level change with respect to 1990 using  $dH/dt = a(T - T_o)$ , where  $a = 3.4 \text{ mm yr}^{-1} \text{ K}^{-1}$ ,  $H$  is sea level,  $T$  is the global mean air temperature, and  $T_o$  is the temperature that is 0.5 K below the 1951-1980 average temperature. Temperature change in panel (c) is with respect to 1990. 1990 temperature was about 0.3 K greater than the 1951-1980 average. We thus add 0.8 K to temperature in panel (c) to get  $T - T_o$ . This gives  $dH/dt$  for 1990 of  $1.7 \text{ mm yr}^{-1}$ , which is within the error of the observed rate [*Church et al.*, 2004].



**Figure 3.** Annual average surface temperature from the mouth of the York River (VIMS pier), the mouth of the Patuxent River (CBL pier), and average throughout the mainstem Bay (Bay average). VIMS pier data were reported in *Austin* [2002] and CBL pier data were reported in *Secor and Wingate* [2008]. VIMS pier data are part of the VIMS Scientific Data Archive, and were acquired from Gary Anderson, Virginia Institute of Marine Science, School of Marine Science, College of William & Mary, Gloucester Point, Virginia. Bay average temperature was computed by David Jasinski, Chesapeake Bay Program Office, using surface temperature measurements from the Chesapeake Bay Water Quality Monitoring Program. Data were first average by month at each station, then by year, before taking arithmetic mean of all stations.

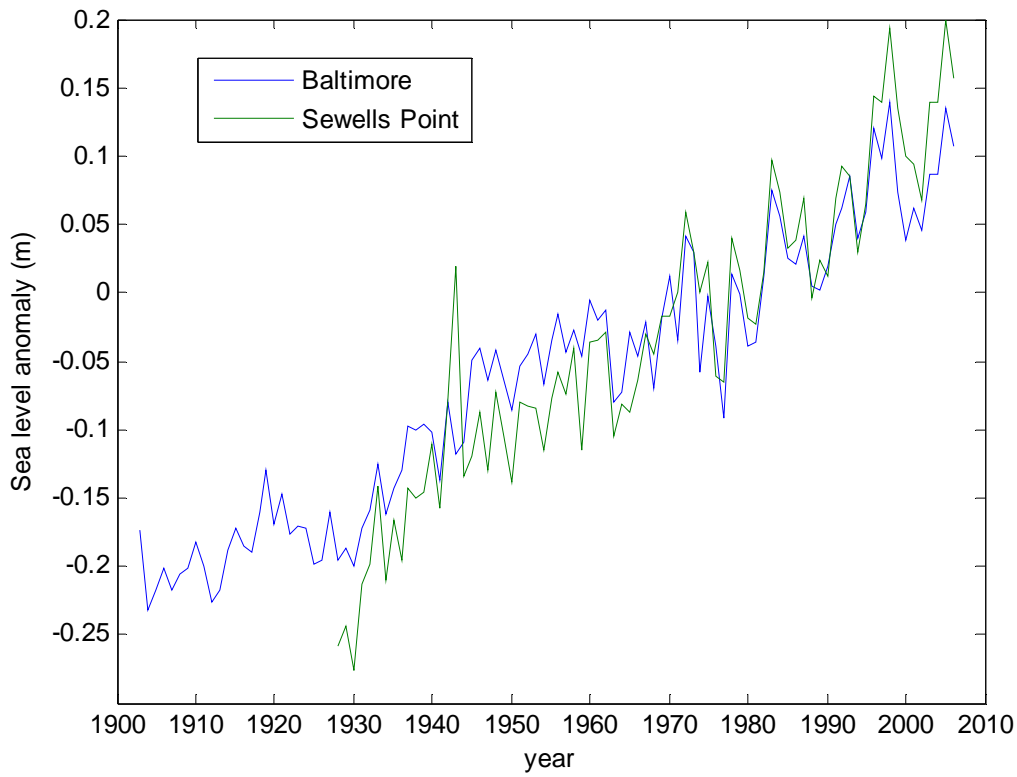


**Figure 4.** Annual and seasonal temperature (top) and precipitation (bottom) changes averaged over the Chesapeake Bay Watershed with respect to 1971-2000 predicted under the A2 scenario for the periods 2010-2039, 2040-2069 and 2070-2099 (reproduced from *Najjar et al.* [2008]).

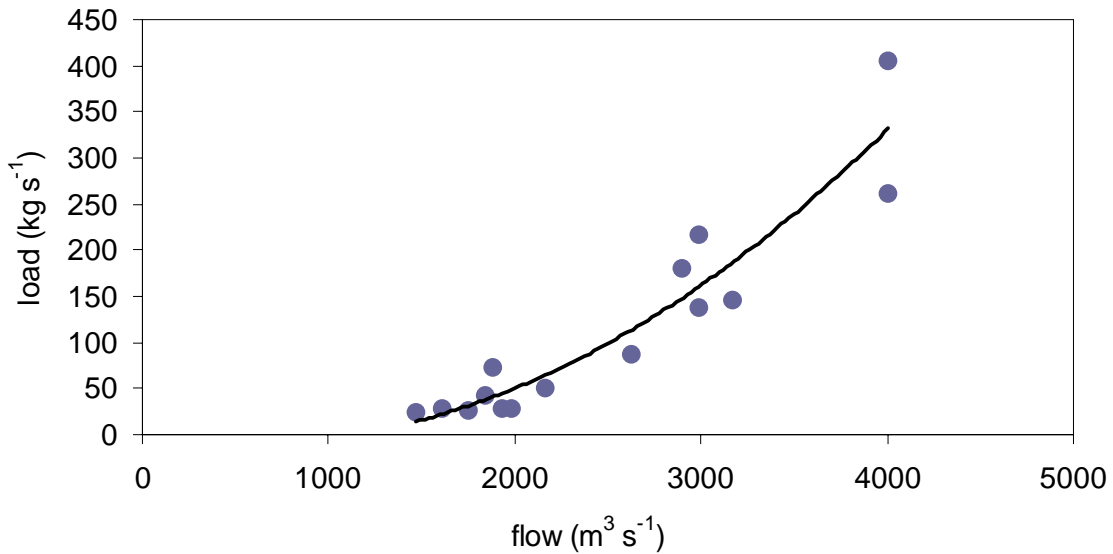


**Figure 5.** Projected change in annual mean temperature (a and c) and precipitation (b and d) of the Chesapeake Bay Watershed for six IPCC scenarios (Figure 2) averaged over seven climate models (a and b) and (c and d) the four ranked highest (reproduced from *Najjar et al.* [2008]).

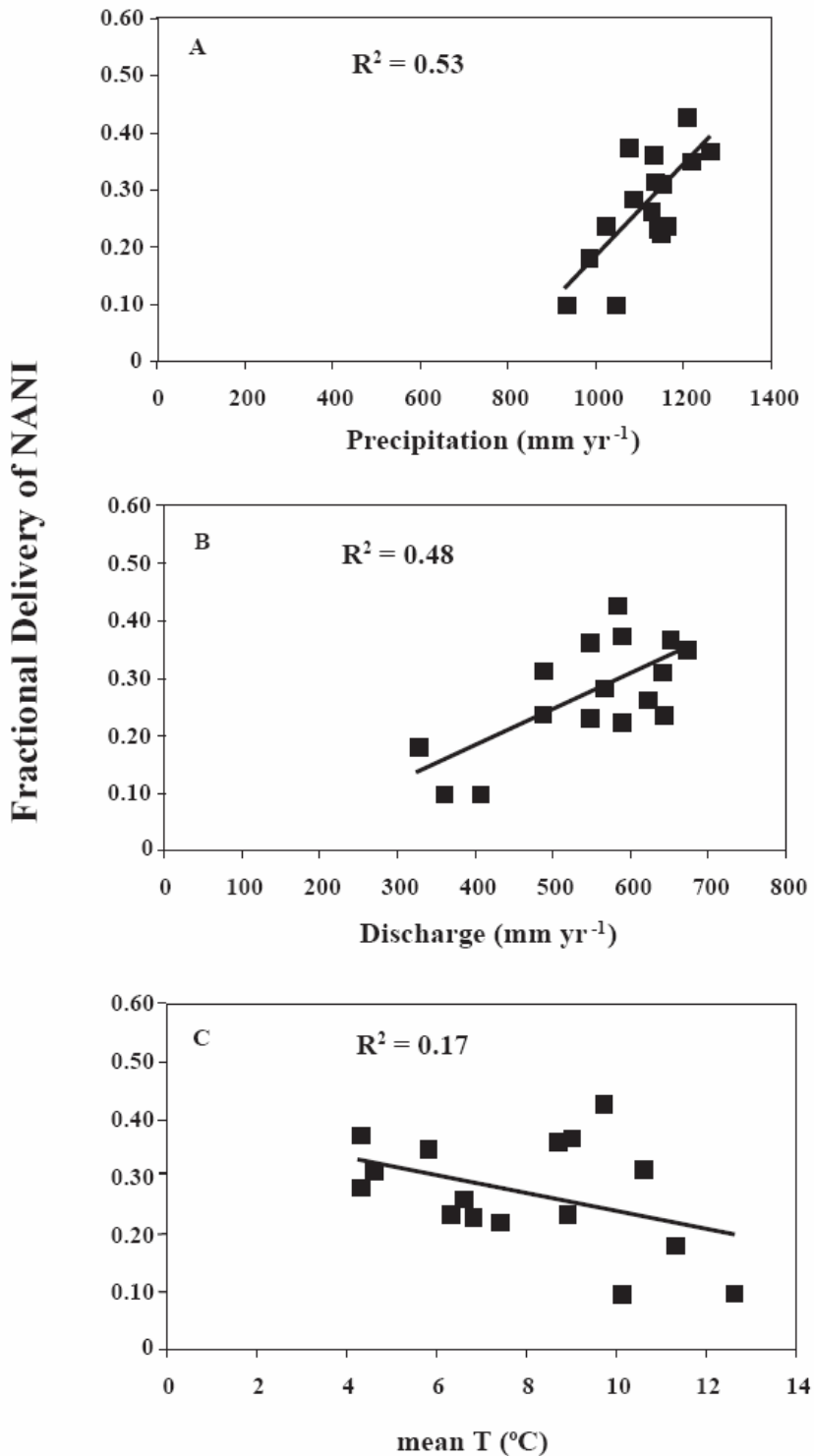




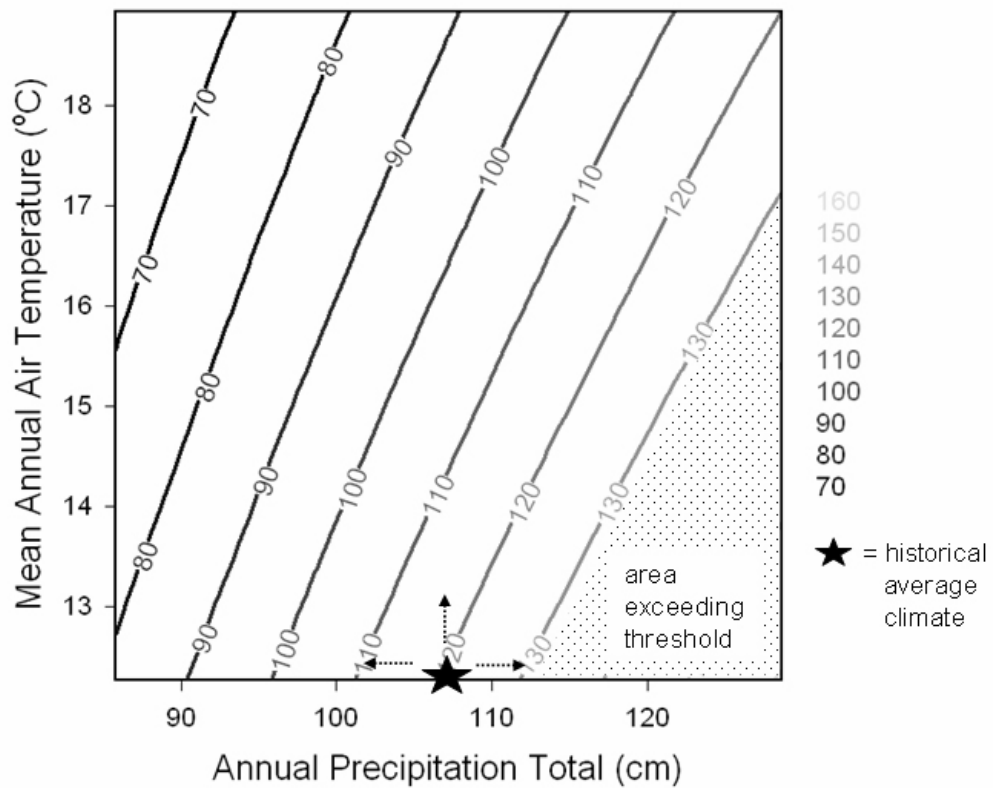
**Figure 6.** Long-term sea-level change at two locations in the Chesapeake Bay: Baltimore, MD (upper bay) and Sewells Point, VA (lower bay). Data are annual mean differences from the 1950-2000 average and were acquired from NOAA’s Center for Operational Oceanographic Products and Services.



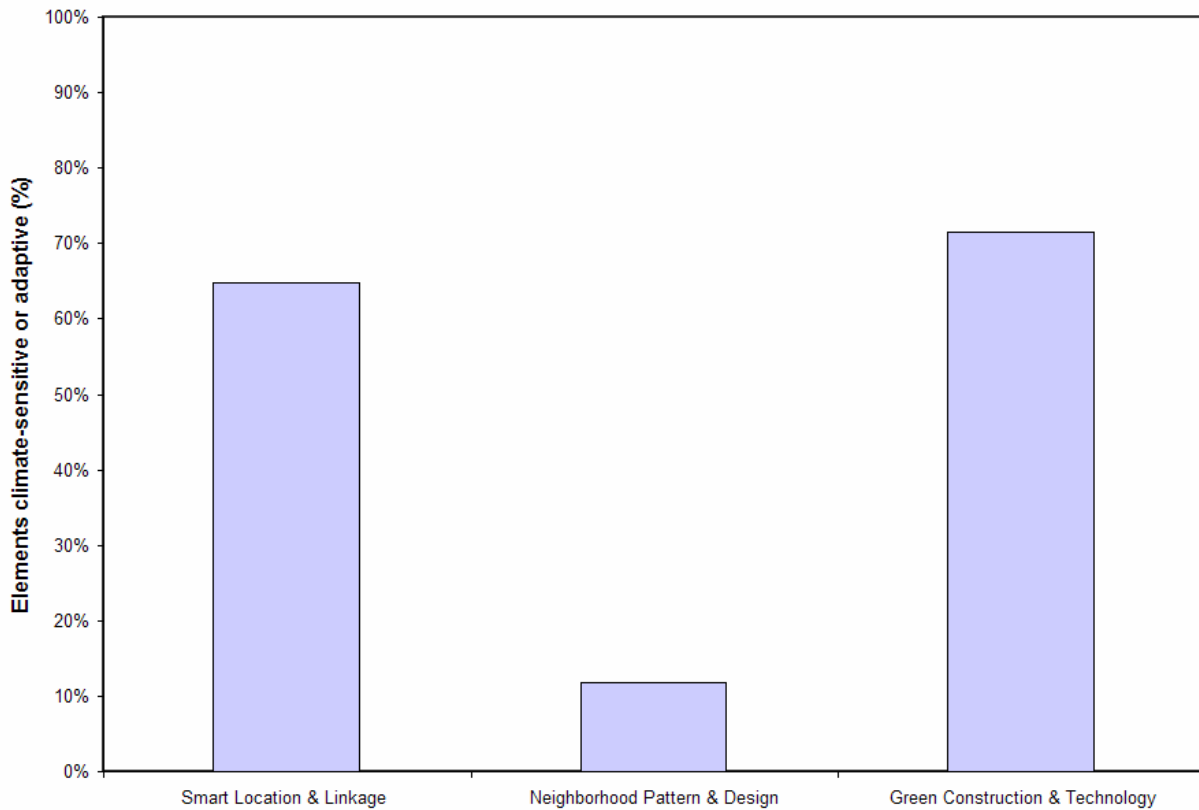
**Figure 7.** Relationship between annual sediment yield and total freshwater inflow to the Chesapeake Bay for the years 1990 to 2004. The curve is a least-squares parabolic fit ( $r^2 = 0.88$ ) with a forced zero intercept:  $y = 3 \times 10^{-5}x^2 - 0.0325x$ . The estimates were obtained from the CBP web site (<http://www.chesapeakebay.net/status.cfm?sid=201>). The annual sediment yields were computed by the United States Geological Survey by summing the products of daily streamflow and riverine Total Suspended Solids (TSS) concentrations. The TSS concentrations are based on a statistical model calibrated with TSS observations from several monitoring stations. Details on the data sources and methodology are given in *Langland et al.* [2006, pg. 13].



**Figure 8.** The fractional delivery of net anthropogenic nitrogen inputs (NANI) for 16 major watersheds in the northeastern United States plotted as a function of mean discharge, mean precipitation, and mean temperature. The relationship for discharge and precipitation are highly significant ( $p = 0.003$  and  $0.0015$  respectively); the relationship for temperature is weaker ( $p = 0.11$ ) (reprinted from *Howarth et al.* [2006]).



**Figure 9.** Annual nitrogen loading ( $10^3 \text{ kg yr}^{-1}$ ) in the Western Branch of the Patuxent River, Maryland, as a function of annual precipitation and mean annual temperature. The plot is based on a series of HSPF model simulations generated using the automated, iterative assessment capability in the BASINS Climate Assessment Tool (reprinted from *Johnson and Kittle* [2007]).



**Figure 10.** Example of results for an analysis of neighborhood design and operational elements in the US Green Building Council’s LEED for Neighborhood Development program (LEED-ND). LEED-ND elements are divided into three categories. Each element was considered qualitatively with respect to its sensitivity to climate change (e.g., implications of changing temperature or precipitation) or potential to be used to adapt to changing climatic conditions (e.g., potential to reduce climatic vulnerability) (from *Pyke et al.* [2007b]).