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Ramifications of Climate Change for Chesapeake Bay Hypoxia

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Excerpted from the full report,
Regional Impacts of Climate Change: Four Case Studies in the United States
Prepared for the Pew Center on Global Climate Change

by

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

In 2007, the science of climate change achieved an unfortunate milestone: the Intergovernmental Panel on Climate Change reached a consensus position that human-induced global warming is already causing physical and biological impacts worldwide. The most recent scientific work demonstrates that changes in the climate system are occurring in the patterns that scientists had predicted, but the observed changes are happening earlier and faster than expected—again, unfortunate. Although serious reductions in manmade greenhouse gas emissions must be undertaken to reduce the extent of future impacts, climate change is already here and some impacts are clearly unavoidable. It is imperative, therefore, that we take stock of current and projected impacts so that we may begin to prepare for a future unlike the past we have known.

The Pew Center has published a dozen previous reports on the environmental effects of climate change in various sectors across the United States. However, because climate impacts occur locally and can take many different forms in different places, *Regional Impacts of Climate Change: Four Case Studies in the United States* examines impacts of particular interest to different regions of the country. This paper is an excerpt from the full report. Although sections of the full report examine different aspects of current and projected impacts, a look across the sections reveals common issues that decision makers and planners are likely to face in learning to cope with climate change.

Kristie Ebi and Gerald Meehl find that Midwestern cities are very likely to experience more frequent, longer, and hotter heatwaves. According to Dominique Bachelet and her coauthors, wildfires are likely to increase in the West, continuing a dramatic trend already in progress. Robert Twilley explains that Gulf Coast wetlands provide critical ecosystems services to humanity, but sustaining these already fragile ecosystems will be increasingly difficult in the face of climate change. Finally, Donald Boesch and his colleagues warn that the Chesapeake Bay may respond to climate change with more frequent and larger low-oxygen "dead zone" events that damage fisheries and diminish tourist appeal. These authors are leading thinkers and practitioners in their respective fields and provide authoritative views on what must be done to adapt to climate change and diminish the threats to our environmental support systems.

A key theme emerges from these four case studies: pre-existing problems caused by human activities are exacerbated by climate change, itself mostly a human-induced phenomenon. Fortunately, manmade problems are amenable to manmade solutions. Climate change cannot be stopped entirely, but it can be limited significantly through national and international action to reduce the amount of greenhouse gases emitted to the atmosphere over the next several decades and thereafter, thus limiting climate change impacts. Managing those impacts requires that we adapt other human activities so that crucial resources, such as Gulf Coast wetlands or public emergency systems, continue to function effectively. The papers in this volume offer insights into how we can adapt to a variety of major impacts that we can expect to face now and in decades to come.

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Ramifications of Climate Change for Chesapeake Bay Hypoxia

A. Introduction

Climate change is likely to significantly complicate the achievement of environmental management objectives that presently command public attention and significant commitment of resources. This is particularly the case for coastal environments that are subject to numerous societal uses and pressures from human activities but also to concerted efforts to restore their ecological health and productivity. The Chesapeake Bay is a global model for such large-scale ecosystem restoration.

The Chesapeake Bay is the United States' largest and best-studied estuary. The bay is more than 190 miles long and its tidal waters cover more than 4,200 square miles. Its 64,000-square-mile watershed extends over six states and the District of Columbia and includes a population of approximately 16 million people. The Chesapeake is situated along the transition between warm-temperate and cool-temperate regions and is influenced both by freshwater runoff and by the Atlantic Ocean. Consequently, the Chesapeake ecosystem has experienced substantial climatic variability over 4,000 years in its present geographic configuration.

Humans had begun altering the Chesapeake Bay ecosystem even before the arrival of Europeans; however, pervasive human effects became obvious only during the late 20th century. In particular, eutrophication—the increase in organic matter loading due principally to inputs of nitrogen and phosphorus nutrients—has been recognized as the chief cause of degradation of the ecosystem and, consequently, has been the central focus of restoration efforts (Boesch et al., 2001; Kemp et al., 2005).

Eutrophication has manifold consequences in coastal ecosystems, including increased production of phytoplankton, including harmful or noxious algal blooms; decreased water clarity, resulting in loss of seagrasses; altered food chains; and severe depletion of dissolved oxygen in the water column (Cloern, 2001). Particularly during the summer, dissolved oxygen can fall to very low levels in denser bottom waters that are isolated from the warmer surface waters (the source of oxygen replenishment). Depletion of dissolved oxygen (hypoxia) to levels that exclude fish, crustaceans, and mollusks, or even the complete absence of oxygen (anoxia), is a phenomenon that has increased in coastal waters around the world (Diaz and Rosenberg, 1995). Commonly referred to as "dead zones," these expanding hypoxic regions have attracted wide attention from the public and policy-makers (Dybas, 2005).

In the late 1980s, a concerted effort to reduce nutrient pollution in the Chesapeake Bay was initiated through the multistate–federal Chesapeake Bay Program. The present goal of the program is to reduce nutrient inputs sufficiently to restore water quality, including healthy dissolved oxygen conditions, by 2010. While the cost to society of the degradation of the Chesapeake Bay ecosystem is difficult to quantify fully, it is estimated that the cost of restoration, largely driven by stringent requirements to reduce hypoxia, exceeds $15 billion (Chesapeake Bay Watershed Blue Ribbon Finance Panel, 2004). Despite already substantial public and private expenditures, reports of record-sized hypoxic zones in 2003 and 2005 raised public concerns about whether progress is really being made. Hypoxia in the Chesapeake Bay, and in most other regions experiencing this phenomenon, is greatly affected by climate, as well as by nutrient inputs from human activities. Indeed, climatic conditions, including some combination of high river inflows, warm temperatures, and relatively calm summer winds, were major factors in the extensive hypoxia that occurred in 2003 and 2005.

This case study examines how both climate variability and potential climate change can affect hypoxia in the Chesapeake Bay and can present additional challenges to ongoing ecosystem restoration. We use past observations to elucidate the multiple influences of climate on hypoxia and its consequences to the ecosystem. Using this empirical basis, we project how climate change during the rest of the 21st century is likely to affect hypoxia, and how climate change will challenge the achievement of restoration goals.

B. Climate Variability and Hypoxia

Recent variations in the climate of the Chesapeake Bay watershed have included a dry period in the 1960s, a wet period in the 1970s, and a period of unusually large inter-annual variability over the past 25 years (Boesch et al., 2001). Multi-year climate cycles such as the El Niño-Southern Oscillation and the North Atlantic Oscillation influence these regional climate variations (Austin, 2002), as do more localized weather patterns and storms. Variations in precipitation and temperature affect the amount and timing of fresh water flowing into the Chesapeake Bay from the Susquehanna, Potomac, James, and other rivers. These inflows influence hypoxia in the bay by delivering nutrients that stimulate biological production and contribute to the density stratification of the estuarine waters (Hagy et al., 2004). Winds also play a role by forcing denser ocean waters into the bay or by vertically mixing the water column in the estuary. For example, the volume of hypoxic water during the summer of 2005 was particularly large in part because summer winds were weaker than normal, allowing bay waters to remain strongly stratified.

Hypoxia thus has both natural and human causes and has occurred at some level in the Chesapeake Bay for more than 2,500 years (Cooper and Brush, 1993). However, hypoxia in the bottom waters of the mainstem bay has become more frequent, widespread, and severe since the 1960s (Hagy et al., 2004). The natural factors that make the bay susceptible to oxygen depletion include its deep central channel, which acts as a basin to contain the dense, low-oxygen waters; the bay's high ratio of watershed area to volume, leading to large nutrient exports from the watershed into a limited volume of receiving water; and high variability of freshwater flow (Kemp et al., 2005). Anthropogenic causes are largely related to the greatly increased nutrient loading that has occurred since the mid-20th century (Boynton et al., 1995; Harding and Perry, 1997). The higher nutrient levels increase phytoplankton biomass, particularly in the spring. The increase in impervious surface area on the landscape (e.g., from roads and other development) and other land use changes may also affect the volume and timing of freshwater runoff (Jennings and Jarnagin, 2002; Jones et al., 2001). Because nutrient loading to the bay is closely tied to freshwater input, the interaction between climate and anthropogenic nutrient loading will be particularly important in determining future hypoxic events in the Chesapeake.

Freshwater flow into the Chesapeake Bay is typically greatest during the spring. This spring freshet—a freshwater pulse resulting partly from snowmelt—delivers sediment and nutrients that act in concert to control the timing, position, and magnitude of a spring phytoplankton bloom—light limitation controls phytoplankton in the upper estuary (closer to the Susquehanna River) and nutrient stimulation enhances it in the middle to lower estuary (closer to the ocean) (Harding, 1994). The freshet is, to a large degree, controlled by the winter weather (Miller et al., 2006). Drier than normal winters mean very little precipitation is stored in the form of snow in the upper watershed, resulting in less spring runoff. Conversely, wet winters that have high frequencies of storm events result in more snow stored in the watershed and later released to the estuary as snowmelt runoff in the spring (Najjar, 1999). The organic matter produced during the spring bloom is retained particularly in the middle reaches of the bay, as the estuarine circulation produces a net return flow of bottom waters (Boicourt, 1993). The settling material is eventually decomposed in the bottom layer by microbes that consume oxygen in proportion to available organic matter and thus cause hypoxic conditions in waters deeper than about 30 feet (10 m; Kemp et al., 1992). Because fresh water is less dense than salt water, the freshet also increases water-column stratification, preventing the resupply of oxygen from the surface.

The resulting hypoxia affects the cycling of nutrients and other materials in the ecosystem, causes stress and mortality in biota, and changes interactions between predators and their prey, thus impairing normal ecosystem function (Breitburg et al., 1997). Small zooplankton swim upward to avoid low oxygen. They may also be subject to increased predation by jellyfish, which are more tolerant of low oxygen than are other predators. Changes in zooplankton biomass and behavior may reduce key prey for larval fish that use the estuary as a nursery. Benthic (bottom dwelling) organisms are especially vulnerable to hypoxia, as they are unable to flee low-oxygen conditions (Diaz and Rosenberg, 1995). Other animals alter their customary behavior—for example, blue crabs (*Callinectes sapidus*) may alter their migration routes to lower-bay spawning areas. Striped bass (*Morone saxatilis*) experience severe habitat restriction and physiological stress in summer as they try to avoid both the high temperatures of surface waters and low oxygen of bottom waters (Coutant, 1985). Therefore, by driving hypoxia, nutrient pollution—as modulated by climate variability—affects commercially and recreationally important fisheries in the Chesapeake Bay (Houde and Rutherford, 1993).

Changes in nutrient inputs, combined with variability in freshwater flow, have produced large inter-annual variability in the spatial extent and volume of hypoxic water in the Chesapeake Bay, as revealed by records extending from the 1950s (Hagy et al., 2004). Understanding these highly variable records provides insights into possible ecosystem responses to future climate change. A wetter climate would likely result in enhanced phytoplankton production that extends farther down the bay, providing more organic matter to fuel summer hypoxia. A drier climate would likely be characterized by smaller input of nutrients, reduced phytoplankton production, and blooms confined to the upper estuary. The location, timing, and magnitude of the spring bloom, and its subsequent degradation, all combine to affect the severity of summer hypoxia.

C. Modeling of Future Climate Change and Ecosystem Consequences

Projecting the ecosystem response to potential climate change requires an understanding of how precipitation, river runoff, sea level, temperature, and wind will vary and interact with biological processes in the future. These multiple drivers and their relationship to hypoxia can vary considerably (Table 1). Effects of some drivers are relatively direct; for example, increased runoff would likely exacerbate hypoxia. For more complex drivers, it is sometimes difficult to predict the direction, much less the magnitude, of their effect on hypoxia. For example, warmer temperatures could expand agricultural production, increasing nutrient runoff, causing increased algal blooms and greater hypoxia. Conversely, reduced soil moisture during the summer could force abandonment of some crops or increase the use of irrigation. Such complex interactions occur on spatial and temporal scales smaller and shorter than can be resolved by the global climate simulation models used to forecast climate changes. Furthermore, necessary simplifications as

Table 1

The Influence of Multiple Climate Drivers on the Extent and Severity of Hypoxia in the Chesapeake Bay

Climate Driver	Direct Effect	Secondary Effect	Influence on Hypoxia
Increased temperature	More evapotranspiration	Decreased streamflow	+
		Land-use and cover changes	+/–
	Less snow cover	More nitrogen retention	–
	Warmer bay temperature	Stronger bay stratification	+
		Higher metabolic rates	+
More precipitation	More streamflow	Stronger bay stratification	+
		More nutrient loading	+
	More extreme rainfall	Greater erosion of soil P	+
Less precipitation	Less streamflow	Weaker bay stratification	–
		Less nutrient loading	–
Higher sea level	Greater bay depth/volume	Stronger bay stratification	+
		Greater bottom water volume	–
		Less hydraulic mixing	+
	Less tidal marsh	Diminished nutrient trapping	+
Weaker summer wind	Less water column mixing	More persistent stratification	+
Stronger summer wind	More water column mixing	Less persistent stratification	–

well as incompletely understood physical feedbacks contribute to uncertainties in the models used to project future climate variability and change. However, newer models are producing results that are increasingly consistent with observations of recent climate trends (DeGaetano and Allen, 2002), inspiring greater confidence in model results, especially regarding temperature projections.

Assessments of climate change impacts in the Mid-Atlantic region, conducted as part of the U.S. National Assessment of Consequences of Climate Variability and Change (Fisher et al., 2000), relied on an earlier generation of coupled ocean-atmosphere general circulation models, specifically the then-available versions of models from the U.K. Hadley and Canadian climate centers. Using these models, Najjar et al. (2000) projected that spring streamflow in the Susquehanna River could change by +12 percent to –4 percent by 2030 and +4 percent to –25 percent by 2095. Based on the 2030 projections, they estimated that average hypoxic volume in the Chesapeake Bay could increase as much as 31 percent or decrease by 10 percent. Earlier, Najjar (1999) used geographically downscaled projections from a version of the GENESIS general circulation model to project an increase in streamflow down the Susquehanna River of 24 ± 13 percent under a doubling of atmospheric carbon dioxide (CO_2).

The newest generation of climate models has improved both spatial resolution and large-scale heat balances. These models no longer require adjustments to match observations as did earlier models (Bader, 2004). On average, the latest models project an increase in annual precipitation for the East Coast of the U.S., but with regional uncertainty (Christensen, 2007). Although applying newer models to project streamflow is beyond the scope of this brief review, it is instructive to examine whether the newer models might change or sharpen earlier projections for future streamflow. A recent high-resolution model covering the continental United States projects only small differences in the degree of change within the Chesapeake Bay watershed for current-generation and earlier models (Diffenbaugh et al., 2005). Thus we examined results for the generalized Chesapeake region from the U.S. Community Climate System Model (CCSM3) and a newer version of the U.K. Hadley Centre for Climate Prediction and Research model (HadCM3) for a range of possible greenhouse gas forcing scenarios.

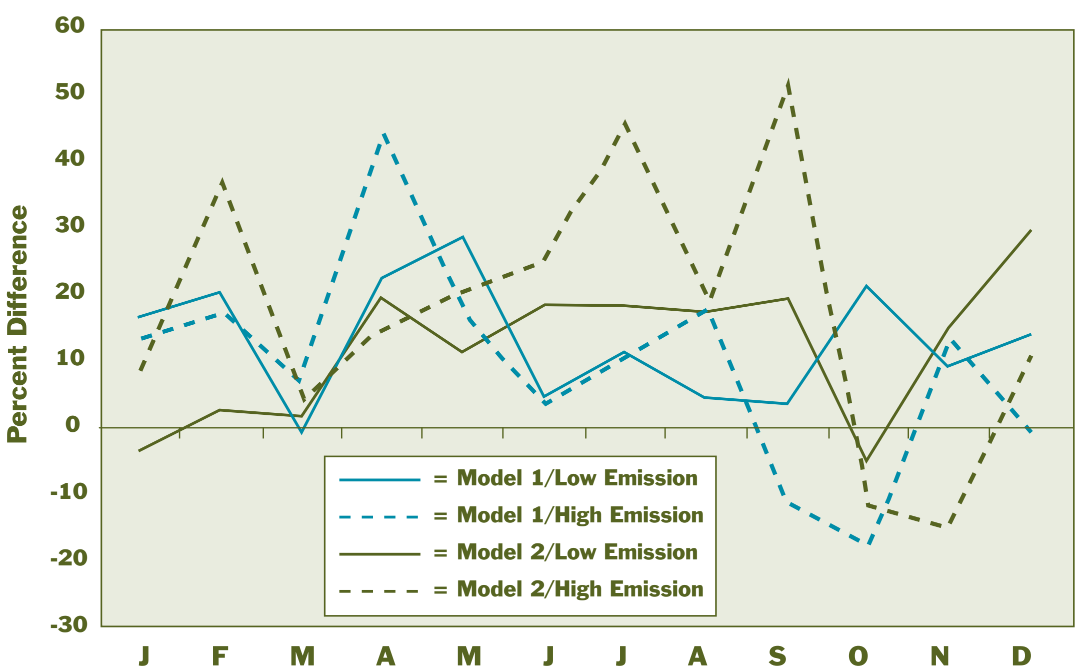
The projected changes in average monthly precipitation for the Chesapeake Bay region by the end of the 21st century are shown in Figure 1 for two scenarios used in Intergovernmental Panel on

Climate Change (IPCC) assessments: the A1B (reversing the growth of greenhouse gases by mid century) and A2 (unrestrained growth in greenhouse concentrations throughout the century). In general, the two models agreed in their projection of more precipitation during most of the year, except during fall, when some modeled scenarios projected decreased precipitation. As would be expected, the more rapidly warming A2 scenario produced wider ranges in precipitation, with increases greater than 30 percent in some months and decreases greater than 10 percent in the fall. One should bear in mind that in a warmer world, increased losses due to evapotranspiration would be expected to moderate the effects of increased precipitation on streamflow, particularly during the summer. Presently, two-thirds of all precipitation returns to the atmosphere via the combined effects of surface evaporation and plant-mediated soil drying (Neff et al., 2000).

Although these results await detailed hydrologic modeling, their implications for inflows to the Chesapeake Bay can be summarized as (1) increased inflows during winter, due to increased

Figure 1

Projected **Changes in Average Precipitation** for the Chesapeake Bay Region



Projections of the changes in average monthly precipitation for the Chesapeake Bay region by the end of the twenty-first century, based on two different climate models (Model 1=HadCM3; Model 2=CCSM3) and two IPCC greenhouse gas emission scenarios (Low emissions=SRES A1B; High emissions=SRES A2). In SRES A1B the growth of emissions reverses by mid century, whereas in SRES A2 emissions growth is unrestrained throughout the century. Both scenarios assume that no steps are taken to reduce greenhouse gas emissions in order to limit climate change.

precipitation and less storage as snow; (2) somewhat increased runoff during spring, but without a pronounced freshet from snowmelt, (3) inflows during summer generally similar to the present; and (4) possibly decreased streamflow during fall. In general, moderate increases (in the range of 10–15 percent) in delivery of fresh water and, potentially, nutrients from nonpoint sources should be expected. Najjar et al.'s (2000) results suggest a wider range of possible changes in precipitation and inflows (because of the inclusion of a Canadian Climate Centre model that produced hotter and drier projections). The newer models are more in agreement with the other model they used as well as with the fine-scale model of Diffenbaugh et al. (2005), which also found modest increases in average rainfall and in extreme rainfall frequency in the Chesapeake watershed for both the A2 and A1B scenarios. Similar projections also appear in a more recent assessment for the northeastern U.S. (Hayhoe et al., 2007).

There is generally a greater degree of confidence in projections of temperature than of precipitation. Both the CCSM3 and HadCM3 models project greater warming of air temperature for the Chesapeake Bay region (3–4.5 °C by the end of the century based on the A1B and A2 scenarios) than for the global averages for those models. Both models predict the greatest warming to occur during summer, with maximum increases ranging from 3.5 to 6.5 ºC and an increase in extremely warm days, clustered in the summer months, under conditions of modest winds. The timing of this warming is significant not only because it would increase evapotranspiration and decrease soil moisture, but also because it would result in warmer water temperatures in the bay during the time that hypoxia is most prominent.

Greater and earlier warming of the bay would have multiple effects on hypoxia. First, higher temperatures would reduce the amount of oxygen that can be dissolved in the water, leading to lower overall oxygen content that would be depleted by respiration of biota. Observations from past years with similar freshwater discharges suggest progressively earlier onset of hypoxia when the deep-water column warms early (Hagy et al., 2004). Second, warmer summertime air temperatures would enhance the stratification (and thereby reduce the exchange) between the warmer surface waters and cooler deep waters. Third, both photosynthesis and respiration are temperature-dependent processes and thus the rates of production, decomposition, and nutrient cycling would likely increase under warmer conditions. Although as much as 70 percent of the variance in the extent of hypoxia is explained by springtime runoff, a significant fraction of the remaining variability is due to whether summertime weather conditions are conducive either to stratification or to wind mixing and oxygenation of the water column. Thus, increased summertime temperatures, especially if coincident with reduced winds, would lead to more persistent stratification and the expansion of hypoxia into shallower areas of the bay.

Chesapeake Bay hypoxia may also respond to accelerated sea-level rise resulting from global warming. Locally experienced sea-level rise is also partially due to land subsidence resulting from the post-glacial rebound of regions to the north, as well as other local effects such as groundwater withdrawal. Coupling regional subsidence with IPCC Third Assessment projections of global sea-level rise, Wood et al. (2002) projected an increase of relative sea levels for the Chesapeake Bay region of 38–87 cm (15–34 inches) by the last decade in the 21st century. Assuming a central estimate of approximately 60 cm (24 inches), this increase is twice the locally observed rise in sea level during the 20th century and would increase the volume of the bay by 9 percent, unless counteracted by the increased infilling of the bay with sediment (Cronin et al., 2003).

Sea-level rise would have two potentially competing effects on the volume and duration of hypoxic conditions. As the depth of the Chesapeake Bay increases, the proportional volume of ocean waters filling the bay would also increase without compensatory increases in freshwater flow. This would allow salty bottom waters to penetrate farther up the bay, thus increasing stratification and hypoxia. Assuming that the depth of the discontinuity between the less dense surface water and the denser water below would remain the same, it would also increase the volume of bottom water from which oxygen would have to be depleted to generate hypoxia. Changes in the circulation in the bay could occur, as increasing water depth reduces the effect of the sill that lies off Rappahannock Spit in the lower Bay. This hydraulic control point currently enhances vertical mixing (Chao and Paluskiewicz, 1991). Reduction in mixing would further isolate the salty bottom water from the upper layer and reinforce stratification over a broader region of the bay.

Although some clues to the changes in hypoxia that might occur under climate change can be gleaned from the responses to inter-annual variations discussed earlier, the Chesapeake Bay ecosystem is physically and biologically complex and therefore somewhat unpredictable. Prolonged shifts in climate and its variability, or in the biota inhabiting the bay, may have unprecedented effects that drive the ecosystem to a new state. Such a change in state may have already occurred during the late 20th century—Hagy et al. (2004) could ascribe only part of the increases in hypoxic volume to enhanced nutrient loading, suggesting that some reduction in the resilience of the ecosystem over time, such as a further reduction in filter feeders (e.g., oysters), may have occurred.

D. Management Implications

Although the Chesapeake 2000 Agreement (Chesapeake Bay Program, 1999) expanded the multiple objectives of the Chesapeake Bay Program, the program's central focus remains alleviating hypoxia and other undesirable effects of eutrophication through the significant reduction of nutrient inputs. New nutrient reduction goals for 2010 were based on inverse computer models, essentially "back calculations" that predict the nutrient load reductions necessary to return water quality to levels needed to support living resources. These water quality objectives were determined based on known biological requirements for oxygen and light in various depth zones along the bay and its major tributaries. The Chesapeake Bay Program has estimated that on a bay-wide basis, reductions of 48 percent and 53 percent are required for nitrogen and phosphorus, respectively (derived from a 1985 baseline load; Koroncai et al., 2003). The most demanding requirement for these new targets is the load reductions needed to reduce hypoxia in the central trough of the bay to levels more typical of the mid-20th century.

Estimates of nutrient inputs to the bay indicate that some reduction has been achieved, but confidence in these estimates is low. Watershed models have been used to track estimated load reductions based on the management actions taken and assumptions about their effectiveness. However, the representation of such virtual accounting as a measure of progress has been sharply criticized in a recent Government Accountability Office (2005) report, which emphasizes the need for real-world measurements and integrated assessments of progress. One such measure of progress is the change in loadings of nutrients from the major rivers discharging to the bay. However, the results of such monitoring are also difficult to evaluate, in large part because of the climatic variability that affects the amount and timing of freshwater discharges. Flow-adjustment techniques used to compare concentrations over time show statistically significant downward trends in nutrient concentrations for many of the major rivers, including the Susquehanna (Langland et al., 2004), but these results often do not match well with watershed model projections. Because climatic variations also affect the processes creating, maintaining, and dissipating hypoxia in the bay itself, these watershed and estuarine processes conspire to create variability that has made it difficult to see much improvement in hypoxia in the bay at present (Chesapeake Bay Program, 2006).

Climate change is likely to affect hypoxia in myriad ways, sometimes with opposing results. In addition to changes to the physical drivers of freshwater discharge, temperature, water depth, and winds, processes in the watershed that govern the delivery of nutrients and sediment are likely to change. Climate-influenced changes in forests, land uses, and agricultural practices will surely occur. Reduction in snow cover could result in less runoff of atmospherically deposited nitrogen during snow melt and more retention within forests. Increases in extreme rainfall events may cause more phosphorus delivery as a result of soil erosion. Other important changes in the estuary itself include the probable reduction in tidal wetlands (which serve as important nutrient traps) due to sea-level rise.

While we lack the full understanding needed to integrate all of these factors into a reliable projection of future hypoxic conditions in the Chesapeake Bay, many of the anticipated changes (increased streamflow, warmer temperatures, calmer summer winds, and increased depth due to sea-level rise) would move the ecosystem in the direction of worsening hypoxia. This conclusion is consistent with the simulations of hypoxia in the Gulf of Mexico performed under climate change scenarios (Justiç et al., 2003). If the bay does face these anticipated changes, nutrient loads would have to be reduced further—beyond current targets—to meet the water quality objectives needed to support living resources. Given the long lag times, both in terms of implementation of nutrient control strategies and in ecosystem response, it is not too early to begin assessing the implications of climate change on management objectives for hypoxia and for Chesapeake Bay restoration in general. At a minimum, the linked watershed and estuarine models used to determine nutrient load reduction targets should be run using reasonable assumptions for a range of mid-21st century streamflows, temperatures, and estuarine volume. This update would provide an estimate of the sensitivity of management objectives related to the alleviation of hypoxia to climate change.

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