CHAPTER TWO

Comprehensive Assessment of Climate Change Impacts in Maryland

REPORT OF THE SCIENTIFIC AND TECHNICAL WORKING GROUP
MARYLAND COMMISSION ON CLIMATE CHANGE

Scientific and Technical Working Group

Donald F. Boesch, Chair, University of Maryland Center for Environmental Science; **Frank W. Dawson**, Co-Chair, Maryland Department of Natural Resources; **Robert M. Summers**, Co-Chair, Maryland Department of the Environment; **William C. Boicourt**, University of Maryland Center for Environmental Science; **Antonio J. Busalacchi**, University of Maryland, College Park; **Donald R. Cahoon**, U.S. Geological Survey; **Frank J. Coale**, University of Maryland, College Park; **Victoria J. Coles**, University of Maryland Center for Environmental Science; **Russell R. Dickerson**, University of Maryland, College Park; **William M. Eichbaum**, World Wildlife Fund; **Brian D. Fath**, Towson University; **Raymond M. Hoff**, University of Maryland, Baltimore County; **David G. Kimmel**, University of Maryland Center for Environmental Science; **Curtis E. Larsen**, Lusby, Maryland (U.S. Geological Survey, retired); **Andrew J. Miller**, University of Maryland, Baltimore County; **Margaret A. Palmer**, University of Maryland Center for Environmental Science; **Louis F. Pitelka**, University of Maryland Center for Environmental Science; **Steven D. Prince**, University of Maryland, College Park; **Brian S. Schwartz**, The Johns Hopkins University; **David H. Secor**, University of Maryland Center for Environmental Science; **Timothy Warman**, National Wildlife Federation; and **Claire Welty**, University of Maryland, Baltimore County.

Members of the Scientific and Technical Working Group reviewing draft materials for the Comprehensive Assessment.

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University of Maryland
CENTER FOR ENVIRONMENTAL SCIENCE

Integration & Application Network

Cover photos: NASA, Peggy Davis, Jane Thomas, and Andrew Bossi.

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REPORT TO THE MARYLAND COMMISSION ON CLIMATE CHANGE
JULY 2008

SCIENTIFIC AND TECHNICAL WORKING GROUP

EDITED BY DONALD F. BOESCH
DESIGNED AND PRODUCED BY JANE M. HAWKEY

Michael Juskelis, Maryland Sierra Club

MDE

UNIVERSITY SYSTEM OF MARYLAND

MARYLAND DEPARTMENT OF NATURAL RESOURCES

Victoria Coles

TABLE OF CONTENTS

EXECUTIVE SUMMARY

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Heritage Festival celebration, Cumberland, Maryland.

THE ASSESSMENT

This is an assessment of the likely consequences of the changing global climate for Maryland's agricultural industry, forestry resources, fisheries resources, freshwater supply, aquatic and terrestrial ecosystems, and human health. It was undertaken by the Scientific and Technical Working Group of the Maryland Commission on Climate Change as part of the Commission's charge to develop a Plan of Action to address the drivers and causes of climate change and prepare for its likely consequences in Maryland.

The Assessment was based on extensive literature review and model projections. In addition to the scientific literature, other international, national, and regional assessments of the impacts of climate change were consulted. The results from supercomputer models of the responses of climate to increased greenhouse gas concentrations were used to project future conditions for Maryland. These were the same models and scenario assumptions that were used in the acclaimed assessment completed in 2007 by the Intergovernmental Panel on Climate Change (IPCC). Model projections were based on averages for multiple climate models, and selected based on how well they replicated both global conditions and those observed in Maryland during the 20th century. Mean projections for 17 selected models produced more reliable results than individual models. Changes in temperature and precipitation were projected through the 21st century.

In order to estimate the degree of climate change in Maryland that could be avoided by actions to reduce emissions of greenhouse gases, two emissions scenarios were employed. The higher emissions scenario assumes continued growth in global emissions throughout the century, while the lower emissions scenario assumes slower growth, a peak at mid-century, and thereafter, a decline to about 40% of present levels by the end of the century.

RECENT & LIKELY CLIMATE CHANGES IN MARYLAND

Maryland's climate warmed after the peak of the last Ice Age 20,000 years ago, but has been relatively stable for the past 6,000 years. Around these long-term average conditions, there have, of course, been variations in temperature and precipitation due to ocean current cycles and solar and volcanic activity. However, atmospheric concentrations of greenhouse gases—gases, such as carbon dioxide, methane, and nitrous oxide, that trap the sun's energy from radiating back into space—have dramatically increased since pre-industrial times. Carbon dioxide concentrations exceed those experienced over at least the last 650,000 year.

Largely as a result of this increase in greenhouse gases, average global temperature and sea level began to increase rapidly during the 20th century. In its 2007 report, the IPCC concluded that the evidence for the warming of the Earth is "unequivocal." The IPCC also concluded that most of the observed temperature increase since the middle of the 20th century is very likely due to the observed increase in greenhouse gases.

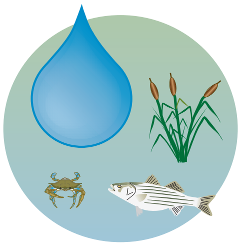
In evaluating the changes in Maryland's climate that we are likely to experience over the 21st century, it should be remembered that climatic regimes will continue to vary across the state. Western Maryland has cooler winters and summers and less precipitation during the winter than the rest of the state. Changes that occur will overlay these regional differences, perhaps with some greater warming during the summer to the west than on the Eastern Shore. Temperature is projected to increase substantially, especially under higher emissions. The increase in average summer temperatures in terms of degrees of warming is greater than that in winter. Annual average temperature is projected to increase by about 3°F by mid-century and is likely unavoidable. The amount of warming later in the century is dependent on the degree of mitigation of greenhouse gas emissions, with summer temperatures projected to increase by as much 9°F and heat waves extending throughout most summers if greenhouse gas emissions continue to grow unchecked.

Victoria Coles

Sailing club event on the Chesapeake Bay.

Precipitation is projected to increase during the winter, but become more episodic, with more falling in extreme events. Projections of precipitation are much less certain than for temperature, but the mean projections indicated modest increases of about 10% or so are likely in the winter and spring. Because of more intermittent rainfall and increased evaporation with warmer temperatures, droughts lasting several weeks are more likely to occur during the summer.

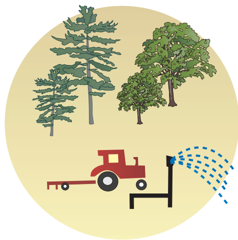
WATER RESOURCES & AQUATIC ENVIRONMENTS



Increased precipitation in the winter and spring would mean that the water supplies in the greater Baltimore area will probably not be diminished, but the adequacy of summer water supplies in the greater Washington region, which rely on Potomac River flows, is less certain. Any increases in precipitation are unlikely to replace groundwater substantially enough to compensate excessive withdrawals of some aquifers. At the same time, summer droughts may increase groundwater demand for agricultural irrigation.

More intense rainfall resulting from the combined effects of global climate change and localized factors, for example, the influence of the urban canopy on rainfall, is likely to increase peak flooding in urban environments. Continued increase in impervious surfaces attendant with development would exacerbate this problem. Aquatic ecosystems will likely be degraded by more flashy runoff and increased temperatures. Intensified rainfall events and warmer surfaces (roads, roofs, etc.) would result in rapid increases in stream temperatures, limiting habitat suitability for native fishes and other organisms. Higher peak flows and degraded streams would also transmit more nutrients and sediments to the Chesapeake Bay and its tidal tributaries, contributing to water quality impairment in the estuaries.

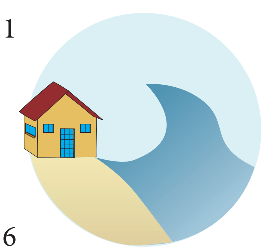
FARMS & FORESTS



Crop production may increase initially, but then decline later in the century if emissions are not reduced. The longer growing season and higher carbon dioxide levels in the atmosphere are likely to increase crop production modestly during the first half of the century. Later in the century, crop production is likely to be reduced due to heat stress and summer drought under the higher emissions scenario. Milk and poultry production would be also reduced by heat stress. These changes will require adaptation by Maryland's agricultural industry, including changes in crop or animal varieties, increased irrigation, and air conditioning for some livestock.

The maple-beech-birch forest of Western Maryland is likely to fade away and pine trees to become more dominant in Maryland's forests. Forest productivity in terms of timber produced is likely to decline late in the century under the higher emissions scenario as a result of heat stress, drought, and climate-related disturbances such as fires and storms. The biodiversity of plants and animals associated with Maryland's forests is likely to decline. Habitat alterations resulting from climate change may force out 34 or more bird species, including the emblamatic Baltimore oriole, although southern species may replace them.

COASTAL VULNERABILITY

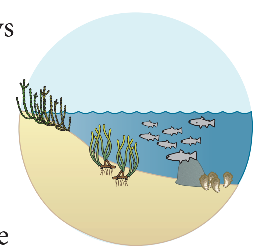


Sea level in Maryland rose by 1 foot in the 20th century, partially because the land is sinking as a result of slow adjustments of the Earth after the last Ice Age. Maryland coastal regions have been subsiding at about a rate of 6 inches per century and should continue at this rate during this century. Additionally, the average level of the sea in this region rose by about the same amount (6 inches) during the past century, resulting in the observed 1 foot of rise of the mean tidal level relative to the land. As a result, Maryland has experienced considerable shoreline erosion and deterioration of coastal wetlands which are a critical component of its bays and estuaries.

Sea-level rise is very likely to accelerate, inundating hundreds of square miles of wetlands and land. Projections that include accelerating the melting of ice would increase the relative sea-level along Maryland's shorelines by more than 1 foot by mid-century and 3 feet by late century if greenhouse gas emissions continue to grow. If sea level rises by 3 feet, most tidal wetlands would be lost—about 200 square miles of land would be inundated. New tidal wetlands developed on newly flooded land would not offset the loss of existing wetlands and significant negative effects on living resources dependent on these wetlands would result. Moreover, if sea level were to rise by 3 or more feet, this would mean that rapid and probably uncontrollable melting of land-based ice was underway and that sea level would rise at an even greater rate during subsequent centuries.

Rains and winds from hurricanes are likely to increase, but changes in their frequency cannot now be predicted. The destructive potential of Atlantic tropical storms and hurricanes has increased since 1970 in association with warming sea surface temperatures. This trend is likely to continue as ocean waters warm. Whether Maryland will be confronted with more frequent or powerful storms depends on storm tracks that cannot yet be predicted. However, there is a greater likelihood that storms striking Maryland would be more powerful than those experienced during the 20th century and would be accompanied by higher storm surges—made worse because of higher mean sea level—and greater rainfall amounts.

CHESAPEAKE BAY & COASTAL ECOSYSTEMS

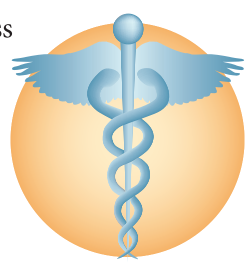


Chesapeake and Coastal Bays restoration goals will likely be more difficult to achieve as the climate in Maryland and the Chesapeake watershed changes. Increased winter-spring runoff would wash more nutrients into the Bays, and higher temperatures and stronger density stratification in the estuaries would tend to exacerbate water quality impairment, the alleviation of which is the prime restoration objective. Consequently, nutrient loads would have to be reduced beyond current targets to achieve water quality requirements. Very significant changes are also likely to occur that affect sediment delivery and sedimentation in the estuaries, but are difficult to quantitatively predict. These include potential increases in sediment loads from rivers as a result of increased runoff and more erosive extreme discharge events, including those caused by hurricanes, and from shoreline and wetland erosion as a result of accelerated sea-level rise.

Living resources will very likely change in species composition and abundance with warming. A mixture of northern, cool water species and southern, warm water species currently resides in the Chesapeake Bay. Northern species such as soft shell clams and eelgrass are likely to be eliminated later in the century, almost certainly if greenhouse gas emissions are not mitigated. Southern species are very likely to increase in abundance because the milder winters would allow or enhance overwintering populations.

As ocean water becomes more acidic, shellfish production could be affected. Increased atmospheric carbon dioxide concentrations in the atmosphere have already lowered pH in the world's oceans, a trend that is very likely to continue. Recent research indicates that the rate at which oysters and other coastal shellfish build their calcium carbonate shells will likely be affected, but whether this would occur in Maryland waters has not been evaluated.

HUMAN HEALTH

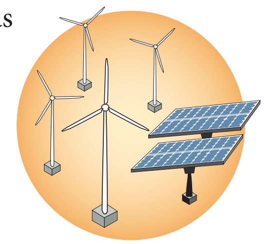


Health risks due to heat stress are very likely to increase, if emissions are not reduced. Under the higher emissions scenario, heat waves are projected to greatly increase risks of illness and death before the end of the century, with an average of 24 days per summer exceeding 100°F. The poor, the elderly, and urban populations are most susceptible. Some, but not all, of these increased risks can be reduced by air conditioning and other adaptation measures.

Respiratory illnesses are likely to increase, unless air pollution is greatly reduced. More ground-level ozone, responsible for multiple respiratory illnesses, is formed under prolonged, high temperatures. Releases of air pollutants (nitrogen oxides and volatile organic compounds) that cause ozone to be formed have been declining, but would have to be reduced much more in a warmer climate to avoid a reversal in progress toward achieving air quality standards.

Increased risks of pathogenic diseases may be less likely. The mortality due to vector-borne and non-vector borne diseases in the United States is low because of public health precautions and treatment, which would likely adapt to changes in disease risks. Climate change might affect the exposure of Marylanders to pathogens such as the West Nile virus, but precautions and treatment could manage this greater risk.

MITIGATION & ADAPTATION



The reduction of greenhouse gas emissions has substantial benefits for Maryland. The mitigation of global emissions by mid-century would very likely result in significantly lower sea-level rise, reduced public health risks, fewer extreme weather events, and less decline in agricultural and forest productivity and loss of biodiversity and species important to the Chesapeake Bay. More serious impacts beyond this century, such as sea-level rise of 10 feet or more, would be avoided.

Based on the projections made in this report, adaptation strategies for human health, water resources, and restoration of Maryland's bays should be evaluated and, where necessary, implemented. Adaptation measures to reduce coastal vulnerability should plan for a 1 foot rise in sea level by mid-century and a rise of at least 2 feet by late in the century. Depending on the course of greenhouse gas emissions, observations, and modeling, planning for increases in sea level of up to 4 feet by the end of the century may be required. The Commission on Climate Change should evaluate additional adaptation strategies related to human health, water resources, forest management, and restoration of the Chesapeake Bay and Maryland's Coastal Bays. The projections of impacts provided in this assessment provide a frame of reference for these evaluations.

Maryland should marshal and enhance its capacity for monitoring and assessment of climate impacts, as a more extensive, sustained, and coordinated system for monitoring the changing climate and its impacts is required. Because of its national laboratories, strong university programs, knowledge-based economy, and proximity to the nation's capital, Maryland is in a strong position to become a national and international leader in regional-to-global climate change analysis and its application to innovative mitigation and adaptation.

Section 1

PURPOSE OF THE ASSESSMENT

US Fish & Wildlife Service

Sunset over Maryland marshlands.

Recognizing the scientific consensus about climate change, the contribution of human activities, and the vulnerability of Maryland's people, property, natural resources and public investments, Governor Martin O'Malley issued an Executive Order on April 20, 2007, that established Maryland's Commission on Climate Change in order to address the need to reduce greenhouse gas emissions and prepare the State for likely consequences of climate change. The Commission was given the task of developing a Plan of Action to address the drivers and causes of climate change, prepare for the likely consequences and impacts of climate change to Maryland, and establish firm benchmarks and timetable for implementing the Plan.

The Plan of Action includes three components:

1. a Comprehensive Climate Change Impact Assessment,
2. a Comprehensive Greenhouse Gas and Carbon Footprint Reduction Strategy, and
3. a Comprehensive Strategy for Reducing Maryland's Climate Change Vulnerability.

This report constitutes the climate change impact assessment and thus a key part of the Commission's Action Plan. It was prepared by a Scientific and Technical Working Group comprised of Maryland-based scientists, engineers and other experts, who worked over ten months to produce this report. Specifically, the Working Group was charged to investigate climate change dynamics, including current and future climate models and forecasts and evaluate the likely consequences of climate change to Maryland's agricultural industry, forestry resources, fisheries resources, freshwater supply, aquatic and terrestrial ecosystems, and human health. In addition, the Working Group was called

Governor Martin O'Malley signs the Executive Order creating the Maryland Commission on Climate Change, joined by Cabinet members and General Assembly leaders.

on to advise the Commission and its other working groups as their work proceeded. In particular, the Scientific and Technical Working Group provided information and analysis for the development of the goals for reducing greenhouse gas emissions and for adaptation strategies for reducing coastal vulnerability.

This Comprehensive Assessment of Climate Change Impacts in Maryland is intended to serve a number of purposes. First, it is one of the three legs of the stool for the Commission's Plan of Action, providing regional context for the importance of reducing Maryland's greenhouse gas emissions and projections of future climate change for which we should be prepared to adapt. For this reason, projections for climate change and its impacts present two scenarios, one assuming continued growth in greenhouse gas emissions and the other assuming global action to reduce these emissions. The second scenario helps to identify the changes that may be inevitable and for which Maryland must be prepared to adapt. In this manner, it seeks to provide a basis for the development of prudent and effective public policy by the Governor and General Assembly.

Secondly, this Assessment is presented so as to be accessible and comprehensible to the citizens of Maryland as they develop their understanding of this unprecedented challenge to humankind and make personal choices and decisions regarding policy options at local, state, and national levels.

Finally, this Assessment is just the first installment of what must be continuous reassessment of Maryland's changing climate, the impacts of this change, and what science and engineering can do to understand, predict, and manage these impacts.

Victoria Coles

Forested mountains and grass meadows of western Maryland.

Section 2

WHY IS THE WORLD'S CLIMATE CHANGING?

KEY POINTS

- **Maryland's climate has been variable but stable for several thousand years.**
  Maryland's climate warmed after the peak of the last Ice Age and has been relatively stable for the past 6,000 years. Around these long-term average conditions there have, of course, been variations in temperature and precipitation due to ocean current cycles, solar activity, and volcanic activity.

- **Atmospheric concentrations of greenhouse gases have dramatically increased.**
  Certain gases that trap the sun's energy from radiating back into space have increased since pre-industrial times. Carbon dioxide concentrations exceed those experienced over at least the last 650,000 years. Average global temperature and sea level began to increase rapidly during the 20th century.

- **Global warming is unequivocal.**
  The Intergovernmental Panel on Climate Change found the evidence for the warming of the Earth to be "unequivocal." The IPCC concluded that most of the observed temperature increase since the middle of the 20th century is very likely due to the observed increase in greenhouse gases.

CLIMATE VARIABILITY & CHANGE

Maryland's climate has changed over millennia as the major planetary forces affecting the Earth's climate caused glaciers to spread and recede. However, after the peak of the last Ice Age about 20,000 years ago, the climate warmed, most of the glaciers melted, and sea level rose, reaching approximately the present conditions about 6,000 or more years ago. The slow, continued rise in local water levels was mainly the result of the slow sinking of the Earth's crust beneath us—this itself is a delayed effect of melting glaciers. The first Native Americans came to Maryland as its climate was becoming more moderate and habitable. For most of the time they have been here and all of the time of occupancy by Europeans, Africans and other subsequent migrants, our climate has been relatively stable. Our society, economy, and quality of life has developed under and adapted to this climatic regime.

Of course, our weather (see Section 4 for a discussion of the differences between weather and climate) still varies from year to year—some years are warmer or wetter than others—and even over cycles that extend over several years to a decade or more. This variability is caused by shifts in large-scale processes in the ocean and atmosphere such as the El Niño cycles in the Pacific Ocean, variations in solar activity, and even volcanic eruptions halfway around the world. But, over the past few thousand years, this has caused climate to fluctuate around a rather consistent average.

During the 20th century, however, scientists have concluded that the Earth's climate was warming and is very likely to warm much more dramatically as a result of human activities that have increased the amount of certain gases in the atmosphere. These gases, most notably carbon dioxide, but also methane and nitrous oxide, trap some of the sun's energy radiating back out into space, much as the glass panes of a garden greenhouse. The presence of these gases warms the atmosphere sufficiently for life to flourish—without these greenhouse gases the average surface temperature of Earth would be 0°F rather than 57°F.[1] But, as these heat-trapping gases continue to increase, the temperature of Earth's atmosphere and oceans will also continue to increase—this is what is meant by global warming.

MAJOR CHANGES DOCUMENTED

There is no doubt that greenhouse gases in the atmosphere have been increasing. Since pre-industrial times (1750) carbon dioxide concentration has increased by 38 percent, methane by nearly

170 percent, and nitrous oxide by 17 percent.[2] The increase in carbon dioxide has been caused primarily by burning of fossil fuels (coal, oil, and natural gas) and the clearing of forests which held reservoirs of carbon in wood and soils and removed carbon dioxide from the atmosphere through photosynthesis. The increase in the other two major greenhouse gases is mostly due to agricultural activities: methane through growing rice and raising cattle, and nitrous oxide from the application of industrial fertilizers to crops, as well as a result of the high-temperature combustion of fossil fuels.

Carbon dioxide concentration in the atmosphere has increased from a pre-industrial value of about 280 parts per million (ppm) to 384 ppm by 2007 (Figure 2.1), exceeding by far the natural range over at least the last 650,000 years as determined from analyses of air bubbles trapped in glacial ice.

The global mean surface temperature, based on both air and ocean temperatures, has increased by more than 1°F (0.6°C) since 1930 (Figure 2.2), with most of this due to a steady and rapid increase since 1980. Twelve of the last thirteen years rank among the warmest years since 1850, when thermometer measurements became widely recorded. In the Northern Hemisphere, where there are numerous data on temperature proxies such as tree ring thickness and ratios of stable isotopes, neither the recent high global mean temperature nor the rapid rate of temperature increase have been experienced during the last 2000 years.[2]

Global warming affects not only air and ocean temperatures but also precipitation and sea level—ocean waters expand as they warm and as melting glaciers and polar ice sheets further contribute to the ocean's volume. Warmer conditions cause

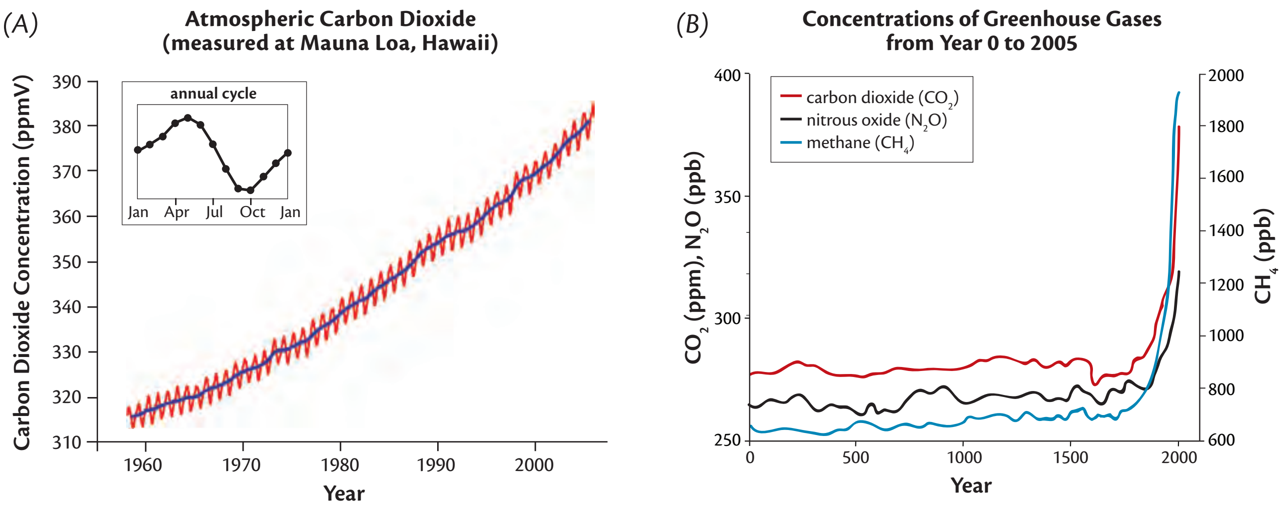


Figure 2.1. (A) Concentrations of carbon dioxide measured at Mauna Loa, Hawaii have shown a continuous increase since measurements began in 1958. Annual fluctuations represent seasonal biological cycles of photosynthesis and respiration. (B) Concentrations of the greenhouse gases carbon dioxide, methane, and nitrous oxide dramatically increased during the 20th century, exceeding by far concentrations that occurred over the last 2,000 years.[2]

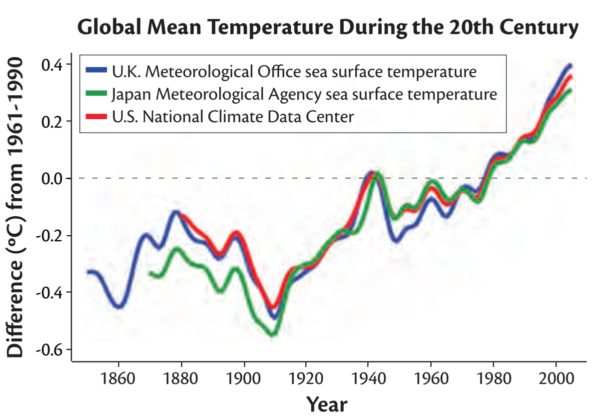


Figure 2.2. Global mean temperature has increased approximately 1.4°F (0.8°C) during the 20th century as reflected in three separate meteorological databases.[2]

NASA Jet Propulsion Lab, CIT

AIRS, a new spaceborne instrument, is designed specifically to measure the amounts of water vapor and greenhouse gases.

more moisture to go into the atmosphere through evaporation and plant transpiration, and this water vapor must come down in the form of precipitation. However, the effect is not uniform, with increased precipitation documented over the middle and high latitudes of the Northern Hemisphere and over tropical land areas, while precipitation declined in the already dry, lower latitude lands.

WARMING IS UNEQUIVOCAL

The conclusion that the warming of the climate system is unequivocal and the preceding observations come from the most recent assessment of the Intergovernmental Panel on Climate Change, an international scientific body established by the World Meteorological Organization and by the United Nations Environment Programme. The IPCC was awarded, along with Vice-President Al Gore, the Nobel Peace Prize for its Fourth Assessment Report[3], released in 2007. The findings of the Panel are careful and deliberate and enjoy the wide acceptance of the climate science community—in fact, scientific criticism that the IPCC was too cautious and reticent[4] is more common than criticism for overstating the case.

Global warming is unequivocal and could cause irreversible damage to the planet

The IPCC concluded that most of the observed increase in globally averaged temperatures since the middle of the 20th century is very likely due to the observed increase in greenhouse gas concentrations resulting from human activities. The Panel also found decreases in snow cover and sea ice extent and the retreat of mountain glaciers during this period. Global average sea level rose with increasing ocean water temperatures. Heavy rains increased in frequency in some regions of the world.

Extensive physical and ecological changes resulting from the changing climate are also described in the IPCC assessment, including thawing of permafrost, lengthening of the growing season in middle and high latitudes, shifts in the ranges of animals and plants toward the poles and up mountain elevation gradients, declines in some plant and animal species, and earlier seasonal flowering of trees, emergence of insects, and egg-laying in birds.[5]

The same detailed appraisal of the relationship of the changes in Maryland's climate and the increase in greenhouse gas concentrations has not been undertaken, and indeed is not practical because of the global scale of the climate system. However, the trends of increased temperature, precipitation, and sea level rise and many of the biological changes that have been observed are very consistent with the assessment of the IPCC for North America.[2,5]

U.S. Geological Survey

Comparison photos of McCarty Glacier in Kenai Fjords National Park, Alaska. McCarty glacier retreated ~12 miles between the period these two photos were taken and is not visible in the 2004 photo.


NPS

The lakes, ponds, and streams of Maryland are a favorite habitat for the twelve-spotted dragonfly.

Section 3

APPROACH TO ASSESSING RECENT & FUTURE CLIMATE CHANGE

KEY POINTS

- **The Assessment was based on extensive literature and model projections.**
  In addition to the scientific literature, other international, national and regional assessments of the impacts of climate change were consulted. The results from supercomputer models of the responses of climate to increased greenhouse gas concentrations were used to project future conditions in Maryland.

- **Model projections were based on averages for multiple climate models.**
  Models were selected based on how well they replicated both global conditions and those observed in Maryland during the 20th century. Mean projections for 17 models produced more reliable results than individual models. Changes in temperature and precipitation were projected through the 21st century.

- **Higher and lower emissions scenarios were employed.**
  In order to estimate the degree of climate change in Maryland that could be avoided by actions to reduce emissions or greenhouse gases, two emissions scenarios were employed. The higher emissions scenario assumes continued growth in emissions throughout the century, while the lower emissions scenario assumes a slower growth peak at mid-century and declines thereafter to about 40% of present emissions levels by the end of the century.

THE PROCESS

The Scientific and Technical Working Group (STWG) developed this assessment using published scientific information on Maryland's climate and environments, the recent IPCC reports, even more recent scientific literature, and several new assessments of specific issues or region impacts. Particularly important among these assessments were various Synthesis and Assessment Products being produced by the U.S. Climate Change Science Program (some drafts still in preparation or review)[6] and regional assessments, especially the Northeast Climate Impacts Assessment (NECIA). The NECIA, led by the Union of Concerned Scientists, produced two very readable reports[7] on climate change, its impacts and solutions in the northeastern United States, defined as the nine-state region including Pennsylvania and New Jersey northward. Because of its proximity, the findings of the NECIA are highly relevant and have been reflected in the Maryland assessment.

The STWG did not have the time or resources to collect or analyze extensive data or to develop new models of Maryland's climate, relying instead on the primary or summary literature as described above. It did, however, use the results of the extensive general circulation models that were run on a global scale for the IPCC assessment. Such models are run on supercomputers using common assumptions about future emissions of greenhouse gases and have become increasingly skillful in reproducing the climatic conditions experienced during the 20th century looking backward in hindcast mode. This gives some level of confidence in their ability to project conditions with future increases in greenhouse gases for at least the near future. The models were used by the IPCC in demonstrating that the warming observed over the past 100 years is unlikely to be due to natural causes, such as the sun and volcanoes, alone. Model results that take into account greenhouse gas emissions and the cooling effects of sulfate aerosols, also emitted by burning fossil fuels, are able to reproduce the observed 20th century warming, while those that only account for the natural climate forces do not (Figure 3.1).

While our understanding of the forces that affect the Earth's climate will improve, the scientific community believes that the current generation of models produces reasonable projections of future climatic conditions. They cannot, of course, predict the weather on a specific place or day, but can represent best estimates of future climatic conditions within a broad region averaged over a decade.

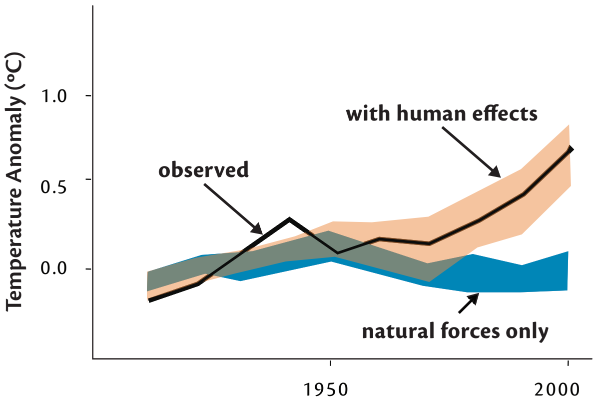


Figure 3.1. Climate models run with just natural forces due to solar activity and volcanoes (blue band) suggest slight declines in global mean temperature during the latter 20th century, while the same models including greenhouse gases and aerosol sulfates from human activities (pink band) show warming very consistent with what was actually observed (solid black line).[2]

OBSERVATIONS

The focus of this assessment is the impacts of future climate change, rather than how much of past climate variability is due to human effects, so the emphasis is on model projections. However, data from stations from the United States Historical Climate Network, corrected for the warming effects of urbanization and the local effects of topography, were used to determine how well models reproduce recent climate in Maryland. These individual weather station records also yield information on the trends in temperature and precipitation that have been experienced.

Beyond temperature and precipitation, sufficiently long records of other climate-sensitive variables are scarce, thus attribution of past changes to climate is difficult. One example of the value of such secondary indicators is the recorded trend toward earlier start of honey production in the Piedmont region.[8] Honey production requires both temperatures high enough to maintain larval bees and an ample source of nectar from flowering trees, thus integrating two measures of climate change. Other examples of observed changes in forestry and agriculture, Chesapeake Bay processes, sea level, and hydrology are highlighted later in the report.

PROJECTIONS

In forecasting the storm tracks of active or developing hurricanes, for example, an ensemble of models is used rather than just relying on one. This allows for a 'best estimate' prediction within a range of plausible tracks. A similar approach was used in the IPCC Fourth Assessment by employing a group of satisfactorily performing general circulation models all run with the same assumptions for greenhouse gas emissions. The archived files of output from these supercomputer model runs were accessed for this assessment.[9] The average of the model outputs yields a better representation of present climate than any single model[10] or the small number of models used in the Northeast Assessment.[7] This ensemble mean gives the best projections because some model inaccuracies are unrelated to the shortcomings of other models, so they cancel out on average.

This assessment used a similar strategy, beginning with the 24 models used for the IPCC Fourth Assessment model intercomparison. The 17 best performing models were selected based on how well the models reproduce the climate in Maryland over the past century.[11] Net error scores were computed for temperature and precipitation based on means, trends over the century, seasonal and ten-year filtered correlations, the standard deviation, and the skill with which the models represent global climate. The subset of better performing models was then averaged over the state of Maryland to estimate changes in future climate in this region.

Projections of the 17 best performing models were averaged

Because the global models require so many hours of supercomputer time to run, they cannot represent regions as small as Maryland with more than a few grid points (Figure 3.2). Thus, the projected changes over the state need to be considered in the context of the large differences in local state climate. For example, one would expect the climate in high elevation regions of western Maryland to remain cooler than the climate on the coastal plain despite similar temperature increases in both regions (see Table 4.1 in the next chapter). The average seasonal cycle for 1979-1999 is removed from each model output prior to determining future changes. This reduces the effect of individual model biases on the projection of future changes and projects future climate relative to the average conditions around 1990.

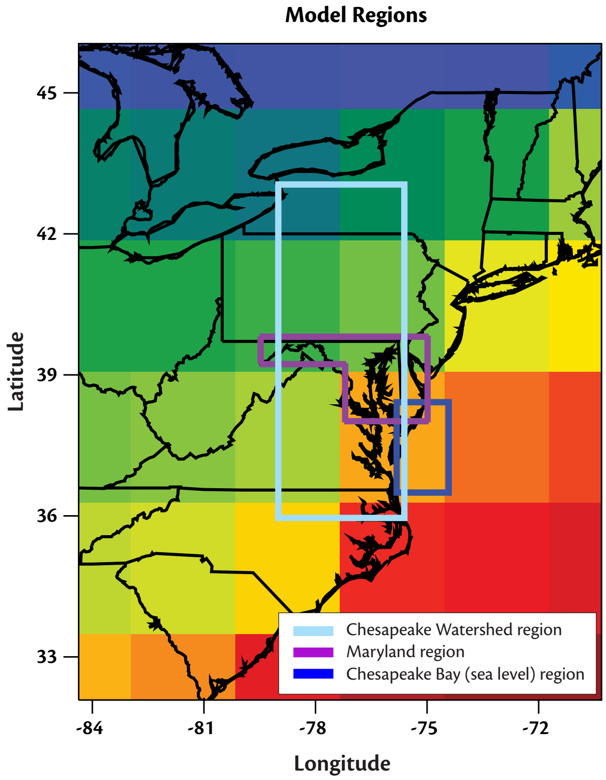


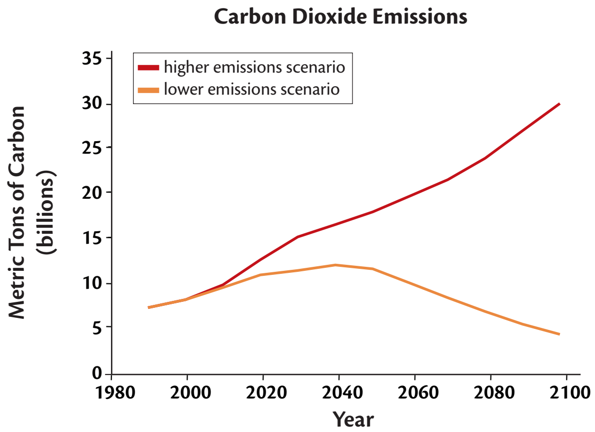
Figure 3.2. Surface air temperature for one of the climate models, showing the number of grid cells covering Maryland, and also the averaging regions employed for this assessment.

EMISSION SCENARIOS

A critical objective of this assessment was to compare future climate impacts under the situation in which greenhouse gas emissions continue to grow throughout the 21st century with the situation that might be realized if global action was taken to reduce greenhouse gas emissions. A similar approach was used in the Northeast Assessment. Two plausible global emissions scenarios were selected from among those used by the IPCC assessments. The higher emissions (A2) scenario assumes a heterogeneous world, with locally self-reliant response to climate change, regional technological and economic development, and faster growing population. The even higher emission, A1Fi, scenario used in the Northeast Assessment was not used because of the limited archived output available for this scenario. The lower emissions (B1) scenario assumes slower population growth, clean technologies are developed and implemented globally, and there is a general emphasis on global solutions to economic and environmental issues.

These scenarios can be viewed representing the 'business as usual' response to climate change versus sustained emissions reduction strategy, although the lower emissions scenario was not developed with that specific assumption in mind. However, the scenarios should not be seen as either a floor or ceiling of possible outcomes. Recent growth in carbon dioxide emissions exceed the higher emissions scenario.[12] On the other hand, the emission reduction goals being actively discussed internationally, i.e. reductions of 60-80% by 2050, would, if implemented, reduce emissions more and result in less warming than the lower emissions scenario. Although the IPCC intends to use several specific emissions mitigation scenarios in its next assessment, projections do not yet exist for such scenarios.

While carbon dioxide emissions for the two scenarios begin to diverge significantly around 2025 and decline in the low emissions scenario after 2050 (Figure 3.3), the cumulative emissions begin to diverge only after 2040. Because carbon dioxide is retained in the atmosphere for a long time, the full effects of this divergence are not fully manifest until late in the century. Thus, in the model projections,



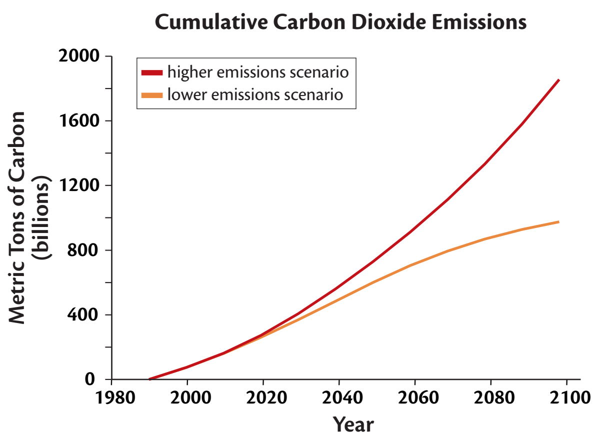


Figure 3.3. Top: Carbon dioxide annual emissions for the low and high emissions trajectories. Bottom: Total carbon dioxide emissions summed from 1990 to 2100.

Smog hangs over a Baltimore highway clogged with traffic.

there is often little difference between the higher and lower emissions scenarios until after 2050 and the differences increase thereafter.

CONFIDENCE

The spread in model predictions is one indication of how well the underlying physics and feedbacks of climate processes are represented. The hydrological cycle, for example, is less well represented than temperature in all of the climate models because coarse spatial resolution of models precludes a good representation of the physics involved in evaporating, transporting, and precipitating water. As a result, we have high confidence in temperature projections for which the physical processes represented in the model are better understood, moderate confidence in trends in temperature extremes, moderate confidence in directional changes in precipitation and other hydrological variables, and relatively low confidence in model projections of precipitation extremes at this scale.

The spread of model projections for a given parameter is used to assess the likelihood of the projected outcome. Throughout this report, the characterization of likelihood of both trends in observations and certainty of projections has followed with the IPCC assessments, except without the discrete probabilities assigned by the IPCC (Figure 3.4). Similar to the assessment of weather and climate extremes by the U.S. Climate Change Science Program[13], this approach allows the communication of the level of certainty that is consistent throughout the report.

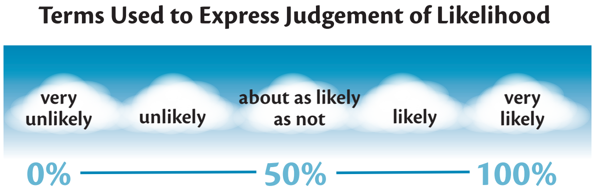


Figure 3.4. Terms used in this assessment to communicate judgment of likelihood.

ABRUPT CLIMATE CHANGE

Finally, a word of caution is offered about the use of climate model projections in planning for future climate conditions. There is greater confidence regarding some variables (such as global and regional temperature) than others (such as regional precipitation). Some variables (such as soil moisture or stream flow) result from the complex interplay of temperature, water, carbon dioxide concentrations, and living organisms, making them difficult to model with great reliability. Still others will be influenced by processes that may dramatically change and thus are inherently challenging for scientists to predict (such as the contribution of future polar ice sheet melting to sea-level rise).

Because of the way they are constructed, climate models can be used to assess gradual trends averaged over decades. They are, at this point in their development, less reliable as a signal of more abrupt climate changes. Various records of past climate changes, including deep sea sediments, ice cores, tree rings, and other natural recorders, indicate that they have often taken place within a fairly short period of time, within a century or even a decade. Scientists are actively conducting research on the causes and consequences of such abrupt climate changes, but few attempts have been made to model them under future global warming conditions. For the purpose of this assessment, it is simply important to keep in mind that the changes that will take place during this century may be more 'jerky' than continuous, with trends reversing for some years and advancing more dramatically over the period of just a decade. This places a challenge both for our observations of trends and for our ability to adapt quickly.

Section 4

RECENT & LIKELY CLIMATE CHANGES IN MARYLAND

KEY POINTS

- **Climatic regimes will continue to vary across Maryland.**
  Western Maryland has cooler winters and summers and less precipitation during the winter than the rest of the state. Changes will occur on top of these regional differences, perhaps with some greater warming during the summer to the west than on the Eastern Shore.

- **Temperature is projected to increase substantially, especially under higher emissions.**
  Average temperature is projected to increase by about 3°F by mid-century and is likely unavoidable. The amount of warming later in the century is dependent on the mitigation of greenhouse gas emissions, with summer temperatures projected to increase by as much 9°F, and heat waves extending throughout most summers.

- **Precipitation is projected to increase during the winter, but become more episodic.**
  Projections of precipitation are much less certain than for temperature, but modest increases are more likely in the winter and spring. Because of more intermittent rainfall and increased evaporation with warmer temperatures, droughts lasting several weeks are projected to be more likely during the summer.

THE CONTEXT

The state of Maryland, although comprising only 12,303 square miles, spans diverse geographic and climatic zones, from the flat Coastal Plain, westward to the Piedmont foothills, and the Appalachian Plateau. Well-defined seasons divide the cool, northwesterly wind-dominated, dormant season for plant growth from the warm summers with southwesterly winds and high humidity in the coastal regions. Spring and fall are highly variable with weather changing almost daily as warm and cool fronts push through mainly from the west. Although Maryland lies south of the main winter cyclone track, the influence of these storms can affect winter climate. Storms originating in the south or coastal regions (Nor'easters) also play a role in destructive winter weather, as they are accompanied by large amounts of rainfall and high tides. Hurricanes and tropical storms, although infrequent with only eight storms affecting Maryland since 1954, also can have a destructive influence on Maryland Coastal Plain regions in particular, primarily through flooding and storm surge.

Figure 4.1 illustrates the seasonal range of temperature across Maryland. While the higher elevations to the west remain cooler in both winter and summer, the rate of temperature increase from 1977 to 1999, is similar across the state, with an increase in the mean annual temperature of 2°F. No weather stations show a temperature decrease. This is significantly more warming than the global average.[2] The rainfall differences across the state are much smaller, with Maryland having little seasonality in rainfall; consequentially, most agriculture relies on precipitation rather than irrigation (see Section 6). Precipitation is highly variable from year to year, and no clear trend emerges from the stations in Maryland, although significant increases in precipitation have been documented to the north.

Adrian Jones

Winter wheat is sometimes planted in a mix with cool-season clovers or field peas to suppress weeds and prevent soil erosion.

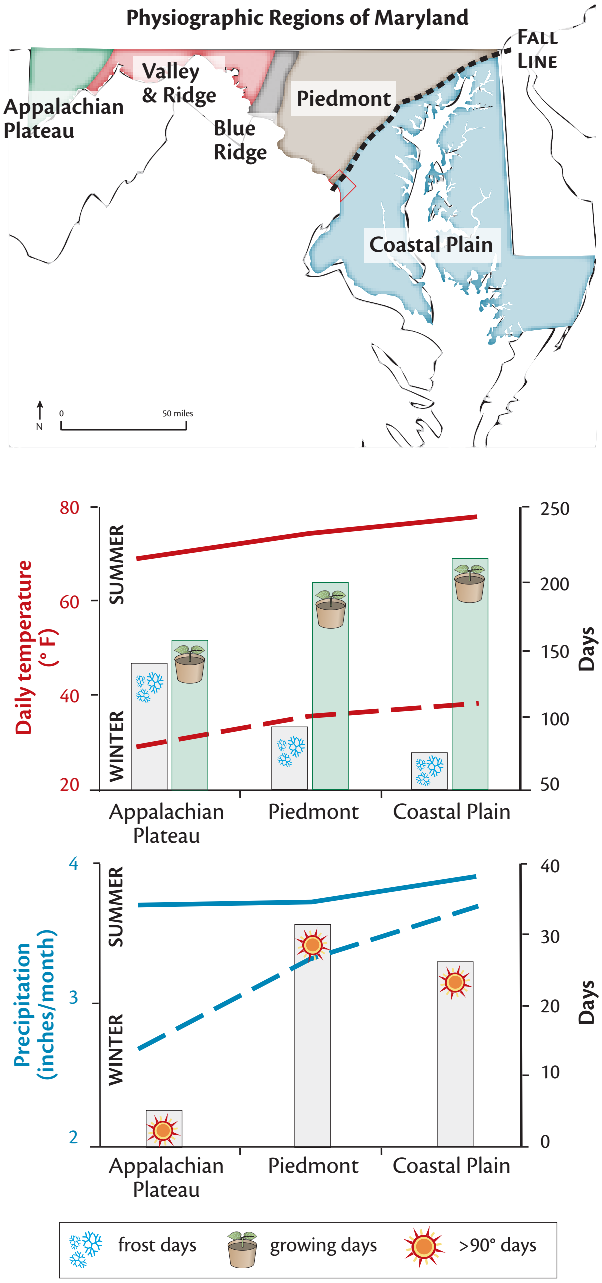


Figure 4.1. Top: The five physiogeographic regions of Maryland. Middle: Temperatures range seasonally across Maryland, with the elevated, inland regions to the west remaining cooler in both winter and summer and experiencing a shorter growing season. Bottom: The precipitation differences across the state are modest, except in winter, when it is lower on the Appalachian Plateau. The average number of days with temperatures greater than 90°F is much lower in the Appalachian Plateau.[13]

TEMPERATURE

Human-induced climate change is most directly linked to global temperature rise. However, atmospheric circulation, interactions of climate with land surfaces and oceans, and other factors drive patterns of heating and cooling that affect the projected temperature increases. On a global scale, temperature increases are generally expected to be greater in the Northern Hemisphere, particularly toward the Arctic regions.[2] Maryland, therefore, will not warm by as many degrees as the New England states.[7] Nonetheless, Maryland will experience significant warming in the coming decades and century (Figure 4.2).

The climate model mean projects an additional 2°F of warming by 2025, regardless of which emissions scenario is followed. By 2050, the policy decisions applying to which emissions path is followed begin to have an effect, and a difference in winter versus summer warming also emerges. The lower emissions scenario warms slightly less by 2050, with summertime temperature increases of nearly 3°F. Temperature under the higher emissions scenario begins to increase sharply after mid-century, with summertime seeing somewhat greater warming than winter.

By the end of the century, the difference between the higher and lower emissions scenario is marked. The low emissions path has held temperature increase to 4.8°F in summer, and 4°F in winter, while the higher emissions scenario leads to warming of nearly 9°F in summer and 7°F in winter in Maryland. One would expect these increases to be above the current mean temperatures for the three regions of the state as shown in Figure 4.1. Summertime average (over both night and day) temperatures in the Coastal Plain would increase from 77°F to 86°F by the end of the century under the higher emissions scenario. However, an ongoing national assessment has produced statistically

Under higher emissions, summers are projected to be nearly 9°F hotter by end of century

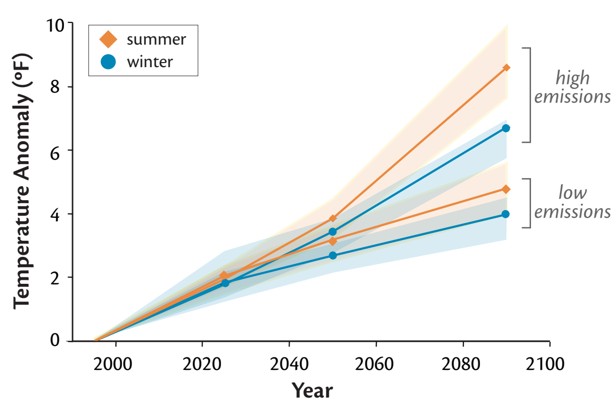


Figure 4.2. Temperature increase (°F) for Maryland from 1990 to the year 2100. The shaded regions depict the 25th-75th percentile spread between all the models.

downscaled maps based on the averages of a similar array of outputs that suggest summertime warming would be greater in Western Maryland and less on the lower Eastern Shore because of the moderating influence of the ocean (Figure 4.3)

These projections have relatively little spread between model projections for a given scenario, thus it is very likely that there will be more warming in summer than winter, and that the higher emissions scenario will result in substantially greater warming than the lower emissions scenario. Confidence in how well models represent the underlying physics of human caused warming is also high. While the likelihood of warming is high, the exact magnitude of the amount of increase is less so. However, none of the models project less than 4°F of warming in summer by 2100.

This is not to say that as the century progresses each year will be warmer than the preceding year. There will likely be months and even years that are on average cooler than the current seasonal norms. This is due to variations in the weather, not changes in climate. This assessment focuses on the average temperature over longer periods, and this continues to increase in all emission scenarios. Thus, any given warm or cold weather episode cannot be unambiguously attributed to climate; rather it is the accumulation of weather over time that gives rise to changes in climate.

HEAT WAVES

These projections for summer and winter are based on temperatures averaged over a three-month season. However, it is not the average temperature that affects our comfort or health, but rather the daily extremes. A 4°F average warming could be derived from an endless succession of slightly warm days or from average summer days interspersed with intense heat waves (operationally defined here as three or more consecutive days with temperatures exceeding 90°F). Figure 4.4 depicts increases in the number of days with maximum daily temperatures above 90°F and 100°F. In the late 20th century, there was an average of 30 days per year with maximum temperatures in excess of 90°F. Of course, this number would be higher in urban areas, and lower at higher elevation or near the ocean (see Figure 4.1). On the average, temperatures reached 100°F on only about two days per year. Recent trends suggest a moderation in the number of high maximum temperature days in the Mid-Atlantic region[14], however the monthly average maximum

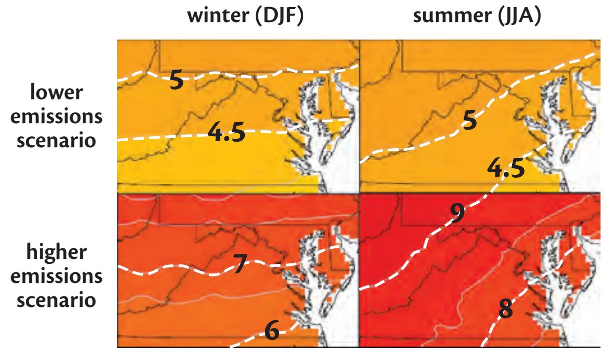


Figure 4.3. National maps of downscaled model projections of mean temperature increases for the period 2080-2099 show results very similar to this assessment. Note the east to west trend in the warming during the summer. Courtesy of Katherine Hayhoe, Texas Tech University.

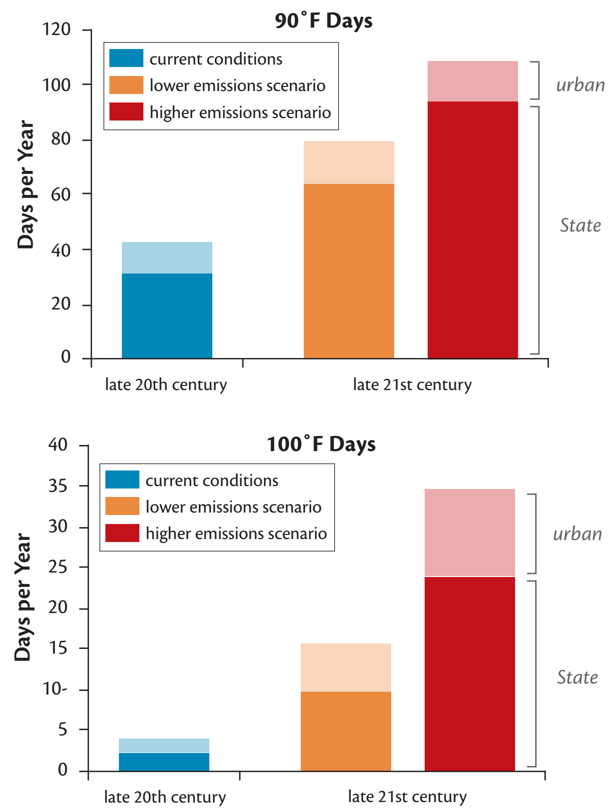


Figure 4.4. Number of days with high temperatures reaching or exceeding 90°F and 100°F in the late 20th century and projected for the late 21st century under higher and lower emission scenarios. Extension of the bars show the number days exceeding these levels in urban settings.

temperature at Maryland weather stations has been increasing faster than the average temperature, suggesting that maximum daily temperature will ultimately follow suit.

The number of days with temperatures exceeding 90°F is projected to double by the end of the century even under the low emissions scenario and triple under the higher emissions scenario in which virtually all summer days would exceed 90°F during an average summer (Figure 4.4). Under the higher emissions scenario, the number of days with temperatures in excess of 100°F is projected to increase by a factor of five, with most summer days exceeding this threshold. While at present, heat waves tend to have a limited duration with only a 13% chance per year of a heat wave lasting longer than 20 days, extended heat waves are likely to be much more frequent and longer lasting, especially under the higher emissions scenario (Figure 4.5). In the low emissions scenario, it remains most likely that any heat wave experienced will be of less than 20 days duration; however, the chance of a longer heat wave increases greatly. Under the higher emissions scenario, any given year is more likely to have a heat wave persisting for 140 days or more than it is to not have a heat wave exceeding 20 days. The predictions for increasing heat waves and temperature extremes are likely, with moderate confidence.

CHESAPEAKE BAY TEMPERATURES

Climate models currently do not resolve at the scale of estuaries, even for an estuary as large as the Chesapeake Bay (see Figure 3.2). However, observations of Chesapeake water temperatures extend back into the 1940s (Figure 4.6). These observations show a trend of increasing water temperature of 0.4°F per decade, with much of that increase over the past 30 years, consistent with increasing air temperatures. This amounts to a warming of 2.8°F over much of the Bay since 1940.

A statistical model was used to quantify the relationship between air temperature, over the preceding month, and Chesapeake Bay surface water temperature based on these observations.

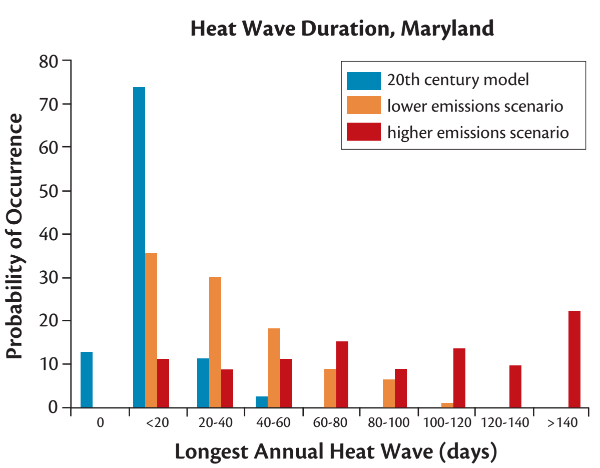


Figure 4-5. The chance that any given year will experience a heat wave of the indicated duration for present day and for the end of the century under low emissions and high emissions scenarios.

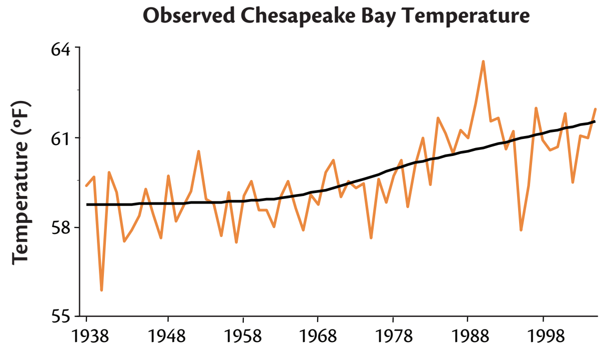


Figure 4.6: Bay temperature at Chesapeake Biological Laboratory at Solomons, MD, annual temperature, and a smoothed line illustrating the trend through 2006.

This relationship was then applied to project Bay temperatures as a function of climate-model projections of air temperature. Because the Chesapeake Bay is shallow in most places, surface water temperature is not only closely related to the air temperature, but also reflects temperatures in the shallows where many benthic organisms such as seagrasses, oysters, or blue crabs live. The temperature increases projected by the model average for Chesapeake Bay closely follow the air temperature increase shown in Figure 4.2, suggesting increases of 4°F by 2050 in the higher emissions scenario and 2.5°F for the low emissions path. This additional warming is of a similar magnitude to that observed in the Bay since 1940 (Figure 4.6). By 2100, the model projections suggest warming of 9°F and 5°F for the higher and lower emissions scenarios, respectively.

Temperatures in the Chesapeake Bay have already warmed by more than 2°F

Another way to express how these temperature changes might affect the ecology of the future Bay, including what plants and animals might live there, is to compare these future conditions with those currently experienced elsewhere along the Atlantic coast where current conditions resemble those projected for the Bay (Figure 4.7). Summertime water temperatures are likely to be similar to those of the North Carolina sounds by 2050. Under the higher emissions scenario, summertime water temperatures in the Bay might approximate conditions in South Florida. The effects of temperature increase and other climate changes on the Chesapeake Bay ecosystem are discussed further in Section 8.

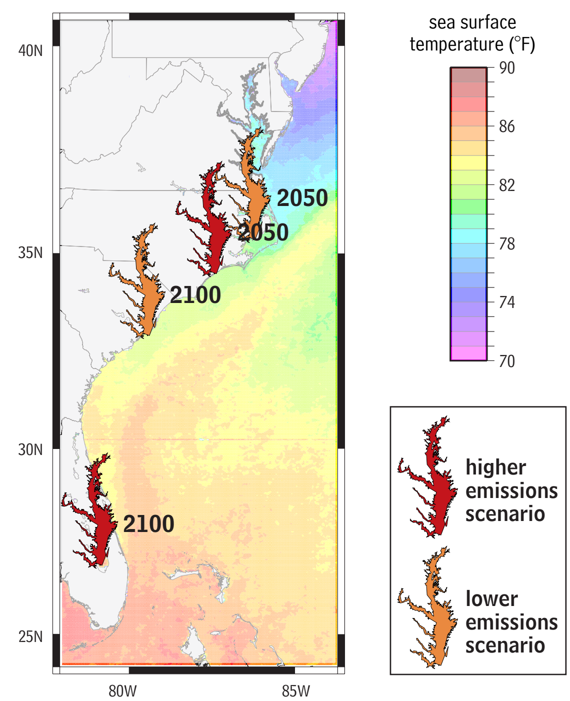


Figure 4.7. Summertime surface water temperatures in the Chesapeake Bay are projected to approximate those of estuaries well down the Atlantic Coast by 2050 and 2100.

PRECIPITATION

There has not been a statistically significant trend in precipitation in Maryland in recent years and this is consistent with the relatively modest changes projected by the climate model ensemble mean (Figure 4.8). Projections of winter rainfall show the greatest change, with increases of 5% by 2025

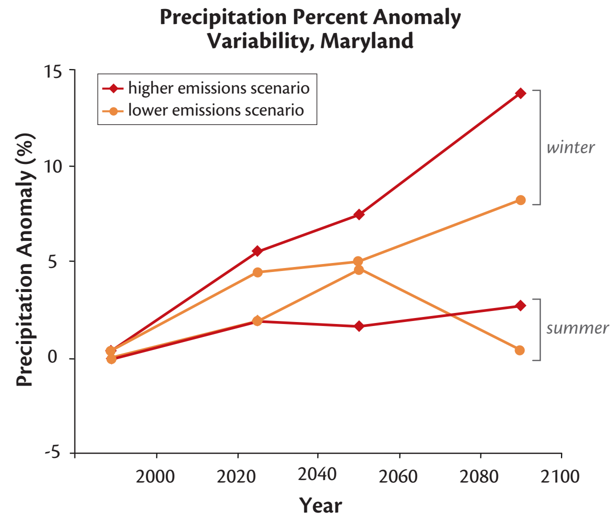
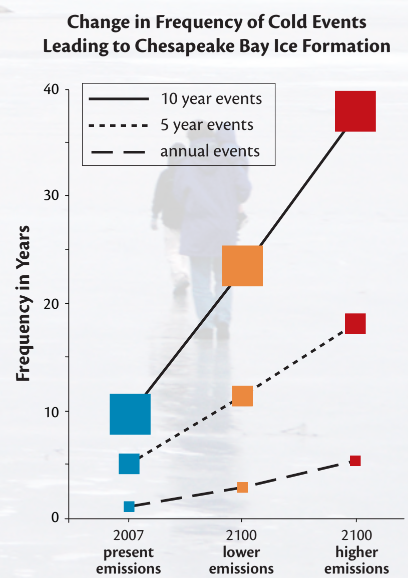


Figure 4.8. Winter and summer percent change in precipitation.

BOX 4.1 CHESAPEAKE FREEZE IS LESS FREQUENT

An ice-covered Chesapeake Bay is an iconic symbol of winter for many Maryland residents. Thin ice presently forms in sheltered embayments in most years. However, at roughly ten-year intervals, the Bay freezes over from shore to shore at the Chesapeake Bay Bridge. While these infrequent ice cover events may have little effect on the ecology of the Chesapeake Bay, they represent an obstacle to shipping, and ice cover reports are routinely issued for Chesapeake Bay by the U.S. Coast Guard. The climate model average predicts that these once every ten year ice cover events are likely to occur much less frequently in the future: every 25 years for the year 2100 low emissions scenario and as infrequently as once every 40 years under the higher emissions scenario (Box Figure 4.1). Ice cover that occurs every year at present may become less common in the future, with ice in the nearshore environment occurring only every 2-5 years by the end of the century under both the lower and higher emissions scenarios. This may have beneficial implications for nearshore oyster communities (see Section 8).



Box Figure 4.1 Time between ice cover events at the end of the century that occur every 1, 5, and 10 years at present.

Victoria Coles

projected for both scenarios, a 6.6 to 6.8% increase by 2050, and increases of 10.4 to 12.6% by 2090 under the lower and higher emissions scenarios respectively. However, there is a very wide band of uncertainty around these mean tendencies and increases of that scale do not approach the level of present year-to-year variability in winter precipitation. No season is projected to experience a substantial decrease in mean precipitation; however, some models project small declines in summer or fall precipitation and larger increases of up to 40% in winter precipitation by the end of the century. At the same time, large decreases are projected in winter snow volume (25% less in 2025 to 50% less in 2100 regardless of emission scenario). While Maryland does not receive large amounts of snowfall compared with states to the north[7], these reductions are large enough to reduce the spring river discharge associated with melting snow. Also, snow accumulation is very likely to be less common in western Maryland, thus affecting winter recreational activities.

When precipitation (P) is compared with the loss of water due to evaporation and plant transpiration (ET) that accompany increased temperatures, the water remaining (P-ET) shows little difference between the higher and lower emissions scenarios. However, the mean P-ET difference, reflecting the water available for runoff or groundwater recharge, is projected to decrease by 2 to 7 mm per month during the summer and increase by 6 to 7 mm (or only about one quarter of an inch) per month during the winter by end of the century; spring and fall projections show more modest changes.

Precipitation is likely to increase, but become more variable

Perhaps more relevant than the average rainfall, is how that rainfall is delivered. There is little change projected for the precipitation in the one-quarter of months that are driest. However, the range of precipitation from 25 to 75 percent of the time suggests a trend to increasing precipitation in the wet winter and summer months. The widening

NOAA

Summer rain drenches the landscape.

of this range in the projections illustrates that the month-to-month precipitation variability is projected to increase.

One measure of this variability is the amount of rainfall delivered in each rainy day. Climate models typically underestimate this at present, having too many days with weak precipitation.[15] However, even with this shortcoming, the mean of model ensemble projects increases in the amount of rain in any given day. The models also predict a increase in the maximum amount of rainfall occurring in any 5-day period, with the likelihood of getting more than 5 inches of rainfall in a storm event increasing from 5% at present, to 8% for the lower emissions scenario, and to 15% for the higher emissions scenario. These projections, coming as they do from models that are not able to spatially resolve many aspects of the hydrological cycle, are only moderately likely; however, they are broadly consistent with observed trends.[16] More accurate model predictions of precipitation will require development of regional climate models with finer spatial resolution.

The Northeast Climate Impacts Assessment (NECIA) report also projected increases in precipitation over the region to the immediate north of Maryland of up to 10% by the end of the century, with larger increases in winter and little change in summer. Indices of precipitation intensity, number of days with precipitation greater than two inches, and maximum five-day precipitation all showed comparable trends with the higher emission scenario used in that assessment yielding greater effects. The NECIA also found that increased evapotranspiration and frequency of short-term droughts were likely, particularly under higher emissions. This is consistent with this Maryland assessment. The NECIA projected less snow accumulation and earlier snowmelt, higher winter stream flows, and longer summer low-flow periods than at present, and these trends are also reproduced here.

SOIL MOISTURE

The effect of changes in temperature and precipitation and their implications for evaporation from water or soil and from plants are integrated in the projections of the changes in soil moisture. In spite of moderate increases in precipitation, increases in temperature in the models lead to decreases in soil moisture throughout the year. This is consistent with recent studies showing a change in the trend in North American soil moisture toward drying over the past 30 years.[17]

Changes represent 10% more drying in summer and fall by 2100 for both emissions scenarios in comparison to present normal summer conditions. Curiously, there is little difference between the lower and higher emissions scenarios, despite the much warmer temperatures projected under the higher emission scenario. This may be due to the very high relative humidity likely to occur, which will limit the rate of evapotranspiration. In years with lower than average rainfall, soil moisture reductions in spring and fall may be important to the local ecosystem and agricultural production. While soil moisture is dependent on the hydrological cycle and thus we have moderate confidence in the underlying physics, there is high agreement among models that summertime soil moisture will decrease, which makes this prediction likely.

GROWING SEASON

The length of the growing season is also important to terrestrial ecosystems in Maryland. The climate models project decreases in the number of frost days, where temperatures dip below freezing, and increases in the length of the frost-free growing season (Figure 4.9). Increases in growing season have been observed over the past fifty years.[18] While an increase in growing season may be a boon for gardeners, the increased active growth time coupled

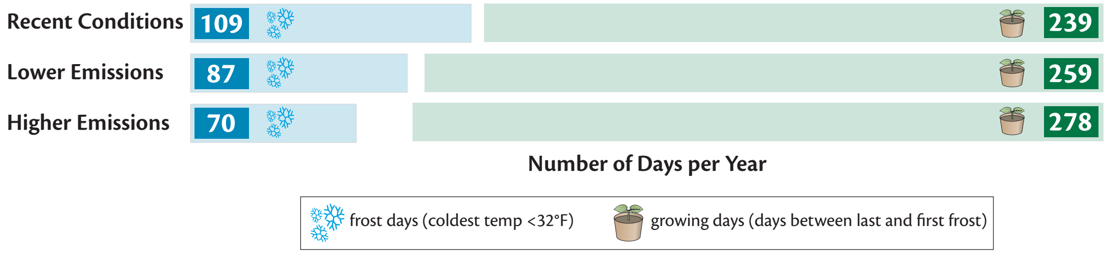


Figure 4.9. The number of frost days and growing season length projected before the end of the 21st century under the lower and higher emissions scenarios compared to recent conditions (end of the 20th century). These represent averages for the state and will vary depending on regional differences (Figure 4.1).

with reductions in soil moisture will likely cause some regions of the state to experience increased water demand for crop and landscape irrigation.

Frost days and growing season length are related to model representation of temperature, and so there is moderate confidence in our understanding of the underlying mechanisms driving changes, although the range of the model predictions leads to only moderate likelihood. Nonetheless, all the models predict reductions in frost days and increases in growing season length.

DROUGHT AND FLOODS

Global climate models do not capture present day extremes in drought or flood very well. Projections for droughts are probably more reliable than for flood conditions, because droughts reflect the influence of weather patterns that develop over large parts of the United States during periods of weeks to months. Floods, on the other hand, are associated with short-term phenomena and more intense weather events of a smaller spatial and temporal scale than resolved in global climate models. Yet, because these extreme events have such devastating effects on humans, the economy, and the environment, it is critical to estimate how the occurrence of flood events may change in the future to ensure adequate time for developing response strategies.

The models project an increase in the duration of annual dry spells, from about 15 days on average at present, to 17 days for the higher emissions scenario, and a smaller increase under the lower emissions scenario. Most of this increase is projected to occur during the latter part of the century. Based on these projections, it is likely that summer-fall droughts of modest duration will increase, especially after the middle of the century and that under the higher emissions scenario, there will be longer periods without rain. This has greater significance for soil moisture and attendant agricultural drought than for water supply. However, it is not the average that affects agricultural drought, but rather the more extreme or unusual events. The models suggest that, at present, a month-long drought can be expected to occur every 40 years, but this might increase to occurring every 8 years in 2100 under the higher emissions scenario, and there would be no appreciable change for the lower emissions path.

Even for drought conditions, it is important to point out that model projections of the two emission scenarios are based on averaging the output of different models, each of which was run for a continuous period extending from 1980 through 2100. Because each model simulation is the result of a single model run rather than multiple runs from which probabilities can be assigned, the modeling results cannot accurately predict rare events with low probability of occurrence (e.g., such as a 100-year or longer recurrence interval). Thus the projections reported here provide guidance on the likelihood of moderate drought conditions, but cannot represent the probability of an extreme multi-year drought such as the drought of the mid-1960s. Water-supply drought is more heavily affected by periods of low precipitation extending over multiple months, and is most strongly correlated with dry periods persisting through winter and spring when soil moisture, water tables, and reservoir levels would normally experience recharge.

Long-term or water-supply droughts, where rainfall deficits of more than 14 inches persist over a period of two years or more occur slightly less than 4% of the time at present in both observations and the models (Figure 4.10). While this number increases slightly to 5% under the higher emissions scenario, the models do not predict a likely increase in incidence of long-term drought. In contrast, the models suggest that two-year precipitation excesses of more than 14 inches, which are almost never observed but occur 4% of the time in the models, will occur much more frequently in the future. The higher and lower emissions scenarios have 14 inch excesses in precipitation occurring 28% and 14% of the time respectively. Thus, the models predict that while some moderate increase in short-term droughts may occur, increases in extreme precipitation events are more likely in the long-

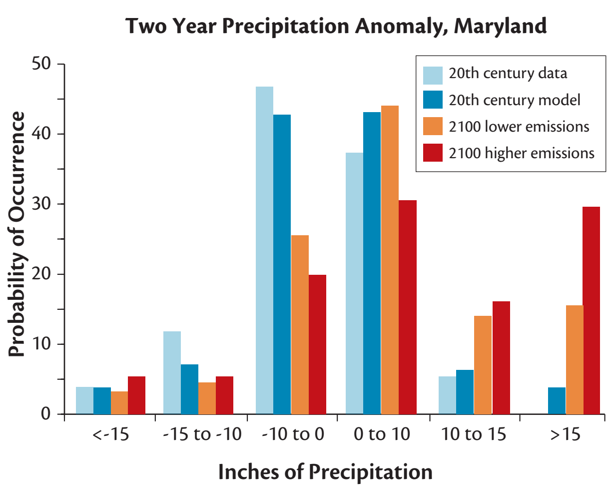


Figure 4.10. Long-term (two-year) drought and flood probability in the present day observations and models, and for the low and high emissions futures at the end of the century.

term. Further efforts to simulate extreme events at a regional scale are needed to reduce uncertainty.

Changes in precipitation extremes in the United States are already apparent in weather records. A report to be published later this year for the U.S. Climate Change Science Program (CCSP) concludes that extreme precipitation episodes (heavy downpours) have become more frequent and more intense in recent decades over most of North America and now account for a larger percentage of total precipitation.[13] Intense precipitation (the heaviest 1% of daily totals) in the continental U.S. increased by 20% over the past century while total precipitation increased by 7%. The CCSP report further concludes that the increase was consistent with increases in atmospheric water vapor, which have been associated with warming resulting from the increase in greenhouse gases, and that precipitation is likely to become less frequent and more intense. Under a medium emissions scenario, daily precipitation so heavy that it now occurs only once every 20 years is projected to occur approximately every eight years by the end of this century over much of eastern North America.

Heavy downpours have become more frequent and intense in the U.S.

For Maryland, the observed increase in frequency of extreme precipitation has to this point only been 3%, which is not a statistically significant increase. However, significant increases in intense precipitation of as much as 41% have been documented for West Virginia, Delaware, and Pennsylvania.[19] As was mentioned in Section 2, as the world warms increases in precipitation are expected to be greater at higher latitudes than lower latitudes. Maryland sits at the transition between the northeastern region where increases in precipitation are very likely in winter and spring, and the southeast region where projections of changes in precipitation cannot be confidently made.

At present, a watershed in Maryland might experience more than 8 inches of rain in a single day only once every 100 years. The climate models, however, consider 2.5 inches of rain in a single day to be a 100-year event. This is partly because the 2.5 inches of rain is spread evenly over more than 15,000 square miles in the model and because it does not provide high resolution at smaller scales (see Figure 3.2).

The percent of total rainfall coming in extreme events is projected to increase modestly but steadily during the century, with a slightly larger increase under the higher emissions scenario. However, this does not necessarily mean that less rain will fall the rest of the time. The model averages project only small changes in the number of days with more than 10 mm (about four tenths of an inch) of precipitation, with a slight increase under the lower emissions scenario and a slight decrease under the higher emissions scenario, by the end of the century. Five-day maximum precipitation is projected to increase more consistently from approximately 88 mm presently to 95-97 mm (i.e., from 3.4 to 3.8 inches), with little difference between higher and lower emissions scenarios. The maximum one-day precipitation over a year, a decade, and a century is projected to increase more, particularly under

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Finally ... some rain hits region

But flood warnings follow drought in Va.

By JANE W. GRAHAM
AFP Correspondent

BLACKSBURG, Va. — Rain finally came to Delmarva last week.

However, it brought the possibility of flooding where drought conditions have existed for months.

"We've gone from drought to flood warnings," Peter Corrigan of the National Weather Bureau in Blacksburg, Va., said on Friday morning.

"The welcome rain that finally arrived in Virginia in late October is a first step toward recovery for farmers across the state who have been experiencing significant drought conditions for months," wrote Todd P. Haymore, the commissioner of the Virginia Department of Agriculture and Consumer Services in an e-mail on Friday morning.

"However," Haymore continued, "when drought is as severe as it has been in some areas, it will take much more than a few inches of rain

Farmers got much-needed rain across most of the region last week. Here, rain filled up some low spots in a field near Easton, Md., where a few ears of corn were left behind.

Sean Clougherty

Maryland newspaper headlines failing corn crop due to lack of rain in 2007.

Frieda Squires

Heavy rain causes flooding and hazardous conditions for roadways.

the higher emissions scenario near the end of the century (Figure 4.11). The projected increases are greater for longer recurrence intervals, consistent with increasing climate volatility. But, again, it's important to remember that the global climate models have limited ability to project extreme rainfall events and tend to underestimate extreme precipitation events.

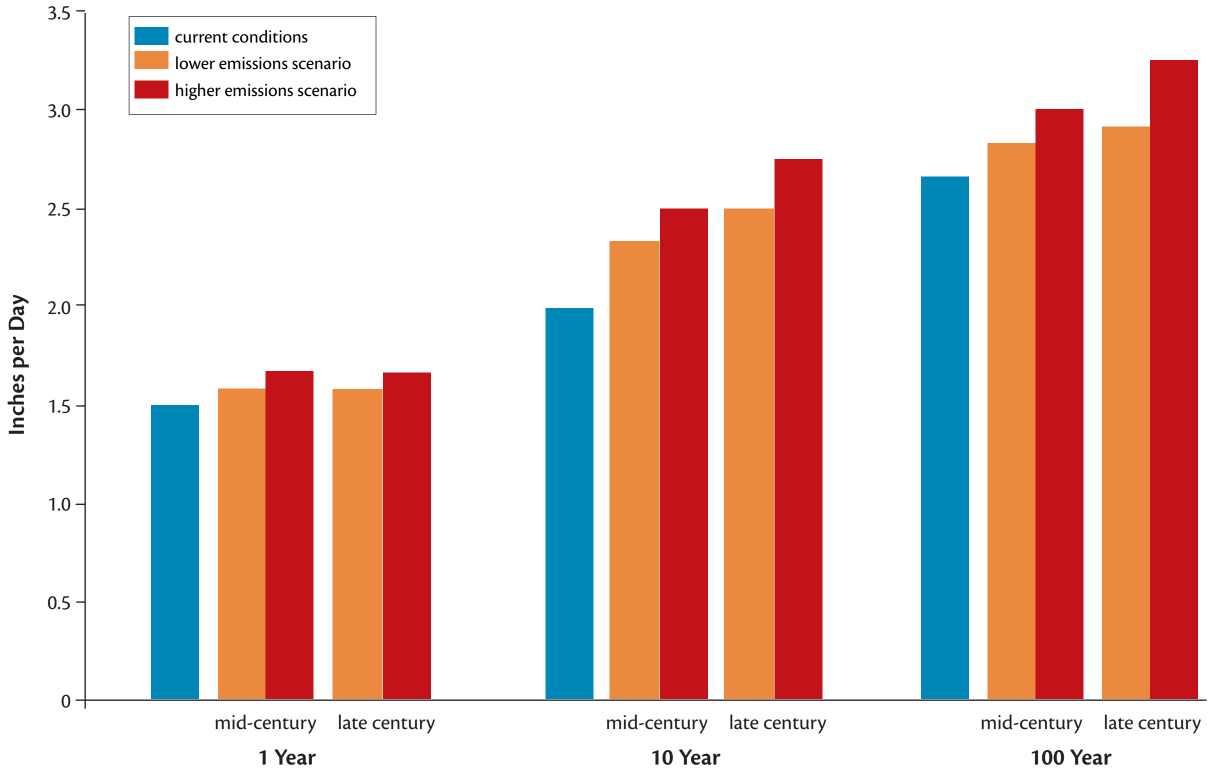


Figure 4.11. Projected one-day maximum precipitation for 1, 10, and 100 year return frequencies. Models tend to under-estimate extreme precipitation amounts, so the relative comparisons rather than the actual amounts are relevant.

Section 5

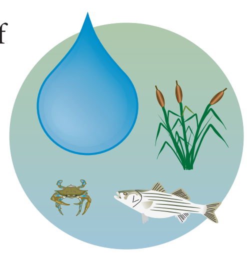
WATER RESOURCES & AQUATIC ECOSYSTEMS

KEY POINTS

- **Increased precipitation would supply reservoirs but not alleviate overdraft of aquifers.**
  Water supplies in the greater Baltimore area should not be diminished, but the adequacy of summer water supplies in the greater Washington region is less certain. Any increases in precipitation are unlikely to alleviate the present over-withdrawal of groundwater and summer droughts may increase groundwater demand for irrigation.

- **Urban flooding will likely worsen because of intensification of rainfall events.**
  More intense rainfall resulting from large-scale and localized (e.g., urban canopy) climate effects are likely to increase peak flooding in urban environments. Continued increase in impervious surfaces attendant with development would exacerbate this problem.

- **Aquatic ecosystems will likely be degraded by increased temperatures and flashy runoff.**
  Intensified rainfall events and warmer surfaces (roads, roofs, etc.) would result in rapid increases in stream temperatures, limiting habitat suitability for native fishes and other organisms. Degraded streams would transmit more nutrients and sediments to the Chesapeake Bay and its tidal tributaries.



The natural waters of Maryland provide essential habitat for aquatic life and support the fundamental needs of every economic sector of society. The water cycle and the physical and chemical character of natural waters are both strongly dependent on climate patterns and trends, including average and extreme weather conditions, such as floods and droughts, that although infrequent are very important. Although this assessment is intended primarily to address predictions associated with climate change, it is important to recognize that such changes will occur in the context of continuing population growth and economic development. Past experience strongly suggests that the combined impacts of climate change and development on water resources and aquatic ecosystems will be far greater than those of climate change alone. Therefore, reasonable predictions about Maryland's future must consider both factors.

This assessment addresses: (1) reliability of freshwater supply, including both surface water and groundwater; (2) changes in flood hazards; (3) effects of changes in runoff and water temperature on aquatic habitats and populations; (4) impacts on water quality with implications for management and regulation of sediments and nutrients; and (5) potential salt contamination of aquifers and freshwater intakes as the boundary between fresh and brackish water shifts with rising sea level. These impacts are examined with reference to climate projections based on the higher and lower emissions scenarios (see Section 3). The projections (Table 5.1) are broadly consistent with previous assessments conducted for the Mid-Atlantic region[20] and to a large extent with the Northeast Climate Impacts Assessment.[7]

Maryland Sierra Club

Burnt Mills Dam, Maryland.

Table 5.1. Summary of general projections of climate models related to water resources.

Property	21st Century Projection
Precipitation	Winter precipitation is likely to increase with smaller changes in other seasons.
Runoff	Wintertime runoff is likely to increase and summer runoff is likely to decrease, but with more frequent and larger summer floods.
Soil moisture	Soil moisture is likely to decrease during the summer and fall toward the end of the century.
Snow volume	Snow volume is very likely to decline substantially during the mid-late century.
Heavy precipitation events	Heavy precipitation events are likely to increase.
Drought	Consecutive dry days and summer-fall (but not multi-year) droughts are likely to increase under the higher emissions scenario.

FRESHWATER SUPPLY

Water stress—the imbalance between water demand and available supply—is anticipated to increase in many areas of the world over the coming decades. This is partly a result of increases in demand and partly a result of decreasing availability in some areas. Water availability must be examined not only in terms of average conditions, but also with respect to the amounts available during droughts that are expected to recur periodically. From a global perspective, the region including Maryland is considered as relatively low stress with regard to the projected ratio of water withdrawals to availability under the higher emissions (A2) scenario for 2050.[21] As the Advisory Committee on the Management and Protection of the State's Water Resources noted in 2004: "Nature provides Marylanders with abundant water, which, if well managed, could meet present and future needs." [22]

On the other hand, this same report identifies potential threats to water quantity and water quality resulting from population growth and land development. And, as recent difficulties in the southeastern U.S. demonstrate, the eastern seaboard is certainly not immune to drought.[23] Within the last six years in Maryland, we have witnessed two of the driest years on record as well as the wettest year on record, and there have been impacts on water supplies during the dry years that required public response. These short-term variations are larger than the range of variation in mean precipitation or moisture availability during this century predicted using global climate models. Sensitivity of water supply to wet and dry cycles is in large measure a function of the nature of the water-supply system, together with the array of management options that are available to be used during times of shortage.

Recent evidence suggests that summer drought may be correlated with patterns of sea-surface temperature—a consequence of multi-year cycles in the Atlantic (Atlantic Multidecadal Oscillation) or Pacific (El Niño-Southern Oscillation and the Pacific Decadal Oscillation) oceans—and that these correlations might be used in drought forecasting over time periods of one or two decades.[24] It has been suggested that superimposing these cycles on longer term trends projected by global climate models could improve forecasting of drought probabilities and provide a tool for water-supply management for the greater Washington area in adaptation for global warming.[25]

Within six years, Maryland experienced some of the driest and the wettest years on record

The Advisory Committee pointed out that total water use in Maryland has not increased even with the increase in population (Figure 5.1).[26] This reflects a complex set of changes in water used by different economic sectors, with declining industrial and commercial use and increasing domestic use, public supply, and irrigation. Demand is anticipated to rise over the next 30 years, coinciding with increased suburban land development, affecting

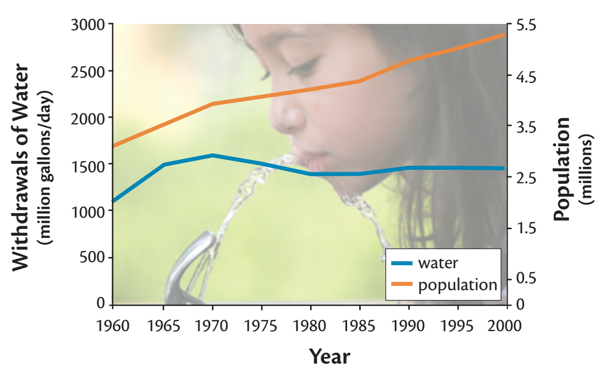


Figure 5.1. Trends in Maryland's water consumption and population.[26]

areas that might otherwise be available for recharge of groundwater, and with increased irrigation needs on agricultural land during summer droughts anticipated with the warmer climate. Summer water demand will increase as temperatures increase and water availability during the summer becomes less reliable. Options for demand reduction do exist but have not been fully explored by utilities and public agencies.

Marylanders rely both on surface water, derived from free-flowing streams and from storage in water-supply reservoirs, and on groundwater retrieved from wells in both shallow and deeper confined aquifers. The relative importance of these sources varies both as a function of urban versus rural location and physiographic province (Figure 5.2). Surface water is the primary source in and around major metropolitan areas with about 3.2 million of the state's population of 5.4 million (based on 2004 estimates; present population is at least 5.7 million) served by public water supply in the Baltimore and Washington, D.C. metropolitan areas.[26] Public and community water-supply systems elsewhere, using a mix of surface water and groundwater, served a cumulative population of 1.3 million. Groundwater is the primary source of supply in rural areas where public water is not available and in most of the Coastal Plain, with 900,000 people relying on private wells. Surface water withdrawals increased by 6% between 1985 and 2000, whereas groundwater withdrawals increased by 21%.

Groundwater withdrawals increased by 21% between 1985 and 2000

Although agriculture accounts for only 3 to 5% of state water use at the present time, agricultural needs of 285 million gallons per day (mgd) statewide are anticipated by 2030—more than currently used by the Baltimore metropolitan area. Much of this increased demand will be associated with irrigated agriculture on the Eastern Shore.[26] Furthermore, over half of the new households anticipated by 2030 will likely be located in the rapidly growing counties of Howard, Harford, Frederick, Carroll, Charles, Calvert, and St. Mary's. Many of these counties are already experiencing water stress because of rapid exploitation of local supplies, resulting in building moratoria in parts of Carroll County[27] and rapid declines in well levels in confined aquifers of southern Maryland.[28]

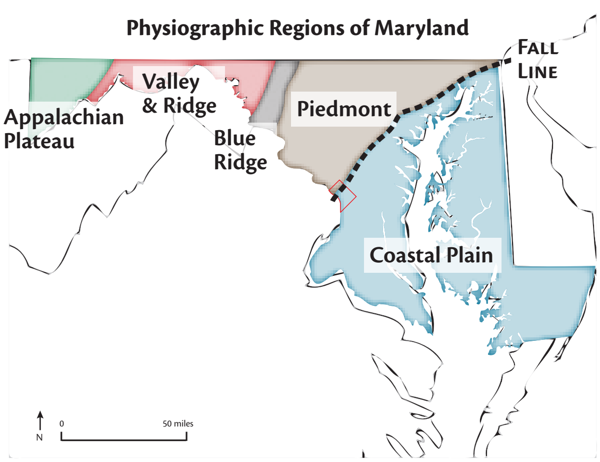


Figure 5.2. Maryland's five physiographic regions.

Surface water

The major metropolitan water-supply systems in Maryland rely on a mix of impoundments and direct withdrawal from major rivers. Baltimore City supplies water to Baltimore County as well as a portion of the public water-supply needs of Anne Arundel, Howard, Harford, and Carroll counties. The City has three major water-supply reservoirs with cumulative storage of 86.7 billion gallons, as well as a pipeline that can be used to augment the reservoir supply with water from the Susquehanna River during times of extreme drought.[29] Cumulative safe yield of the reservoirs is nearly 240 mgd and the intake on the Susquehanna River currently has a capacity of 250 mgd with ultimate capacity of 500 mgd. There are additional pumping stations on Deer Creek that can expand capacity further if necessary.

The climate change scenarios described in Section 3 suggest an increased frequency of short-term drought despite a net increase in average annual flow. Baltimore has managed to weather two severe droughts since 2000 without serious negative impacts, although it was necessary to pump water from the Susquehanna and this involved increased treatment costs. It is likely that Baltimore City's water-supply system should be sufficient to meet demands under the projected climate change. Greater winter-spring precipitation will increase the likelihood that reservoirs will be full heading into the drier summer periods, resulting in protection from water-supply shortages for areas served by the reservoirs.[30]

The Washington Metropolitan Area's water supply situation is somewhat more precarious. Average annual water use (including Maryland, D.C., and Virginia users) currently is about 488 mgd and projections call for an increase to 572 mgd by 2025.[31] About 75% of the water supply is derived from the Potomac River, the flow of which is largely unregulated. A total storage volume of about 17 billion gallons is available in reservoirs to augment the supply of the Potomac River during dry periods, and additional storage of about 18 billion gallons is available in other suburban reservoirs that do not connect directly to the Potomac supply. A Water Supply Coordination Agreement and a Low Flow Allocation Agreement among the various water suppliers are intended to coordinate the operation of all the water utilities in the region and to allocate shortfalls when water is insufficient to meet all demands.

The Interstate Commission on the Potomac River Basin (ICPRB) has estimated that the existing system is adequate to meet 2025 demand, and even 2045 demand, under a repeat of the worst historical drought conditions.[31] The ICPRB concluded that, even accounting for uncertainties associated with climate change, contingencies in place to restrict demand could be used to avert a water-supply crisis. However, Maryland's Advisory Committee on the Management and Protection of the State's Water Resources observed that planning has been complicated by the outcome of a 2003 Supreme Court case that gave Virginia the right to remove water from the Potomac River without following Maryland's permit regulations.[22] Furthermore, even if this issue can be resolved by mutual agreement, other measures, including development of additional supplies and water reuse, may be necessary to meet local needs.

Groundwater

Groundwater in the Piedmont and Appalachian Plateau regions occurs principally in fractured bedrock and the overlying layer of weathered material that can be as much as 100 feet thick (Figure 5.3).[32] The volume of storage available in these shallow aquifers is typically quite limited and there are strong connections between groundwater and local surface water, such that a reduction in groundwater storage is likely to be reflected in reduced base flow to local streams. Because of the complex flowpaths and connectivity of the fracture network, the spatial pattern of groundwater availability is unpredictable and is therefore unsuitable for large-scale water-supply development. Groundwater availability is sensitive to short-term climate fluctuations and to alteration of the land surface by development. These factors, plus the growing demand, led to the building moratoria near Westminster in Carroll County that were mentioned previously.[27]

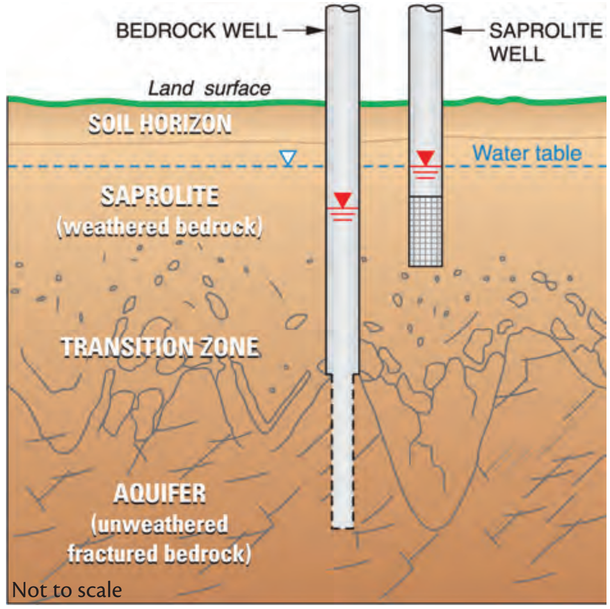


Figure 5.3. In the Piedmont, shallow wells draw from unconfined weathered bedrock and deep wells from bedrock aquifers.[32]

Although climate models generally project changes in water availability under average conditions, the likelihood of more frequent short-term drought poses a challenge to the reliability of water supply dependent on shallow groundwater during the late summer and fall in rural areas. Even with significant increases in winter and spring precipitation, it is not clear how much of the increase will contribute to recharge of groundwater in the Piedmont and Appalachian provinces if significant amounts are instead diverted to increased runoff.

The situation in the Coastal Plain of Maryland is quite different. Most groundwater is stored in deep, confined aquifers (Figure 5.4) that are not in direct contact with the surface or with overlying streams. Because the water that recharges these

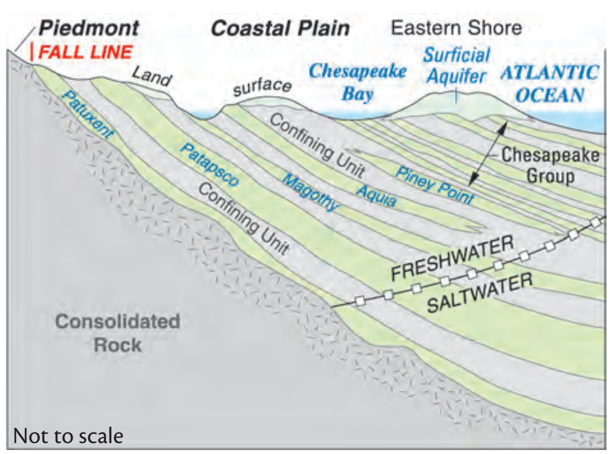


Figure 5.4. Schematic cross-section of the Coastal Plain aquifer system.[33]

aquifers may travel over long distances, these aquifers are not sensitive to short-term weather fluctuations. They are more likely to experience changes in storage and in well levels that are tied to long-term trends in the balance between recharge and water withdrawal. Thus, climate change projections in which precipitation increases more than evapotranspiration are less likely to pose a serious problem for aquifer storage, even if there are short-term droughts superimposed on the long-term trends.

A serious challenge does arise, however, as a result of pumping trends associated with rapid urban and suburban development in the Coastal Plain counties. Long-term trends showing declining well levels have accelerated sharply since the 1980s (Figure 5.5).[33] In many cases, the rate of decline exceeds 2 ft/yr and in the areas of most active pumping it can be substantially higher.[32] The Maryland Department of Environment uses an 80% rule to regulate groundwater extraction from confined aquifers—pumping is not supposed to lower well levels more than 80% of the distance between the pre-pumping water level and the top of the confined aquifer. At present, however, farmers are not required to report the amount of water pumped for irrigation and there are no significant ongoing monitoring studies to document head losses associated with irrigation. While the declines in well levels currently observed are mainly a result of urban and suburban uses, this lack of reporting and monitoring could pose a problem if demand for crop irrigation substantially increased.

Well levels have declined as much as 2' per year in Maryland's Coastal Plain

If the regional declines in confined aquifers continues or accelerates, regional land subsidence over the affected areas may exacerbate local relative sea-level rise as discussed in Section 7. Changes in freshwater storage and in relative sea level may also cause the freshwater/saltwater boundary illustrated in Figure 5.4 to move landward and to reach shallower depths. This may pose a particular problem for withdrawals from shallow aquifers on the Eastern Shore.

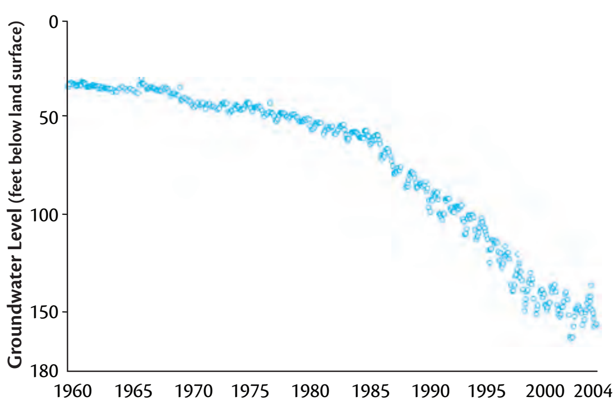


Figure 5.5. Water level decline in a well in the Aquia aquifer in Calvert County, Maryland.[33]

FLOOD HAZARDS

Because floods represent the extreme end of the frequency distribution of streamflows, prediction of flood probabilities is subject to uncertainty even under the best of circumstances. Estimation of the probability or return period of a flood of a given size typically is accomplished using historical records, and standard estimation techniques assume that flood occurrence is essentially a random process and that the underlying probabilities are not changing over time. Therefore, climate change presents a challenge to standard approaches in flood-frequency estimation because the future will no longer resemble the past.

Trends toward increased river runoff are already apparent beginning about 1970 in portions of the eastern United States, including the Mid-Atlantic region.[34] Annual runoff has further been projected to increase in the eastern United States by the middle of this century[35], consistent with increases in atmospheric water vapor and precipitation intensity.[36] The probability of occurrence of a great flood (defined as having a 100-yr return period) in a number of large river basins had increased substantially during the 20th century[37], prompting a group of leading hydrologists to write recently that climate change has undermined a basic assumption about the relevance of past observations for management of future water supplies, demands, and risks.[38] The authors suggest that new modeling approaches are needed to improve our ability to estimate flood hazards under alternative future scenarios. Although intense rainfall is the most important contributor to flood hazards, there are other aspects of land-surface conditions that determine how efficiently intense rainfall is converted into flood flow. These cannot be predicted on a statewide basis for all watersheds with information that is currently available; therefore, this report focuses on the probability of intense precipitation as the primary indicator of flood probability.

Susquehanna River Basin Flood Forecasting and Warning System

The Susquehanna River Basin is one of the most flood-prone watersheds in the nation. The main stem and its tributaries drain 27,510 square miles of New York, Pennsylvania, and Maryland.

As discussed earlier, probabilities of flood inducing rainfall are not well represented in global climate models that predict average conditions over large grid cells. A possible exception would be large-scale events such as powerful extratropical storms occurring in winter, particularly where rain on snow is a key element. These may generate large floods over very large drainage areas comparable to the model grid cells. Such events occur infrequently in Maryland, but can be important in the Susquehanna River Basin, which lies mostly in Pennsylvania and New York and supplies about one-half of the freshwater inflow to the Chesapeake Bay. The January 1996 flood in the Susquehanna River basin is an example of such an event. The magnitude of the flood was in part a result of the large volume of moisture already stored on the landscape in the form of snow, which was released very rapidly as it melted during the precipitation event. Although climate models project higher precipitation totals and greater intensity of rainfall during the winter season, the reduction in volume of snow stored on the landscape may well cause a reduction in the likelihood of this type of extreme flood even as moderate floods become more likely in winter and early spring.

Another major cause of flood hazards in the region is the occurrence of hurricanes and tropical cyclones. The flood of record for many locations in Maryland (including the Susquehanna River at Conowingo Dam) is still Hurricane Agnes, which struck the region in June 1972.[39] By the time it reached Maryland, Agnes was not a major cause of storm surge, wind damage or coastal flooding; its primary impact was as a rainfall-runoff event. Hurricane Floyd, in September 1999, dropped as much as 12.6 inches of rain on Maryland's Eastern Shore and generated floods in some Eastern Shore rivers with estimated return periods of 100-500 years.[40] As discussed in greater depth in Section 7, the current scientific consensus is that tropical cyclones are projected to increase in rainfall intensity even though their frequency may decline.

Precipitation intensities in small watersheds are underestimated in climate models

For small watersheds, the likelihood of flooding depends not only on total amount of precipitation but also on its intensity at smaller spatial and temporal scales. While climate models may be useful for projecting maximum one-day precipitation averaged over a large area (Figure 5.2), they cannot predict the actual rainfall over short periods or areas at a scale comparable to a storm cell. Point and small-area rainfall intensities associated with flood generation will be much higher. This is illustrated by comparing the predicted probabilities of intense precipitation from the model projections with precipitation frequencies based on regional observations for points within the Baltimore-Washington metropolitan area (Table 5.2).[41] Observed rainfall amounts associated with recurrence intervals of 1 to 100 years are already 170 to 300 percent greater than the one-day rainfall amounts projected from the climate models near the end of this century.

If flood magnitudes change in a manner commensurate with the trends in maximum rainfall predictions (Figure 4.11), then one might indeed

Table 5.2. Maximum rainfall amounts for four recurrence intervals based on observations in the Baltimore-Washington area, as summarized in NOAA Atlas 14 and projected for 2090 under higher and lower emissions scenarios.

Recurrence Interval (yr)	One-day Rainfall Amounts (inches) Observed[41]	Higher Emissions	Lower Emissions
1	2.6	1.7	1.6
5	4.1	2.4	2.0
10	4.9	2.6	2.3
100	8.5	3.2	2.7

expect to see larger, more extreme floods in smaller watersheds as the century proceeds. The magnitude of such an increase is necessarily speculative; the point values of extreme rainfall under the present climate are already so much higher than those predicted by these GCM scenarios that only the general trends are relevant, and they are not based on simulation of the actual physical processes associated with extreme precipitation. Nevertheless, if one accepts the comparisons in maximum one-day rainfall as representative of likely changes in flood magnitude, then we might anticipate a 20% increase in the magnitude of the 100-year flood under the higher emissions scenario and a 10% increase under the lower emissions scenario. Comparable increases for the 10-year recurrence interval would be approximately 29% and 16%, respectively, with the increase in peak flood flows under higher emissions approximately double the increase under lower emissions.

These increases are consistent with the trends identified by the IPCC Fourth Assessment, the Northeast Climate Impacts Assessment, and the U.S. Climate Change Science Program concerning the increased likelihood of intense, flood-generating precipitation. However, it is important to remember that land development has had and will continue to have a major effect on increasing flood probabilities in smaller drainage areas. As the area of impervious surface and storm drain networks increase, runoff is accelerated.[42] Also, as was demonstrated with a 2004 event in Baltimore, the urban 'canopy' effect can play an important role in determining the conditions favoring intense thunderstorms.[43] Because of both these effects—surface properties affecting runoff response and atmospheric interactions affecting rainfall intensity—flood peak magnitudes in small urban watersheds may be several times larger than for comparable rural watersheds. This can be illustrated by plotting flood peak discharge as a function of drainage area for thunderstorms in Baltimore compared to some record floods in the Mid-Atlantic region (Figure 5.6). The straight lines are thresholds defining the upper range of extreme flood peaks that may attain values between 1000 and 2000 cfs/mi². The urban floods were, with one exception, events with recurrence intervals of the order of 5 to 10 years; yet these events, represented by blue dots on the plot, were comparable in magnitude to Mid-Atlantic floods that occur much less frequently.

Land development and urban microclimates intensify floods

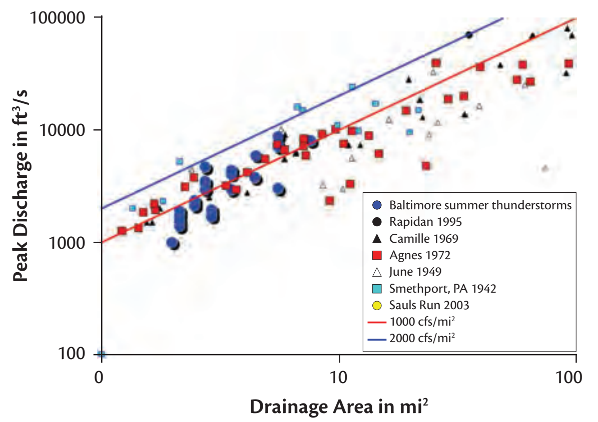


Figure 5.6. Relationship between peak discharges and watershed drainage area for urban floods in Baltimore and historic floods in the Mid-Atlantic region.

The increased frequency and magnitude of floods in urban watersheds has implications not only for flood protection and water allocation, but also for the design of treatment plants, dams, and even bridges. Prediction of future estimates will require the development of new modeling approaches that can incorporate the effects of changing climate superimposed on trends in urban development. Using such an approach, a recent study projected that the number of days with extreme rainfall in the New York metropolitan area is likely to increase from 1-2 days to 3-4 days by the end of the summer under the higher emissions (A2) scenario.[44] Building on efforts like this one, smaller scale atmospheric models linked with global climate models could more accurately project precipitation and those predictions could be used to drive hydrologic models to predict flood probabilities associated with combined climate change and urbanization scenarios.

WATER QUALITY & AQUATIC BIOTA

Freshwater ecosystems provide multiple goods and services (Table 5.3) valued highly by people and inextricably linked to water flows and the interaction of flow with the landscape. The ability of aquatic ecosystems to provide these benefits depends on how 'healthy' they are—that is, the degree to which physical and biological processes that maintain normal ecological functioning are working properly. Climate changes may modify these critical processes and thus diminish the health of the ecosystem.

Of particular concern are climate-induced changes that exacerbate human-caused stresses,

Table 5.3. Freshwater ecosystems (wetlands, rivers, streams, lakes, etc.) provide a number of goods and services that are critical to their health and provide benefits to society. The major services are outlined along with the ecological processes that support the function, how it is measured, and why it is important.[45]

Ecosystem Service	Consequences of Losing the Service	Supporting Ecological Process	Ecosystem/ Habitat
Water Purification a) nutrient processing	Excess nutrients (eutrophication) can build up in the water making it unsuitable for drinking or supporting life; Algal blooms resulting from excess nutrients can lead to anoxic conditions and death of biota	Retention, storage, and transformation of excess nitrogen and phosphorus; Decomposition of organic matter	Floodplain, river and streambeds, wetlands, lake littoral zones
b) processing of contaminants	Toxic contaminants kill biota; Excess sediments smother invertebrates, foul the gills of fish, etc; Water not potable	Biological removal by plants and microbes of materials such as excess sediments, heavy metals, contaminants, etc.	Floodplain and wetland soils and plants; Bottom sediments of rivers, lakes, and wetlands
Water Supply	Loss of clean water supply for residential, commercial, and urban use; Irrigation supply for agriculture	Transport of clean water throughout watersheds	Lakes, rivers, streams
Flood Control	Without the benefits of floodplains, healthy stream corridors, and watershed vegetation, increased flood frequency and flood magnitude	Slowing of water flow from land to freshwater body so flood frequency and magnitude reduced; Intact floodplains and stream-side vegetation buffer increases in discharge	Floodplains, wetlands, stream-side zones
Infiltration	Lost groundwater storage for private and public use; Vegetation and soil biota suffer; Increased flooding in streams	Intact floodplain, stream-side, wetland vegetation increase infiltration of rain water and increase aquifer recharge	Wetlands, streams, floodplains
Carbon Sequestration a) primary production	Water and atmospheric levels of CO_2 build up, contributing to global warming	Aquatic plants and algae remove CO_2 from the water and atmosphere, convert this into biomass thereby storing carbon	Freshwater ecosystems with sunlight, but particularly shallow water habitats such as wetlands or mid-order streams
b) secondary production	Water and atmospheric levels of CO_2 would build up contributing to global warming	Production of biomass by microbes and metazoans stores carbon until their death	All freshwater ecosystems but particularly the bottom sediments for microbes
Nitrogen Sequestration primary and secondary production	Secondary production supports fish and wildlife	Creation of plant or animal tissue over time	All freshwater ecosystems and habitats
Food Production a) primary production	Reduction in food and food products derived from aquatic plants such as algae, rice, watercress, etc.; Decreased production (secondary) by those consumers who rely on primary production as a food source	Production of new plant tissue	All freshwater ecosystems and habitats with sunlight but particularly shallow water habitats such as wetlands

Table 5.3. Continued.

Ecosystem Service	Consequences of Losing the Service	Supporting Ecological Process	Ecosystem/ Habitat
Food Production b) secondary production	Reduction in fisheries including finfish, crustaceans, shellfish, and other invertebrates	Production of new animal tissue or microbial biomass	All freshwater ecosystems and habitats, but particularly the water column and surficial sediments
Biodiversity	Loss of aesthetic features, impacts aquarium trade, potential destabilization of food web, loss of keystone species can impact water quality	Diverse freshwater habitats, watersheds in native vegetation, complex ecological communities support multiple trophic levels	All ecosystem and habitat types, but particularly wetlands for plants and rivers for fish
Temperature Regulation	If infiltration or shading are reduced (due to clearing of vegetation along stream), stream water heats up beyond what biota are capable of tolerating	Water temperature is 'buffered' if there is sufficient soil infiltration in the watershed; Shading vegetation keeps the water cool; Water has a high heat capacity which stores excess heat	Shallow water habitats, especially wetlands
Erosion/Sediment Control	Aquatic habitat burial impacts fisheries, decreases biodiversity, increases in contaminant transport, reduces downstream lake or reservoir storage volume	Intact stream-side vegetation and minimization of overland flow	Wetlands, streams, and rivers
Recreation/ Tourism/Cultural, Religious, or Inspirational Values	Lost opportunities for people to relax, spend time with family; Economic losses to various industries, particularly tourist oriented ones	Clean water, particularly water bodies with pleasant natural surroundings such as forests, natural wildlife refuges, or natural wonders	Lakes, rivers, and streams

Victoria Coles

A beautiful day is enjoyed on a family hike in western Maryland.

such as depletion of water flows and urbanization, both of which are already affecting streams and rivers over much of the State. As is the case with flood probabilities, the influence of urban development signal is likely to be at least as strong through the remainder of this century as the climate signal, and these two signals combined will tend to reinforce trends pointing in the same direction, i.e., more highly variable flows. Global warming will also directly change the temperature regimes, causing shifts in the species inhabiting the ecosystems.

Anticipating the future condition of a river in the face of climate change requires explicit consideration not only of the current climatic, hydrologic, and ecological conditions but also of how it is currently managed and how human behavior will affect the ecosystems. Thus, consideration of how climate change is likely to impact Maryland's freshwater ecosystems rests not only on the assumptions underlying climate models and scenarios, but also on future decisions regarding water use and watershed management. Options also exist for adapting these practices to reduce the impacts of climate change on freshwater ecosystems.[46]

Except for deep reservoirs, fresh waters are generally well mixed and respond to changes in atmospheric conditions fairly readily. Thus, they would become warmer as air temperatures increase.[47] As the water warms, individual growth and reproductive rates of biota are expected to increase so long as thermal tolerances are not exceeded.[48] Faster growth rates and time to maturation typically result in smaller adult size, and, because size is closely related to reproductive output in many aquatic organisms, population sizes may decline over time. The spawning time of native fish may also shift earlier if waters begin to warm earlier in the spring, and species that require prolonged periods of low temperatures may not survive.

For fish, amphibians, and water-dispersed plants, habitat fragmentation due to small dams (which are surprisingly common in Maryland's streams) or the isolation of wetlands and tributaries due to drought conditions may also result in elimination of their local populations. Because higher temperatures result in lower concentrations of dissolved oxygen in all but swift flowing waters, this may present an additional stress on organisms.[49]

Aquatic ecosystems in watersheds with significant urban development are expected to experience not only the greatest changes in temperature, but also greater temperature spikes during and immediately following rain storms that could result in the local loss of species. Such temperature spikes of 6 to 12°F occur in urban streams near Washington, D.C., and are strongly related to the amount of warm impervious surfaces (Figure 5.7).[50]A recent modeling study demonstrated how the combined effects of urbanization and climate change on suburban Washington streams would be greater than either alone. Under a moderate emissions (B2) scenario, warming produced an increase in stream temperatures of 6°F late in the century, while urbanization produced an increase of 7°F (Figure 5.8). However, when both urbanization and climate change were imposed, an increase of over 12°F resulted. The urbanization effects alone would stress 8 of the 39 fish species, but with additional effects of climate change as many as 29 species would be stressed. Almost every recreationally important species (trout, bass, yellow perch, and bluegill) would experience decline in the growth and reproduction ranging from 40% to 90%.

Changes in flow regime toward greater frequency

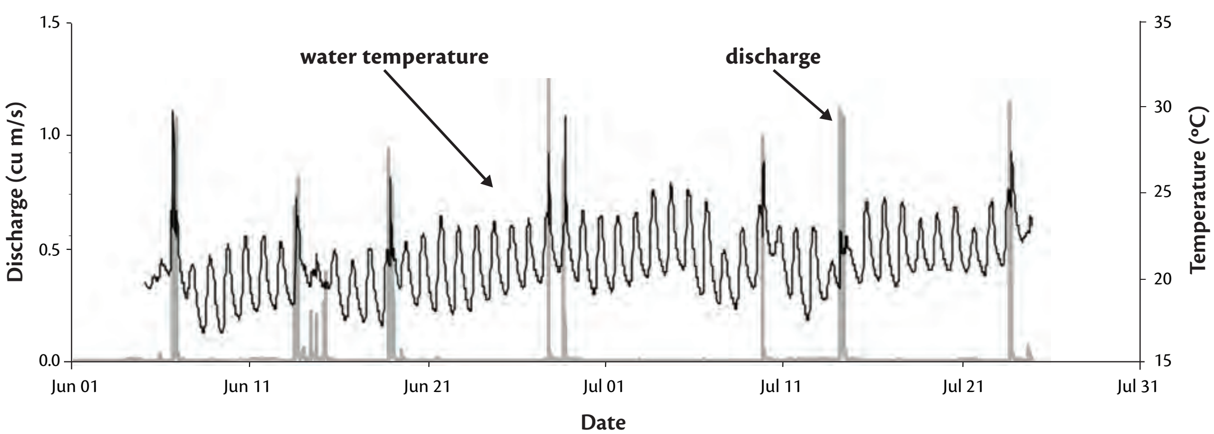


Figure 5.7. Temperature record for an urban stream north of Washington, D.C. Grey spikes represent episodes of warm runoff immediately following rain. Spikes such as these are largely dampened in watersheds with low levels of impervious cover.[50]

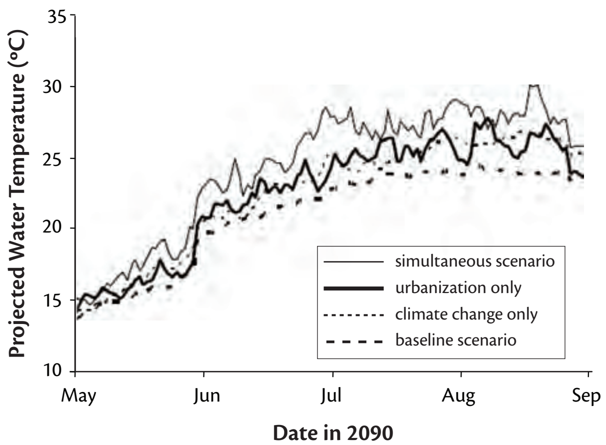


Figure 5.8. Model projections of water temperatures in a central Maryland stream under a moderate emissions (B2) scenario, the influence of urbanization and both simultaneously.[49]

of both wetter and drier conditions are projected under both the higher and lower emissions scenarios. While these changes are anticipated to be incremental, similar but much stronger effects are observed in urbanizing environments. Storm runoff occurs more rapidly and generates higher velocities and larger flood peaks, with serious consequences for the aquatic biota.[51] Higher peak flows associated with urbanization result in well-documented decreases in native biodiversity.[52] Higher flows increase suspended sediment and bedload transport, which interferes with animal feeding, while subsequent sediment deposition reduces the habitat availability for insects and spawning areas for fish.[53] Where flows increase sufficiently to prevent sediment deposition, eroded sediment will ultimately be deposited downstream or in the estuaries fed by the rivers and streams. The higher flows and increased inputs of sediment typically degrade stream habitat quality even when there is no net sediment deposition.

Higher runoff peaks degrade stream beds and transport more pollutants to the Bay

Increased flashiness and higher runoff peaks are likely to mobilize chemicals associated with sediment particles. Changes in the transport and processing of nutrients and organic matter are likely, but difficult to predict under changing climatic conditions. There is a considerable uncertainty about how rates of ecological processes affecting nutrients in wetlands and streams—an important factor in affecting the amount of nutrients reaching the already over-enriched Chesapeake Bay—will be influenced by climate change. Dissolved inorganic nitrogen (as nitrate) levels may decrease if rates of denitrification are increased by higher temperatures and associated lower dissolved oxygen levels. On the other hand, if discharge and sediment transport increase, then the downstream movement of nitrogen (as ammonium or organic nitrogen) and phosphorus (as phosphate) may increase. Concentrations of toxic contaminants in the form of petroleum hydrocarbons and combustion byproducts, metals, pesticides, and other organic compounds are typically much greater in urban settings and are related in part to the density of roads and efficiency of storm sewers in conveying materials from impervious surfaces directly into the drainage network.[54] Additional sources of trace contaminants may be derived from leaking sanitary sewers and include oxygen-demanding organic matter, pathogens, and a whole class of emerging contaminants including pharmaceutical compounds and trace constituents from personal care products.[55]

Drier conditions during summer months are likely to result in the loss of small wetlands and intermittent or ephemeral streams, potentially resulting in negative impacts on the water quality downstream. This impact will be particularly exacerbated in urbanized regions. With increased impervious area and less infiltration, there is less groundwater storage and lower baseflows in urban streams than in more natural streams. However, baseflow during dry periods could also be augmented by some combination of leaking infrastructure and lawn irrigation. A tendency toward reduced infiltration and baseflow would tend to exacerbate the lower summer stream flows projected by the climate models, while any baseflow augmentation would reduce the impacts of summer dry periods. Wetlands and streams experiencing reductions in water levels or baseflow often have stressed biota and stream-side vegetation, reduced dissolved oxygen levels, and loss of habitat for species that depend on currents.[56] Physiological stress and increased predation resulting from crowding, combined with habitat fragmentation (isolated stream pools and wetlands), may dramatically reduce survival and constrain dispersal.

Jane Hawkey

Herbicides are applied to a farm field.

Adrian Jones

Crop production is likely to be reduced under the higher emissions scenario.

Section 6

FARMS & FORESTS

KEY POINTS

- **Crop production may increase initially, but then decline if emissions are not reduced.**
  Longer growing season and higher CO_2 levels are likely to increase crop production modestly during the first half of the century. Later in the century, crop production is likely to be reduced due to heat stress and summer drought under the higher emissions scenario. Milk and poultry production would be also reduced by heat stress.

- **Northern hardwoods will likely disappear and pines become more abundant.**
  The maple-beech-birch forest of Western Maryland is likely to fade away and pine trees to become more dominant in Maryland forests. Forest productivity is likely to decline late in the century under the higher emissions scenario as a result of heat stress, drought, and climate-related disturbances.

- **Biodiversity of plants and animals associated with Maryland forests is likely to decline.**
  Habitat alterations resulting from climate change may force out 34 or more bird species, including the Baltimore oriole.

Maryland's landscapes, from the high mountains of the Appalachian Plateau to the barrier islands of the Eastern Shore, provide diversity and enjoyment to its people and visitors as well economic wealth from the productivity of its farms and forests. This section addresses the potential impacts of climate change on the land, including the living resources that are exploited economically and other natural resources that provide indirect services to us, not the least of which provide recreation and aesthetic satisfaction.

Prediction of the future of Maryland's natural resources is subject not only in the projections of climate model, but also because of the complexity of the responses of both living organisms and human decisions when faced with changing climate. The response of one species can affect others, for example warmer winters could allow some insect pests to survive in greater numbers, possibly increasing forest defoliation—and consequently, a loss of birds and other animal species—and runoff of materials from the watershed. Furthermore, the changes in vegetation may affect the regional climate itself, for example, through changes in the evapotranspiration, albedo (how an object reflects sunlight), and surface roughness of vegetation. Moreover, organisms influence the concentrations of greenhouse gases in the atmosphere by taking up or releasing carbon dioxide, methane, and nitrous oxide. Partially as a result of this complexity, knowledge of the impacts of climate change on terrestrial resources is less developed and predictions more difficult than for other sectors of the climate impact assessment for Maryland.

Climate change is not new for Maryland's terrestrial ecosystems. During the warming after the last Ice Age, very large changes in the biota occurred, but this was a slow warming that allowed migration and adaptation of plants and animals, unlike the rate of climate change projected over the 21st century. As discussed previously, the mean temperature of the Earth's atmosphere has been relatively stable until warming commenced about 50 years ago. After some basic considerations related to terrestrial ecosystems, in general, this section evaluates the likely impacts of projected climate change on Maryland's agriculture and forests.

SOME BASIC CONSIDERATIONS

Before getting to the specifics of the assessment of climate change impacts on Maryland's terrestrial ecosystems, it is useful to consider the complexity of likely responses to climate change, the other human activities that influence these responses, the means of observing changes, and the particular geographic conditions that may influence outcomes.

Responses are complex

Shifts in distribution of terrestrial vegetation of hundreds of miles in eastern North America occurred in association with the 3.6°F increase in global average temperature following the last Ice Age.[57] For example, one tree species, Jack Pine, moved about 800 miles north from the southern U.S. to Canada, passing through Maryland at an average of a quarter of a mile per year.[58] Numerous studies documenting more recent geographical shifts of the distribution of species toward the poles (in Maryland northwards) and toward higher elevation due to climate warming were summarized in the IPCC Fourth Assessment[5] and a recent CCSP synthesis report.[59] A small state such as Maryland can expect a greater proportion of its species to be lost to the north and gained from the south than in a larger state. These changes could be beneficial or deleterious. Not all species can adjust successfully. Biomes (broad geographic zones having distinct climates and species) that shift in a quickly warming world are likely to lose a portion of their species complement.[59] This loss could also disrupt important ecosystem functions if one or more ecologically important species is lost.

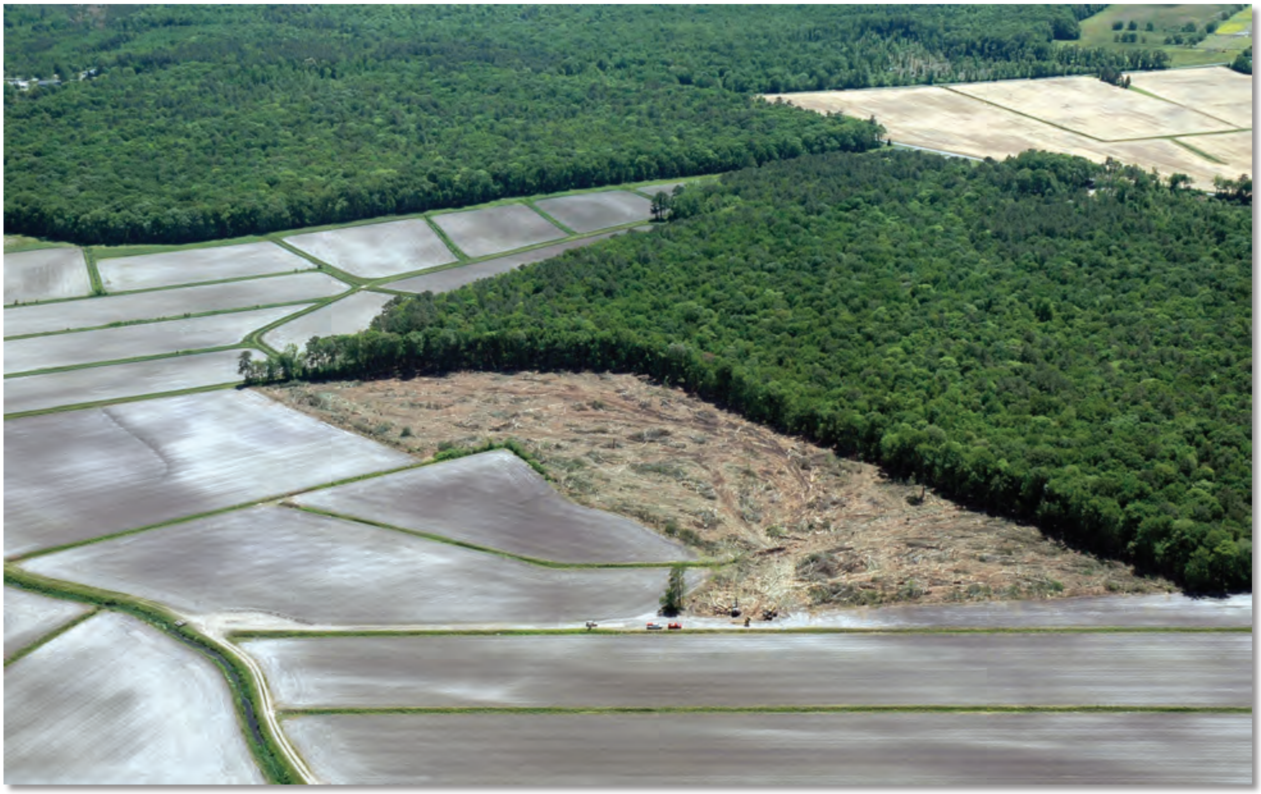
In agriculture and commercial forestry, human skill and knowledge can allow for some adaptation to climate change; for example, by changing crop and plantation tree species, and controlling new pest and diseases artificially. If all else fails, products that can no longer be produced in Maryland economically could be imported from elsewhere. And, other commodities will be produced that are not produced under today's climate. Some impacts on agriculture and forestry may be seen as beneficial and others would require adaptation but at an increased cost.

A significant and already apparent effect of warming on plants is to hasten the beginning of the growing season and prolong it in the fall. But while a shorter winter and earlier arrival of cherry blossoms may be welcomed, overwintering of plant pests that currently are killed by winter cold could also occur. Heat waves and drought can cause mortality directly through increased stress and reduced growth. Forests which grow more rapidly because of the CO_2 fertilization effect—plants require carbon dioxide for photosynthesis and an increase in atmospheric carbon dioxide can increase growth—may become increasingly fire-prone or subject to insect outbreaks. Animals, both livestock and wildlife, are affected directly by climate and indirectly through changes in the frequency and extent of pest outbreaks, spread of invasive species, animal and plant diseases, extreme weather events, and wildfire.

As ecosystems respond to climate changes, there will be not only changes in species found in

Ben Fertig

Wicomico County, Maryland, marshlands and forest share waterway with agriculture and development.



Jane Thomas

Forest cleared for agriculture in one watershed of Maryland's Coastal Bays.

Maryland and in biodiversity, in general, but also in the ecosystem services they provide. Ecosystem services are the benefits to humans that arise from the functioning of ecosystems, but without deliberate action by humans. These include purification of air and water by plants, decomposition of wastes by microbes, soil renewal, pollination of crops, groundwater recharge by wetlands, maintenance of potentially-useful genetic races, removal of greenhouse gases from the atmosphere by carbon sequestration, and provision for recreation in aesthetically pleasing landscapes.

Land use will affect responses

Climate change is taking place in the context of other rapid changes affecting terrestrial ecosystems, agriculture, and forestry. These include continued exurban development, conversion of natural vegetation to farms and pastures, and changes in air and water quality. Many of these factors affect more than one ecosystem or resource simultaneously and interact with each other, often compounding their individual effects.

An important factor in the response of living organisms to current and future warming that did not exist during the post-glacial warming is the extensive fragmentation of natural landscapes by cities, suburbs, farms, highways, and other features. Some species will be slowed in their northward migration by their requirement for specific habitats of suitable size—habitats that, for these species, are now broken into fragments within an impassable matrix of the human landscape. This will favor species capable of "jump dispersal," in which a few individuals can reach new, suitable habitats by occasional transport over long distances by wind and water or hitching a ride on vehicles or birds. Some species, such as weedy plants, are more likely to move by jump dispersal; others such as amphibians are very unlikely to do so. Species with very specific habitat requirements and limited dispersal capability, including many plants, may fail to move and could become, at least locally, extinct.

Observing changes is challenging

Our current capacity to observe meteorological and ecological changes is insufficient to provide early indicators and assess the effects of climate change on Maryland's agriculture, forestry, and terrestrial ecosystems. Meteorological sites on the ground are few in number and limited in the range of measurements they make. The role of these sites in weather forecasting has not been diminished by the development of satellite measurements and computer models; in fact, higher quality observations are required by the models.

Furthermore, ground meteorological stations are irreplaceable for documenting climate variability and change. Studies in other regions have documented changes in the distributions of various plants and animals that are likely the result of recent climate change.[60] Earth resource satellite observations offer a different approach. Satellite data can provide a record of changes in vegetation types and extent, carbon fixation, land cover and human habitation—all essential components of a climate change monitoring and adaptive management system. While satellite measurements have been made over Maryland for over 30 years, the data have not been systematically acquired and archived. The existing record of crop yields by the National Agricultural Statistics Service (from 1961), the Forest Inventory and Analysis program (from 1953), the Maryland Biological Stream Survey (from 2000), the Breeding Bird Survey (from 1966), and Christmas Bird Count (from 1900) all contribute key information in a period of rapid climate change, but they are alone.

A slice of the regional landscape

Maryland is a cross-section of the Mid-Atlantic, from the eastern Atlantic Coastal Plain to the Appalachian Plateau. Altitude varies from sea level to 3,306 ft. There are substantial differences in climate across the state and within microclimates, such as the rain shadows of western mountains and local effects of ocean breezes. Although the global climate models used in this assessment are too coarse in spatial resolution to reveal all of the patterns of change that may be realized, it should not be forgotten that these changes are superimposed on the substantial cross-state and local differences that already exist.

At Hancock, Maryland, the State narrows to less than two miles from its northern boundary with Pennsylvania to its southern boundary with West Virginia and, even at its widest, Maryland is a relatively narrow slice of the eastern United States. The modest area of the State belies the fact that it crosses the full range of physiographic and climatic regimes of the Mid-Atlantic region and is therefore exceptionally diverse with respect to its area. Its small area also means that the species that may take the places of those unable to compete in a changed climate, including pest species, depend on the conditions in bordering states. Thus, Maryland cannot be separated from its context in a continuum of physiography, climate, geology, soils, and biota extending from Maine to Georgia.

AGRICULTURE

Maryland's agricultural commodities account for less than one percent of the value of all U.S. commodities, yet agriculture plays an important role in the economy, social fabric, and landscape diversity of the State. Despite the decline in agricultural lands as a result of urbanization, fully one-third of Maryland's land remains in agricultural land uses. The production of poultry (broilers, turkeys, and eggs) accounts for 36% of the $1.6 billion 2006 value of agricultural commodities, and the corn and soybeans largely grown to feed these birds represents another 17% (Figure 6.1).[61] Horticulture (greenhouse/nursery) accounts for 22% of the value of Maryland's agricultural output, reflecting the State's high population density and demand for landscaping and plants.

Greenhouses and nurseries are second only to broilers in agricultural value

Crop production

Crop species differ in their critical temperature range for growth and development. Growth and development of a particular crop requires temperatures at some minimum temperature, are fastest at some optimal temperature, and slows down and finally ceases at a temperature maximum. Vegetative development usually has a higher optimum temperature than reproductive development. At elevated temperatures, the life cycle of a grain crop will progress more rapidly but may reduce yield owing to the shorter time available to fill the grain. High temperatures can also result in failure in pollination and grain setting. Yield responses to temperature vary among species based

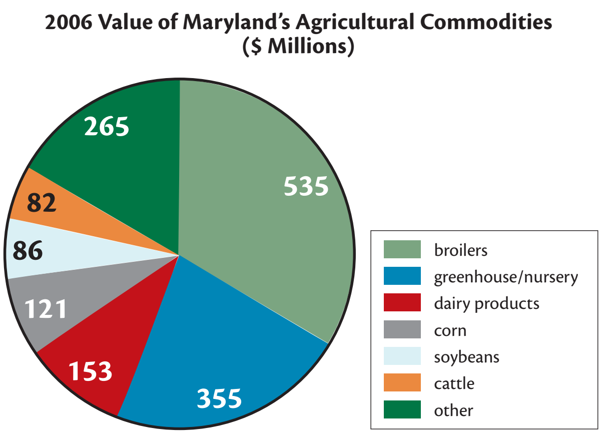


Figure 6.1. The value of Maryland's agricultural commodities in 2006.[61]

A Maryland farm surrounded by forest.

on the crop's temperature requirements. Plants that have an optimum range at cooler temperatures will exhibit significant decreases in yield as the temperature increases above this range. On its own, the projected increase in mean temperature of 2 to 3°F by 2040-2050 could decrease corn and wheat yields by 8-14%[62], but may have little effect on soybean yield.[63] Under the higher emission scenario, toward the end of the century, summer heat stress is likely to be a significant limiting factor in crop production unless there is a transition to new crops or varieties, which may be an expensive proposition for farmers.

Heat stress likely to limit crops under higher emissions scenario

Crop development and yield are also affected by the amount of water available in the soil, which is itself affected by elevated temperature. Furthermore, because evapotranspiration increases with temperature, maintaining soil moisture sufficient for germination, growth and grain setting will be a significant factor in determining the response of crop production to climate change. Despite the mean projection of increased annual precipitation by the climate models, moderate declines in soil moisture are likely to be experienced in summer and fall during the second half of the century under both lower and higher emissions scenarios. Furthermore, rain is likely to be delivered in more intense events, separated by weeks to months with less rain. One has only to recall 2007, a year with relatively high winter and early spring precipitation and a disastrous, weeks-long summer drought as an example of what might occur more frequently. Under these conditions, farmers are likely to increase the use of irrigation—currently, just over 5% of Maryland's crop lands are irrigated—compounding the aquifer drawdown already taking place in some parts of the state (Section 5).

Plant growth is also dependent on the availability of the carbon dioxide required for photosynthesis. Plants respond differently to elevated carbon dioxide concentrations. Cold-season and broad-leaved weeds and cold-season grain crops, including wheat and barley, respond most dramatically to increased carbon dioxide. An increase of carbon dioxide concentrations to 550 ppm could increase the yield of these plants by 10-20%[5], mainly through increased grain production rather than grain size. Corn and many summer weed grasses respond less dramatically to carbon dioxide enrichment, with corn yields increasing less than 10% given the same increase in carbon dioxide.[64] However, high temperature stress during reproductive stages can negate the overall carbon dioxide effects on yield even though total plant biomass may increase and attaining even these modest productivity increases requires more fertilizer, unrestricted root growth, and effective control of weeds, insects and disease.[7]

Under the higher and lower emissions scenarios, atmospheric carbon dioxide concentrations would increase late in the century to 940 ppm and 550 ppm, respectively. By mid-century a modest (5 to 9%) increase in crop yield, except for corn, might be experienced as a result of fertilization.[65] However, under the higher emissions scenario this effect would diminish as concentrations exceed 600-800 ppm. Deficiencies in soil moisture could further limit yield and require increased irrigation.

While carbon dioxide enrichment can stimulate the production of leafy vegetables such as lettuce, spinach or radish, their greater leaf area increases their water requirement during the warmest and driest part of the growing season. Some moderation of this effect may be caused by a decrease in plant evapotranspiration as the stomata on the leaves constrict under higher carbon dioxide concentrations, leading to a reduction in water loss and increase in crop yield. This effect, however, is very likely to be small in comparison to the effects of temperature and carbon dioxide fertilization.

Wheat and barley grain and potato tubers contain 10 to 15% less protein when grown under carbon dioxide concentrations of 540 to 958 ppm, diminishing their nutritional value and performance in food processing, for example, producing sufficient gluten for making bread).[66] This effect can be counteracted by providing the plants more nitrogen, but in Maryland that would require more fertilizer, compounding the nutrient pollution problem in the Chesapeake Bay (see Section 8).

Ground level ozone is created on warm days by the reaction of sunlight with nitrogen oxides (NOx) and volatile organic carbon (VOC) compounds, present because of air pollution. Despite efforts to reduce this pollution, Maryland experiences some of the highest ozone in the country. As discussed in more depth in Section 8, warmer temperatures from global warming threatens to increase the concentrations of ground-level ozone and the frequency of high-ozone events. In addition to its effects on human health, ozone is toxic to many plants and particularly to crops such as soybean and wheat. Even mild chronic exposure (40-60 ppb) decreases yield in soybean.[67] However, these effects may be moderated by the reduction in the apertures of plant stomata under elevated carbon dioxide. While the net effects on crop production may be relatively small during the first half of this century, if the pollutant loads of NOx and VOC are not substantially reduced, the added stress of ozone together with heat stress and desiccation are likely to lead to declines in crop production during the second half of the century.

Crop production is affected by competition with weeds. Because the geographic range of many weed species is determined by temperature, climate warming is very likely to lead to a northern shift in the distribution of some economically significant weed species.[68] These include witchweed, cogongrass, and itchgrass that at present are found south of Maryland and the proliferation of invasive kudzu that is already here.[7] On the other hand, some current weed species may become less of a problem. On-going studies in Maryland are showing that weeds grow much faster under higher temperatures and carbon dioxide concentrations likely to be experienced in the next 30 to 50 years—these conditions simulated by experiments conducted in Baltimore.[69] The growth of many weed species is stimulated more by carbon dioxide enrichment than are the cash crops they invade, presenting an additional challenge for weed control.[69]

Weeds thrive under high temperature and CO_2

Beneficial and harmful insects, microbes, and other organisms present in agricultural ecosystems will also respond to climate change. Numerous studies have shown changes in spring arrival, over-wintering, and/or geographic range of several insect and animal species due to climate change.[5] Diseases caused by leaf and root pathogens may increase in Maryland if increases in humidity and frequency of heavy rainfall events occur, but will decrease if more frequent droughts occur.

Animal production

For optimum production, livestock require temperatures that do not significantly alter their behavioral or physiological functions needed to

Baltimore Sun

An increase in droughts may reduce reservoir water levels.

maintain a relatively constant body temperature. As their core body temperatures move outside normal boundaries, animals must begin to conserve or dissipate heat. This reduces the energy available for growth or the production of products such as milk, and ultimately affects reproduction. The onset of heat stress often results in declines in physical activity and eating or grazing. Hormonal changes, triggered by environmental stress, result in changes in cardiac output, blood flow to extremities, and digestion rates.[70] Adverse environmental stress can elicit a panting or shivering response, which increases the baseline energy requirements of the animal and contributes to decreases in productivity. The temperature thresholds of these responses depend on the species in question and the animal's genetics, temperment, and health.

Heat stress could affect milk production late in the century

The most important forms of animal production in Maryland are poultry (broilers), comprising 36% of all agricultural cash receipts, and dairy production, comprising over 11% (Figure 6.1). There are no quantitative assessments of the impacts of climate change on poultry production in this State, however housing large numbers of birds with a high metabolism in close quarters already makes them susceptible to heat stress during hot summers, when large numbers of birds can die. To reduce the chance of death requires costly insulation and ventilation of growing sheds. The temperature projections after mid-century, particularly under the higher emissions scenario, will pose a much more serious problem of heat stress on confined poultry production.

The Northeast Climate Impacts Assessment projected little increase in heat stress on dairy cattle and no significant heat-related reductions in milk production for the next several decades. However, under a higher emissions scenario generally similar to the one used here, by mid-century New Jersey and southern Pennsylvania were projected to experience moderate heat stress in July and declines of milk production of up to 12%. By late century, the declines are projected to be 10% under the lower emissions scenario and 15-20% under the higher emissions scenario. Similar or greater declines in dairy production are likely in Maryland.

To maintain levels of production under climate change, livestock producers will select breeds that are genetically adapted to the new, warmer climate. However, breeds that are more heat tolerant are generally less productive.

Climate change is also likely to affect the parasites, pathogens, and disease vectors that affect domesticated animals. Similar effects on pest migration and over-wintering as discussed for cropping systems are likely to be observed for some livestock parasites and pathogens. Also, accelerated development of pathogens and parasites due to the earlier spring and warmer winters is likely.

Warming and associated variation in weather patterns will likely result in more livestock being managed in climate-controlled facilities, even in a more energy-constrained world. Furthermore, agriculture, in general, and the animal production industry, in particular, will surely be under pressure to reduce its greenhouse gas emissions, particularly of methane and nitrous oxide.[71] This could incur additional costs to production, thereby affecting profitability and hence the nature of the agricultural industry in Maryland.

Summary of impacts on agriculture

In summary, agriculture in mid-latitude regions

Tom Hollyman

Increased temperatures can cause heat stress in chickens.

www.cornucopia.org

Heat stress can cause a decline in milk production.

such as Maryland may experience moderate warming benefits in the form of crop and pasture yields under moderate increases in temperature (2-5°F) and increases in atmospheric carbon dioxide and rainfall. However, increased risks of drought in summer and early fall and unknown changes in weed and pest damages will generate uncertainty among farmers and animal producers regarding adaptation to climate change. The warming in the lower emissions scenario during the latter part of this century is projected to have increasingly negative impacts as it approaches or passes the upper end of optimum ranges of different crop and animal species if the higher emissions scenario proves more accurate (Figure 4.3). Therefore, without mitigation of greenhouse gas emissions, the changing climate is likely to pose serious problems for Maryland agriculture resulting from heat stress and summer-fall drought that might increase groundwater demand for crop irrigation.

FORESTS

Although Maryland accounts for only 0.3% of the nation's softwood production and 1.6% of its hardwood production, the forest products industry is economically important in parts of the State, resulting in product output worth $262 million. Paper products account for 60% of that total. Forest products industries employed 9,326 in 2006 and generated $0.4 million in State tax receipts.

Climate change and forest productivity

Forest productivity in the United States has generally been increasing slightly since the middle of the 20th century[72], although there is no assessment specifically for Maryland forests. Forested area has increased dramatically from a minimum at the beginning of the 20th century as areas of the eastern U.S. that had been cleared for agriculture and other purposes have been reclaimed by forests. The potential causes of the increase in productivity include increases in temperature, atmospheric carbon dioxide and nitrogen deposition, but these are difficult to isolate. Temperature, water, and solar radiation are the primary climatic factors that affect forest productivity. Increased precipitation, higher temperature, and a longer growing season will increase productivity where those factors are currently limiting. Consequently, a modest increase in forest yields and regrowth is likely. During the latter part of the century under the higher emissions scenario, however, heat stress and the greater likelihood of summer-fall drought could obviate gains in forest productivity due to global warming earlier in the century. If forest species, such as loblolly pine, currently found farther south, migrate into Maryland or are planted and replace existing species, this could at least partially compensate for some of the lost productivity

Large departures from typical conditions and extreme events, such as late frosts, drought, and wind storms, can damage or kill trees. The occurrence and severity of such extreme events associated with climate change are projected to increase. These indirect effects of climate on factors such as wildfires and insect outbreaks are likely to contribute to reduction of forest production. The interaction of climate change and these factors could create unprecedented conditions, the effects of which are very difficult to predict. Forests can take decades to re-establish after disturbances are caused by fire, insect outbreaks, and wind and ice storms. These effects are likely to become more important than the direct effects of climate itself in shaping future forest ecosystem structure and functioning. All of these changes will be influenced by the legacy of the logging in the 19th and 20th centuries and the more recent period of fire suppression that has led to dominance by an even-aged community of trees now reaching old age.

Modest increase in forest yields likely early in the century

Carbon dioxide fertilization

As discussed under agriculture, the projected increases in atmospheric carbon dioxide concentration are likely to increase forest growth due to a fertilization effect, but this will depend greatly on the type of forest and its environmental

NPS

Fall colors illuminate a mountain forest.

conditions. The response of tree growth to elevated CO_2 also depends on the age of the trees; younger trees respond more strongly than older ones.[5] Maryland forests will likely absorb more CO_2 and retain more carbon in wood and soils as atmospheric CO_2 increases, but this will depend on the specifics of how climate changes and on such factors as the age of the forest and the degree of fertilization by nitrogen deposition. These factors are highly relevant when devising strategies to increase forest carbon sequestration for mitigation plans.

Atmospheric pollution

Forest growth and dynamics are affected by air pollution in two important ways: the toxic effects of ozone created by emissions of NOx and VOCs from power plants and vehicles, and the stimulatory effects of nitrogen deposited as a result of these NOx emissions. Nitrogen deposition in the eastern U.S. can exceed 10 kg of nitrogen per hectare (or 9 lbs per acre) per year and has increased 10 to 20 times above pre-industrial levels.[73] Although nitrogen deposition has declined recently in Maryland as result of air pollution controls[74], future emissions are uncertain. Forests are generally limited by nitrogen availability and increased deposition will enhance forest growth. However, if it increases too much, it can have negative effects on forests and on aquatic ecosystems that receive runoff from the forests. The interactions of elevated CO_2, temperature, precipitation, ozone pollution, and nitrogen deposition are likely to be important in determining forest growth and species composition, but the net result of these factors and their interactions is poorly understood. Continued nitrogen deposition on forests can have the result of stimulating the degradation of organic matter in soils by microbes, thus reducing any carbon sequestration resulting from faster growth in a CO_2-enriched world.

Combined effects of temperature, ozone, CO_2, and nitrogen deposition are difficult to predict

Insect outbreaks

Outbreaks of forest insects and diseases affect forest composition and production, leading to altered cycles of matter and energy, and changes in biodiversity and ecosystem services. Damage to Maryland forests caused by outbreaks of defoliating insects and other pests cost several million dollars per year.[75] Weather plays an important role in influencing outbreaks of serious forest insect pests, including the gypsy moth, southern pine beetle, hemlock woolly adelgid, spruce budworm, and western spruce budworm. Temperature affects the rate of insect life-cycle development rates, the synchronization of mass attacks that overcome tree defenses, and insect winter mortality rates. Climate also affects the insects indirectly through effects on the host trees. Drought stress, resulting from decreased precipitation and warming, reduces the trees' ability to resist insect attack.

Outbreaks and expansion of some non-native insect species, such as the hemlock woolly adelgid (Box 6.1), are known to be influenced by climate. The introduced gypsy moth has defoliated millions of acres of Maryland forests. Projections indicate that Maryland's changing climate is likely to increase the frequency and severity of gypsy moth outbreaks in the future.[76] Longer growing seasons and higher carbon dioxide concentrations might allow forests to recover more quickly after such disturbances. But defoliation disturbances affect carbon uptake, nutrient cycling, and stream hydrology, resulting in the loss of nitrogen from the forest where it is needed, to the Chesapeake Bay where it is harmful.[77]

Joanna Woerner

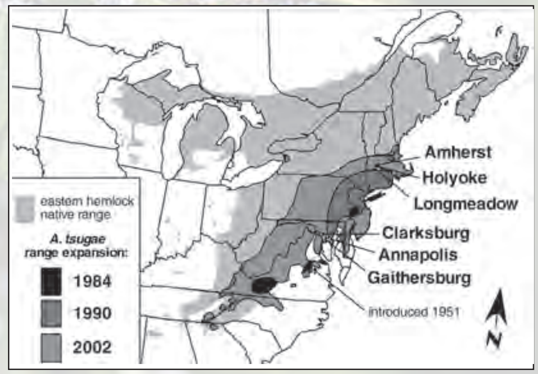
Industrial emissions.

NPS

Hemlock forest, ravaged by insect pests.

BOX 6.1 THE EASTERN HEMLOCK & WOOLLY ADELGID

The hemlock woolly adelgid, an aphid-like insect native to Asia, was first recorded in 1951 in Virginia, and has since spread, causing a severe decline in vitality and survival of eastern hemlock in North American forests (Box Figure 6.1). Once it arrives at a site, complete hemlock mortality is just a matter of time and damaged hemlock stands are replaced by black birch, black oaks, and other hardwoods. While plant biodiversity increases in the canopy and understory, several bird species, including the blue-headed vireo and Blackburnian warbler, have a high affinity for hemlock forests and are at risk as a result of adelgid expansion. Also, changes in the forest canopy affect hydrology and nutrient cycling, resulting in longer periods of dry streams, which, in turn, reduce the abundance of brook trout, brown trout and other fish. Low winter temperatures presently check the spread of the hemlock woolly adelgid, but increasing temperatures and the capacity of the adelgid to develop greater resistance to cold shock indicates that more hemlock forests will succumb in future years.



Box Figure 6.1. Expansion of the range of the hemlock woolly adelgid (*Adelges tsuagae*) with regard to the range of the eastern hemlock.[59]

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Species composition

As the changing climate after the last Ice Age resulted in the northward shift in the distribution of tree species in eastern North America, 21st century warming will very likely result in the northward sift in the range of trees and forest types currently that exists in Maryland. Trees that need cold winter conditions (for example, sugar maples) or are susceptible to diseases or pests under warmer conditions will retreat northward, possibly replaced by species currently found south of Maryland. Plant hardiness zones for horticultural plants have recently been revised to take account of the changes in the potential ranges of garden plants that have already taken place (Figure 6.2).

By relating the preferred environmental conditions of various forest types to current temperature and precipitation, it has been possible

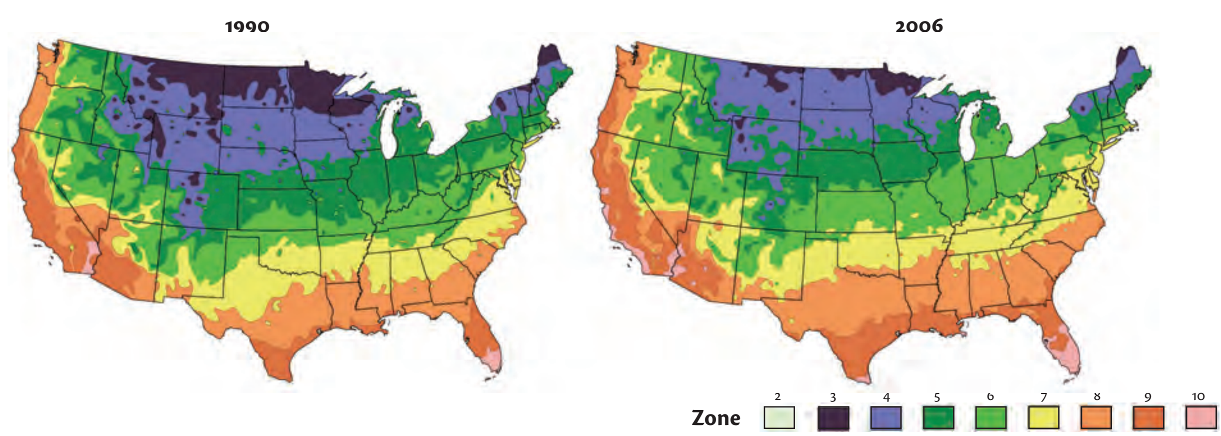


Figure 6.2. U.S. Department of Agriculture plant hardiness zones for 1990 compared to those delimited by the National Arbor Day Foundation's for 2006.

to estimate future ranges as climate changes in eastern North America.[55] Under a doubling of CO_2 concentrations—likely to be experienced in the latter half of the century under the low-emissions scenario—the maple-beech-birch forests of Allegany and Garrett counties are likely to disappear, replaced by oak-hickory forests. The oak-hickory forest type that presently characterizes most of the Piedmont and Coastal Plain west of the Chesapeake is likely to transition to an oak-pine forest.

The NECIA concluded that the region's species would shift northward by as much as 350 miles by the late-century under the lower emissions scenario, and as much as 500 miles under its higher emissions scenario. The NECIA projected that the maple-beech-birch forests that presently characterize most of Pennsylvania would move to northern Pennsylvania, and thus out of Western Maryland, under the lower emissions scenario and retreat to Upstate New York under its higher emissions scenario. In general, then, one would expect that by late-century, Maryland forests would look much like those in eastern Virginia and North Carolina do today, with many more pines.

Maple-beech-birch forests are likely to be eliminated from Western Maryland

Forest ecosystems

Forests provide many other benefits beyond the lumber and fiber. These ecosystem services, including watershed protection, water quality, flow regulation, wildlife habitat and diversity, climate regulation, carbon storage, air quality, recreational opportunities, and aesthetic fulfillment, are important for the well-being of Marylanders. The market values of few of these ecosystem services have been quantified, but they are nonetheless essential and irreplaceable. All of these services are subject to the direct and indirect effects of climate change as forest productivity and composition changes and disturbance by heat stress, seasonal drought, severe storms, fire, disease, and pest outbreaks increase.

The biodiversity of forest plants, animals, and microbes is also likely to be affected in ways that are difficult to predict let alone quantify.[78] Biodiversity is already being affected at the landscape, species, and genetic levels by a variety of human activities, including habitat loss and fragmentation, invasive species, and air pollution.[79] Climate change poses yet another stress that is likely to reduce biodiversity.[80]

Climate changes have been shown to affect the timing of critical processes of growth and reproduction (for example, flowering and fruiting) in thousands of plant and animal species around the world.[5,81] These changes can disrupt previously synchronized relationships among species (for example, pollination, prey availability for predators, and food sources for migrant birds). The reduction in population sizes caused by these adverse effects sets the stage for local or global extinctions of species.[82] The American Bird Conservancy estimated that habitat alterations due to climate change may force out 34 or more bird species from Maryland.

The most emblematic of birds that may no longer breed in Maryland because of the unsuitability of habitats is the state bird, the Baltimore oriole. The NECIA also projected that various migratory bird species with northerly or high altitude distributions, including the American goldfinch, purple finch, rose-breasted grosbeak, and black-capped chickadee would experience declines in abundance in the Northeast, while the tufted titmouse, northern cardinal, and indigo bunting have the potential to increase in both range and incidence.[7]

Summary of impacts on forests

Maryland forests are likely to experience a modest increase in productivity over the first half of the century as a result of longer growing seasons and elevated atmospheric carbon dioxide concentrations. Later in the century, the composition of Maryland forests is likely to undergo pronounced changes as the maple-beech-birch forests of Western Maryland begin to disappear and pine trees become more prominent in oak-hickory forests of central Maryland. Also, later in the century, heat stress, seasonal droughts, and outbreaks of pests and diseases are likely to diminish forest productivity,

University of Texas

Maryland's state bird, the Baltimore oriole.

particularly under the higher-emissions scenario. This could result in impairment of important ecosystem services that forests provide, including carbon sequestration, control of the water cycle, and maintenance of biodiversity. The extent to which and rate at which other tree species from the south would replace the current species and the services the present forests provide cannot be readily predicted.

NPS

Maryland forests provide many resources as well as recreational opportunities.

Section 7

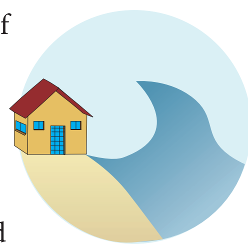
COASTAL VULNERABILITY FROM SEA-LEVEL RISE & STORMS

KEY POINTS

- **Sea level in Maryland rose by 1 foot in the 20th century, partially because the land is sinking.**
  Coastal regions of Maryland have been sinking at about a rate of 6 inches per century and this should continue. Additionally, the average level of the sea in this region rose by about the same amount. As a result, Maryland has experienced considerable shoreline erosion and deterioration of coastal wetlands.

- **Sea-level rise is very likely to accelerate, inundating hundreds of square miles of wetlands and land.**
  Projections, that include accelerating melting of ice, extend to more than 1 foot by mid-century and 3 feet by late century. If the highest rates are realized under the higher emissions scenario, most tidal wetlands would be lost, about 200 square miles of land would be inundated, and an even greater sea-level rise would occur in subsequent centuries.

- **Rains and winds from hurricanes are likely to increase, but their frequency cannot be predicted.**
  The destructive potential of Atlantic tropical storms and hurricanes has increased since 1970 in association with warming sea surface temperatures. This trend is likely to continue as ocean waters warm. Whether Maryland will be confronted with more frequent or powerful storms depends on storm tracks that cannot yet be predicted.



Mention effects of climate change in Maryland and most people would think first of the threat of coastal inundation due to sea-level rise and the increased risks of storm damage. The record storm surge flooding associated with the passage of Hurricane Isabel in 2003 is still fresh in the minds of Marylanders. With its 3,100 miles of tidal shoreline and extensive low-lying lands, especially on the Eastern Shore, Maryland's coastal zone is particularly vulnerable to climate change. Indeed, the central charge to the Adaptation and Response Working Group of the Commission on Climate Change is to "recommend strategies for reducing the vulnerability of the State's coastal, natural, and cultural resources and communities to the impacts of climate change, with an initial focus on sea-level rise and coastal hazards (e.g., shore erosion, coastal flooding)." The Commission is thus tasked with developing appropriate guidance to assist the State and local governments with identifying specific measures (e.g., local land use regulations and ordinances) to adapt to sea-level rise and increasing coastal hazards.

This section explores what we know about sea-level rise in Maryland and the Chesapeake Bay region, and applies the latest models and scientific results that provide insights into the sea-level rise that may be experienced during the present century and beyond. Projections are made for the higher and lower emission scenarios as has been done for temperature and precipitation in Section 3. The section further explores current scientific knowledge of the likely consequences of global warming for extratropical storms, such as Nor'easters, and the tropical cyclones that we know as hurricanes. The potential impacts on tidal wetlands, coastal lands and development, and storm surges are then evaluated.

SEAS RISING OR LAND SINKING?

As mentioned in Section 1, sea level rose rapidly as glaciers melted after the peak of the last Ice Age 20,000 years ago. At that time, the Atlantic shoreline was near the edge of the continental shelf, more than 80 miles off Ocean City, and the rivers ran across the present shelf to the sea. By 8,000 years ago, sea level had risen to the point of flooding the lower Susquehanna River valley, creating a tidal estuary, the nascent Chesapeake Bay (Figure 7.1).[83] The rate of sea-level rise during this period of rapid melting of glaciers was about 16 mm/year. (Throughout this discussion, metric units are used for annual rates to facilitate presentation and calculation, but rates over longer periods are converted to feet for ease in comprehension.) By 5,000 years ago, the rise of the ocean virtually ceased, but the Bay continued to deepen and expand, filling the lower valleys of the Potomac, Patuxent, Patapsco, Choptank, and other rivers. This was because the land was sinking as the bulging of the Earth's surface, resulting from the tremendous burden on the crust by the very thick glaciers that occupied what is now Hudson Bay and Quebec, subsided. This rate of subsidence was relatively rapid initially, but continues to this day as a slow-motion rebounding of an event that peaked 20,000 years ago.

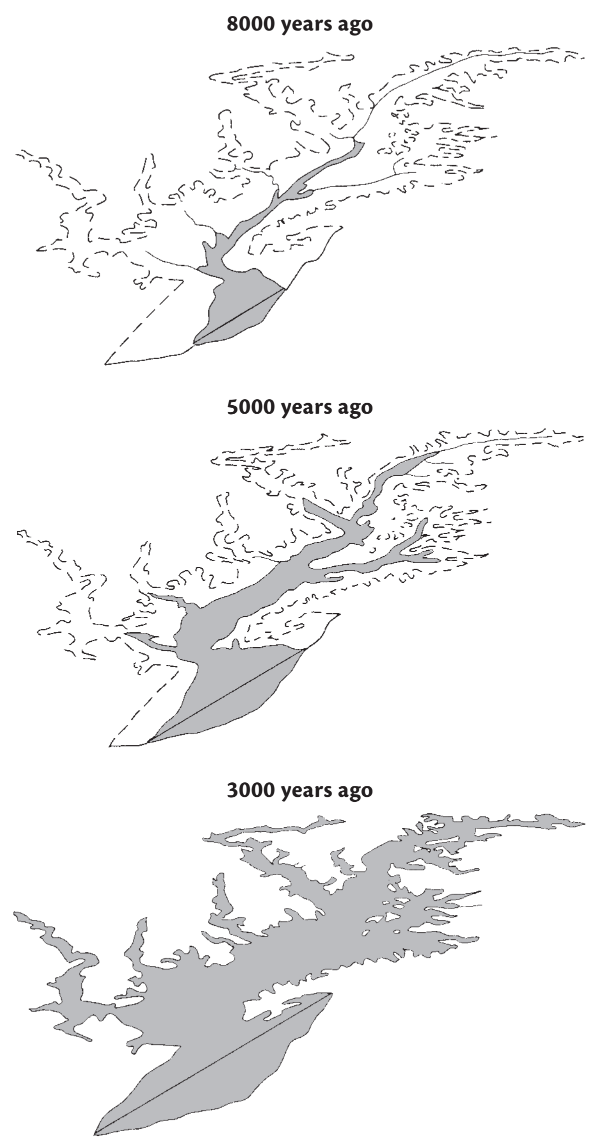


Figure 7.1. The rising ocean began to fill river valleys 8,000 years ago creating the general configuration of the Chesapeake Bay by 3,000 years ago.[83]

Because different coastlines around the world are sinking at different rates—or actively rising in some previously glaciated or geologically active regions —sea-level rise experienced at specific places will differ, even with a comparable rising of the level of the ocean itself. It is, then, appropriate to refer to "relative sea-level rise"—the water level relative to the land at that place. This is typically estimated by tide gauges that have long been fixed in place. The tide gauge record for Baltimore, which is one of the nation's longest, shows that the water levels there are highly variable as a result of weather events, strong seasonal variations, and longer oscillations in the North Atlantic Basin. On the average, however, relative sea level increased approximately one foot over the 20th century (Figure 7.2). Note, however, that for the first 30 years of the record the rate of relative sea-level rise was slower, with a disproportionate part of the rise in the mean level coming since 1930.

Sea level at Baltimore rose by 1 foot during the 20th century, mostly since 1930

Analysis of many such tide gauge records from around the world, including those from more geologically stable locations, allowed the IPCC to conclude that the global mean sea-level rise, once the effects of land subsidence or emergence are removed, was approximately 1.8 mm/year between 1961 and 1993.[2] Relative sea level at Baltimore rose at a rate of about 3.5 mm/year, indicating the local rate of subsidence was 1.7 mm/year or roughly half a foot per century. The effects of regional land subsidence on relative sea-level rise is apparent

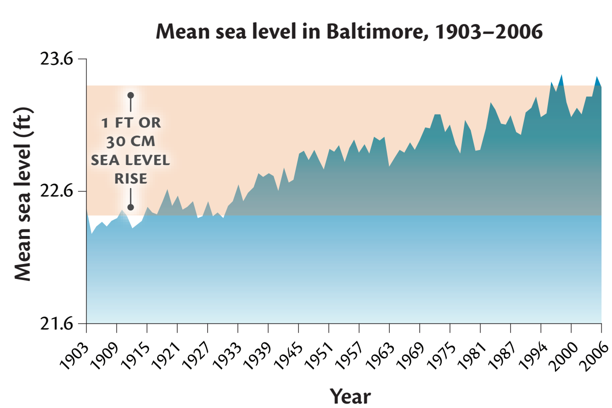
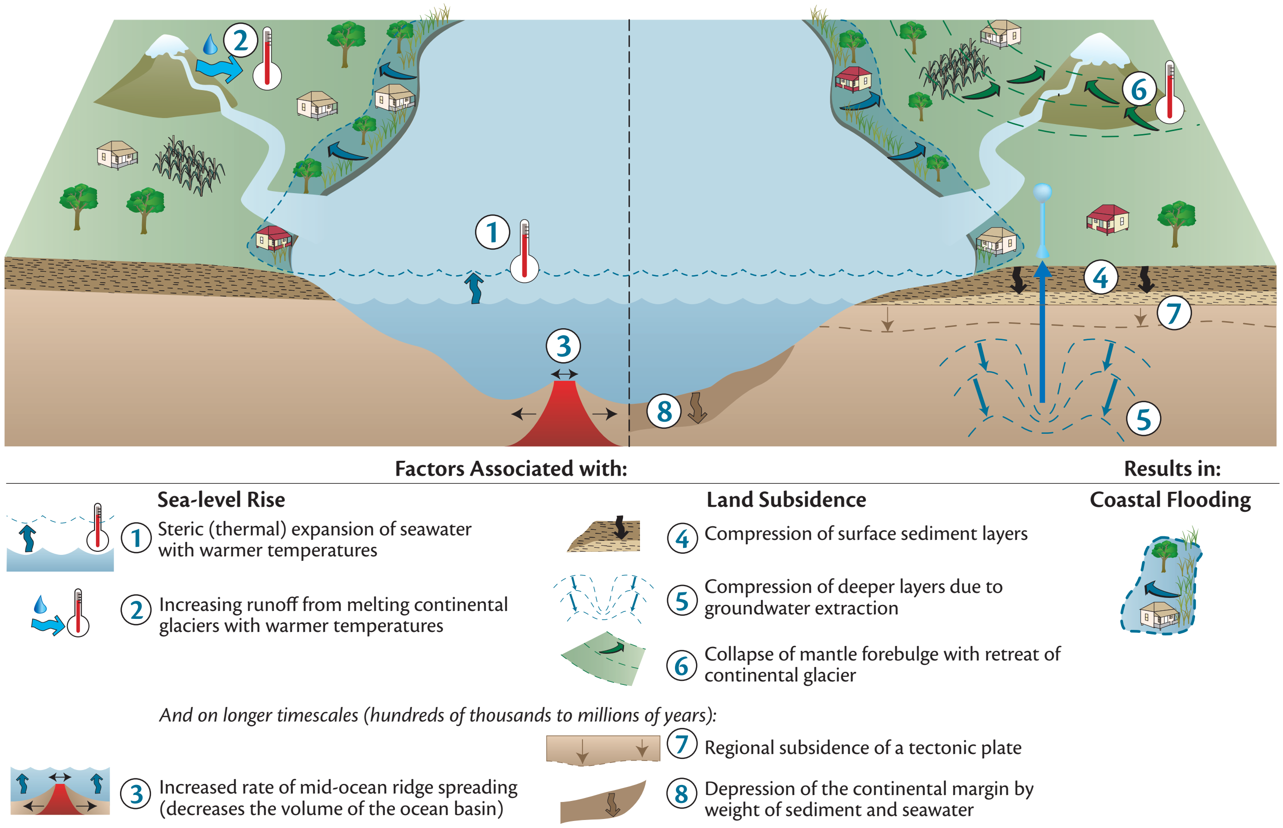


Figure 7.2. Tide gauge record for Baltimore.

Relative Sea-level Rise is a Combination of Sea-level Rise and Land Subsidence



by comparing tide gauge observations along the Atlantic coast (Figure 7.3).[84] Glaciated areas to the north experienced less relative sea-level rise than those located in the glacial forebulge region that are still subsiding. This subsidence (reflected by the difference between relative sea-level rise and the global mean) diminishes to the south of the Chesapeake Bay region. Note, however, that subsidence rates vary within the Bay region, with Hampton Roads (Norfolk) experiencing a relative sea-level rise of 4.2 mm/year. This is likely the result of groundwater extraction from permeable rock or sediments, which can cause localized subsidence of the ground surface. Similar localized areas of greater subsidence resulting from large groundwater withdrawal may exist around Solomons and Cambridge, Maryland. However, for the Chesapeake Bay as a whole, the relative sea-level rise of about one foot during the 20th century resulted from near equal parts of subsidence and global sea-level rise. And, there is no reason to expect that the regional forebulge subsidence, which is in the process of adjusting over thousands of years, will be different than what was observed over the past century.

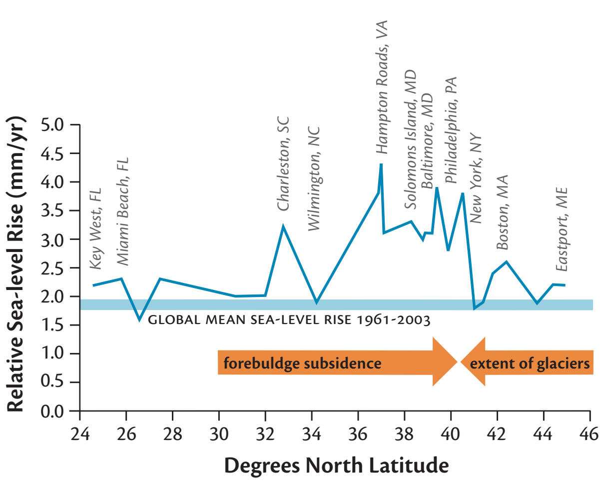


Figure 7.3. Relative sea level rise during the later 20th century along the U.S. Atlantic coast compared to the global mean sea level rise during 1961-2003 (band represents the confidence limits around the mean).[2]

GLOBAL SEA-LEVEL RISE

The limited records available indicate that global sea level, adjusted for land movements, was nearly stable during the 19th century but began to increase around the turn of the century and then accelerate from the 1930s onward (Figure 7.4). Based on tide gauge data, the mean rate of sea-level rise was estimated by the IPCC to have been 1.8 mm/year between 1961-2003.[2] Since late 1992, there have been satellites deployed with the capability of very accurately measuring their altitude over the ocean's surface. Large numbers of measurements can be averaged over a 10-day period to develop precise maps of the surface of the ocean. Based on analysis changes in the ocean's elevation between 1993 and 2003, the IPCC noted a global average of 3.1 mm/ year (black line in Figure 7.4), although the level of various regions of the ocean changed at different rates. While the degree to which the differences with sea-level rise estimates derived from tide gauges represent methodological differences or an actual acceleration of the rate of global sea-level rise has not been fully resolved, such an acceleration is consistent with the observed warming of the ocean surface and melting of glaciers, both of which expand the ocean's volume (Figure 7.5).

Sea-level rise during the recent past is caused primarily by expansion of the volume of the warming ocean and, secondly, by the observed melting of glaciers and ice caps. The melting of the massive polar ice sheets on Greenland and western Antarctica were only a small component of sea-level rise, although the contribution of Greenland seems to be growing. It is unlikely that the total melting of the Greenland Ice Sheet would occur this century and produce the kind of 25-foot inundations seen in popular dramatizations of sea-level rise, although this could happen sometime in the future.

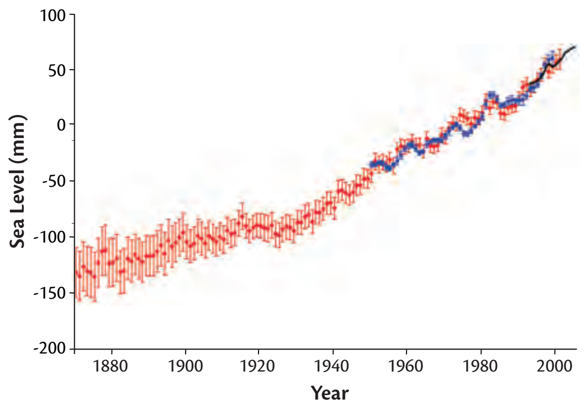


Figure 7.4. IPCC compilation of global data since 1870 shows acceleration of sea level rise during the 20th century.[2] The blue curve shows coastal tide gauge measurements since 1950 and the black curve is based on satellite altimetry.

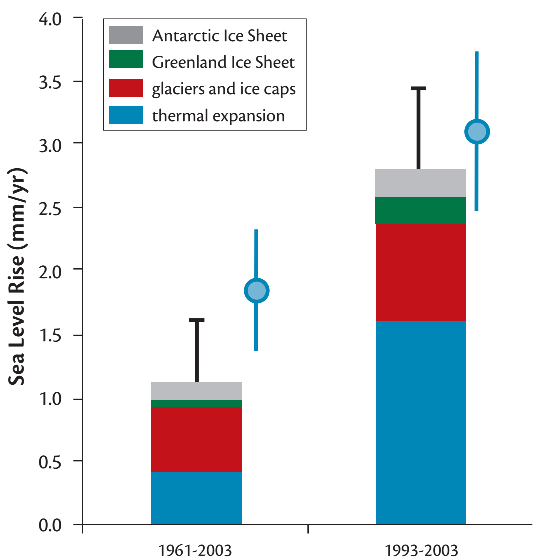


Figure 7.5. The IPCC attempted to estimate the factors responsible for increasing the ocean's volume, including thermal expansion and melting of glaciers and polar ice sheets.[2] These are compared with the global mean (dot) and range of observed sea-level rise. These estimates come closer to explaining the higher rates of sea level rise based on satellite observations during 1993-2003.

FUTURE SEA-LEVEL RISE

How much sea-level rise will Maryland experience over the coming century in a warming climate? The IPCC projected that global sea level would rise by 7 to 15 inches under the lower emissions (B1) scenario and 9 to 20 inches under the higher emissions (A2) scenario, although the IPCC specifically stated that these projections cannot "provide a best estimate or an upper bound for sea-level rise."[2] Adding to those projections the expectation that land subsidence in coastal Maryland would continue at the rate observed during the 20th century yields the relative sea-level rise projections labeled as IPCC projections in Figure 7.6. These projections suggest that Maryland would experience a rise in sea level ranging from just slightly more than the one foot experienced during the past century to more than twice that amount. However, the IPCC sea-level rise projections have been widely criticized as too conservative because they do not account for rapid changes in ice flow that could be experienced.

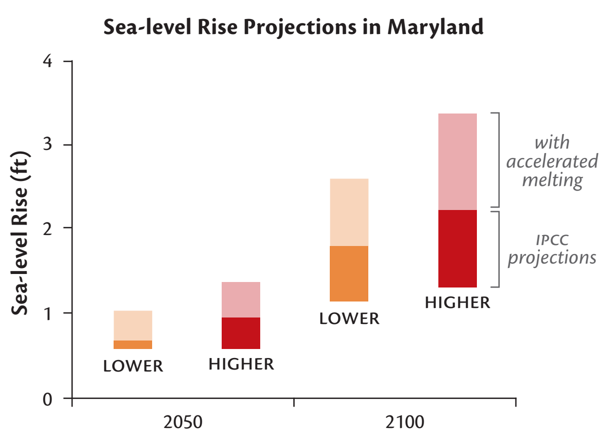


Figure 7.6. Projected relative sea level rise in Maryland during the 21st century under the higher and lower emissions scenarios.

The IPCC readily admitted that such effects were excluded because these ice flow dynamics could not reliably be modeled when its Fourth Assessment was being prepared and cautioned that sea-level rise could be higher as a result.

The melting of ice floating on the sea has no effect on sea level, much as ice cubes melting in a glass do not cause the glass to overflow. But, how much higher could sea-level rise if losses of ice that rests on land accelerate? This was estimated by examining three scientific reports appearing since the publication of the IPCC Fourth Assessment. They projected potential 21st century sea-level rise using three different methods. One used a statistical approach relating sea-level rise to observed temperature increase[85]; another assumed that the continuation of the rate of recently observed acceleration of ice loss, primarily from glaciers and ice sheets[86]; and a third estimated an upper limit of ice sheet contribution during the 21st century in projecting sea-level rise in the state of Washington.[87] The statistical model projected a mean increase of 34 inches in global sea level under the higher emissions (A2) scenario, compared to the IPCC projection of 9 to 20 inches. A word of caution, though, in that the statistical range of possibilities extended to 47 inches in the range of scenarios tested. Remarkably, the other two studies produced estimates of accelerated melting that, when added to the IPCC projections, resulted in very similar global sea-level rise at the end of the century under the higher emissions scenario. When coastal Maryland subsidence rates are taken into account, the additional relative sea-level rise based on the assumptions of these studies is represented in Figure 7.6 by the lighter-colored extensions above the darker-colored boxes that represent the IPCC projections. This suggests a sea-level increase of as little as 0.6 feet (probably unlikely because this is scarcely above the 20th century rate) to much as 1.3 feet could be experienced along the Maryland's coast by the middle of the century. By the end of the century, accelerated melting could produce a relative sea-level rise from 2.7 feet under the lower emissions scenario to 3.4 feet under the higher emissions scenario.

Accelerated ice melting could result in 3 feet of sea-level rise if emissions continue to increase

These adjusted estimates based on the IPCC projections should not be considered as model forecasts, but as reasonable bases for assessment and

Jane Thomas

A mature buffer zone helps reduce nutrient runoff from entering a saltmarsh on a tributary of the Chester River, Maryland.

planning that take account of the admitted high-end uncertainties in estimating future sea levels. They do not consider the upper bounds of the confidence limits presented in the statistical study, but can be used with confidence in concluding that it is likely that Maryland will experience sea-level rise of 2 feet by the end of the century. Further, this estimation indicates that, at this time, there is no scientific basis for projecting sea level rise of more than 4 feet during this century. Of course, sea-level rise will not stop at the end of the century and an important difference between the higher and lower emissions scenarios is that the higher emissions scenario is much more likely to move global temperatures over a threshold that would lead to the irreversible melt down of at least the Greenland Ice sheet, that would result during succeeding centuries in the 25-foot inundation of cities depicted in some frightening animations.

COASTAL WETLANDS

This section assesses the impacts of sea-level rise on shorelines and low lying lands. Section 8 will further explore the consequences of sea-level rise on the Chesapeake Bay and Maryland's Coastal Bays. An important part of these coastal ecosystems is, however, the coastal wetlands that fringe the estuaries. Maryland has some 200,000 to 285,000 acres of coastal wetlands[88] that provide critical nursery grounds for commercially important fisheries, important feeding grounds for migratory waterfowl, and home to furbearers and other wildlife. These wetlands buffer shorelines from erosion during storms, trap sediments and associated nutrients and pollutants, and provide a variety of outdoor recreational opportunities, such as sport fishing, hunting, kayaking, and bird-watching. The quantity and quality of these resources and opportunities available for future generations of Maryland residents will be directly affected by climate change.

Tidal wetlands will persist only if they build vertically through the accumulation in their soils of mineral (sand, silt, clay) and organic (plant material, especially plant roots) matter at a pace equal to or greater than sea-level rise—otherwise they will become submerged and convert to shallow open water habitat. In addition, given the generally shallow slopes over much of the Maryland coastal zone, those tidal wetlands that are able to keep pace with sea level will migrate and expand inland, but only so long as there are no barriers to migration (such as shore stabilization structures, houses, and roads).

As sea level rises, the fate of coastal wetlands in Maryland will be determined largely by how the needed build-up of soils is impacted by natural processes, human activities and the effects of the changing climate. Changes in the river runoff and shoreline erosion would affect the mineral sediment available for soils. Droughts could affect the accumulation of organic matter. More intense storms and greater storm surge could erode wetlands, but also transport mineral sediments onto the wetlands

When sea level rises, tidal wetlands must build up the soil or migrate inland

Jane Thomas

The loss of wetlands at the Blackwater National Wildlife Refuge, Maryland, due in part to sea-level rise, erosion, and subsidence.

and affect accumulation of organic matter by the negative effects of salt-water intrusion on plant growth.

Wetland survival during sea-level rise will vary among coastal wetlands depending on their location and the degree to which they are able to build up the soil surface. Marshes behind barrier islands on the seaside Eastern Shore increase their soil level vertically primarily as a result of sand driven over the islands during storms. An increase of storm intensity or frequency could build and expand the marshes as sea levels rise. Estuarine marshes depend more on organic matter and fine-grained resuspended sediments to build their soils. Without some significant source of mineral sediments such as discharge from a river, organic soils can only build so fast to keep up with sea-level rise—beyond some threshold, the marshes begin to deteriorate as plants die because their roots become continuously inundated and wetlands convert to shallow ponds.

As sea level has risen in the Chesapeake Bay, the gradual inundation of the low lying land on the lower Eastern Shore has led to the formation of tidal marshes that are built atop submerged uplands, particularly in Dorchester and Somerset counties. Accretion rates in these marshes are typically less than the current rate of sea-level rise.[89] At the Blackwater National Wildlife Refuge, land surface adjustments related to shallow soil subsidence[90] and possibly to groundwater withdrawal[91] have locally increased the rate of relative sea-level rise, contributing to severe wetland loss.[89] In addition, the effect of local stressors on vegetation growth, including intense herbivory by nutria, burning of the marsh for wildlife management, and altered flooding and salinity patterns related to roads and other construction activities, may be limiting soil buildup needed to counteract sea-level rise, which contributes to severe wetland loss.

Coastal wetlands, such as at Blackwater National Wildlife Refuge, are already deteriorating

If sea level were to rise at 6 mm/year, most of the remaining wetlands would be converted to open water (Figure 7.7).[92] Marsh elevation is not accreting appreciably under present rates of sea-level rise.[86] Consequently, it is unlikely that these marshes could build additional soil to keep pace without some external sediment subsidy. The placement of sediment dredged from channel maintenance in the Chesapeake Bay is currently under evaluation as a way to sustain these drowning wetlands.

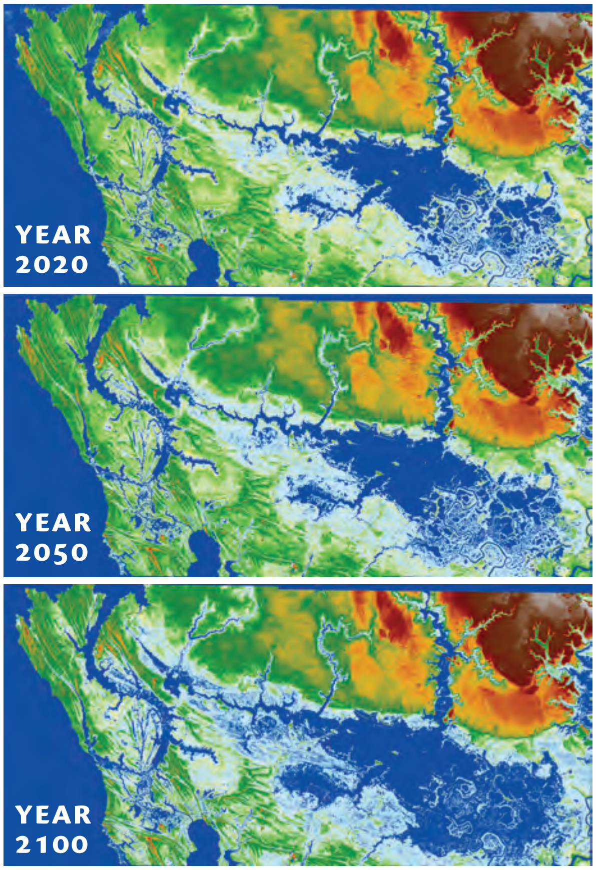


Figure 7.7. Projected inundation of coastal wetlands at Blackwater National Wildlife Refuge that would result from 6 mm/year sea level rise.[92]

Coastal responses to accelerated sea-level rise are difficult to predict over an area as large as Maryland, but a panel of wetland experts considered existing knowledge of responses and likely climate changes to project wetland survival for the Chesapeake Bay and Coastal Bays during this century.[93] Three relative sea-level rise scenarios were evaluated: 3 mm/year (approximating the current rate), 5 mm/year, and 10 mm/year. The fate of the wetlands was assigned to one of three possible outcomes: keeping pace, marginal (able to maintain elevation under optimal conditions, and loss (flood to the point of loss of

Intensive development and the loss of marsh impact the health of Maryland's Coastal Bays.

emergent vegetation). The findings summarized below are intended to provide a regional perspective and should not be applied to site-specific cases:

- **For the Maryland Coastal Bays:** marshes are able to keep pace with 3 mm/year of sea-level rise; at 5 mm/year, their ability to do this would be marginal and depend on the frequency of storms to mobilize and deliver sediments; and, at 10 mm/year, there would be marsh loss to shallow open water.
- **For the Chesapeake Bay:** estuarine marshes on the lower Eastern Shore are already experiencing high rates of loss and their survival is considered marginal at 3 mm/year and subject to substantial loss under either of the accelerated rates; estuarine marshes in the northern portion of Chesapeake Bay and on the western shore are keeping pace with 3 mm/year, but would be marginal at 5 mm/year and subject to loss at 10 mm/year; and, tidal freshwater marshes and swamps accumulate both mineral sediment and large quantities of plant organic and are considered sustainable under accelerated sea-level rise assuming salinities do not increase and sediment supplies are maintained.

To put these expert judgments in the context of the sea-level rise projections under the higher and lower emissions scenarios (Figure 7.6), based on the IPCC projections, the rate of sea-level rise over the first half of the century is likely to range from 3.5 to 5.8 mm/year, with the average for the higher emissions scenario 4.7 mm/year versus 3.8 mm/year under the lower emissions scenario. Except in tidal freshwater environments or where there is a significant supply of mineral sediments, the survivability of coastal wetlands is likely to be marginal, at least under the higher emissions scenario.

During the second half of the century sea level is projected to rise, based on the IPCC, by an average of 4.8 mm/year under the lower emissions scenario versus 5.7 mm/year under the higher emissions scenario, however, the upper end of the range under higher emissions is 7.8 mm/year. Consequently, the difference in the path of global emissions of greenhouse gases is likely to determine whether there is marginal survivability of at least some of Maryland's tidal wetlands and the predominance of wetland loss. However, with accelerated melting, the rate of sea-level rise could exceed 10 mm/year by the middle of the century, resulting in loss of the substantial majority of Maryland's 430 square miles of tidal wetlands. While some new tidal wetlands will be created over land that is presently dry, the dry land and nontidal wetlands potentially available for inland migration is only about 10% of the area of existing tidal wetlands.[94]

A recently completed, parallel analysis by the National Wildlife Federation[94] also projected losses of a majority of the brackish marshes, tidal swamps, and estuarine beaches in the Chesapeake Bay under a 27-inch rise in sea level by the end of the century. Clearly, the intertidal habitats that are important to the characteristics and productivity of the Chesapeake Bay ecosystem are at risk as a consequence of global warming.

EROSION & INUNDATION

In addition to causing the deterioration and landward migration of coastal wetlands, projected sea-level rise will cause the erosion and retreat of shorelines and, ultimately, the inundation of presently dry land. Based on general estimates derived from the Maryland Department of Natural Resources airborne surveys using a highly accurate laser instrument called LIDAR (Figure 7.8), it is roughly estimated that over 180 square miles of land would be inundated by the end of the century under the higher emissions scenario, assuming the

Potential Inundation on Maryland's Eastern Shore

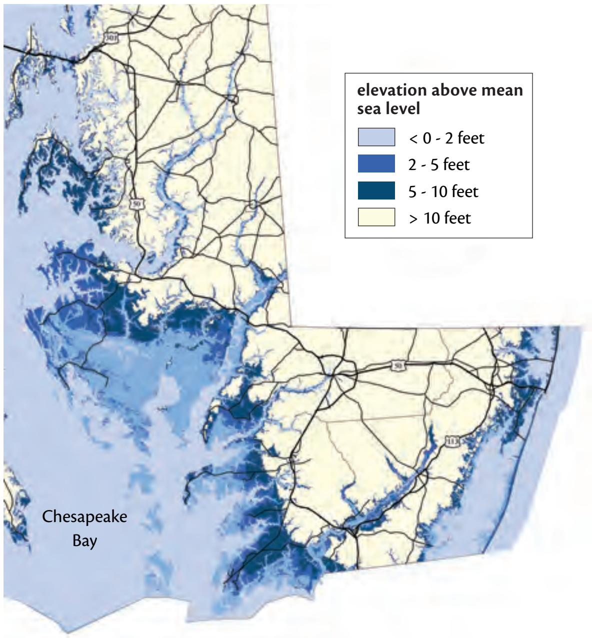
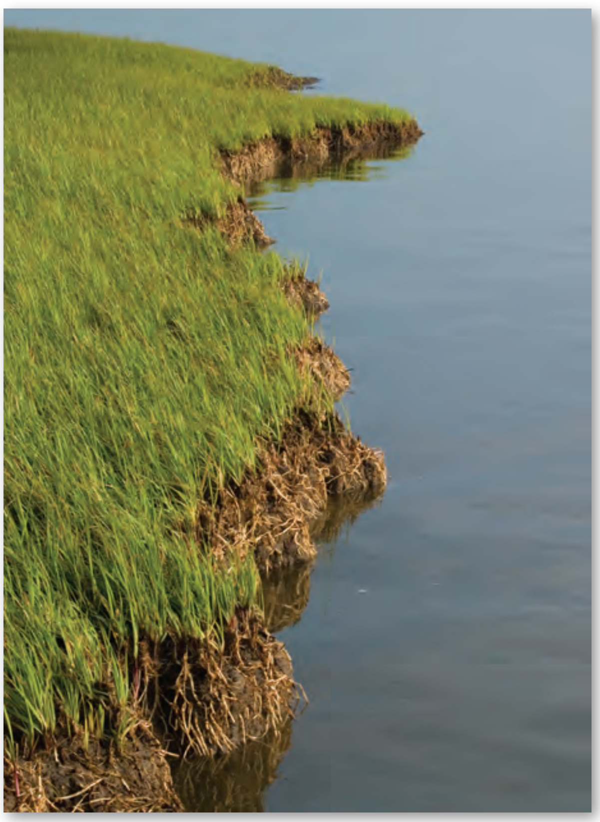


Figure 7.8. Extensive areas of wetlands and low-lying lands less than 2 feet above mean sea level (light blue) are likely to be innundated this century. Lands with elevations between 2 and 5 feet (medium blue) are also potentially at risk. Image based on aircraft LIDAR mapping by the Maryland Department of Natural Resources.

higher sea level rise rates driven by accelerated ice melting (Figure 7.6). If the growth of greenhouse gas emissions is not mitigated, the inundation of land could be more than 60% if the growth of emissions were reversed by mid century, based on comparison of sea-level rise projections under higher and lower emission scenarios. The extent of inundation of dry lands will, of course, be dependent on steps taken to respond to rising sea level, but these estimates reflect the amount of present land that will be below the level of normal spring high tides. One has to also keep in mind that as sea level rises, the volume of the Chesapeake Bay will increase and this will affect the normal range of the tides, in general, making the high tides a little higher (see Section 8).

Over 180 miles of land could be inundated if greenhouse gas emissions are not reduced

Most of the land subject to inundation is naturally located in the lowest lying parts of the State, notably along the Chesapeake Bay side of the lower Eastern Shore in Dorchester, Wicomico, and Somerset counties (Figure 7.8). Several islands (including Smith Island) and necks in this region, some inhabited, may be completely inundated or cut off within this century. Outside of this region, parts of Talbot, St. Mary's, Anne Arundel, and Baltimore counties are similarly susceptible. Assuming the projection included accelerated melting (resulting in sea-level rise to just over 3 feet; Figure 7.6), the homes of thousands of Marylanders would be lost. With a relative sea-level rise of just half that, which should be regarded as likely within the century, 264 miles of roadway, 226 miles of rail line, and 31% of the port facilities in Maryland would be at risk of inundation.



Adrian Jones

Eroding Chesapeake Bay shoreline.

In addition to inundation, of course, substantial shoreline erosion will very likely occur, but the distance of shoreline retreat will vary greatly by location, depending on the land forms, soils, exposure, structural protection, and other factors. Even shorelines characterized by high bluffs are susceptible to retreat due to undermining and slope failure. The barrier islands of Maryland's ocean shore already experience morphological changes through erosion and overwash. If sea-level rise accelerated to 5 mm/year, as projected under the higher emissions scenario sometime during the middle of the century, it is very likely that northern Assateague Island, south of Ocean City, would fragment with one or more new inlets opening to the Coastal Bays.[95] This would dramatically impact not only this National Seashore but also the Coastal Bays, by exposure to waves and storm surge.

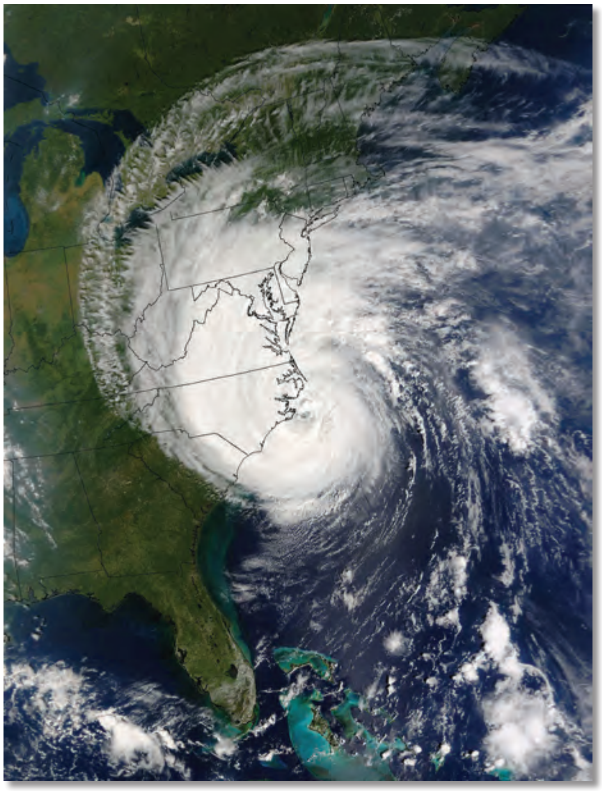
STORMY WEATHER AHEAD?

The relationship between climate change and storms has received much attention after the devastation of Hurricane Katrina in 2005, which produced record storm surge and property loss and awakened the nation to its vulnerability. This relationship has been hotly debated within the scientific community, but another U.S. Climate Change Science Program (CCSP) synthesis report recently provided a consensus perspective based on the latest scientific results and analysis.[13] The Atlantic tropical storm and hurricane destructive potential increased since 1970 in association with warming Atlantic sea surface temperatures. And, it is likely that the annual numbers of tropical storms, hurricanes, and named hurricanes increased over the past 100 years during which the sea surface temperatures also increased. Also, it is very likely that the increase of greenhouse gases contributed to this ocean warming. The CCSP synthesis concluded that it is likely that hurricane rainfall and wind speeds will increase in response to global warming, but could not predict any change in frequency in hurricanes during this century. Two very recent studies have actually projected a decrease in hurricane and tropical storm frequency, but an increase in their wind intensity and rainfall.[96]

There has been a northward shift in the tracks of strong non-tropical storms, such as Nor'easters, but evidence is inconclusive in the Atlantic to draw conclusions about the strength of these storms. The CCSP synthesis concluded that there are likely to be more frequent strong non-tropical storms, with stronger winds and more extreme wave heights.

The degree to which Maryland will be confronted with more frequent or powerful storms depends heavily on the storm tracks, which scientists are not yet able to predict for future decades. However, because of the above projections of storm intensification and because hurricanes will be able to travel farther north as a result of the warming sea surface conditions, it is likely that Maryland will experience more powerful hurricanes or tropical storms and more powerful and frequent non-tropical storms than in the 20th century. It is not now possible, however, to quantify this increased risk.

While more intense storms (for example, with higher wind velocity and greater precipitation) generally produce greater storm surge (raising of the water level by high winds and reduced atmospheric pressure), the storm surge experienced depends greatly on the size, approach, and speed of the storm. For example, Hurricane Katrina produced much higher storm surge along the Mississippi Gulf Coast than Hurricane Camille, which hit more or less the same area with higher winds. Hurricane Isabel in 2003 produced record storm surges throughout much of the Chesapeake Bay because its path carried it up the western side of the Bay, with its counterclockwise winds driving water north all the way.[97] But, its storm surge was higher by about one foot than a large storm with a similar track that hit in the 1930s—the difference being the relative sea level rise that had taken place since then (Figure 7.2). This means that assessments of future vulnerability to storm surges must take into account both the moving baseline of sea-level rise and the greater potential of more intense storms.


NASA

The 2003 Hurricane Isabel makes landfall on the Mid-Atlantic.


www.wetlandswatch.org

Flood damage caused by Hurricane Isabel, Benedict, Maryland.

Section 8

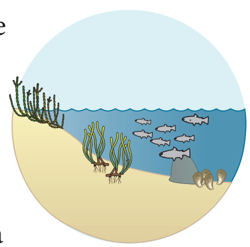
CHESAPEAKE BAY & COASTAL ECOSYSTEMS

KEY POINTS

- **Chesapeake and Coastal Bay restoration goals will likely be more difficult to achieve.**
  Increased winter-spring runoff washing more nutrients into the bays, higher temperatures, and stronger density stratification tend to exacerbate water quality impairment, alleviation of which is the prime restoration objective. Nutrient loads would have to be reduced beyond current targets to achieve water quality requirements.

- **Living resources will very likely change in species composition and abundance with warming.**
  A mixture of northern, cool water species and southern, warm water species currently resides in the Chesapeake Bay. Northern species such as soft shell clams and eelgrass are likely to be eliminated by later in the century. Southern species are very likely to increase in abundance because of milder winters.

- **As ocean water becomes more acidic, shellfish production could be affected.**
  Increasing atmospheric carbon dioxide has already lowered pH, a trend that is very likely to continue. Recent research indicates that the rate at which oysters and other coastal shellfish build their calcium carbonate shells will likely be affected, but whether this would occur in Maryland waters has not been evaluated.



In many respects, the Chesapeake Bay defines Maryland, extending through the center of the state, providing abundant resources, rich cultures, a port to the world, and commanding a major commitment for its protection and restoration. The changing climate will have multiple and complex effects on the Chesapeake Bay as well as on Maryland's Coastal Bays and the nearshore ocean environment. Warming of water temperatures throughout the year, earlier warming and later cooling, changes in precipitation and freshwater runoff, sea-level rise, and stronger winds and tropical and non-tropical storms will affect these coastal ecosystems and economies, including navigation, energy, tourism, and fishing industries. As discussed in the previous section, sea-level rise is very likely to have major consequences for coastal wetlands and shorelines, but will also deepen the bays, affecting both water circulation and biota.

Climate change will complicate the effects of nutrient pollution, the reduction of which is a central objective of the restoration and protection of the bays. Milder winters could lead to increased disease and parasitism in coastal living resources and changes in the species able to live here. Not all effects on Maryland's coastal ecosystems and industries will necessarily be negative. Shorter winters could mean longer growth seasons for blue crabs and improved fishery yields. Reductions in the frequency of ice formation could allow oysters to grow along shorelines and in very shallow water, much as they do in South and North Carolina.

The projected changes in temperature, precipitation, droughts, and floods that would affect coastal ecosystems during the century are described in Section 4; the likely consequences of global climate change on sea levels and storm intensity are described in Section 7. It is very likely that temperature and sea level will increase with the limits projected in Figures 4.2 and 7.6, respectively. For the reasons discussed in Section 4, there is less confidence in the trends and extent of precipitation and runoff.

Moving the Chesapeake Bay south along the coast as depicted in Figure 4.7 is a way to put the warming of the Bay in context. The Bay is displaced by matching the projected future Bay summer-fall temperatures with those presently experienced in estuarine waters to the south.[98] Warming by 2050 under either emissions scenario is likely to change seasonal temperatures to those currently experienced in North Carolina estuaries. The emissions scenarios would make a big difference by the end of the century, however, with conditions approximating present day southern North Carolina under the lower emissions scenario but south Florida under the high emissions scenario!

But, the vision of the future Chesapeake Bay harboring shrimp and alligators should be counter-balanced with caution. Warming will likely not geographically shift ecosystems; the Chesapeake is not likely to be just like Pamlico Sound by the middle of the century, harboring the exact same fish, plants, and animals and supporting similar coastal industries. Rather, changes in these ecosystems cannot be fully predicted and will probably yield novel species combinations, ecosystem adjustments, and mixes of living resources. Differences in the physical environment (for example, tidal range) will continue and changes in river flows and salinity will also affect the future ecosystems. Furthermore, geographic barriers may exist for more southern species to invade the Chesapeake Bay as conditions favor their colonization and native species could adapt to new conditions if they occur gradually.

NUTRIENT POLLUTION

Over-enrichment by human nutrient inputs, or eutrophication, has degraded the entire Chesapeake Bay ecosystem in pervasive ways, and reducing nutrient pollution is the lynchpin of the Chesapeake Bay Program. The Chesapeake 2000 Agreement commits the Bay states and federal government to reduce nutrient inputs in order to restore the quality of tidal waters sufficient to remove them from their listing as impaired, and this was determined to require a 48% reduction of nitrogen loading and a 53% of phosphorus loading, derived from a 1985 base load.[99] Reversing and controlling eutrophication is also a central management objective for the Coastal Bays.[100] While nutrients are essential for productive estuaries, excess nutrients contribute to reduced water clarity, loss of submerged vegetation, and low oxygen in bottom waters during summer months (hypoxia or so-called "dead zones"; Figure 8.1). By affecting temperature, precipitation and runoff, sea level and winds, and possibly nutrient loading, climate change will affect the capacity of Maryland's estuaries to assimilate nutrients and recover from eutrophication.

Reducing nutrient pollution is critical for restoring Chesapeake and Coastal Bays

River flows, nutrients, and hypoxia

Freshwater inflows into the Chesapeake Bay affect salinity and circulation and, thereby, the distribution of organisms and the functioning of the ecosystem. Freshwater inflow typically peaks during the spring as snow melts and precipitation increases.[101] The spring flow delivers a pulse of nutrients that, along with light and rising temperatures, fuels a bloom of microscopic planktonic algae, particularly diatoms, in the upper- to mid-Bay.[93] The spring

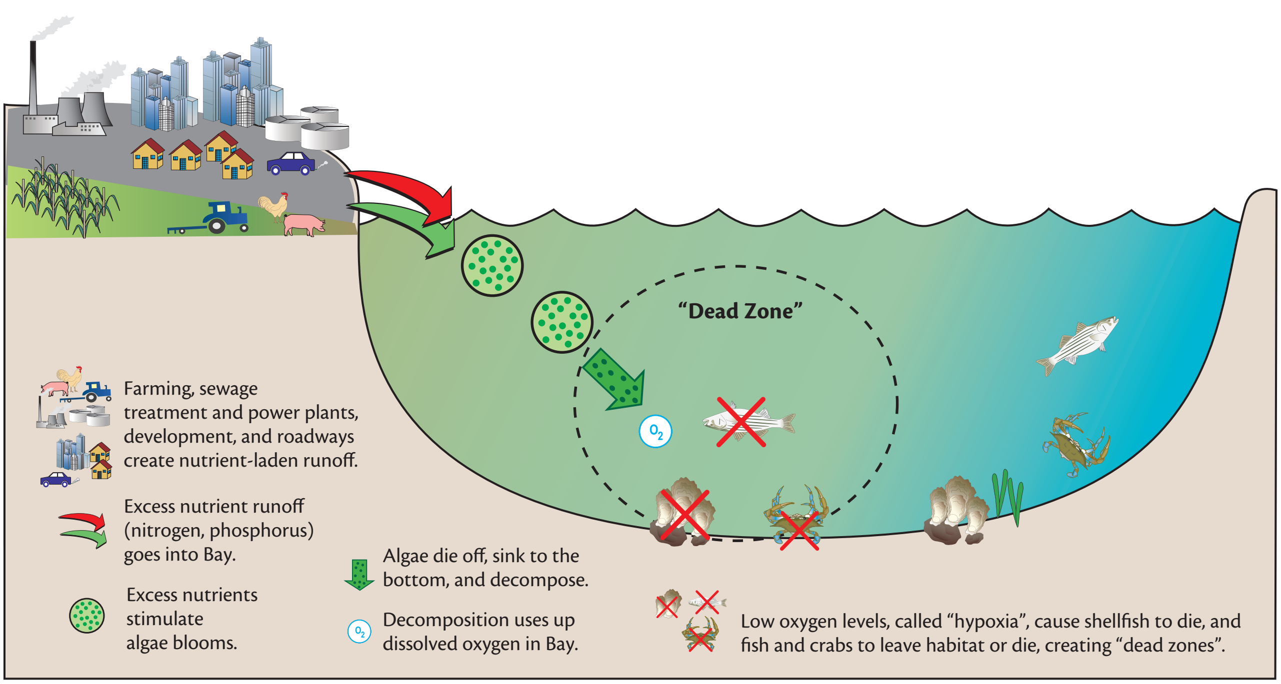


Figure 8.1. Processes contributing to severely low dissolved oxygen levels (hypoxia) in the Chesapeake Bay,

phytoplankton bloom, maintained by the nutrient input and sufficient mixing of the water column, is largely not consumed by zooplankton. Most of the biomass produced sinks to the bottom where it is eventually decomposed by bacteria as temperatures warm toward the summer. The respiration of bacteria consumes dissolved oxygen, which is not replenished by mixing because the bottom water is cooler and saltier, and therefore denser. This density stratification prevents reoxygenation of bottom waters, but when mixing events occur, the nutrients released by microbial decomposition stimulates more algal blooms, thus continuing a vicious cycle that maintains hypoxic (low oxygen) or anoxic (no oxygen) conditions.

Climate models project increasing winter temperatures (by an average of 4 and 7°F for lower and higher emissions scenarios, respectively; Figure 4.2) and rainfall (by about 10-13% under either scenario; Figure 4.8) over the century for Maryland. On the other hand, warming over the Susquehanna River Basin is very likely to reduce the storage of water in the form of snow in the watershed[7] and therefore even out the inflows to the Bay during the winter-summer period. A reduction in the peak spring inflows could result in a reduced spring phytoplankton bloom as nutrients would be delivered more evenly over the winter and spring. Warmer winter temperatures could cause an earlier occurrence of a smaller spring bloom centered in the upper Chesapeake Bay.

Dead zones are likely to expand with higher temperatures and precipitation

These outcomes are largely speculative and based on understanding of recent conditions, but illustrate the complexity of the physical, chemical, and biological process that regulate the production of organic matter in the nutrient-enriched Chesapeake Bay. Of course, these processes will also be subject to change as the climate changes. Temperature increases affect the production of phytoplankton biomass and the grazing of this

Caroline Wicks

An excess of nutrients can lead to large algal blooms that cover shorelines.

Jane Hawkey

Stormwater runoff from roads and parking lots enter Maryland waterways.

biomass by zooplankton.[102] A reduction in winter-spring phytoplankton biomass has been observed in Narragansett Bay, Rhode Island, during unusually warm winters.[103] In particular, and potentially quite significantly, if relative sea level were to increase by as much as 3 feet, as considered in Section 7, the volume of the Chesapeake Bay would increase by about 14%, shifting the salinity gradient, changing physical processes resulting from mixing of fresh and ocean water, and increasing the volume of bottom waters susceptible to hypoxia.

In spite of this complexity, climate change is likely to exacerbate hypoxia. Warmer waters can hold less oxygen to begin with, delivery of nutrients from the watershed would increase with increased precipitation and runoff, and salinity decreases and temperature increases may increase density stratification between surface and bottom waters. Considering these facts, it is more likely than not that hypoxia will worsen as a result of 21st century climate change unless greater reductions in nutrient loading are achieved and sustained.[104,105]

Harmful algal blooms

Harmful algal blooms (HABs) are a growing problem affecting aquatic ecosystems worldwide, including the Chesapeake Bay.[106] These blooms yield high densities of algae that negatively affect other organisms or produce toxins harmful to animals.[107] Humans may be affected by HAB toxins either through direct exposure or by consumption of seafood containing the toxins. The Chesapeake Bay and the Coastal Bays are home to several potential HAB-forming species, including dinoflagellates (e.g., *Pfiesteria piscicida, Prorocentrum minimum, Karlodinium micrum*), a raphidophyte (*Heterosigma akashiwo*) and a cyanobacterium (*Microcystis aeruginosa*).[108] HABs are commonly associated with nutrient over-enrichment, although many other factors affect their occurrence and prevalence. Some species of harmful dinoflagellates, such as *Prorocentrum*, and cyanobacteria (blue green algae) seem to be favored and grow faster under high temperature.[109]

Climate change is very likely to produce warm surface water temperatures and prolonged density stratification between surface and bottom waters conditions that favor dinoflagellate and blue green algal species, some of which are HAB-forming. But without more specific evidence and consideration of other moderating effects, such as predators and competitors, it is not possible to conclude that HABs will increase as a result of warmer temperatures alone. Nutrient inputs will remain the key factor in controlling algal blooms in the warmer bays.

Effects on harmful algal blooms are difficult to predict

Habitat squeeze

The high oxygen requirements for respiration under high temperatures and expansive dead zones act to reduce the habitats that can be used by fish such as striped bass, or rockfish as they are locally known. These factors may co-occur to the point of acute stress and fish kills, which already occur with some frequency in the Chesapeake Bay and in poorly flushed tidal creeks and canals in the Coastal Bays. Alternatively, the fish might swim away to avoid the stressful conditions in what might otherwise be preferred habitats. This can lead to increased risk of predation and capture by fishers or to increased competition within the reduced, remaining habitat (Figure 8.2). The high densities of fish in the few

Weems Creek fish kill due to low dissolved oxygen, June 2007.

Squeeze Zone for Striped Bass

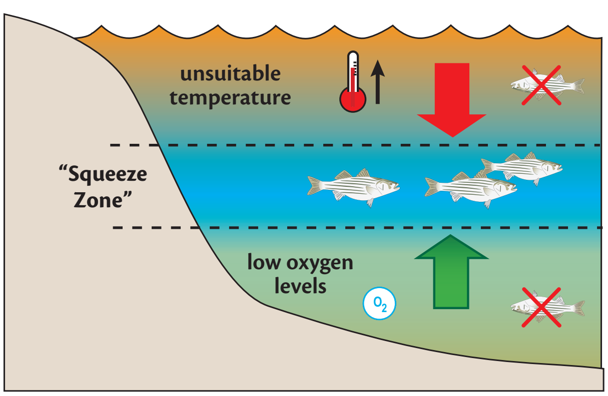


Figure 8.2. Climate change could compress the habitats suitable for striped bass by increasing surface water temperature to physiologically stressful levels and expanding the volume of bottom waters experiencing hypoxia or anoxia.

remaining suitable areas can also increase the risk of disease and parasitic infection or infestation, contributing additional stress to a fish that is already behaving, feeding and growing below par. Habitat squeezes in the Chesapeake Bay due to the degraded water quality and warming temperatures since 1950 may have already contributed to local extinctions of sturgeons, which are among the least tolerant Chesapeake Bay species to hypoxic summertime conditions.

Management implications

Although still far from reaching the restoration goals for the Chesapeake Bay, considerable reduction of nitrogen and phosphorus loads to the Bay has been accomplished though large public investments in waste treatment facilities and land management practices to reduce the runoff of nutrients. In addition to effects that climate change might have on hypoxia, harmful algal blooms, and habitat suitability, it could affect agricultural practices and forest health, and increase the frequency of flooding in ways that deliver more nutrients to the estuaries and worsen the symptoms of eutrophication as well as cause additional challenges in those sectors. If this happens, nutrient loads would have to be reduced beyond current targets in order to meet the water quality need to restore living resources.

> Greater reductions in nutrient loads may be required to achieve restoration goals

ESTUARINE SEDIMENTS

The sediment that lines both the shoreline and the bottom of Chesapeake Bay and the Coastal Bays also shapes the varied habitats of its productive ecosystem. If this sediment remains on the shore or on the bottom and if inflowing rivers run clear, then the clarity and productivity of the Bay's waters are only limited by the nutrient supply and perhaps the stratification. However, if sediment is stirred into these waters, by waves, currents, and their associated turbulence, or delivered by muddy rivers, then it may deprive submerged vegetation of needed light, deprive oysters their ability to sustain viable reefs in the face of siltation, and alter the foraging or predation of animals dependent on visual cues. Because a portion of the bottom sediment is easily erodible, estuarine circulation creates a zone of maximum turbidity near the head of Chesapeake Bay.[110] Although this turbidity maximum is confined to a limited reach of the estuary, it constitutes an ecosystem crucial to early life stages of important fisheries.[111]

Over geological time, estuaries are ephemeral

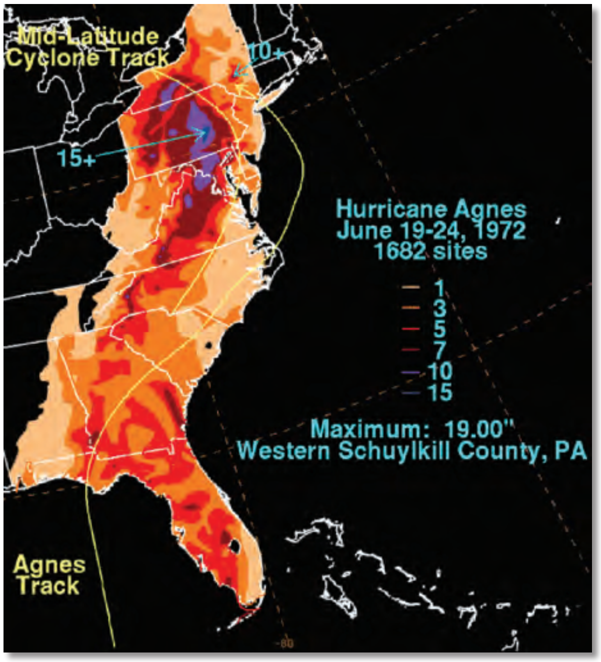
Jane Thomas

A plume of sediment, possibly from an adjacent construction site, fills a river.

features, ultimately losing the battle between sea-level rise which acts to create them and the movement of sediment off the land to fill their shallow depths. With the slowing of the rise of sea level 5,000 years ago (Figure 7.1), despite the fact that land subsidence was still raising the water levels, the filling of the Chesapeake Bay with sediments was also occurring, both from the head with sediments coming down the Susquehanna and the other great rivers and from the mouth with sand transported into the mouth of the Bay from the continental shelf. Land clearing during the 17th and 18th centuries resulted in large influx of sediments, filling in many smaller tributaries that were navigable during the colonial period. Continued relative sea-level rise a century ago, dominated by the sinking of the land rather than the rising of the ocean (see Section 7), eroded shorelines and upland deposits, bringing more sediments into the estuary. The gradual disappearance of Chesapeake Bay islands provides a graphic testament to this progression.[112]

The processes that control delivery of sediment to the Bay's waters—shoreline erosion, resuspension, or erosion in the watershed and subsequent delivery by rivers—are, in turn, controlled by the weather. As in other bodies of water, sediment transport in the Bay and its watershed occurs as a comparatively slow, inexorable process occasionally punctuated by episodes of wholesale erosion and deposition driven by violent storms. Hurricanes are especially effective because they combine extreme winds and extreme precipitation. As far as sediment is concerned, extreme precipitation is the greater concern because it rapidly erodes the watershed. Increased flashiness in runoff due to both land development and, more recently, attributable to climate change washes more sediment off the land surface and erodes stream beds. Storm-driven water flow can be devastatingly effective in moving large quantities of sediment in a short interval. As Hurricane Agnes passed through the Chesapeake watershed in 1972, dropping 3 to 6 inches of rain onto already saturated soils, some 31 million metric tons of sediment were swept into the Bay, depositing 40 years worth of sediments based on the average deposition rate.

The scale and geometry of Chesapeake Bay make it particularly vulnerable to tropical cyclones that travel a path with their center or eye moving on the west side of the Bay.[113] While eastern-track storms act to force water out of the Bay, these western storm tracks create destructive storm surges, such as occurred during the recent 2003 Hurricane Isabel. The linear nature of the Bay and its larger tributaries



Hurricane Agnes rainfall accumulations.

enables long fetches that allow efficient transfer of wind forces that drive these larger surges; these surges enhance the natural two-day oscillation of water level in the Bay.

As discussed in Section 7, global climate is very likely to accelerate sea-level rise and thus the erosion and inundation wetlands and low-lying lands. Erosion, as the shoreline retreats inland, will disperse sediment into the Chesapeake Bay and Coastal Bays, further contributing to the excess turbidity that limits light penetration. Stronger hurricanes and non-tropical storms, which are likely in this warming era, will increase the probably of sustained heavy downpours such as experienced during Hurricane Agnes. Such large storms that are accompanied by heavy and widespread precipitation throughout the watershed can have pervasive and lasting impacts on coastal ecosystems. Hurricane

Shoreline erosion from storms.

Agnes not only added a huge quantity of sediments to the Chesapeake Bay, but also added nutrients and organic matter, devastated oyster reefs and aquatic vegetation beds, and affected key species, with repercussions to the ecosystem lasting for decades.

LIVING RESOURCES

Present mixture of cool and warm species

The Chesapeake Bay is famous for its role in supporting spawning, nursery, and feeding habitats for diverse and important living resources. Historically, U.S. fisheries for shad, herrings, striped bass, menhaden, and oysters were centered here in the Chesapeake Bay. The Chesapeake Bay remains one of the most important nurseries for striped bass, croaker, eels, and blue crabs. The Atlantic menhaden fishery is now principally limited to the lower Chesapeake Bay, reflecting the productive feeding conditions that occur there during summer and fall months. Size, surrounding geography, tides, currents, and other physical features all contribute to the Chesapeake Bay's productive food webs. But the diversity and year-to-year abundances of living resources also depend heavily on the Chesapeake Bay's latitude and seasons. The Chesapeake Bay represents a transition zone between more southerly ranging temperate-subtropical species and more northern range boreal-temperate species. Interestingly, the Chesapeake Bay also shows the greatest seasonal temperature range of any other major U.S. Atlantic estuary. Therefore, in the future, warming in the Chesapeake will likely diminish the role of boreal-temperate species (Figure 8.3) and affect seasonal temperature fluctuations, which currently have an important role in nursery function and how food webs and fish communities are structured.[114]

Chesapeake Bay is a transition zone between northern and southern species

Shift to warm species

More northerly, cool temperature species such as eelgrass, soft shell clams, and sturgeons have already been in decline in the Chesapeake Bay. Soft shell clams occur at their southern limit in the Chesapeake Bay and their Maryland landings have declined from over 6 million pounds in the 1960s to less than 300,000 pounds in recent years.[115] Trends of diminished production of soft shell clams in Europe are related to climate, with poor juvenile production linked to warming at the southern extreme of its range in the Netherlands portion of the Wadden Sea.[116] Warming in the Chesapeake and Coastal Bays, coupled with existing stresses due to disease, pollution, and sediments, is likely to eliminate commercial harvests of the once economically important soft shell clam in the coming decades and may extinguish its local populations all together. As indicated below, warming will also confound efforts to restore eelgrass and sturgeons, compounding the other stresses, such as turbid waters and hypoxia, presently limiting their recovery.

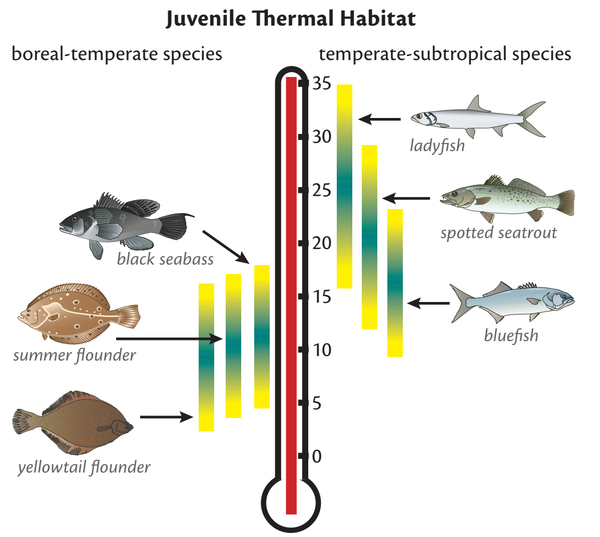


Figure 8.3. Thermal ranges for juvenile fishes native to U.S. Atlantic coastal waters (temperature in degrees C).[114]

Atlantic croaker is a subtropical fish that is already making significant inroads in temperate estuaries like the Chesapeake and Delaware Bay. Croaker juveniles can reside during winter months in Mid-Atlantic estuaries but can occasionally experience lethally cold temperatures, particularly to the north. During recent decades, more moderate winter temperatures in the Chesapeake Bay have increased juvenile growth and survival. Indeed during the last twenty years, Chesapeake landings

Atlantic croakers are expanding their range in the Mid-Atlantic.

of Atlantic croaker have increased ten-fold to 8.6 million pounds in 2006 and now exceed commercial landings for striped bass (3.6 million pounds).[117]

The Atlantic croaker belongs to the drum family, which also include black drum, red drum, weakfish, spotted and speckled sea trout, spot, and Northern and Southern kingfish. Other members of this family of fishes, together with other more sub-tropical species, are likely to become more frequent and longer term visitors to the Chesapeake Bay. Fish species that already occur in Virginia coastal waters that should also become more prevalent and abundant with increased coastal water temperature include southern flounder, cobia, spadefish, Spanish mackerel, mullet, tarpon, and pinfish. On the other hand, more temperate species such as yellow perch, white perch, striped bass, black sea bass, tautog, summer and winter flounders, silver hake, and scup will be stressed by warming of the coastal waters.

Milder winters could also allow brown and pink shrimp to complete their life cycles in the Chesapeake and Coastal Bays, where they are now only occasional summertime visitors. These shrimp are abundant in North Carolina (e.g., Pamlico Sound), where they support important fisheries. Establishment of shrimp populations in the Chesapeake Bay could result in important commercial opportunities in the future, but would also have important but unpredictable effects on both the prey and predators of shrimp.

Warming could also favor the establishment of invasive populations of nonnative species. This is particularly true for species from distant parts that hitchhiked on or in the ballast water of ships. Also, species may escape captivity and establish local populations. For example, the beautiful lionfish, a native of the Indo-Pacific and popular with salt-water aquarists, was inadvertently introduced in Florida in the early 1990s and has expanded its range northward to North Carolina, achieving populations equal in number to those of native groupers.[118] Adding an additional species, such as the lionfish, to the mix has the potential to adversely affect native fishes through competition for prey and habitat and by directly eating native juveniles. With warming of coastal ocean temperatures, the lionfish is expected to continue a northward range expansion (Figure 8.4). Similarly, warmer waters may aid the spread (accidental or otherwise) of northern snakehead fish, which now occurs in the Potomac River[119], to other parts of the Chesapeake watershed.

Warmer winter temperatures could open the door to more non-native, invasive species

NOAA

Figure 8.4. Locations in the Atlantic Ocean where lionfish have been reported as of May 2003.

Changed seasonality

Several important fish species show cycles of dominance that are the opposite of each other. Bluefish were abundant in the 1970s and 1980s but then declined during the recent period of high striped bass abundance. These cycles are thought to be due to the seasonal patterns of temperature and precipitation. Winter and early spring conditions seem particularly important in 'setting the clock' for patterns of juvenile production observed during the subsequent summer and fall seasons. Cold winter temperatures and high winter flows are associated with high abundance later in the year of juvenile Atlantic silversides (an important forage fish), striped bass, white perch, and Atlantic needlefish.[120] Species associated with the converse—low winter flows and high winter temperatures—include bluefish, spot, bay anchovy, and northern puffer.


Wikipedia Commons

Striped bass from the Chesapeake Bay.

Shifts between these two groups occur even when winter temperatures differ less than 2°F, well within the range of warming projected in the next fifty years. Species will adapt to some degree to changing environmental changes, but because this will require generational time scales, lowered abundance of the group of species that includes striped bass are likely for the Chesapeake Bay.

Milder winters would lead to longer growing seasons for species such as sea grasses, oysters, blue crab, eels, white perch, and the resident portion of the striped bass population. Blue crabs become functionally dormant during winter months when temperatures drop below 50°F. Below 41°F in bottom waters, winter temperatures become lethal.[121] Winter temperature projections indicate a 20% reduction in the number of days with less than 50°F by 2050 and, under the higher emissions scenario, a 36% reduction by 2100. The projections suggest that by mid-century there would be no severe winters with more than a week of water temperatures below 41°F. These warmer conditions are likely to shorten the time it takes for blue crabs to grow and reproduce, leading to increased productivity and yield to commercial fisheries. Of course, this assumes that there would be sufficient prey for blue crabs and that warming during the summer does not reduce the growth rate or increase the death rate as a result of greater disease incidence or expanded hypoxia.

Milder winters could mean longer growing seasons for species such as blue crabs

The degree to which the Chesapeake Bay freezes over is already much reduced in comparison to fifty years ago. The reduced occurrence of ice in shoreline habitats could permit oysters to colonize sheltered shorelines and very shallow waters to form reefs that emerge at low tide, much as they do now in North Carolina. Such reefs could provide new opportunities for restoration and aquaculture by enabling access and enforcement of protection of rebuilding or leased bottom reefs.

Warming and the shifting of seasons are likely to affect migration and spawning behaviors of Chesapeake Bay fish. Striped bass, shads and other fish that migrate into the Chesapeake for spring spawning will likely shift their arrival times to earlier dates. Such a shift is already apparent in migrating fish in other regions. Spawning migrations by Atlantic salmon in the Connecticut River are now over ten days earlier than in 1978.[122] American shad migrated five weeks earlier in 1993 than in 1949 in the Columbia River.[123] Changes in timing of spawning migrations by adult fish can influence early survival and growth of their offspring. For instance, fish larvae in the Chesapeake Bay rely on spring plankton blooms to support their growth and development. Early spawning migrations by adults could result in a 'mismatch' [124] between spawning and plankton blooms needed to support the growth and survival of larvae (Figure 8.5).

Another type of mismatch that can occur is between migration timing and fishing regulations. If changes in the timing of migration are sufficiently large, they may impact the timing and duration of a fishing season. For example, the Maryland 'trophy' striped bass recreational season targets post-spawning individuals. Here, early spawning could effectively reduce the fishing season if the season has a fixed start date. In response to increasing temperatures, management agencies may need to explore temperature-specific regulations, rather than fixed fishing seasons.

The Great Shellfish Bay

Native Americans referred to it as Chesepiooc, or

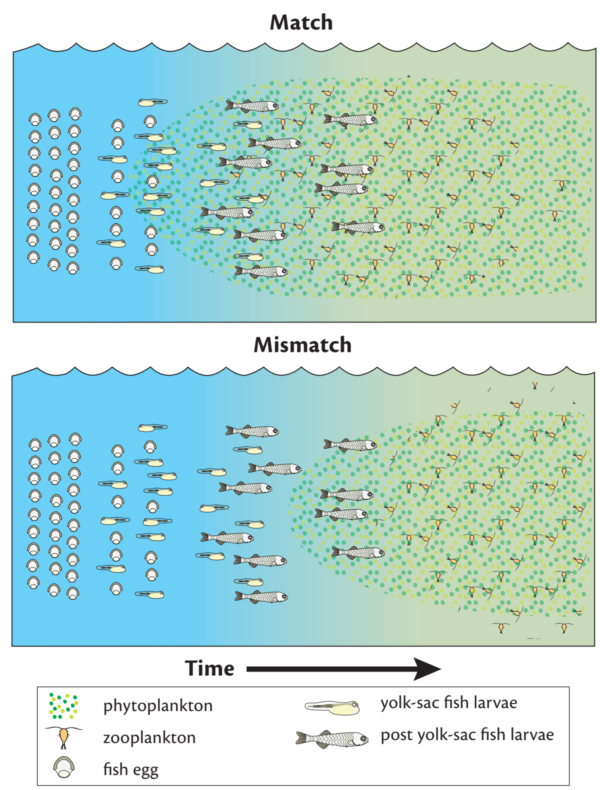


Figure 8.5. Matching of first-feeding fish larvae with the timing of zooplankton peak abundance. A match occurs when spawning is well-timed and there is overlap between the occurrence of first feeding larvae and peaks in zooplankton abundance and favors early growth and survival. Mismatches of timing and location correspond to poor growth and survival conditions.

great shellfish bay, because of the vast abundance of oysters that once characterized the Chesapeake Bay. Decimated initially by overharvesting that resulted in removal of their reefs themselves and later by introduced diseases, native oysters are present at a very small fraction of their original abundance. Substantial efforts are underway to try to determine how to increase oyster aquaculture and to restore oyster reefs for the role they play in providing habitat for other organisms and clearing up estuarine waters by their filter feeding.

Variations in climate have always been important in determining the success of oysters. Temperature and precipitation—through its effect on salinity—affect reproduction, the development of larvae, and the survival of newly settled oyster spat. Still, through the 1970s, the abundance of juvenile oysters in one year was heavily influenced by the abundance of the adult parents the year before.[125] Recently, it appears that at such low abundance, the number of adults has relatively little influence on the number of juveniles, which is now predominantly determined by water temperature and particularly salinity.[126] If higher river runoff regularly lowers Bay salinity, fewer juvenile oysters would be expected to survive, but if sea-level rise increases the volume of the Bay sufficiently to increase salinity, the reverse would be true.

The two prevalent oyster diseases, commonly called Dermo and MSX, are also likely to respond to climate change. Dermo epidemics are more severe in Chesapeake Bay after dry and warm winters. Increased water temperatures cause more rapid cell growth by the Dermo parasite once it has infected an oyster.[127] As conditions have warmed, Dermo has extended farther up the East Coast, even to New England.[128] But it may be the case that the Chesapeake Bay is already warm enough so that temperature is not a factor limiting Dermo epidemics except under higher salinity conditions. MSX is also more prevalent in oysters after dry and warm winters and less so following cold winters (less than 37°F) and under low salinity.[129] Successive cold winters keeps MSX in check, but, as this becomes less likely with the warming waters of the Chesapeake Bay and Coastal Bays, this disease is likely to remain at least as prevalent if not more so.

Warmer conditions have allowed oyster diseases to spread

Overall, the net effects of climate change on oyster populations, aquaculture, and restoration are difficult to project. They will depend not only on the direct effects of salinity and temperature on oyster growth and survival, but importantly on how the changing conditions affect the prevalence and virulence of the disease organisms, which warmer conditions should favor. Still, it should be remembered that native oyster populations prosper in Gulf Coast estuaries, which experience higher temperatures and more variable salinities.

Aquatic vegetation

Submerged aquatic vegetation (vascular plants that live underwater) constitutes a very important component of the Chesapeake Bay and Coastal Bay ecosystems. These plants increase water quality in shallow water areas by reducing the resuspension of sediment and releasing oxygen to the sediments, thereby enhancing nutrient recycling. The vegetation provides habitat for many animals, including blue crabs, which use it as a refuge from predators during early life.[130] There is currently a worldwide decline in coastal submerged plants, or seagrasses, including in the Chesapeake Bay and Coastal Bays.[131] Much

NOAA

Oyster reef, Chesapeake Bay.

Jane Hawkey

Aquatic vegetation provides habitat for juvenile fish and crabs.

of this loss is a result of nutrient over-enrichment, which increases shading by phytoplankton and stimulates the growth of algae on the blades of vegetation, thereby reducing the light needed for photosynthesis.[93]

Aquatic vegetation requires suitable temperature, salinity, nutrients, and, in particular, light.[132] Climate change could affect, directly or indirectly, all of these variables. As in the case of fish and other animal species, aquatic plant species have different latitudinal distributions that are closely related to their temperature tolerance. The dominant aquatic plant species under the higher salinity conditions of the lower Chesapeake Bay and the Coastal Bays is eelgrass (*Zostera marina*), a boreal-temperate species with a southern limit of distribution in North Carolina.[133] Largely as a result of declining water quality and increased light limitation, eelgrass has become much less abundant in Maryland bays. During the high salinity and high water clarity conditions that existed in the 1960s, eelgrass was found as far up the Chesapeake Bay as Kent Island, but now is largely limited to the Tangier Sound region (Figure 8.6), where it provides valuable habitat for early juvenile blue crabs and refuge for the highly vulnerable soft stages of adults.

Eelgrass is at risk of elimination and other species will replace it

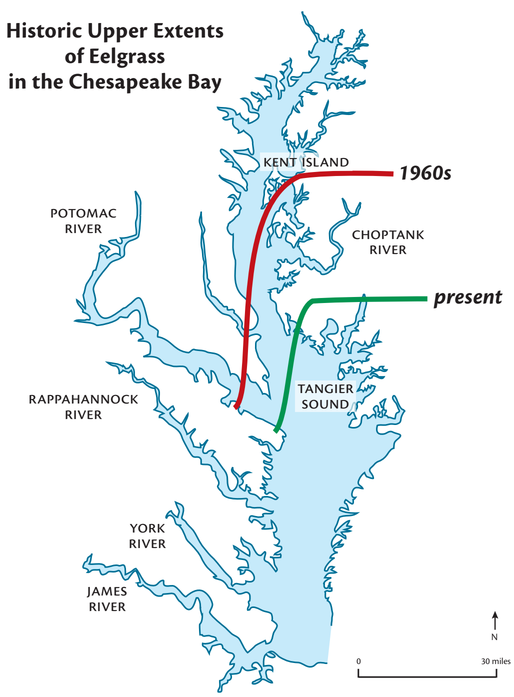


Figure 8.6. Changes in the distribution of eelgrass (*Zostera marina*) in the Chesapeake Bay.

At high summer temperatures, eelgrass photosynthesis cannot keep pace with its respiration and the plant loses its leaves and even its below-ground rhizomes may die.[134] During unusually hot summers, for example in 2005, the dieback of eelgrass was extensive and recovery in the following year was dependent on the bank of seeds left in the sediment. Because eelgrass seeds do not remain viable for over a year, if there were a succession of hot summers, eelgrass populations could be eliminated from the Bay. Consequently, the outlook for eelgrass in the warming bays is not promising. By mid-century, it is as likely as not that eelgrass beds will no longer exist in the Chesapeake Bay under the lower emissions scenario, and likely that it will be functionally eliminated under the higher emissions scenario. It is very likely that eelgrass will be completely extirpated by the end of the century under either scenario. It is possible, however, that shoalgrass (*Halodule beaudettei*), a subtropical species that is abundant in higher salinity portions of North Carolina's sounds could colonize the Chesapeake Bay and Coastal Bays as the winters warm. However, it does not tolerate low salinity as much as eelgrass and, thus, its distribution in the upper Bay would be more limited. Shoalgrass is also more ephemeral and provides less robust habitat than eelgrass.

As sea level continues to rise, increasing water depths will reduce the light available to aquatic vegetation where it presently occurs. However, the vegetation could migrate shoreward and even occupy areas that are presently tidal wetlands or dry land. However, as wetlands erode away, hard clay-rich deposits often remain, a consolidated remnant of older wetland soils. These clay deposits are not suitable soils for submerged vegetation and until covered by a veneer of sand will not be colonized.[135] With the increased volume of the Chesapeake Bay because of accelerated sea-level rise, higher salinity conditions are likely to extend farther up the Bay. While greater intrusion of salinity may be beneficial to seagrasses such as eelgrass and shoalgrass (if it successfully colonizes the Bay), it could constrict the habitat suitable for plants originating from fresh waters, such as redhead grass and sago pondweed, that are prevalent in lower salinity regions, where aquatic vegetation is currently expanding as water quality improves.[93]

While the net effects of climate change on aquatic vegetation are difficult to predict because of the complex and interacting effects of temperature, salinity, water quality, and sea level, it is very likely that the biomass, species composition, and distribution of aquatic vegetation in the Chesapeake Bay and Coastal Bays will be significantly affected by climate change.

OCEAN ACIDIFICATION

In addition to its greenhouse effect, the increase in the concentration of carbon dioxide in the atmosphere is gradually acidifying, or lowering the pH, of the ocean. Much of the carbon dioxide that is released from human activities is actually taken up by the ocean, moderating its effect on global warming. However, when carbon dioxide dissolves in sea water, it decreases its pH. From the beginning of the industrial era, pH has declined about 0.1 units from its normal 8.18, and may decline by a further 0.3 to 0.5 units by 2100.[2] While this will not make the oceans actually acidic (below 7 pH units), such a decline in pH affects the ability of organisms to create shells or skeletons of calcium carbonate because lowering the pH decreases the concentration of the carbonate ions that are required.

Ocean acidification is the sleeper issue of global change, because not only are the potential effects on the world's coral reefs profound, but the process of acidification also reduces the ocean's capacity to absorb more carbon dioxide from the atmosphere. The effects of ocean acidification have just recently been receiving attention, most of which is focused on corals and the plankton of the open ocean. Recent studies have shown that mollusks that are ecologically and economically important in coastal waters may be vulnerable to the effects of ocean acidification. Mussel and oyster calcification rates were projected to decline by 25 and 20%, respectively by the end of the century[136], as well as the ability of oyster larvae to form their thin shells when pH was reduced to 7.4 through addition of carbon dioxide.[137]

Declining ocean pH affects ability of oysters and other shellfish to form shells

Research on the processes and effects of acidification in Mid-Atlantic estuaries and coastal waters has scarcely begun. Important questions remain regarding the interaction of the bicarbonate created when carbon dioxide dissolves in these waters with other chemical constituents. This will affect the level of acidity likely to be experienced and the effects that might be realized not only on mollusks, but also crustaceans, starfish, and other organisms that create calcareous skeletons.

Holly Weiss

Maryland beach.

Ben Fertig

The native eastern oyster, *Crassostrea virginica*.

Section 9

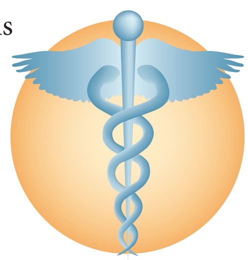
HUMAN HEALTH

KEY POINTS

- **Health risks due to heat stress are very likely to increase if emissions are not reduced.**
  Under the higher emissions scenario, in particular, heat waves are projected to greatly increase risks of illness and death before the end of the century, with an average of 24 days per summer exceeding 100°F. Some, but not all, of these increased risks can be reduced by air conditioning and other adaptation measures.

- **Respiratory illnesses are likely to increase, unless air pollution is greatly reduced.**
  More ozone, responsible for multiple respiratory illnesses, is formed under prolonged, high temperatures. Releases of air pollutants (nitrogen oxides and volatile organic compounds) that cause ozone to be formed have been declining, but would have to be reduced much more to avoid a reversal in progress toward achieving air quality standards.

- **Increased risks of pathogenic diseases are less likely.**
  The mortality due to vector-borne and non-vector borne diseases in the United States is low because of public health precautions and treatment. Climate change might affect the exposure of Marylanders to pathogens such as the West Nile virus, but precautions and treatment could manage this risk.



Human well-being is obviously affected by the weather and the changing climate will have multiple ramifications for human health as well as comfort and enjoyment. Human health has the greatest sensitivity to climate change with regard to heat stress; the effects of storms that generate floods and extremely high winds; air pollution effects, particularly as they cause or exacerbate asthma and other respiratory maladies; and diseases caused by pathogens that are borne by insects and other vectors, water, and food.[138] The risk of storms and floods are addressed earlier in this assessment. Here the potential impacts of climate change-related heat waves, air quality, and pathogenic diseases on human health in Maryland are evaluated.

HEAT WAVES

Global warming is likely to result in substantially higher temperatures both in winter and summer in Maryland. While there could be some benefits in terms of reduced deaths from cardiovascular disease (for example, as result of milder winters) Maryland's population experiences very few deaths with its temperate climate related to extreme winter temperatures. Rather, most assessments in the United States have appropriately focused on the health risks of extreme heat. In six out of ten recent years, heat has been the leading weather-related killer in the United States.[7]

Concerns about the increased health risks from heat waves caused by global warming are not far-fetched. The death of an estimated 35,000 people, attributable to the August 2003 heat wave in Europe, was a sobering experience.[139] Parts of France experienced seven consecutive days with temperatures more than 104°F and 14,800 people died in that country alone. The situation in Europe

NOAA

Dawn brings on the day's heat.

was particularly acute because the population was not acclimated to warm summers and there was little air conditioning. Most of those who died were elderly. Closer to home, a 1995 heat wave in Chicago resulted in an estimated 696 deaths.[140] While the European heat wave was related to unusual weather patterns and not primarily to climate change, climate models predict frequent summer conditions not unlike those in 2003 during the latter part of the 21st century, indicating that, for many purposes, the 2003 event can be used as an analog of future summers in climate impact assessments.[141]

Heat stress can result in illnesses caused by heat cramps, fainting, heat exhaustion, and heatstroke and result in death.[142] Except for cramps, heat-related illnesses are the result of the body's failure to regulate its internal temperature. Our bodies respond to hot weather by an increase in blood circulation and increase in perspiration, both in an attempt to rid the body of heat. The effectiveness of such heat loss is reduced when air temperature and humidity increase. The ability to increase circulation may be limited by heart rate and the blood volume, which is reduced because of the loss of body fluids.

Several factors can increase the risk of heat-related illness. Both individuals over 65 and the very young are at higher risk because they have less ability to control internal temperatures and are more susceptible to dehydration. Reduced physical fitness, obesity, existing illnesses, and the use of medicinal drugs such as stimulants and beta-blockers all increase the risk of heat stress. Individuals not acclimated to high temperature or suffering from exertion are also more susceptible. City dwellers, particularly those of lower economic status who cannot afford air conditioning, are at greater risk because of the urban heat island effect, where buildings and paved surfaces hold the heat well into the night.[143] Many of those who die of heat stress live alone and do not seek treatment or are not discovered until it is too late. And most of those who die in urban areas as a result of heat stress succumb during the night, when temperatures are expected to rise even more than during the daytime.[42]

The average annual frequency of days with a maximum temperature exceeding 90°F in Maryland is projected to grow gradually over the century, but more dramatically later in the century. Near the end of the century under the lower emissions scenario, the model averages project about 64 days per year would exceed 90°F and 10 days per year would exceed 100°F (Figure 4.4). Under the higher emissions scenario, these numbers would grow to 95 and 24 days per year, respectively. These numbers would be higher in urban areas due to the urban 'heat island' effect. These projections are generally similar to those derived by the Northeastern Climate Impacts Assessment for Philadelphia (Figure 9.1).[7] Put another way, these projections indicate that toward the end of the century under the high emissions scenario, it would be a rare summer day when the high temperature did not top 90°F and there would be nearly a month where temperatures reached 100°F. A considerable increase in 90°F days is very likely inevitable, even if greenhouse gas emissions were reduced around the middle of the century (lower

With continued growth in emissions, 24 days per summer are projected to exceed 100°F

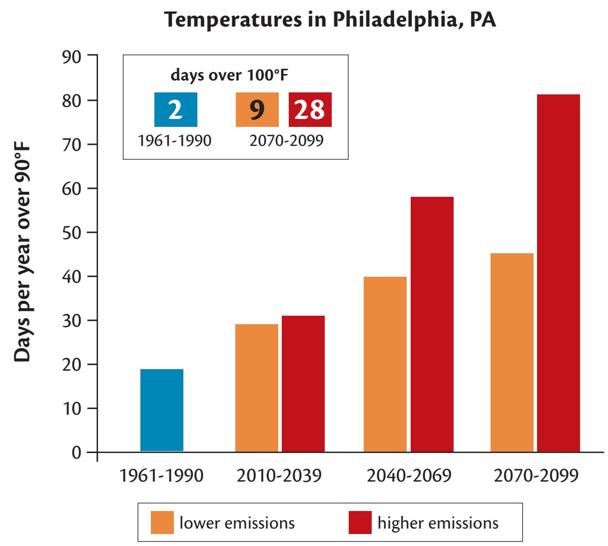


Figure 9.1. Model projections of number of days per year that the maximum temperatures would exceed 90°F and 100°F in Philadelphia according the NECIA.[7] The higher emissions scenario employed assumed more rapid growth of greenhouse gas emissions than the higher emissions scenario in this assessment.

Andrea Hetherington

Cooling off in the intense summer heat.

emissions scenario), but only about half as many 100°F days would occur if emissions were reduced.

Of course, as the frequency of very hot days increases so does the likelihood that there will be a successive number of these days, i.e., a heat wave. Based on the model projections, there is a high probability that, late in the century, heat waves with daily temperatures exceeding 90°F would last more than 60 days under the higher emissions scenario. Under the low emissions scenario in most years, heat waves would not exceed 20 days. The difference between the scenarios is even greater for severe heat waves such as experienced in Europe in 2003 (successive days with temperature exceeding 100°F).

Based on these temperature and heat wave projections, Maryland is likely to confront substantially increased heat-related health risks by the mid-century and beyond. By late in the century under the high emissions scenario, this situation is likely to become very serious, with life threatening conditions developing nearly every year, particularly in the Baltimore and Washington urban areas because of the urban heat island effect and more at-risk individuals living there. Beyond threatening life for the most vulnerable, these oppressive conditions would curtail outdoor activities and diminish productivity in commercial activities requiring outdoor work. Under the lower emissions scenario, heat-related health risks would increase substantially from the present condition but much less so than with the unmitigated growth in emissions.

Of course, there are steps that can be taken to lower these health risks. Within limits, acclimation to higher outdoor temperatures and various adaptation measures can lower the incidences of heat-related deaths. Adaptation measures include effective early warning and response plans for heat waves, air conditioning, and better education about personal precautions, such as drinking more fluids, wearing light colored and loose fitting clothing, and limiting outdoor activity. Over the longer term, building codes can be designed to reduce the urban heat island effect, for example, by increasing the tree canopy and including reflective or green roofs. More frequent and severe heat waves will very likely increase requirements for air conditioning, extend the air-conditioning season, and increasing peak-load electricity demands at the very time there will be a premium on energy conservation to mitigate greenhouse gas emissions.

Heat-related health risks likely to increase significantly in urban environments

AIR QUALITY

Global climate change could affect human respiratory health by changing levels of air pollutants and the types and levels of pollen. For the United States, impacts of climate change on ground level, or tropospheric, ozone are much more likely to be more important than for other air pollutants. This is due to the importance of high temperature in the formation of ozone as well as the large areas of the country currently affected by ozone levels exceeding national standards (Figure 9.2). Central Maryland is among the most affected regions in the nation.

Ozone can affect human health by irritation of the respiratory system, reducing lung function, aggravation of asthma by increasing sensitivity to allergens, increased susceptibility to respiratory infections, and inflammation and damage to the lining of the lungs, causing chronic obstructive pulmonary disease (COPD). Effects can range from coughing and shortness of breath to permanent

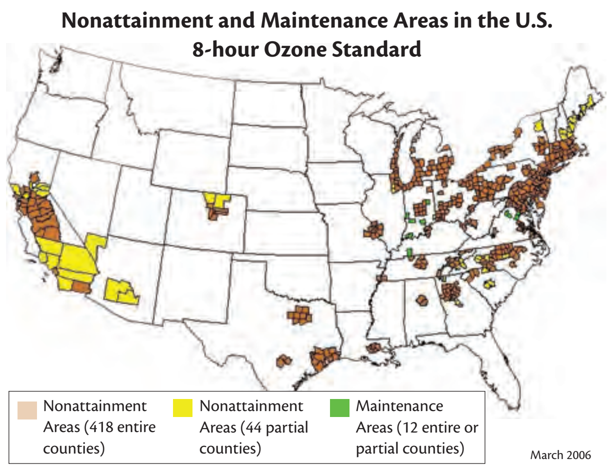


Figure 9.2. Counties not attaining the 8-hour ozone standard include most Maryland counties.

University of North Carolina

Physicians review lung x-rays.

scaring of the lungs and even death. Central Maryland has some of the highest incidence of asthma and acute respiratory illness in the country. It is estimated that about 2,000 Marylanders die each year because of chronic lower respiratory illnesses.

Maryland has made substantial progress in controlling air pollution. Baltimore and Washington areas are on a path leading to compliance with the National Ambient Air quality Standards (NAAQS) by 2009, but changes in the global background could reverse this progress and require even deeper reductions of the pollutants responsible for ozone formation. Human activities do not emit ozone per se, but our activities result in the release to the atmosphere nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOCs). NOx and CO are emitted mainly by the combustion of fossil fuels and VOCs are emitted from incomplete combustions of fuels and the evaporation of petroleum fuels and chemicals and by certain plants. These compounds react with oxygen in the atmosphere in the presence of sunlight to create ozone (O3; Figure 9.3).

The process of ozone formation depends on high air temperatures, which explains why we do not have ozone alerts during the winter even though emissions of NOx and VOCs are just as high then. As Figure 9.4 shows, there is a clear relationship between the maximum temperature at the Baltimore-Washington International Airport (BWI) and ozone concentrations in the Baltimore non-attainment area.[144] Furthermore, heat waves (multiple successive days with very high temperatures) create the optimum conditions for ozone formation. This is apparent in the Baltimore non-attainment area where the number of days where ozone concentrations exceed the 8-hour "Code Orange" standards in a year shows

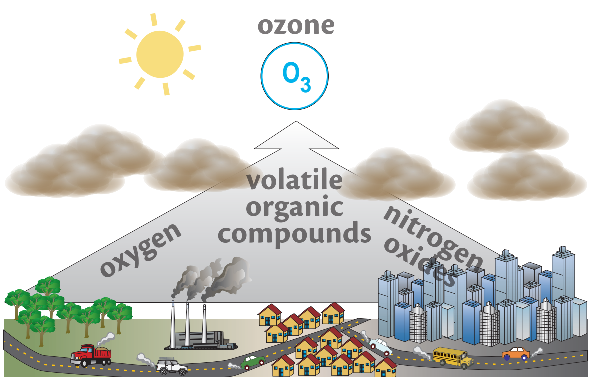


Figure 9.3. Ozone is created by the chemical reaction of air pollutants in the presence of sunlight.

NPS

The top image shows the reduced visibility (25 miles) in the downtown Washington, D.C. area in July 2006. The bottom image was taken in October 2005 where the visual range was 55 miles.

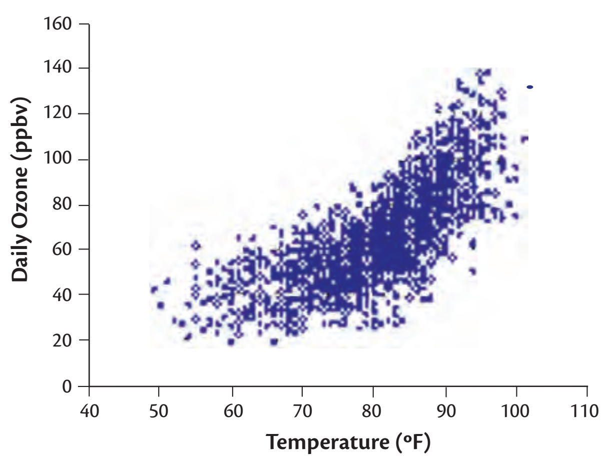


Figure 9.4. More ozone is formed under higher temperatures. Peak 8-hour ozone concentrations in the Baltimore region for May-September, 1994-2004, compared to maximum temperature at BWI Airport.[138]

close relationship with the number of days where maximum temperatures exceed 90°F (Figure 9.5).

Climate change is also likely to decrease the occurrence of cyclonic waves (low pressure system with associated weather fronts), thus lengthening

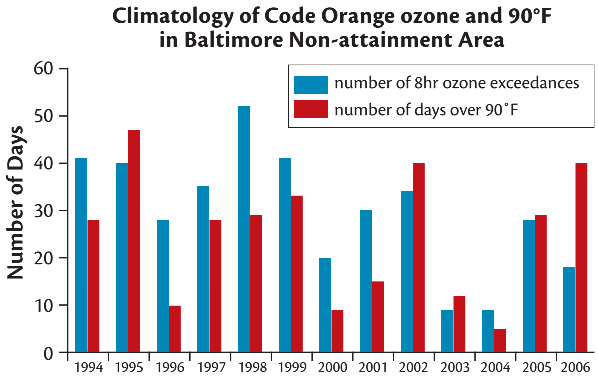


Figure 9.5. Heat waves (multiple days with temperatures exceeding 90°F) increase the buildup of ground-level ozone.

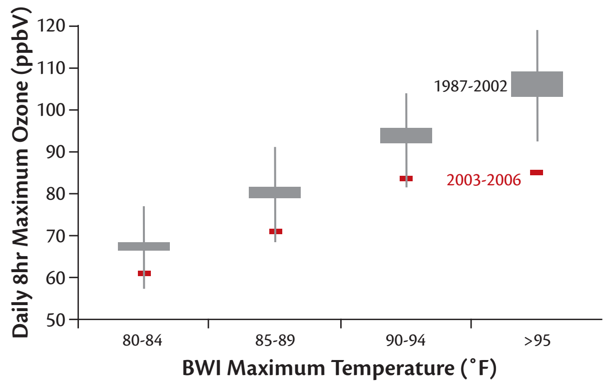


Figure 9.6. Maximum ozone concentrations have declined for each temperature range in recent years as a result of the reduction of emissions of air pollutants.

the duration of stagnant, high pressure events (hot and hazy periods) and delay the onset of cold fronts that clean up air pollution episodes.[145] Such smog episodes not only decrease the visual range but can also cause human illness and death due to higher concentrations of fine particulate matter. The persistent Bermuda High leads to weak or stagnant winds, high daytime temperatures, and intense UV radiation reaching the Earth's surface. Pollution and VOCs build up from gasoline vapors and even trees, particularly pines and oaks that are favored by global warming. All of this is exacerbated by the urban heat island effect.[146]

Ozone alert days likely to grow, requiring more aggressive reduction of air pollution

Based on the increase in summer temperatures and heat waves and these changes in weather patterns, scientists have projected anything from a 3-5 ppb[147] to a 10-20 ppb[148] increase in 8-hour average ozone concentrations over the eastern United States by the end of the century, assuming emissions of the ozone-precursor pollutants remain constant. One recent study projected a 28% increase in the average number of days exceeding 8-hour ozone standards for Baltimore and a 50% increase for Washington, D.C. by 2050.[149] On the other hand, if emissions of NOx are reduced by 50%, then ozone concentrations could, according to another study, actually decline by 11-28% despite the warming conditions.[150] The decline in observed ozone concentrations in the Baltimore region for given temperature ranges (Figure 9.6) provides clear evidence of the importance of reducing precursor emissions.

In summary, it is very likely that without significant additional reductions in air pollution by NOx and VOCs, ground level ozone concentrations will increase and pose additional health risks to people residing in central Maryland. In addition to mitigation by reducing pollutant emissions, adaptive responses are similar to those for heat stress: warning systems, air conditioning, avoiding exertion and outdoor activity, and increasing tree cover.

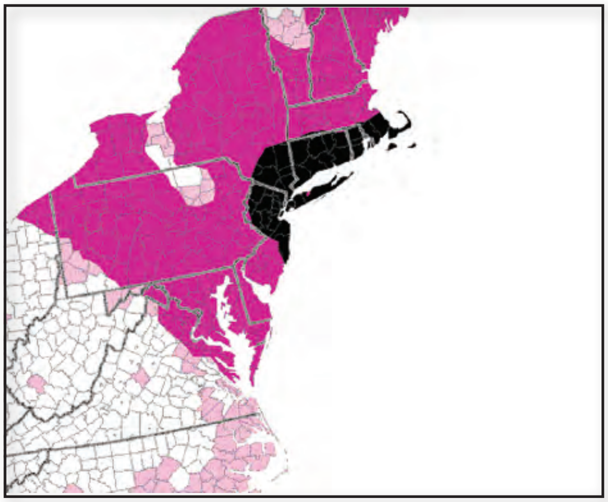
Maryland Power Plant Research Program, MD DNR

There are 34 power plants operating in Maryland as of 2006.

PATHOGENIC DISEASES

Climate change can increase human exposure and vulnerability of diseases caused by pathogenic microorganisms.[138] These include diseases borne by various animal vectors, such as malaria, dengue, Lyme disease, and encephalitis, a type of which may be caused by the West Nile virus. Global warming could increase the range or abundance of the animal vectors. Climate change could also affect exposure to non-vector borne diseases such as hantavirus, cryptosporidiosis, and cholera. The incidence and associated mortality of most of these diseases in the United States is relatively low because of public health precautions and the availability of treatment. For Maryland, the increased risks due to heat stress and respiratory impairment are likely to be more serious than for pathogenic diseases.

Moreover, it is difficult to project how climate changes would impact pathogenic transmission and human health because of the complexity of climatic effects on vectors and other environmental factors.[138] Cryptosporidiosis is an intestinal disease caused by a bacterium that is abundant in livestock feces and can be transported during high rainfall events. The bacterium is small and resistant to chlorination, making it difficult to kill or filter out of water supplies. Lyme disease has become the most important vector-borne diseases in the United States and a large majority of cases occurs in the Northeast, although it is less prevalent in Maryland than in the states to the north. The ticks that transmit Lyme disease prefer cooler temperatures during the summer, so the projected warming could reduce tick populations and disease risk.[7] Continued encroachment of suburbs into former woodlands presents a far greater risk for contraction of Lyme disease. Outbreaks of West Nile virus in humans seem to occur when extreme heat and drought are followed by heavy rains. It is thought that birds that host the virus migrate to wetter areas during the drought and the mosquitoes that normally prey on birds switch to humans when they hatch following the rains.[7]



American Lyme Disease Foundation, Inc.

The dark pink area, which includes most of Maryland, represents a medium density of host-seeking ticks that have been shown to be infected with Lyme disease bacteria.

University of Maryland

Heavy rains and coastal flooding combined with warm weather provides perfect conditions for an explosion of mosquitoes.

Section 10

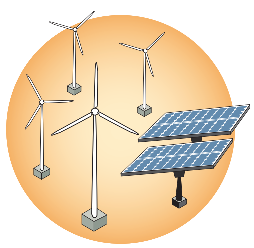
IMPLICATIONS FOR MITIGATION & ADAPTATION

KEY POINTS

➤ **Reduction of greenhouse gas emissions has substantial benefits for Maryland.**
Mitigation of global emissions by mid-century would very likely result in significantly lower sea-level rise, reduced public health risks, fewer extreme weather events, less decline in agricultural and forest productivity, and loss of biodiversity and species important to the Chesapeake Bay. Even more serious impacts beyond this century would be avoided.

➤ **Develop adaptation strategies for human health, water resources, and restoration of bays.**
Adaptation strategies to reduce coastal vulnerability should plan for a 2 to 4 foot rise in sea level during the century. The Commission should evaluate additional adaptation strategies related to human health, water resources, forest management, and restoration of the Chesapeake Bay and Maryland's Coastal Bays.

➤ **Organize and enhance Maryland's capacity for monitoring and assessment of climate impacts.**
A more extensive, sustained, and coordinated system for monitoring the changing climate and its impacts is required. Maryland is in a strong position to become a national and international leader in regional-to-global climate change analysis and its application to mitigation and adaptation.



This assessment of the impacts of climate change on Maryland was undertaken as one of three integrated components of the Plan of Action of Maryland's Commission on Climate Change. To that end, it is appropriate to draw implications from the impacts assessment to inform the other efforts to mitigate climate change by reducing greenhouse gas emissions and to adapt to changes likely, thereby reducing Maryland's vulnerability. This concluding section briefly summarizes the findings of the impacts assessment related to those two objectives.

MITIGATION

Reducing emissions soon is required

The Intergovernmental Panel on Climate Change has demonstrated that on a global scale, there are likely to be large changes in climate and substantial and serious effects on natural ecosystems, resources, and human populations and societies.[3] The IPCC showed that some of these changes are inevitable because they have already begun and cannot easily be stopped, even with dramatic and immediate reductions in greenhouse gas emissions. However, the path that humankind will follow in either continuing to increase those emissions or reducing them will have a large effect on the extent of climate change and magnitude of its consequences.

This assessment seeks to identify both those changes in Maryland that are likely inevitable and those changes that can be avoided with action to reduce emissions through the use of the lower and higher emissions scenarios. A point made earlier bears repeating: the higher emissions scenario is not

Improved fuel economy and less vehicles on the road could provide some reduction in greenhouse gas emissions.

and does not represent a ceiling nor the most extreme changes that are likely, and the lower emissions scenario is not a floor and does not represent the minimum effects that may be achievable. Currently, emissions are growing faster than the higher scenario assumes. The IPCC estimated that it would require early reductions of global greenhouse gas emissions of 50 to 85% by 2050 to constrain the increase in the global mean temperature to 3.6 to 4.5°F,[3] a level of warming generally thought to have dangerous consequences, and would, therefore, still have many negative consequences as this report attests. Under the lower emissions scenario used in this assessment, the emissions in 2050 would be declining but still be about 30% higher than today. For that reason, the IPCC is planning to develop scenarios incorporating earlier and more dramatic emission reductions in its future assessments.

For the most part, the projections of impacts under the lower and higher emissions scenarios are similar or only modestly different at the middle of the 21st century. This is hardly surprising because the cumulative emissions are little different between the two scenarios by that point in time (Figure 3.3). The differences become starker towards the end of the century, even though the lower emissions scenario shows only about a 50% reduction in emissions by that time. Thus, the lower emissions scenario projections represent what might be considered the maximum change that could be expected if the mitigation strategies now being advanced in international negotiations are implemented. With that in mind, the following are some of the more severe impacts projected for late 21st century climate change in Maryland that could potentially be avoided by global action to reduce greenhouse gas emissions during the first half of century:

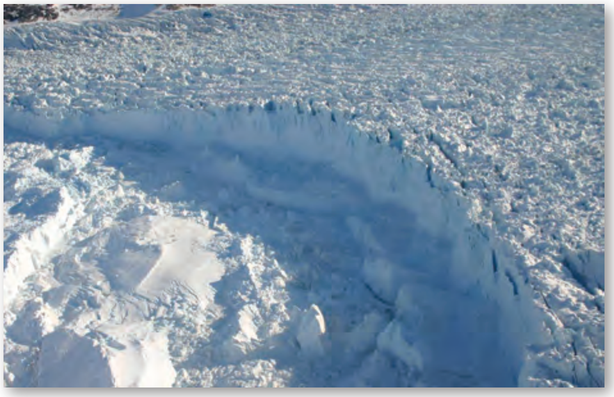
- Sea-level rise of up to 3.5 feet as opposed to less than 2 feet; the loss of virtually all coastal wetlands; inundation of more than 100 square miles of presently dry land and loss of the homes of thousands of Marylanders; and the likely initiation of a 20-feet or more rise in sea level in later centuries as a result of unstoppable melting of polar ice sheets.
- Heat waves lasting most of the summer, with an average of 30 days each summer exceeding 100°F (like Phoenix but with high humidity) creating life-threatening conditions in Maryland's urban environments during most years; and increased respiratory health risks due to ground-level ozone concentrations unless pollution emissions are dramatically reduced.

Wikipedia Commons

Record energy use and heat waves often coincide.

- More extreme rainfall events, but also longer lasting summer droughts, not unlike the unusual conditions seen in Maryland over the past year.
- Declines in agricultural productivity, which may be initially enhanced due to warmer temperatures and higher carbon dioxide concentrations, as a result of severe heat stress and the summer droughts.
- Reduced forest productivity and ability to sequester carbon, after a modest increase during the first half of the century, as a result of heat stress, seasonal droughts, and outbreaks of pests and diseases; the loss of maple-beech-birch forests of Western Maryland and an increase in pine trees in the landscape of the rest of the state; and the withdrawal of northern bird species such as the Baltimore oriole from Maryland.
- The permanent loss of important species such as eelgrass and soft shell clams from the Chesapeake Bay; highly stressful summer conditions for striped bass and other fish as the dead zone expands and surface waters heat up; and a substantially more difficult challenge in restoring the health of the Bay by reducing nutrient pollution.

Limiting the projected impacts in this assessment to the 21st century undervalues the full benefits of mitigation of greenhouse gas emissions taken early in the century. The impacts of unmitigated climate change will not stabilize in 2100 but continue beyond, in some cases at an accelerated pace. In fact, some responses have a long lag effect, meaning that the effects will continue to grow over centuries.[2] This is particularly true for sea-level rise


NASA/Wallops

This image shows the calving front, or break-off point into the ocean, of Helheim Glacier, located in southeast Greenland. The image, taken in May 2005, shows high calving activity associated with faster glacial flow. This glacier is now one of the fastest moving glaciers in the world.

because of the slow process of warming the ocean and the continued melting of polar ice sheets. If emissions continue to grow at the pace of the higher emissions scenario or greater, it is likely that the climate system will be committed to an accelerated melt down of the polar ice sheets over the next few centuries that could not be stopped by reducing greenhouse gas emissions. Lest one think that is such a long time in the future, remember that European colonization of Maryland began 374 years ago and Maryland became a state 227 years ago.

Impacts of climate change will not stabilize in 2100, and sea level will continue to rise

Changing conditions affect mitigation

Conditions will change in ways that affect mitigation options. For example, forests that are stressed by heat and low soil moisture during the summer will cease to take up and hold (or sequester) carbon from the atmosphere. Instead, they will tend to release stored carbon back into the atmosphere as carbon dioxide. Heat stress will increase the demand for air conditioning and extend the cooling season. At times, air conditioning will not be a luxury, but a matter of survival. This would offset mitigation savings through energy conservation and increase peak electricity demand, which determines the generation capacity required.

Some of the projected climate changes are likely to make the accomplishment of present environmental objectives more difficult, for example, attaining ozone concentration standards by reducing air pollution or achieving the Chesapeake Bay restoration goals by reducing nutrient agricultural and urban runoff of nutrients and sediments. However, most of the projected impacts of climate change will not be realized until the middle of the century or later, and some are not yet very predictable. Therefore, there is ample opportunity to continue to pursue those environmental objectives aggressively because this would lessen the impacts of climate change later on. Freezing action due to the uncertain effects of climate change would result in unavoidable and more severe consequences.

ADAPTATION

Sea-level rise and coastal vulnerability

Based on the current scientific understanding of the complex processes that will affect future sea level as considered in the projections of this assessment, it is prudent to plan now for one foot of relative sea level rise by the middle of the century and at least two feet by the end of the century. For major, long life-time investments in property and infrastructure, it would be prudent to consider an additional margin of safety by planning for a four foot rise in sea level. New observations of the global and local rates of sea level rise, new scientific understanding of the processes of melting of polar ice sheets, and improved capabilities for long-range storm forecasting could alter this advice, but more severe impacts are not likely to be realized until the second half of the century. Consequently, plans and policies should be periodically reevaluated with regard to this emerging understanding and the progress in reducing greenhouse gas emissions.

Subsequent adaptation strategies

The Maryland Commission on Climate Change will


Adrian Jones

Coastal development is vulnerable to sea-level rise and storm surge.

continue to evaluate adaptation strategies in addition to sea-level rise and coastal vulnerability over the next year or more. Although detailed evaluation of adaptation options is beyond the scope of this report, the assessments provided here should serve as a useful basis for evaluation of adaptation strategies appropriate for Maryland in the areas of human health (heat and respiratory stress), water resources (particularly emphasizing the Potomac Basin, groundwater resources, and reducing the effects of urbanization on flooding and stream health), forest management (changing sequestration potential and managing forest succession, diseases and pests), and restoration of the Chesapeake Bay and Maryland's Coastal Bays (building on the recent analysis of the Scientific and Technical Advisory Committee of the Chesapeake Bay Program). These issues are ripe for further evaluation by the Commission.

Monitoring, assessment, and forecasting

In general, there is insufficient monitoring of Maryland's climate, environmental conditions, and resources to characterize their present state and variability. Now that we realize that all of these are changing and will be changing more rapidly in the future, a better system of observations is required—one that is reliably continuous, strategically targeted, and thoroughly integrated. Reliable observations, interpreted with scientific understanding, and innovative models can dramatically reduce uncertainty about the path of climate change in Maryland and its consequences, allowing us to make better informed and wise decisions about the State's future. It is clear that traditional approaches to adaptation will not suffice in a future that no longer resembles the past. Climate models can be downscaled to incorporate locally important phenomena, such as urban heat island and forest cover effects, and resolve important differences across our slice of the Mid-Atlantic landscape.

Maryland is in a strong position to become a national and international leader in regional-to-global climate change analysis and its application to mitigation and adaptation. There is already considerable, world-recognized expertise within our public and private universities on which to build. And, Maryland has the unmatched advantage of the location of the Goddard Space Flight Center, which leads the National Aeronautics and Space Administration's earth science program at Greenbelt; headquarters of the National Oceanic and Atmospheric Administration's line offices at Silver Spring; and National Weather Service's Climate Prediction Center soon to be relocated to College Park. Marshalling and enhancing this capacity for continually improving climate impact assessment would greatly benefit not only our State of Maryland, but our planet, Earth.

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Jane Hawkey

Turk’s Cap lily, a native of the Chesapeake Bay watershed.