PREPARING FOR A CHANGING CLIMATE

The Potential Consequences
of Climate Variability and Change

Mid-Atlantic Foundations

A Report of the Mid-Atlantic Regional Assessment Team

Compiled by

Penn State's core MARA Team:

Ann Fisher, David Abler, Eric Barron, Richard Bord,
Robert Crane, David DeWalle, C. Gregory Knight,
Ray Najjar, Egide Nizeyimana, Robert O'Connor,
Adam Rose, James Shortle, Brent Yarnal

and the research associates, assistants,
and external collaborators listed in Appendix A

Sponsored by

The U.S. Environmental Protection Agency,
Office of Research and Development,
Global Change Research Program
(Cooperative Agreement No. CR 826554-01)
with Janet Gamble as Project Officer

and the following Pennsylvania State University units:

Earth System Science Center and
Center for Integrated Regional Assessment
within the College of Earth and Mineral Sciences,
Department of Agricultural Economics & Rural Sociology
and the College of Agricultural Sciences,
and the Environmental Resources Research Institute

December 2000

About this publication

This Foundations report documents the methods, findings and recommendations from the first two years of the Mid-Atlantic Regional Assessment (MARA) of potential impacts from increased climate variability and change. The MARA examines both beneficial and damaging impacts, accounting for how people and ecosystems are likely to respond to these changes.

The Foundations report provides details that back up the summary presented in *Preparing for a Changing Climate–The Potential Consequences of Climate Variability and Change: Mid-Atlantic Overview* (Fisher et al. 2000). It is intended as a companion to the *Overview*, with more depth for use by officials elected at the federal, state and local level and by people in their role as citizens, business employees, and members of community or other organizations. It also gives additional regional texture to complement the reports prepared by the National Assessment Synthesis Team.

Our assessment includes two key features: 1) an interdisciplinary approach using the best science available, and 2) substantial stakeholder participation. Aided by financial support from the U.S. Environmental Protection Agency (EPA), Penn State's MARA team (i.e., the core faculty, research associates and assistants, and external collaborators, listed in Appendix A) is committed to an integrated assessment approach. Few studies have taken an integrated approach at the scale of a region such as the Mid-Atlantic, so our initial plan was to demonstrate the MARA approach on two or three sectors likely to be affected by climate change. Meetings with our Advisory Committee confirmed available research suggesting a broad range of potential impacts, with none overwhelming the others for this region. This convergence of scientific implications and stakeholder interests led to assessing impacts for each of the following: agriculture, forests, water resources, coastal zones, ecosystems and human health. Their order of coverage reflects linkages among the first four that tend to flow downstream; ecological and human health impacts are more cross-cutting. The assessment focuses on the year 2030 because the discussion of impacts for 2100 (the other date emphasized in the National Assessment) is necessarily more speculative.

My thanks to each MARA team member for the enthusiastic teamwork that accomplished an astounding amount on a very compressed schedule. Appendix A lists them as well as our large Advisory Committee. Synergism between researchers and the Advisory Committee has resulted in many modifications and improvements. On behalf of the MARA team, thanks to the Advisory Committee members for their insights and thoughtful responses to our requests. Special thanks to EPA Project Officer Janet Gamble, and to William Pike and Rose Ann Alters (who did the report's layout). Thanks also to Otto Kinne of Inter-Research, who arranged copyright permission for our use of manuscripts from *Climate Research SPECIAL 2000* (*CR* Volume 14:2); specific articles are identified at the beginning of each chapter below. This report includes additional analyses and commentaries.

Three features can help in getting the most from this report: 1) the glossary in Appendix D, 2) the list of acronyms in Appendix E, and 3) a broad range of information available on the MARA web site http://www.essc.psu.edu/mara/.

A March 2000 draft was circulated for peer review. Experts and members of the MARA Advisory Committee provided thoughtful, often extensive comments on the March draft. An August 2000 revision incorporated changes in response to the peer review comments, and was placed on the MARA website (www.essc.psu.edu/mara) for a 60-day public-comment period. This final report has been improved by incorporating the constructive suggestions from peer reviewers and the public. For those who may have printed the August 2000 version, this final report has changes in the coastal and ecosystem chapters, and in the response document (in addition to this “about this publication” section). Otherwise the changes are cosmetic – to indicate the report’s final status. We describe how we responded to each comment in the Comment Response Document that appears along with this December 2000 Foundations report.

Our next step is to conduct more targeted Phase II MARA activities. When results are available, they also will be posted on the MARA website. In the meantime, the MARA Team looks forward to your comments (e-mail: fisherann@psu.edu; phone: 814-865-3143; fax: 814-865-3746; mail: PSU/AERS, 107 Armsby Building, University Park, PA 16802).

Ann Fisher
December 2000

Table of Contents

Setting the Stage

Chapter 1. Introduction[*]

The widespread drought in the Mid-Atlantic region during the summer of 1999, followed by the largest peace-time evacuation in U.S. history to protect people from Hurricane Floyd, are reminders of how much weather and climate influence people and their well-being. Growth in population and the corresponding increase in impervious surfaces lead to more severe impacts from the same shortfall in precipitation (as prior to growth), or from the same intensity of hurricane. It is challenging to understand interactions among influences such as population growth, changes in land use, and climate variability, to determine the seriousness of consequences from these interactions, and to evaluate options for moderating undesirable consequences. Fortunately, emerging integrated assessment techniques can help with such challenges.

Integrated assessment uses diverse perspectives and many types of expertise to focus attention on the most important aspects of a societal issue (Carter et al. 1994). Integrated assessment accounts for the interaction among influences and can identify which influences will make the situation better or worse. It can be a starting point for evaluating individual, community and societal actions to improve the situation. It also highlights what is known and what is not known about the issue and alternative actions. The assessment process described here examines the regional implications of climate change. The results are intended as input for making smarter decisions in the Mid-Atlantic region, as related to climate change. However, the description also can be the basis for similar integrated assessments of other issues, ranging from population growth to land use change to education to health care.

The First National Assessment

Noting that "industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few generations" the U.S. Congress passed the Global Change Research Act of 1990 (P.L. 101-606). This Act requires the US Global Change Research Program (USGCRP) to report to the President and Congress, at least every four years, on the potential

[*] This chapter is based on Fisher, Neff and Barron, (2000) "The Mid-Atlantic Regional Assessment: Motivation and Approach," *Climate Research*, 14:2. It appears with permission of Inter-Research.

national impacts of global change.

In 1997 the National Science and Technology Council (NSTC) Subcommittee on Global Change Research (SGCR), which coordinates the USGCRP, initiated the First US National Assessment. It focuses on the local, regional and national implications of climate variability and climate change. The organizational structure for this assessment is shown in Figure 1.1 and described below.

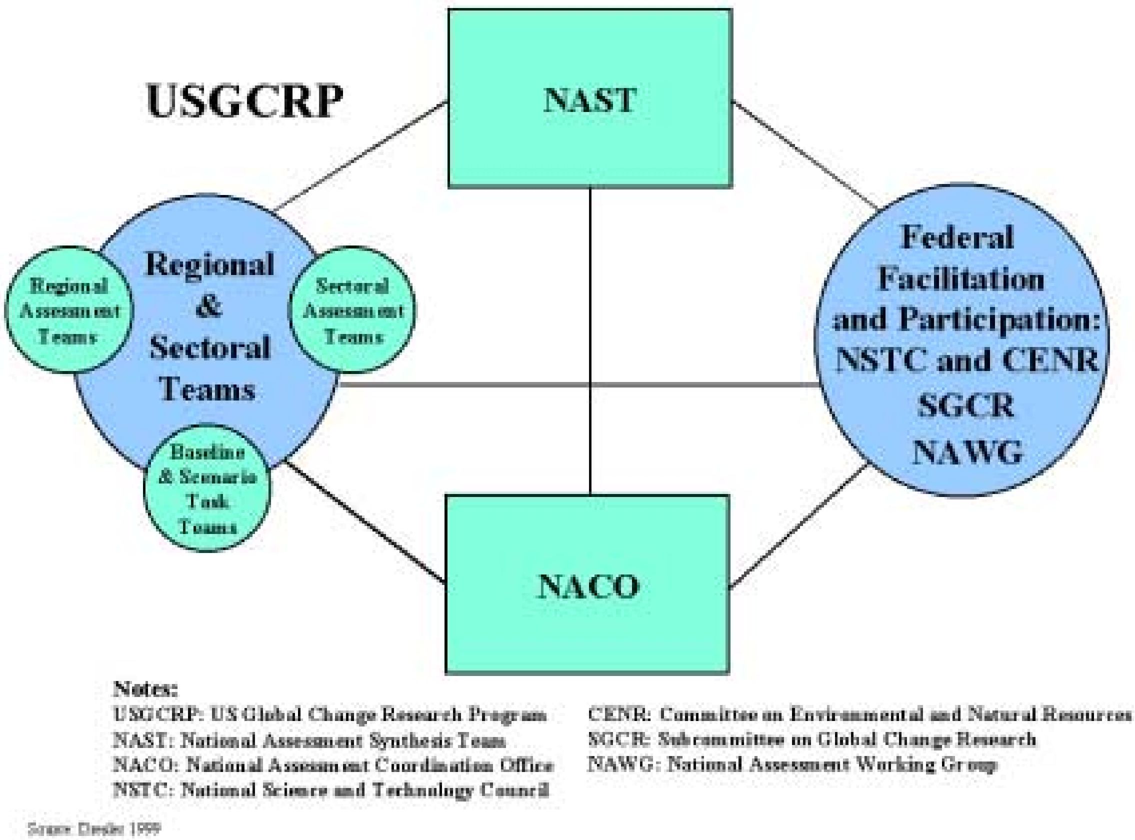


Figure 1.1. Organizational Structure for the National Assessment.

Some of the processes regulating vulnerability to climate change operate at local scales and thus the impacts of climate change will differ across regions. Such differences could be missed in aggregate national and global studies, so the USGCRP has been collaborating with federal agencies (represented in the National Assessment Working Group, NAWG) to sponsor 19 regional workshops that span the nation and its territories, including a working group for Native Peoples/Native Homelands (Figure 1.2). Assessments are being conducted for 16 of these. The

USGCRP also has sponsored nation-wide assessments of five cross-cutting "sectors:" coastal areas and marine resources, fresh water, agriculture, forests and human health.

The over-arching goal is to provide scientific information useful to society by identifying how people and their surroundings will be affected by climate change, how individuals and communities can take advantage of opportunities and reduce vulnerabilities resulting from climate change, and what additional information and research are needed to improve decisions related to impacts from climate change. Note that these assessments are not examining the need for, or ways to accomplish, reductions in greenhouse gas emissions; other activities are exploring these issues. The assessments are challenging because of the uncertainties in projecting climate change as well as how society will evolve with or without climate change. They are unique because of their reliance on multi-disciplinary integrated approaches and substantial stakeholder participation. The integrated approach used for the Mid-Atlantic Regional Assessment (MARA) is introduced in the next section of this chapter. Stakeholder participation is described throughout, and in Appendix C.

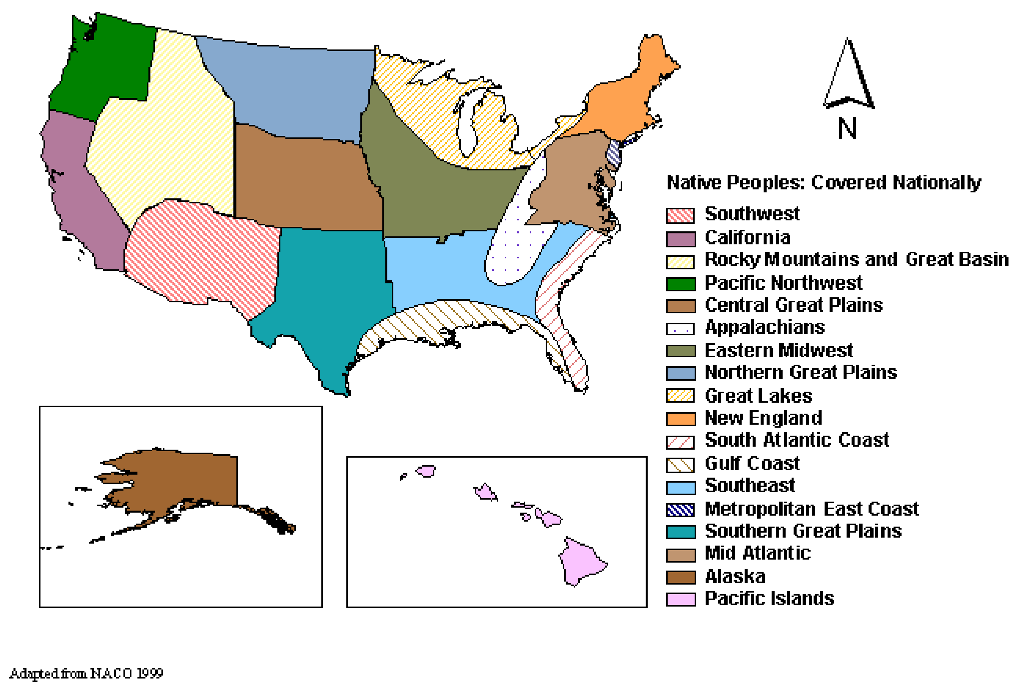


Figure 1.2. US National Assessment Regions.

The SGCR set up an interdisciplinary National Assessment Synthesis Team (NAST), whose members represent academia, government and business. Summarizing the potential national impacts from changes in climate and climate variability, the NAST is expected to integrate, evaluate and interpret findings, and discuss the uncertainties associated with the findings.

As shown Figure 1.1, the National Assessment Coordination Office (NACO) has provided support to the NAST as well as coordination among the Federal participants and the regional and sectoral teams. A November 1997 US Climate Forum elicited input from experts and stakeholders about the scope for a national assessment. The teams planning and working on the national, regional and sectoral assessments gathered about once a year for in-person sharing of methodologies, data and insights. The NACO also has set up meetings for the NAST. Ideally, the regional and sectoral assessments would have been coordinated to ensure comparability and completed before the NAST conducted its synthesis. In reality, unevenness in funding and the challenges of conducting such complex integrated assessments combined to make some assessments start late or progress more slowly than anticipated. The short period for planning and executing the suite of assessments has meant that some of the regional and sectoral assessments were not available in time for the NAST to use in its synthesis report. However, interaction among the assessment teams has allowed the NAST report to convey important differences across regions and sectors.

The NACO also maintains the National Assessment Web-site (http://www.nacc.usgcrp.gov/), which includes the newsletter, *Acclimations*. The NACO and the Federal participants provided models, data and projections to enable comparability across the regional and sectoral assessments. These include socioeconomic projections to the year 2050 at a county level, for a range of potential futures that might occur in the absence of climate change (NPA 1999), historic climatology for the period 1895-1993, and general circulation models that simulate from 1895 to 2100 (thus overlapping the historical climatology). Chapters 2 and 3 provide more detail on the economic and climate models. Assessment teams have been encouraged to use additional models and data applicable for their regions or sectors, and to consider the "what if" implications of extreme climate or socioeconomic conditions.

The Intergovernmental Panel on Climate change (IPCC) has been working on its third (global) assessment simultaneously with the US National Assessment activities, which has led to substantial interaction among individuals responsible for different components of the National and IPCC assessments. These interactions include sharing of models, data and perspectives.

The assessments are intended to be open, comprehensive and iterative and to link scientific research to stakeholders' needs, all in the context of scientific excellence (Dresler 1999). Additional goals include providing scientific information that will enable sound decisions; fostering partnerships among stakeholders, agencies and assessment teams; building stakeholder networks; and refining the US research agenda related to potential impacts from climate change.

The first US National Assessment has been an ambitious undertaking for several reasons. First, the climate-related issues differ across sectors and regions, calling for differing mixes of disciplines across the assessments. Individuals have to communicate effectively among the disciplines represented within their own team, as well as across assessment teams. The emphasis on stakeholder participation reinforces the need for effective communication. Second, the simultaneous nature of the work by distinct sectoral, regional and national teams creates challenges so that output from one team will be timely as input for another. Third, the NAWG has been charged with developing a plan for assessments after the first US National Assessment. The form and scope of subsequent assessments will be influenced by the success of the first one. Appendix B has more information about the national assessment process.

Questions guiding the assessment

This report documents the Mid-Atlantic Regional Assessment (MARA) methods, findings, and recommendations. Four questions guide all of the National Assessment activities, with tailoring for whether the scope is national, regional or sectoral. For the MARA, these questions are:

1. What are the region's current environmental stresses and issues that provide context for impacts from climate change?

2. How could climate change and variability exacerbate or ameliorate these stresses, or create new ones?

3. What actions could increase the region's resiliency to climate variability, reducing negative impacts and taking advantage of opportunities created by climate change?

4. What are the short-term and long-term priorities for new information and research to better answer questions 1) and 2) and to evaluate adaptation options?

Assessment approach

An interdisciplinary Pennsylvania State University (Penn State) team has been leading the first Mid-Atlantic Regional Assessment (MARA) of climate change impacts. The core team includes 13 faculty members, 6 post-doctoral or associate researchers, 33 graduate assistants and 11 undergraduate interns. The core team's expertise has been expanded by substantive collaboration with another 14 researchers at Penn State and other universities plus 4 at private organizations and 4 in government. Substantial input and feedback also come from the MARA Advisory Committee (see Appendix C).

Penn State's approach to these questions is based on a framework developed by its Center for Integrated Regional Assessment (CIRA) (Knight et al. 1999) and shown in Figure 1.3. Assessment can begin at any point in the diagram; the logic follows a continuous loop. For example the assessment could 1) start with causes, 2) examine how the causes lead to climate changes, 3) project the biophysical and socioeconomic consequences of these climate changes and 4) project human responses to the consequences, and then use an iterative approach for examining the extent to which those human responses become causes.

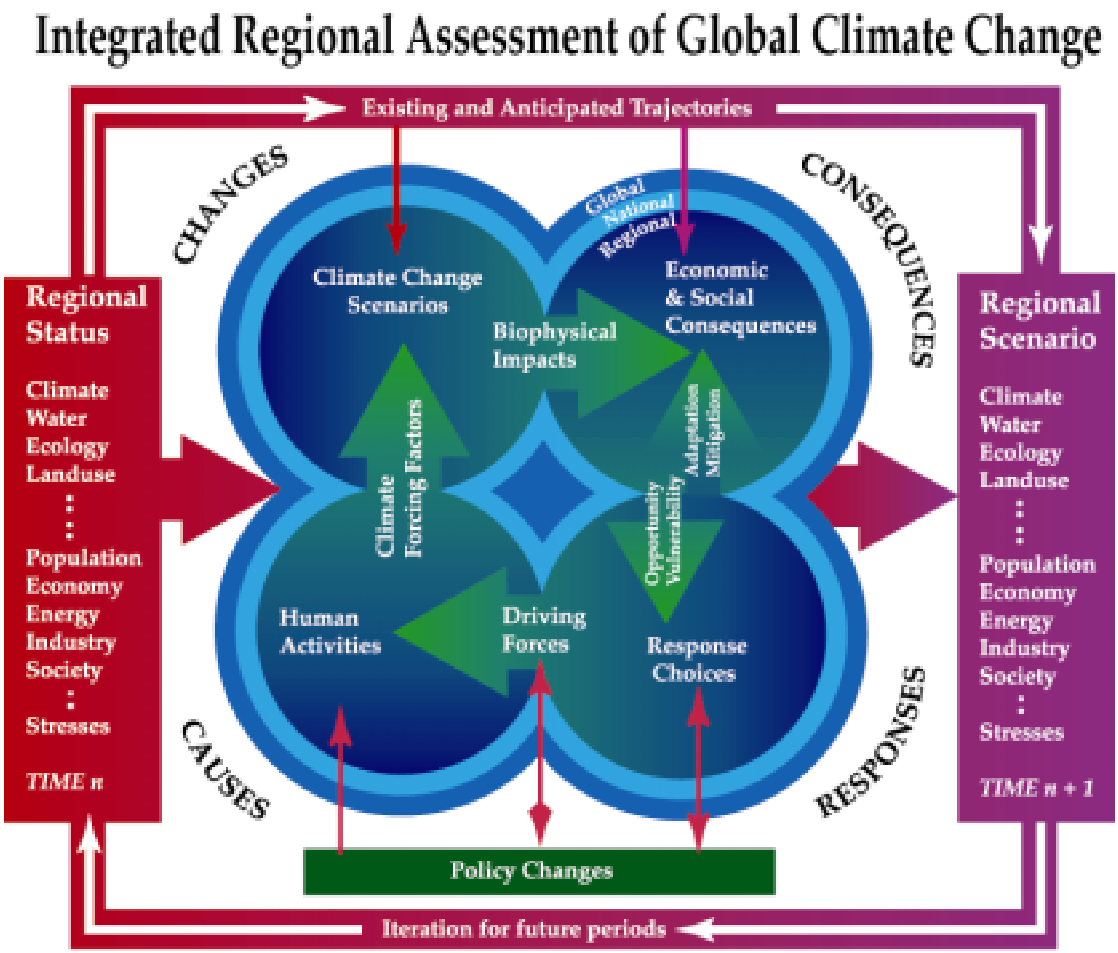


Figure 1.3. Framework for Integrated Regional Assessment of Global Climate Change.

Dialogue with the policy community and other stakeholders helps identify the most important components and focus the framework's iterative, increasingly complex quantitative and qualitative analyses. The framework diagram also accounts for hierarchical relationships among different scales. The MARA is based on the assumption that the causes of climate change are mainly outside the region, but that climate change could engender important interactions among the ecological and physical responses within the region. Because human responses include actions that in turn generate climate change at a national or global scale, the national synthesis needs to account for the aggregate effects of similar actions across regions.

The first step for the MARA has been to describe the region's land forms, natural resources, demographics, economy and climate as they are at present, with some historical context (Chapter 2). This description provides a starting point for understanding the impacts of climate change. Next, because the region's society and economy will evolve regardless of whether climate change occurs, the second step is to envision that evolution, with special attention to components that are sensitive to climate (Chapter 3). The third step is to assess how the region's climate might change over the next century (also Chapter 3). The fourth step builds on the first three, to assess the incremental impacts from climate change on the MAR (Chapters 4-9). This step accounts for the responses by people and their institutions, as well as ecosystems, to take advantage of new opportunities or to reduce damages presented by climate change. The fourth step also identifies anticipative actions that can be taken now or in the near future that would reduce vulnerabilities or enhance opportunities for the future, plus information and research still needed to improve decisions related to the regional impacts of climate variability and change (Chapters 10-11).

The enormity of the assessment task made it necessary to choose both a set of impact categories and the depth with which each would be examined. The MARA team used several criteria, including: 1) the importance of the impact category to the region's economic, social and environmental well-being; 2) expected sensitivity of the impact category to climate variability and change; and 3) the feasibility of performing a credible assessment of each impact category, given the available time and resources. In applying these criteria, we were informed by existing knowledge about the region's environmental stresses, and expectations about which ones might be affected by climate variability and change. In addition to the team members' prior research and literature reviews, our input was supplemented by participation at the Summer 1997 Aspen Global Change Institute workshop, "Preparing for a US National Assessment," the November 1997 "U.S. Climate Forum," and the Summer 1998 and Spring 1999 workshops, "U.S. National Assessment: The Potential Consequences of Climate Variability and Change." These meetings led to interactions among the teams conducting the regional assessments, the sectoral assessments, and the National Assessment.

Crucial input also came from extensive interaction with stakeholders - those who might be affected by climate change in the MAR or who might make decisions based on output from the assessment. Much of this interaction has been with the MARA Advisory Committee, which has more than 90 stakeholders and experts. An early step in this dialog was a September 1997 scoping workshop that focused on the area surrounding the Chesapeake and Delaware Bays (Fisher et al. 1999). The 92 participants represented federal, state and local government, industry, academia and public interest groups. The workshop enhanced their knowledge about climate change and its potential for regional impacts. They were enthusiastic about education and information dissemination, especially for reducing uncertainties about climate variability at scales fine enough to help water managers and farmers with their planning. They expressed strong concerns about potential impacts from sea-level rise on ecosystems and recreation and about human health impacts.

Another step in this dialog was a June 1998 researchers' meeting to explore questions raised during the September 1997 workshop and identify available data bases and current research useful for the MARA. At an October 1998 event, the MARA Advisory Committee provided input on the scope for the region's first assessment of climate change impacts. This open process showed the need to address the five major topics being emphasized in the National Assessment – forests, agriculture, fresh water resources, coastal zones and human health – as well as cross-cutting ecosystems issues.

Dialog has continued through frequent interaction with the MARA Advisory Committee, which is kept up-to-date through periodic mailings and requests for feedback. Its members have provided input on draft outlines, scenarios, meeting agendas and reports. The members met in May 1999 to react to initial findings and suggest strategies for disseminating results to potential users. Now that working relationships have been established, more recent interaction has been through e-mail, regular mail, phone calls, fax, and one-on-one meetings. Evidence of the MARA team's responsiveness to stakeholder participation is shown by the fact that more than 40 stakeholders took the time to prepare comments on the Overview draft. Its revision is more accurate and more useful as a result of their thoughtful feedback. The MARA team looks forward to working with stakeholders to develop messages and dissemination strategies that will make it easier for people to understand how climate variability and change in the MAR might affect their family, their employment, and their community–and what they might do to adapt to negative impacts or enhance positive impacts. Appendix C includes additional information about stakeholder participation in the MARA process.

The MARA Overview report (Fisher at al. 2000) summarizes baseline conditions and how human and natural systems might be affected by climate change. It brings together information about diverse beneficial and detrimental impacts in the region. The MARA team documented how they responded to the peer review comments in revising the Overview report, which has been printed as one of a set of companion documents to the National Assessment report (Fisher et al. 2000). The Overview and the documentation of responses can be found on http://www.essc.psu.edu/mara. A more technical summary of components in the Overview draft can be found in the May 2, 2000 *Climate Research* Special Issue (14:3) (*CR Special)*, which also is the basis for many chapters in this Foundations report. Material from the *CR Special* is used with the publisher's permission

This Foundations report documents the methods, findings and recommendations from the first phase of MARA activities. The MARA team now is filling gaps in the assessment. Some of these gaps are for components that could not be completed during the initial activities; others address issues identified during the assessment process as more important than anticipated, including a) interactions among sectors, b) feedback effects that could strengthen or weaken impacts, and c) consequences for special populations and special places.

Periodic updates on the continuing work are posted at the MARA web site (http://www.essc.psu.edu/mara/). Team members continue to present results at professional meetings and submit journal manuscripts for peer review. The products will serve as baselines for future assessments and as examples for others who conduct regional assessments.

References

Carter, T.R., Parry, M.L., Harasawa, H., and Nishioka, S. (1994). *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. CGER-I015-'94. University College: London.

Dresler P (1999) US National Assessment: The potential consequences of climate variability and change. MARA Advisory Committee meeting, May 2-3 1999 (accessed 1 October 1999): available at http://www.essc.psu.edu/mara/events/advisory_May99/index.html

Fisher A, Barron E, Yarnal B, Knight CG, Shortle J (1999) *Climate change impacts in the Mid-Atlantic Region--a workshop report* (to the U.S. Environmental Protection Agency, Washington DC under cooperative agreements CR 826554 and CR 824369). Pennsylvania State University, University Park

Fisher A, et al. (2000) *Preparing for a changing climate: the potential consequences of climate variability and change - Mid-Atlantic Overview*, prepared for USGCRP First National Assessment, sponsored by U.S. Environmental Protection Agency, Cooperative Agreement CR 826554. Pennsylvania State University, University Park

Knight CG et al. (2000) The CIRA framework for integrated regional assessment, appendix in *Center for Integrated Regional Assessment Progress Report*, University Park PA, (March 1): 47-50.

The Mid-Atlantic Region: Present Status and Potential Futures

In its simplest form, assessing the regional impacts from climate change is a three-step process. First, a baseline scenario is established where the contemporary status of the natural and human environments is assessed and extrapolated into the future, assuming that no climate change will occur. Second, prescribed changes in climate are imposed on the baseline account. Third, climate change impacts on the baseline variables are estimated by calculating the differences between the no climate change scenario and the changed climate scenario, at which point they are evaluated for significance. (A more detailed account of this process can be found in Carter et al [1994].) Chapters 2 and 3 contribute to the first and second steps of an ongoing assessment of likely climate change impacts for the Mid-Atlantic Region (MAR). Chapters 4 to 9 provide the more detailed sector-specific analyses necessary to achieve the third step. The basic physical and human geographies and the economy of the Mid-Atlantic Region, as well as their evolution over the past three decades, are described in Chapter 2, along with the region's historical climate. Scenarios of future economy and climate are developed in Chapter 3.

Chapter 2. The Mid-Atlantic Region's geography, economy, and climate*

Defining the MAR

Figure 2.1 shows the Mid-Atlantic region (MAR) with state boundaries. Several factors influenced the choice of regional boundaries. A primary consideration was the region's major watersheds (Chesapeake Bay, Delaware River basin, Albemarle-Pamlico Sounds, as shown in Figure 2.2), particularly because of interstate compacts that enable management across political boundaries. For example, small portions of New York are included because they are parts of the watersheds for the Chesapeake and Delaware Bays.

*This chapter is based on Polsky et al., (2000) "The Mid-Atlantic Region and its climate: Past, Present, and Future," *Climate Research*, 14:2. It appears with permission of Inter-Research.

Figure 2.1: Mid-Atlantic Region

Figure 2.2: MAR watersheds.

A second factor was the need for data on land use, land cover, and ecological characteristics. The U.S. Environmental Protection Agency's (EPA's) Mid-Atlantic Integrated Assessment (MAIA) and Mid-Atlantic Highlands Assessment (MAHA) provide baseline data on the environmental status of Pennsylvania, West Virginia, Maryland, Delaware, Virginia (and the District of Columbia) (Jones, et al. 1997). Given the economic linkages between the Chesapeake Bay watershed and the areas to its west, and the fact that many environmental and land management decisions occur at a state level, we expanded the MAR to cover all of the MAIA territory.

Third, New Jersey's western counties are in the MAR as part of the Delaware River basin. We added the southeastern New Jersey counties to ensure their inclusion among the regional assessments. Remaining portions of New Jersey, New York and North Carolina are being covered by other regional assessments.

MAR land forms and land cover

The Mid-Atlantic Region as defined for this assessment (Figure 2.1) includes all of five states (Delaware, Maryland, Pennsylvania, Virginia, West Virginia), parts of three states (south-central New York, western and southern New Jersey, northeastern North Carolina), and the District of Columbia. In all, the Mid-Atlantic Region covers about 5 percent of the land area in the 48 contiguous United States (Bureau of Census 1997).

The Mid-Atlantic region contains 358 counties intersecting four principal physiographic regions oriented along a northeast-southwest axis as shown in Figure 2.3 (Cuff et al 1989; Polsky et al. 2000). On the eastern edge, there is the relatively flat Coastal Plain, composed mostly of sedimentary rock and extending inland from the oceans and estuaries. This zone traverses all of Delaware and parts of New Jersey, Maryland, Virginia, and North Carolina. The Piedmont is the foothills region covering the eastern, lower portion of the Appalachian Mountain range. This area is composed mostly of metamorphic and igneous rock, and covers north-central New Jersey, southeastern Pennsylvania and the central portions of Maryland, Virginia and North Carolina. The Ridge and Valley zone contains primarily sedimentary rocks and exhibits folded terrain with a series of parallel, eroded mountains of equal height. This strip of land extends from the northwest corner of New Jersey to the southwest, passing through Pennsylvania, Maryland and Virginia. The Appalachian Plateau is a complex swath of land extending from the New York portion of the Mid-Atlantic Region through north-central and western Pennsylvania, the western edge of Maryland and most of West Virginia. This region is composed of rolling hills in places and relatively flat sedimentary rock in others, dissected throughout by meandering waterways (Cuff et al 1989; Marsh and Lewis 1995).

Land use and land cover in the Mid-Atlantic Region are largely defined by forest and agricultural activities (Jones et al. 1997). As shown in Table 2.1, these two categories account for about 90 percent of regional land cover. The highest concentrations of forest area are in and around West Virginia and north-central Pennsylvania. Agriculture is the predominant land use in the lowlands to the east.

The ecological health of Mid-Atlantic Region water bodies is in flux because local activities associated with economic development are generating pollution. For example, two significant sources of aquatic pollution (agriculture operations and roads located near streams) are found in many regional watersheds (Jones et al. 1997). Among the ecologically important areas of the region are the nation’s two largest estuaries, the Chesapeake Bay and the Albermarle-Pamlico Sounds. For the Chesapeake Bay, two-thirds of its nutrient and sediment loading come from upstream, non-point pollution sources. This is of particular concern given the Bay’s 350-day flushing rate, one of the slowest for a water body in the United States (NOAA 1998).

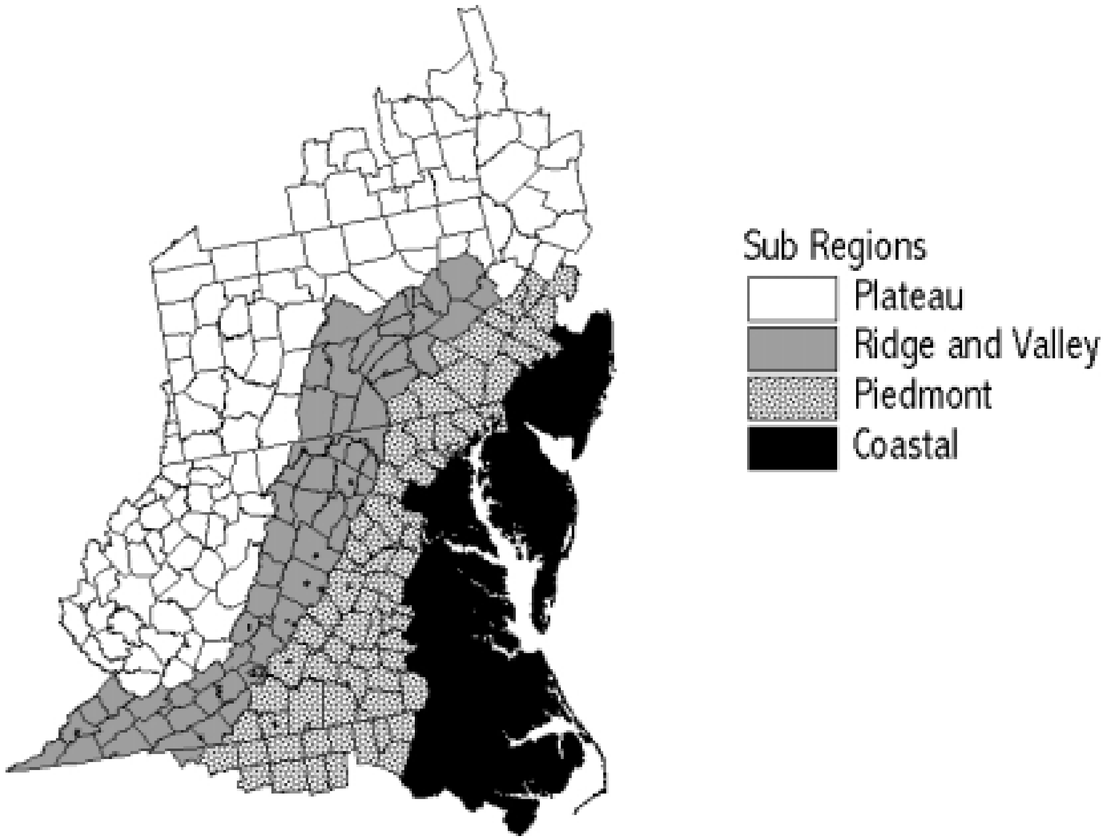


Figure 2.3. Mid-Atlantic Region counties and physiographic regions.

Table 2.1. Land use in the Mid-Atlantic Region, 1992.

Land Use Category	Percentage of Total Land Area
Forest	64.5
Agriculture	25.0
Wetlands	4.1
Commercial, Industrial, and Residential	3.6
Open Water	1.6
All Other Land Uses	1.2

Source: MARA, 1999.

The MAR population and economy

Broad economic and demographic characteristics of the Mid-Atlantic Region are provided here, by physiographic sub-region for the year 1995 (Table 2.2) and for the region as a whole for the past three decades (Table 2.3). As indicated in Table 2.2, in 1995 the Mid-Atlantic Region had a population of 35.2 million people, 20 million of whom were employed, earning a collective income of $859 billion (NPA 1998). These figures represent in each case about 15 percent of the respective US totals (Bureau of the Census 1998a), about three times the expected rate based on land area alone. Nearly ninety percent of the Mid-Atlantic Region population is under the age of 65. Close to two-thirds of the total working-age population, income and jobs are found in the eastern half of the region, i.e. the Coastal Plain and Piedmont. This eastern weighting translates into a markedly higher per capita income for these two sub-regions compared to the Ridge and Valley and Appalachian Plateau, and is associated with the relative prominence of urbanization and high value-added sectors there.

Table 2.2. Geographic distribution of important socioeconomic variables for the Mid-Atlantic Region, 1995 (percent and value).

	Coastal Plain		**Piedmont**		**Ridge & Valley**		**Appalachian Plateau**		*Totals*
Population (million people)	*36%*	12.7	*29%*	10.1	*10%*	3.5	*25%*	8.9	35.2
Age 0-19	*37%*	3.5	*28%*	2.7	*9%*	0.9	*25%*	2.4	9.5
Age 20-64	*37%*	7.6	*29%*	6.1	*10%*	2.0	*25%*	5.1	20.8
Age 65+	*33%*	1.6	*27%*	1.3	*10%*	0.5	*29%*	1.4	4.8
Income (billion 1995$)	*38%*	$327	*22%*	$277	*8%*	$70	*22%*	$186	$859
Income per Capita (1995$)	$25,794		$27,450		$19,852		$20,812		$24,417
Total Employment (million jobs)	*38%*	7.5	*30%*	5.9	*10%*	1.9	*23%*	4.5	19.7
Total Farm Employment (thousand jobs)	*19%*	48	*30%*	77	*21%*	53	*30%*	76	254

Source: NPA, 1998.

While less than 4 percent of the Mid-Atlantic Region surface area is urban, collectively the region's cities constitute an important US population concentration. Of the Mid-Atlantic Region urban areas, Philadelphia, Pittsburgh, Baltimore, Washington, D.C., Richmond, and Norfolk are among the largest cities in the United States. These cities alone have accounted for about one-half of the total Mid-Atlantic Region population since 1980 (Bureau of the Census 1998b, NPA 1998).

Table 2.3. Changes in important socioeconomic variables for the Mid-Atlantic Region: 1967-1995.

	Total Change (%)	**Average Annual Change (%)**
Total Population	19	0.6
Age 0-19	-16	-0.6
Age 20-64	34	1.0
Age 65+	72	2.0
Income	116	2.8
Income per Capita	82	2.2
Total Employment	55	1.6
Total Farm Employment	-42	-2.0

Source: NPA, 1998.

The Mid-Atlantic Region population increased by approximately 20 percent between 1967 and 1995, a rate of about 0.7 percent per year on average (Table 2.3). This trend is considerably lower than for the nation as a whole, which grew by 33 percent at a rate of 1 percent per year (Bureau of the Census 1998a). The Mid-Atlantic Region has experienced a steady increase (1.0 percent per year) of working-age residents since the late-1960s, and a steady decrease (0.6 percent per year) of people under the age of twenty, although in recent years this latter trend has reversed. In contrast, the elderly population in the Mid-Atlantic Region grew by about 70 percent during the same period (2.0 percent per year).

Inflation-adjusted aggregate income more than doubled over this period, and real per capita income grew by 82 percent (Table 2.3). Income in the services sector recorded the largest growth over the period, over 300 percent (NPA 1998). Total employment has increased by more than half since 1967, fueled largely by non-farm industries such as services, which more than doubled over the period (NPA 1998). In contrast, farm-related employment declined by almost one-half. From an economic perspective, agriculture in the Mid-Atlantic Region is becoming progressively less important over time, reflecting the broader national trend (Shane et al. 1998).

The region's annual output ($1.67 trillion in 1995) amounts to about 13 percent of the nation's (IMPLAN 1997). Manufacturing and Services are the largest economic sectors, accounting for 26 percent and 20 percent of MAR output respectively. Sectors directly sensitive to climate–Agriculture and Forestry–each represent about 1 percent of the region's gross output.

Input-output analysis shows strong linkages among economic sectors in the MAR, with all industries except Agriculture and Mining (at the broad 1-digit Standard Industrial Classification or SIC level) purchasing between 50 and 80 percent of their intermediate inputs within the region. This means that activity in one part of the region's economy can have ripple effects in other sectors. The region also is highly integrated with economies in the rest of the nation and the rest of the world. For example, imports are 32 percent and exports are 28 percent of the region's total gross output. Agriculture, Mining, and Manufacturing account for the largest shares of this trade. The region's economy also is affected by migration, tourism, and communications. These linkages to other regions provide a buffer against impacts within the MAR. They also transmit impacts from other regions to the MAR. Appendix F has more detail about alternative economic approaches for measuring intra- and interregional economic linkages and their changes.

Human stresses on the environment

The region's relatively large population (15 percent of the nation's population in 5 percent of the contiguous land area) and economic development have stressed many of its ecological resources, particularly the nation's two largest estuaries: the Chesapeake Bay and Albemarle-Pamlico Sounds. These estuaries, along with the Delaware River basin, are stressed by nutrient runoff from agricultural and urban areas. The region's forests, wetlands, and fresh water streams are affected by habitat loss and degradation, pollution and nonnative invasive species. The primary habitat threats for these ecosystems are forest fragmentation and loss, wetland drainage, stream channelization and dams. Existing and future ecosystem stresses are described more fully in Chapter 8.

MAR climate

Box 2.1 distinguishes between weather and climate. Over the period 1895-1997, the mean annual temperature of the Mid-Atlantic Region was approximately 52° Fahrenheit (11°C), while the mean monthly precipitation was about 3.4 inches (87 mm) (calculated from the data in Figure 2.4). Temperature experienced a minor upward linear trend over the period ($y = 0.0024X + 10.828$, based on the metric temperature figures), which amounts to an increase of approximately 1°F (0.5°C). A second order polynomial fits the temperature data better than the linear trend line, however, and shows that temperature trended upward in the first half of the data record but trended downward in the second half. Precipitation rose roughly 10 percent ($y = 0.0892X + 82.236$, based on the metric precipitation figures); a linear trend fits the precipitation data better than any low-order polynomial. Within these regional averages and trends, there were significant interannual and interdecadal variations, regional trends, and counterintuitive changes in extremes.

Box 2.1 Weather and Climate

*Distinguishing clearly between weather and climate can improve understanding of this section. **Weather** is the hour-to-hour and day-to-day state of the atmosphere, such as being rainy or sunny, warm or cold, windy or calm. **Climate** can be thought of as average weather, and encompasses a locale's typical weather patterns as well as the frequency and intensity of storms, cold outbreaks, and heat waves.*

*Some reports define climate variation as natural variation in climate, and climate change as those variations and trends in climate attributable to human activity. For this report, whether the cause of an impact is natural or anthropogenic is less important than whether it has to do with long-term trends or shorter patterns of variation. Thus we use more intuitive definitions: **climate variability** refers to day-to-day, year-to-year, and decade-to-decade patterns of weather and climate. **Climate change** refers to longer term trends in average weather and climate, usually measured by temperature and precipitation.*

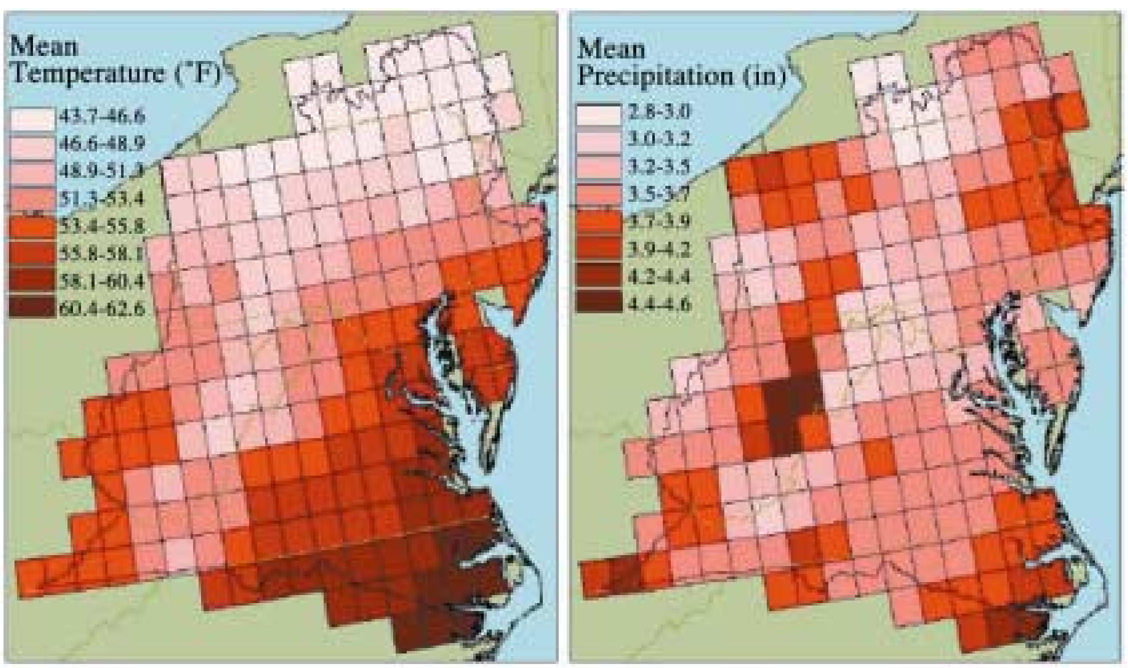


Figure 2.4. Observed mean annual temperature and mean monthly precipitation over the Mid-Atlantic Region, 1985-1997. The VEMAP methods and data used to calculate the 0.5 degree latitude-longitude grids are described in Kittel et al. (1995) and Rosenbloom and Kittel (1999).

Recent climate variation

There are clear relationships among the precipitation and temperature variations of the Mid-Atlantic Region (Figure 2.5). In general, from the beginning of the record to about 1930, the climate was cool and dry. The early 1930s saw a couple of exceedingly hot, dry years associated with the Midwestern Dust Bowl. This short, sharp drought was followed by nearly three decades of relatively warm, moist climate. This period was in turn followed by a cool and very dry climate in the 1960s. In contrast, the 1970s were exceedingly wet, but varied between warm and cold. Since the late 1970s-early 1980s, precipitation and temperature have varied dramatically above and below the long-term mean.

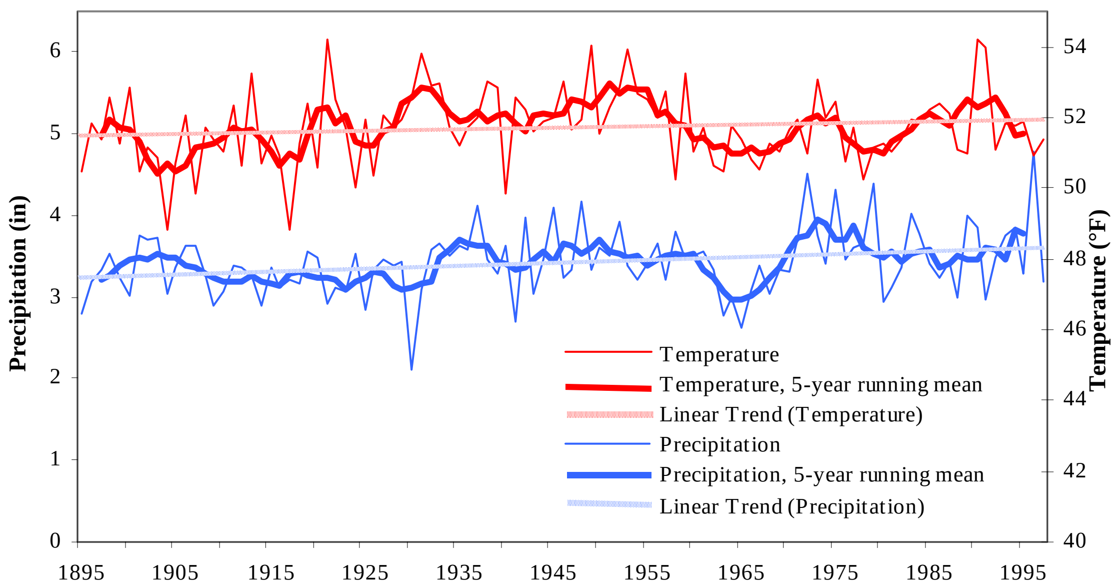


Figure 2.5. Mean monthly precipitation (inches) and mean annual temperature (°F) in the Mid-Atlantic Region, 1895-1997. The thin line denotes average annual values, while the bold curving line is a five-year running mean and the bold straight line is a linear trend. For this analysis, the MAR is defined by the watershed boundaries of the Chesapeake and Delaware Bays (Fig. 2.2). Data are derived from the US climatic divisions data set (Guttmann & Quayle 1996).

The variations in Mid-Atlantic Region climate since World War II can be explained by changes in the atmospheric circulation. (Earlier periods lacked the upper-air data needed to make the following generalizations. See Box 2.2 for more about climate measurements.) A zonal regime dominated the atmospheric flow over North America through the late 1940s and early 1950s (Yarnal and Leathers 1988). (Figure 2.6 illustrates typical flow regimes over North America.)

Box 2.2 Climate History in the Mid-Atlantic Region

Even the short record of measurements can help in understanding climate. For example, observations of winds up to 10 miles above the Earth's surface have been available only since World War II. These show that changes in atmospheric circulation can explain variations in MAR climate. A strong west-to-east atmospheric flow prevailed over North America through the late 1940s and early 1950s (Yarnal and Leathers 1988), producing average to slightly above-average temperatures and variable precipitation over the MAR. Then the circulation shifted to a weaker north-to-south flow that became entrenched by the 1960s. A deep trough of continental polar air and a storm track southeast of its long-term position prevailed during this decade, so that precipitation often fell off the Atlantic coast. This regime led to a relatively cool, dry MAR climate. The MAR experienced higher temperatures and more precipitation when the trough migrated westward during the 1970s. Since the late 1970s, large variations in the shape and positioning of the month-to-month and year-to-year jet stream flow over North America have produced a highly variable surface climate.

Insights about earlier climate can be gleaned from cores taken from sediments of the Chesapeake Bay (Cronin et al. 2000), from tree rings (Cook and Jacoby 1977, 1983), and from diaries, newspapers and periodicals (Baron 1995). Such paleoclimate reconstructions suggest as much climate variability in the MAR during the 16th-19th centuries as observed during the 20th century. Especially noticeable are "megadroughts" in the 16th and 17th centuries that were more severe than 20th century droughts, as well as very wet periods that occurred once or twice every century and lasted nearly 20 years. The effects of El Niño-Southern Oscillation events and the North Atlantic Oscillation also are observed in the record (Cronin 1997).

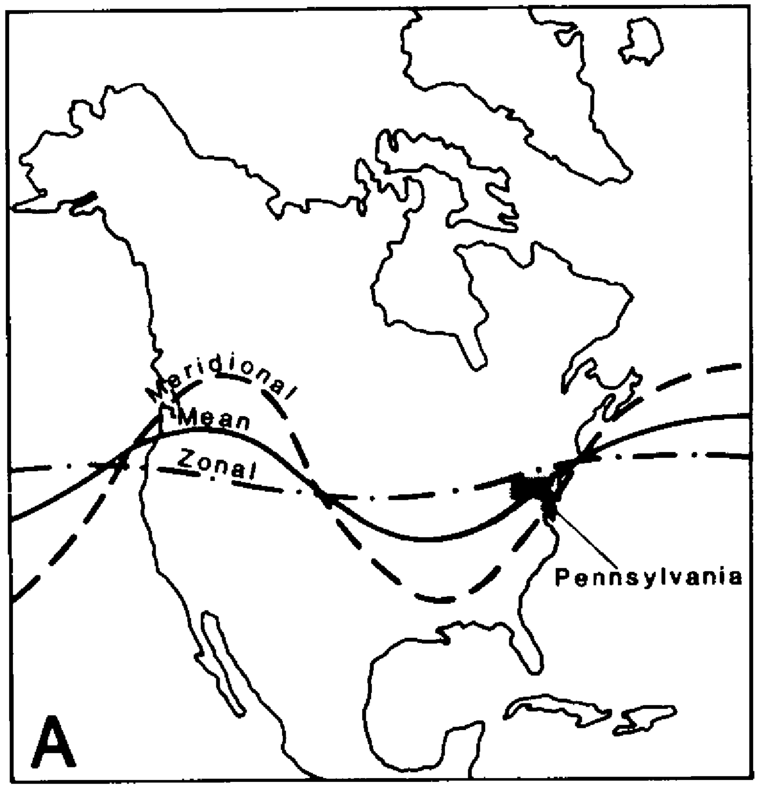


Figure 2.6. The average positions of the Polar Front Jet stream during meridional, zonal, and average flow regimes (modified from Yarnal and Leathers, 1988).

Such a regime produced normal to slightly above-normal temperatures and variable precipitation over the Mid-Atlantic Region. Then in the mid- to late 1950s, the circulation experienced a transition from zonal to meridional flow, and became fully entrenched by the 1960s. During this decade, the Mid-Atlantic Region was influenced by an anomalous, deep trough of continental polar air and a storm track southeast of its long-term mean position, with precipitation often falling off the Atlantic coast. This regime promoted a relatively cool, dry climate. The early 1970s saw the continuation of this meridional regime, but the average position of the trough migrated westward, putting the storm track over the Mid-Atlantic Region. This change raised temperatures and caused a significant increase in precipitation. Finally, the mid-to-late 1970s brought a large change in the atmospheric circulation. The period following this transformation––which has extended to the present—has been associated with unusually large variations in the shape and positioning of the month-to-month and year-to-year jet stream flow over North America.

It is not possible to determine the direct causes of these intra- and inter-annual variations in circulation, but limited previous (e.g., Yarnal and Leathers, 1988) and ongoing work (e.g., Cronin 1997, Cronin et al. 2000) suggests associations between the variations and global-scale circulation anomalies, such as the Pacific-North American pattern and the North Atlantic Oscillation. The Pacific-North American pattern and the North Atlantic Oscillation are the two most common teleconnection patterns in the Northern Hemisphere and have been well-known to climatologists for decades. Teleconnection patterns link the climates of distant places because the planetary atmosphere is a continuous fluid medium; when a change takes places in one region, it affects many downstream areas. On decadal scales, major shifts in the planetary-scale circulation were observed in the mid- to late 1950s (e.g., Kalnicky 1974, Balling and Lawson 1982) and in the mid-1970s (e.g., Trenberth 1990). Such major variations in circulation have produced a highly variable surface climate.

Extremes

An extreme weather or climate event is one that lies outside the normal range of weather or climate for a particular place and, therefore, is infrequent or rare. Determining the historical frequency of regional extreme events is crucial to a regional climate change impact analysis because severe storms, heat waves, droughts, arctic air outbreaks and other such events have the potential to cause human and ecosystem hardship. Unfortunately, finding trends in the occurrence of extreme events in the historical climate records is difficult because extreme event data are seldom collected systematically. However, it can be concluded *a priori* that if climate change results in more extreme weather and climate, then the current estimates of climate change impacts (which typically exclude this dynamic) will prove to be too optimistic and will therefore require more costly adaptive measures (Francis and Hengeveld 1998).

Notwithstanding the lack of direct data on extreme events, it is possible to infer these events from daily climate data. The limited findings are at odds. For temperature, Baron (1995) found that the number of very hot summer days in the region appears to be decreasing. At the same time, he observed that the last frost of spring is coming progressively earlier and that there are fewer very cold winter days; i.e., winters are warming. Overall, he found the regional climate to be moderating. In contrast, using 13 stations in the Historical Climate Network (HCN) located in the Mid-Atlantic Region (Figure 2.7), we discovered that from 1931 to 1997 the average number of days per year with maximum temperatures above 90°F (32.2°C) decreased linearly from roughly 23 to 16 (Figure 2.8a). Over the same period, the average number of days per year with minimum temperatures less than 0°F (-17.8°C) had a slight linear increase from 2.6 to 3.0 (Figure 2.8b). Thus, we did not find the overall moderation observed by Baron.

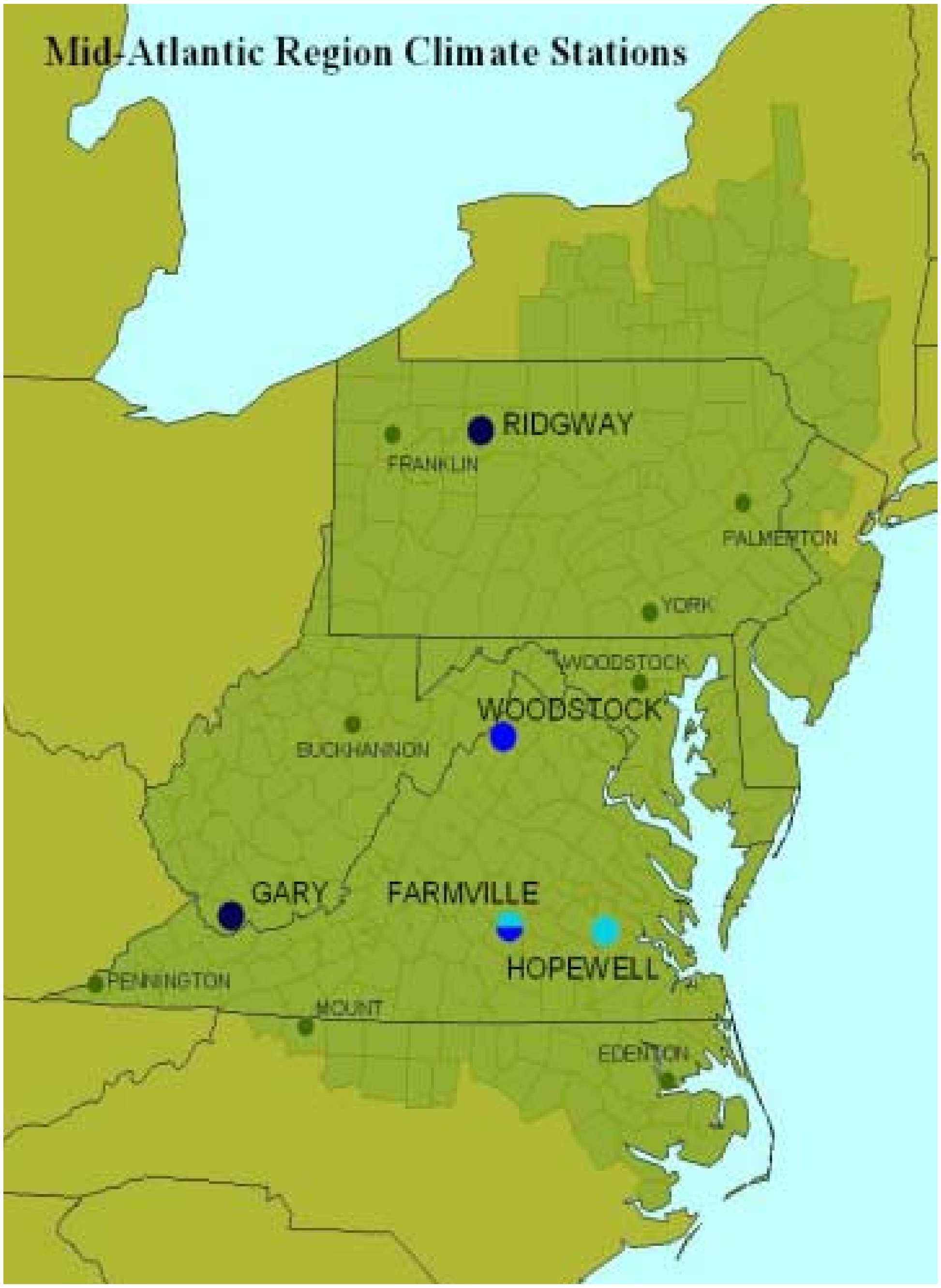


Figure 2.7. Thirteen stations from the Historical Climate Network daily data set (T. Karl, personal communication) used in the analysis of extreme daily events and of intra-regional variation. Colors are keyed to the transects used in the intra-regional analysis.

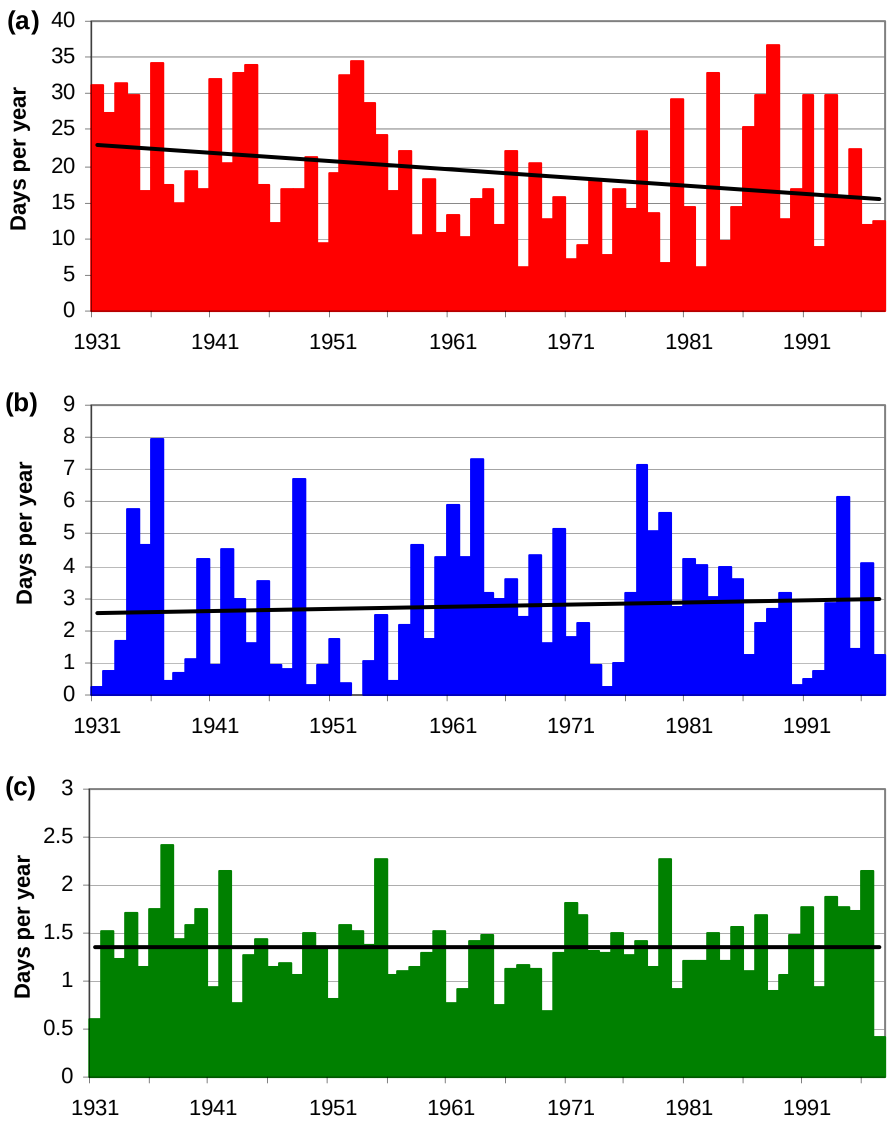


Figure 2.8. Interannual variation in selected extreme events for the Mid-Atlantic Region, 1931-1997: (a) days per year with temperatures exceeding 90°F (32.2°C); (b) days per year with temperatures less than 0°F (-17.8°C); and (c) days per year with precipitation total exceeding 2.0 inches (5.08 cm) in 24 hours. Data derived from the Historical Climate Network daily data set (T. Karl, personal communication).

Karl et al. (1996) found that extreme precipitation, expressed as the number of rainfall events exceeding 2 inches (5.08 cm) in 24 hours, has increased in the Mid-Atlantic Region during the 20th Century. Karl and Knight (1998), using another measure of extreme precipitation for the same century-long window, had similar results. These statistically significant findings mirror the overall increase in precipitation experienced in the region since 1895 (Figure 2.5). However, using the 13 HCN stations in the Mid-Atlantic Region, we found no overall linear trend (Figure 2.8c). This finding appears to be in agreement with Kunkel et al. (1999; see their Figures 2.4 and 2.5), who also used data beginning with 1931. In short, the trend of extreme precipitation events in the region is unclear because of spatial and temporal differences in the data sets used in the studies reported here. Clarification requires further investigation to reconcile the differing spatial and temporal scales of these studies.

While there is ambiguity in the extreme short-duration temperature and precipitation findings, the region appears to be experiencing increasing inter- and intra-annual swings in climate (Figure 2.5). For example, the three coldest winters in the record occurred successively in 1976-77, 1977-78, and 1978-79 (Diaz and Quayle 1980), while some of the warmest winters—all associated with El Niño events—occurred in 1982-83, 1994-95, and 1997-98. The region has experienced several severe droughts in the last two decades, but the wettest year in more than a century was 1996 and the second wettest year was 1972. In most of the Mid-Atlantic Region, three of the snowiest winters were 1992-93, 1993-94, and 1995-1996, while the El Niño winters of 1994-1995 and 1997-98 were two of the least snowy winters on record.

The Mid-Atlantic climate has also exhibited extreme variations within individual seasons and years. For instance, December 1989, the coldest December on record, was followed by the warmest January-February in the books. Interestingly, these extremes of opposite sign canceled each other so that climatological winter 1989-1990 was an average winter statistically. Precipitation has behaved similarly. The first half of 1998 was the wettest on record in many areas in the Mid-Atlantic Region and it appeared that calendar year 1998 was going to beat 1996 easily for the all-time wettest year. In spite of that, drought gripped the region during the second half of 1998, making it an average year statistically. Calendar year 1999 was the driest year on record in much of the Mid-Atlantic Region.

In sum, the limited record of weather and climate extremes in the region produces a mixed signal. There are conflicting indications of increasing moderation and increasing extremes on daily time scales and of increasing extremes in seasonal and interannual climate. More research is needed on this crucial topic.

Intra-regional variation

Climatic transects across the region generally reflect the influences of latitude, elevation, and physiography. Temperatures decrease from the south (Figures 2.9a and 2.9b), where temperatures are highest because of the relatively low latitude and the low elevations of the Piedmont physiographic province, to the north, where temperatures are lowest because both latitude and elevations are higher on the Appalachian Plateau. Temperatures also decrease from east to west (Figures 2.10a and 2.10b) because elevations are lowest in the coastal plain and highest in the mountains.

Regional precipitation patterns are more complicated. The south-north transect (Figure 2.9c) shows the influence of temperature and proximity to moisture when comparing the two more southerly stations. In this case, the station that is farther south and closer to the Atlantic Ocean has higher precipitation totals. In contrast, the third, northernmost station is cooler and removed from the ocean, but receives considerable precipitation from another mechanism—lake effect precipitation (Ellis and Leathers, 1997). The lake effect is weaker during zonal flow regimes, but has higher interannual variability; it is stronger with lower variability during meridional regimes. The east-west transect (Figure 2.10c) is even more complex and is difficult to generalize.

Frequencies of extreme temperature events in the Mid-Atlantic Region are a function of latitude and elevation. Southerly (northerly) stations have far more (far fewer) days over 90°F, while northerly (southerly) stations have far more (far fewer) days less than 0°F (Figures 2.11a and 2.11b, respectively). Similarly, low-elevation (eastern) stations have more very hot days and fewer very cold days than high-elevation (western) stations (Figures 2.12a and 2.12b). Although the trends are less evident for extreme precipitation events, the same south-north and lowland-highland gradients appear in these data (Figures 2.11c and 2.12c, respectively).

MAR climate summary

Over the last century, there has been an upward trend of nearly 1 degree Fahrenheit (0.6 degrees Celsius) in temperature. From 1901 to 1998, the average number of very hot days per year decreased slightly and the average number of very cold days increased. Thus although average temperatures are rising, the MAR is experiencing fewer very hot days but more very cold days. Variation in the region's climate also shows up in seasonal patterns. For example, the three coldest winters on record were 1976-77, 1977-78 and 1978-79, while some of the warmest winters occurred in 1982-83, 1994-95 and 1997-98.

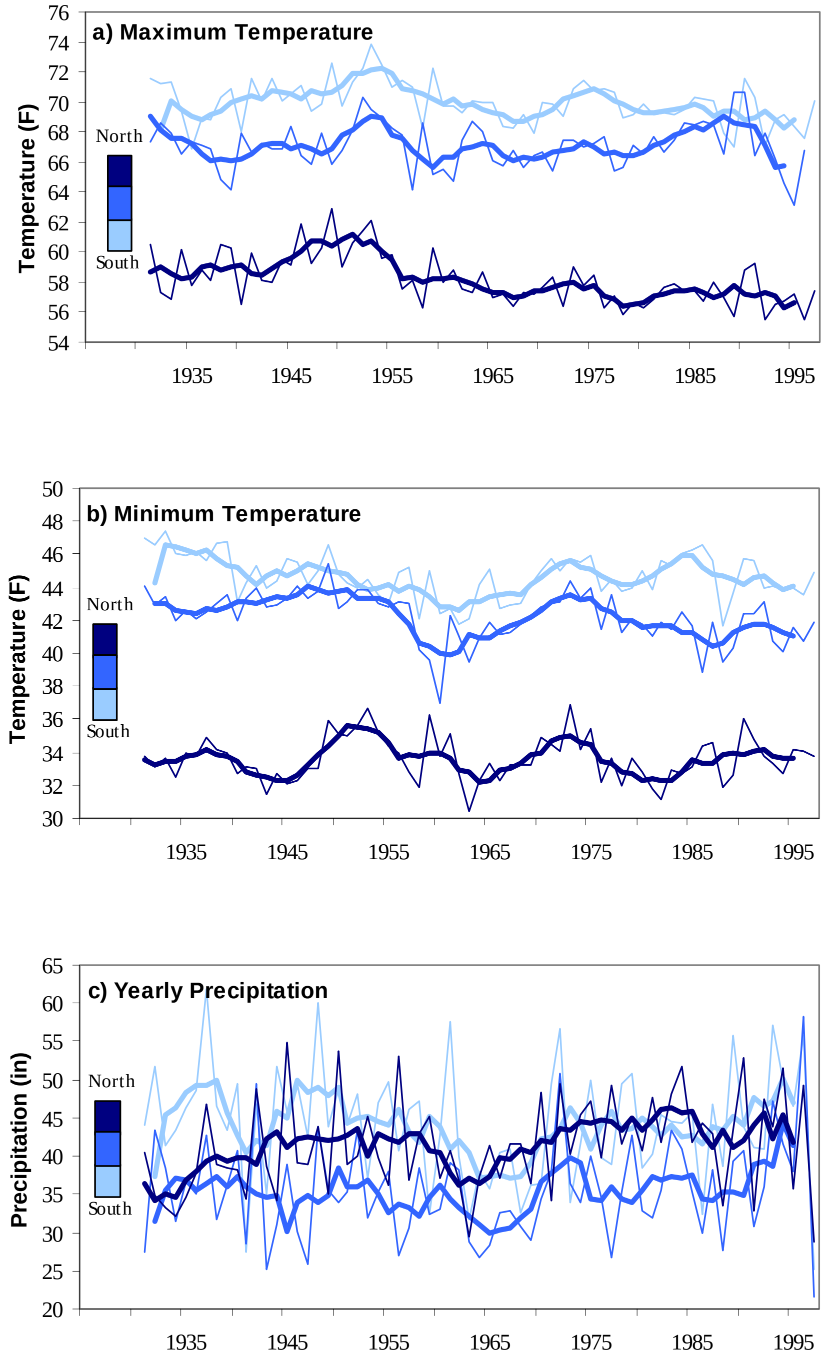


Figure 2.9. A south-north transect in the Mid-Atlantic Region of (a) maximum temperature, (b) minimum temperature, and (c) total precipitation for various years starting in 1931 and concluding in 1997. The stations in the transect are color coded to Figure 2.7 and come from the Historical Climate Network daily data set (T. Karl, personal communication).

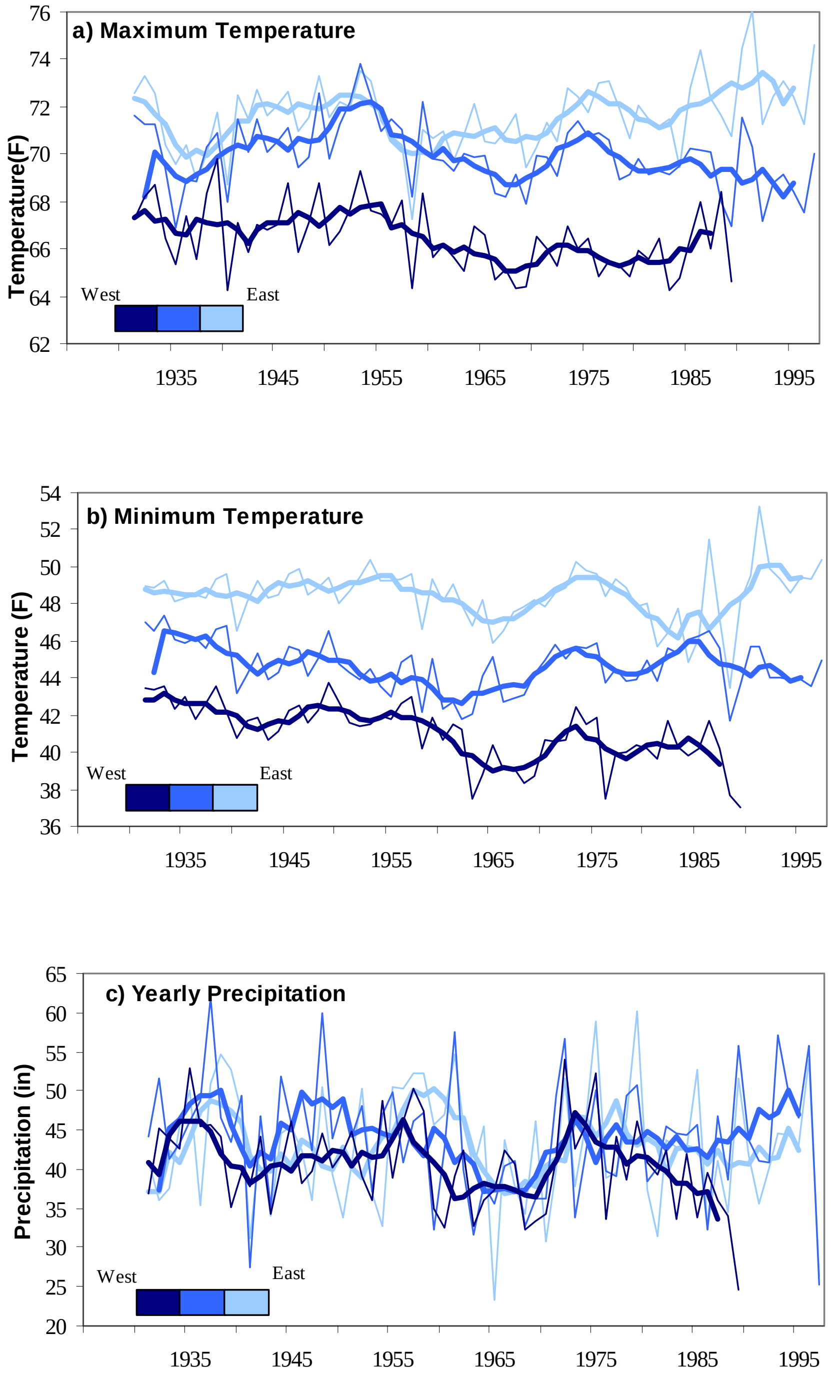


Figure 2.10. As in Figure 2.9, but for an east-west transect.

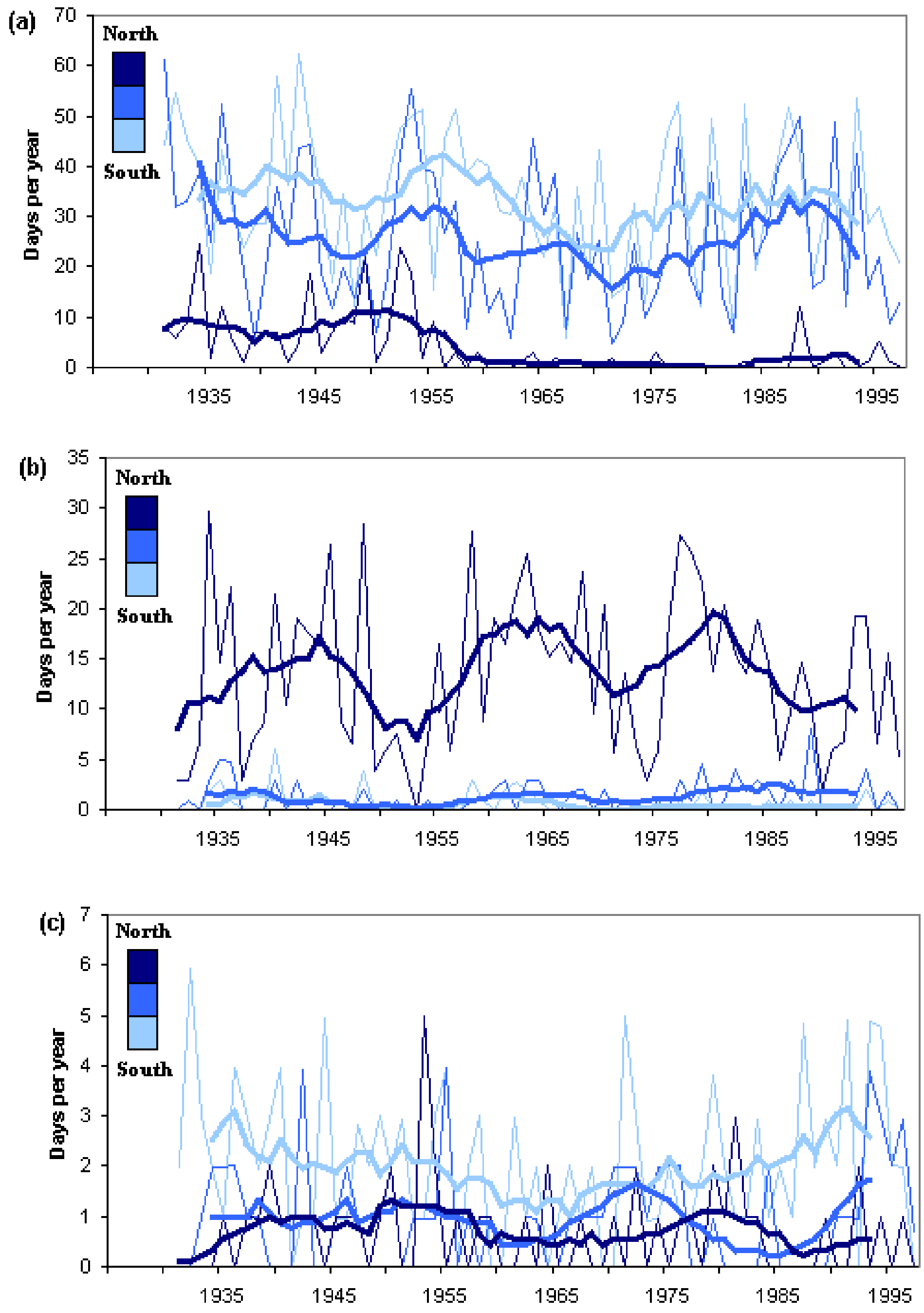


Figure 2.11 Inter-annual variation in selected extreme events for the south-north transect of Figure 2.9. (a) days per year with temperatures exceeding 90°F (32.2°C); (b) days per year with temperatures less than 0°F (-17.8°C); and (c) days per year with precipitation total exceeding 2.0 inches (5.08 cm) in 24 hours. Data derived from the Historical Climate Network daily data set (T. Karl pers. Comm.).

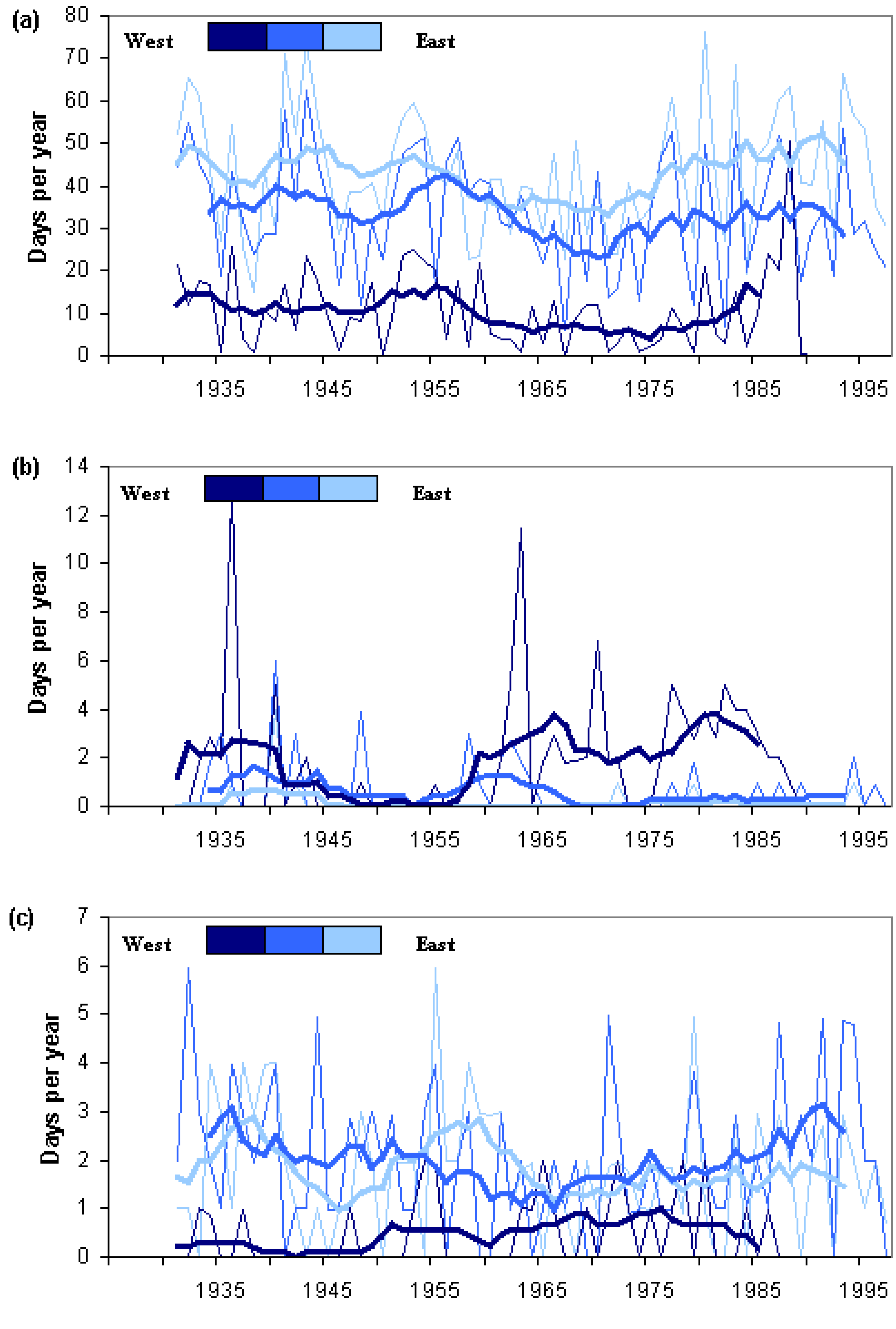


Figure 2.12 As in Figure 2.11, but for the east-west transect of Figure 2.10.

Over the last century, there also has been an upward trend in precipitation, amounting to about a 10 percent increase. At the same time, if we express extreme precipitation events as occurring when precipitation exceeds two inches in 24 hours, then the MAR has slightly fewer of these extreme events now than it did 100 years ago. In short, precipitation is increasing, but it does not seem to be because of more frequent severe rainfalls and snowfalls. It can be assumed, therefore, that the cause of the precipitation increase is higher magnitude severe precipitation events, higher magnitude non-severe precipitation events or more frequent precipitation events in general. More investigation is needed to determine which of these factors is responsible for the increase in precipitation.

Thus, identifying whether climate is changing is difficult for many reasons. One is the complexity of the climate system and the large variations in year-to-year and decade-to-decade weather. Other reasons include the climate system's tendency to change slowly, the basic physics that determine a locale's climate, and the relatively short record of climate measurements. In the end, only continued monitoring and careful research will make it possible to detect climate change in the MAR.

References

Balling RC Jr., Lawson MP (1982) Twentieth century changes in winter climatic regions. Climatic Change 4:57-69.

Baron WR (1995) Historical climate records from the northeastern United States, 1640 to 1900. In: RS Bradley and PD Jones (eds) Climate Since AD 1500. Routledge, London, p 74-91.

Bureau of the Census (1997) 1997 Statistical Abstract of the United States. http://www.census.gov/prod/3/97pubs/97statab/cc97stab.htm, US Bureau of the Census, Washington, DC.

Bureau of the Census (1998a) Historical National Population Estimates. http://www.census.gov/population/estimates/nation/popclockest.txt, US Bureau of the Census, Washington, DC.

Bureau of the Census (1998b) State and Metropolitan Area Data Book 1997-98 (5 th Edition). Washington DC.

Carter TR, Parry ML, Harasawa H, Nishioka S (1994) IPCC Technical Guidelines for Assessing

Climate Change Impacts and Adaptations. Intergovernmental Panel on Climate Change, WMO/UNEP.

Cook ER, and Jacoby GC (1983) Potomac River streamflow since 1730 as reconstructed from tree rings." *Journal of Climate and Applied Meterology* 222:1659-1672.

Cook, ER, and Jacoby, GC (1977) Tree-ring drought relationships in the Hudson Valley, New York. *Science* 198:399-401.

Cronin T (1997) Perspectives on Current Impacts and Adaptation to Climate Variability in the Mid-Atlantic Region. Oral presentation at the Workshop on Climate Change Impacts in the Mid-Atlantic Region, The Pennsylvania State University, University Park, PA, September 9-11.

Cronin T, Willard D, Karlsen A, Ishman S, Verardo S, McGeehin J, Kerhin R, Homes C, Colman S, Zimmerman A (2000) Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments. Geology (in press).

Cuff DJ, Young WJ, Muller EK, Zelinsky W, Abler RF (eds) (1989) The Atlas of Pennsylvania. Temple University Press, Philadelphia.

Diaz HF, Quayle RG (1980) An analysis of the recent extreme winters in the contiguous United States. Monthly Weather Review 108:687-699.

Ellis AW, Leathers DJ (1997): A synoptic climatological approach to the analysis of lake-effect snowfall: potential forecasting applications. Weather and Forecasting 11: 216-229.

EPA (1997) An Ecological Assessment of the United States Mid-Atlantic Region: A Landscape Atlas. Office of Research and Development, US Environmental Protection Agency, Document #EPA/600/R-97/130. Washington, DC.

Francis D, Hengeveld H (1998) Extreme weather and climate change. Climate Change Digest Special No.2, Atmospheric Environment Service, Environment Canada, Downsview, Ontario.

Guttman NB, Quayle RG (1996) A historical perspective of US climate divisions. Bulletin of the American Meterological Society 77:293-303.

IMPLAN (Minnesota IMPLAN Group) (1997) Impact Analysis for planning (IMPLAN) system, Stillwater, MN.

Jones, K.B., et al. 1997. An Ecological Assessment of the United States Mid-Atlantic Region: A

Landscape Atlas. US EPA, Office of Research and Development: Washington, DC. Document #EPA/600/R-97/130.

Kalnicky RA (1974) Climatic change since 1950. Annals of the association of American Geographers 64:100-112.

Karl TR and Knight RW (1998) Secular trends in precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.*, 79: 231-261.

Karl TR, Knight RW, Easterling DR, Quayle RG (1996) Indices of climate change for the United States. Bulletin of the American Meteorological Society 77:279-292.

Kittel TGF, Rosenbloom NA, Painter TH, Schimel DS, VEMAP Modeling Participants (1995) The VEMAP integrated databse for modeling United States ecosystem/vegetation sensitivity to climate change. Journal of Biogeography 22:857-862.

Kunkel KE, Andsager K, Easterling DR (1999) Long-term trends in extreme precipitation events over the conterminous United States and Canada. Journal of Climate 12:2515-2527.

Marsh B, Lewis PF (1995) Landforms and human habitat. In: EW Miller (ed) A Geography of Pennsylvania. Penn State University Press, University Park, p17-43.

NOAA (1998) Our Crowded Shores: Balancing Growth and Resource Protection. CD-ROM produced by the US National Oceanic and Atmospheric Administration National Ocean Service and InterNetwork Media, Incorporated.

NPA (1998) Regional Economic Projection Series. NPA Data Services, Inc. Washington, DC.

Polsky C, Allard J, Curritt N, Crane R, Yarnal B (2000) The Mid-Atlantic Region and its climate: Past, present, and future. *Climate Research* in press.

Rose et al. (2000) Simulating the economic impacts of climate change in the Mid-Atlantics Region. *Climate Research* in press.

Rosenbloom N, Kittel TGF (1999) A User's guide to the VEMAP Phase I Database. http//www.cgd.ucar.edu/vemap/users_guide.html, Climate System Modeling Program, University Corporation for Atmospheric Research, and the Ecosystem Dynamics and the Atmosphere Section, Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, August.

Shane M, Roe T, Gopinath, M (1998) U.S. Agricultural Growth and Productivity: An Economywide Perspective, U.S. Department of Agriculture, Agricultural Economic Report No. 758.

Trenberth KE (1990) Recent observed interdecadal climate changes in the Northern Hemisphere. Bulleting of the American Meteorological Society 71:988-993.

Yarnal B, Leathers DJ (1988) Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate. Annals of the Assocation of American Geographers 78:624-641.

Chapter 3. Envisioning the MAR's socioeconomic, environmental and climate future*

By definition, regional climate change impact analysis involves comparing what the region would be like "with" and "without" climate change. Climate impact research typically generates climate scenarios using a range of assumptions about changes in emissions of greenhouse gases and other forces that drive climate change. Then societal and other impacts are analyzed, based on the climate scenarios. Climate scenarios are, however, only one type of scenario needed to assess the impacts of climate change (Shortle, Abler and Fisher 1999). The profound effects that humans have on the environment from local to global scales make it essential to use socioeconomic scenarios for understanding how climate change will affect people and assessment endpoints such as agriculture, water, coasts, and forests. The long-term nature of climate change requires that assessments consider potential economic, demographic, technological, institutional and ecological conditions many years into the future. The MAR, like other regions of the United States and the World, has changed dramatically over the last century, and there is no reason to expect slowing in its pace of rapid economic change. The region undoubtedly will be substantially different in the future than today, in terms of its sensitivity to climate change and potential for response and adaptation. Therefore it is important to envision the impacts of climate change in an evolving society that will differ in many ways from the current society. Our limited ability to forecast reliably beyond just a few years implies large uncertainties about what the future will be like-with or without climate change.

Rather than assuming that a particular future will exist, it is more useful to explore scenarios that could exist, examining the ramifications of those "what if' scenarios. Imagining where we might be headed reduces the complexity and unpredictability, allowing decisions that can accommodate both positive and negative impacts (Schwartz 1991). Developing useful scenarios involves both art and science. The MARA team relied on broad input from experts and stakeholders in identifying crucial scenario components and the ranges that guided the assessments described in Chapters 4-9. The scenario development process and results are summarized in this chapter.

Socioeconomic and environmental future

In 1900, it was difficult to predict dramatic 20th century changes such as the decline in farm employment that accompanied huge increases in agricultural productivity, the widespread use of computers, or the shift from horses to cars that reduced manure disposal problems in large cities

* This chapter is based on Polsky et al., (2000) "The Mid-Atlantic Region and its climate: Past, Present, and Future," *Climate Research*, 14:2. It appears with permission of Inter-Research.

but increased air pollution. Mining, forestry, agriculture and manufacturing were the largest components of the Mid-Atlantic Region's economy at the beginning of the 20th century, but are much smaller components today. Similarly, the economy and society of the region undoubtedly will be substantially different in the future than today in terms of their structure, producer and consumer technologies, the range of available goods and services, and public and private institutions. In turn, these differences may affect the region's environmental status as well as the region's sensitivity to climate change and its potential to respond or adapt.

Thus, the socioeconomic and environmental picture now for the year 2100 is just as unclear as the picture for the year 2000 was in 1900. For example, population cannot be predicted accurately at a regional level because of the difficulty in predicting regional migration patterns. Similarly, predicting employment and income is complicated by the ease with which technology and other resources move across regional boundaries. Point estimates almost certainly would be incorrect. However, trends and expectations about future labor force participation rates, birth rates, immigration, capital investment and improvements in productivity can be used to calculate ranges for potential population, employment and income. Trends suggest a continued increase in population over the next 30 years in the MAR, with a continued shift to the Coastal and Piedmont subregions. This population growth will create additional pressures for converting agricultural land to urban and suburban uses, especially in the corridor from Norfolk to New York City. In turn, land development is likely to create additional stresses on the region' s ecosystems, particularly the Chesapeake and Delaware Bays. General expectations such as these help determine the input for more formal projections provided by USGCRP and shown in Figure 3.1 (NPA 1998). (NPA Data Services, Inc. is the firm that the USGCRP commissioned to provide socioeconomic projections.) These calculations serve as a baseline for the region's future socioeconomic conditions in the absence of climate change. Note that the uncertainties increase dramatically as the horizon moves farther into the future, or as the regional scale becomes smaller.

These baseline ranges establish upper and lower bounds for socioeconomic conditions on which climate change is overlaid. Climate change, as well as expectations of climate change, will stimulate socioeconomic responses to reduce risks and exploit opportunities (Shortle, Abler and Fisher 1999). These responses will shape the final impacts. For instance, the final impacts on agricultural production will be shaped by actions farmers take to cope with climate-induced changes in temperature, precipitation and pests. It is relatively straightforward to identify responses that are feasible under current technology and institutions, but it is difficult to project changes in technology and institutions. Thus any point estimate of the future certainly will be incorrect. If there are n values for each of k variables that define socioeconomic futures, then there are n^k cases to assess. For instance, if each of 5 variables can have a "high," "medium," and "low" value, then the number of potential futures is $3^5 = 243$. If there are 10 variables, the number of possible futures becomes $3^{10} = 59,049$. Rather than point forecasts or exhaustive lists,

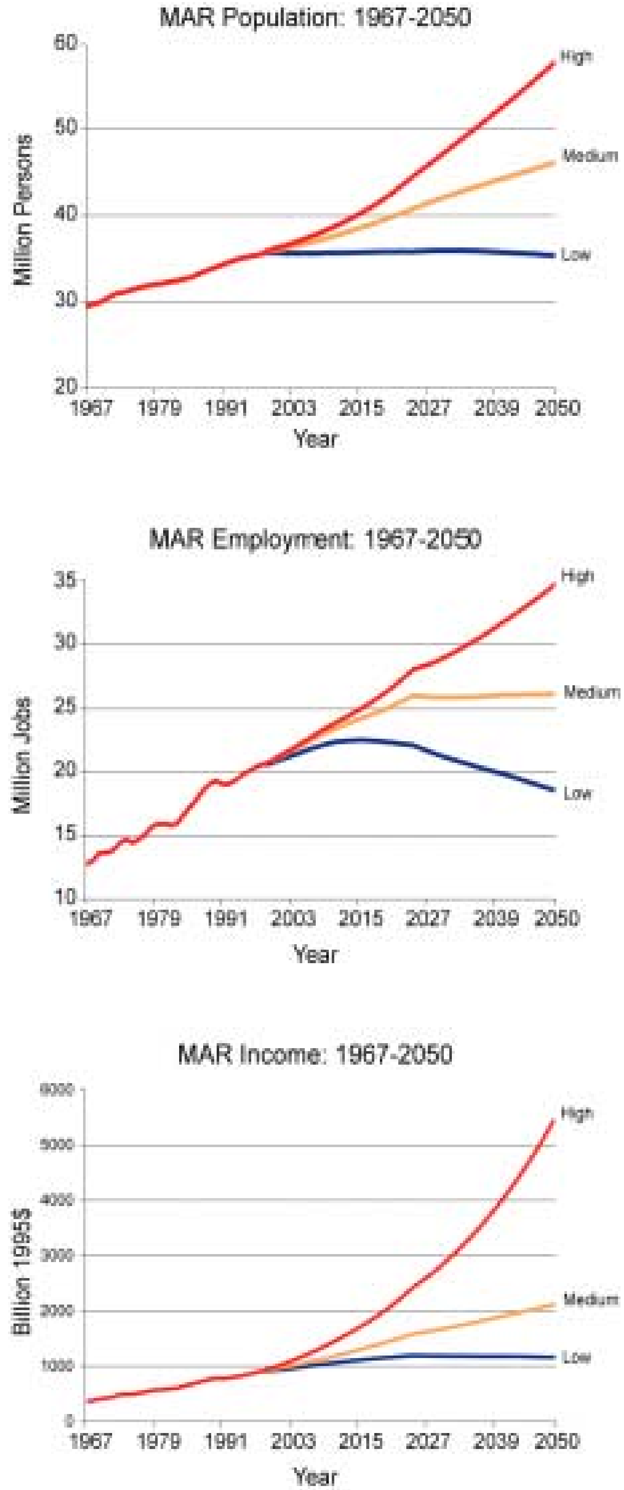


Figure 3.1. NPA's population, employment and income projections for the MAR, to 2050.

Table 3.1. Potential size of climate impacts.

		Socioeconomic/Ecosystem Adaptation	
		Large	***Small***
Socioeconomic/Ecosystem Sensitivities to Climate			
	Large	*Small impacts*	*Largest impacts*
	Small	*Smallest impacts*	*Small impacts*

it is more useful to select a small set of scenarios that identify and bound major potential threats and opportunities. This is illustrated in Table 3.1 for both socioeconomic and ecosystem sectors.

The most serious risk of adverse impacts emerges from scenarios that combine the greatest increases in socioeconomic or ecosystem sensitivities with increased climate stresses and little socioeconomic and/or ecological adaptation. For a given climate change, Table 3.1 shows that large socioeconomic or ecosystem sensitivities to climate variability and change will have small impacts if there are large adaptive capabilities in the socioeconomic structure or ecosystem, but large impacts if adaptive capabilities are small. Similarly, reduced risks or the lower bounds for adverse climate impacts emerge in scenarios that combine reduced baseline socioeconomic or ecosystem vulnerability with substantial ability to adapt. Such tables can be a starting point for examining a range of climate, socioeconomic and ecosystem conditions. Combinations of climate and socioeconomic scenarios with offsetting effects may yield greater or smaller risks. The ranges between the upper and lower bounds could be viewed as confidence intervals.

The set of scenarios is kept tractable by first identifying sectors likely to be sensitive to climate change and then by identifying and selecting risks within those sectors. The resulting scenarios serve as a starting point for identifying incremental socioeconomic impacts from changes in climate. To illustrate, the primary climate-sensitive sectors identified for the MAR are: agriculture, forests, fresh water, coastal zones, and human health-with ecosystems as a cross-cutting issue. Within the agriculture sector, for example, we identified four key potential risks: food availability and cost, agricultural income and employment, rural landscape, and environmental impacts of agricultural production. Because food availability and cost are almost entirely determined by factors external to the region, we chose to focus on the latter three. Similar decisions were made for the remaining sectors. For some sectors, specific values can be projected for each variables allowing a quantitative analysis of socioeconomic impacts. An example is given in the forest chapter. The substantial uncertainties and the need to aggregate variables often necessitated a more heuristic description of "what if' scenarios, such as that shown in the agriculture chapter.

Future climate

The U.S. Global Change Research Program (USGCRP) provided data from two state-of-the-art global climate models to promote a common ground for developing climate change scenarios across the country. Two models were provided because the organizers of the National Assessment preferred to have data from more than one modeling group to reflect the uncertainties in projecting future climate. They also stipulated that the models had to:

- cover both the last century and the next century,
- use a consistent set of assumptions about the rate of increase in greenhouse gas concentrations and sulfate aerosols, and
- be available prior to the start of the formal assessment process.

Given these guidelines, two models were available-the Canadian Climate Centre (CCC) model, and a model from the Hadley Centre for Climate Prediction and Research in Great Britain.

Thus, the Mid-Atlantic Region climate change scenarios are derived from two transient numerical models of the global climate system. The Hadley Centre for Climate Prediction and Research developed a model to simulate the global climate from 1860 to 1990 and then to estimate the global climate change for the period 1990 to 2099. The Hadley climate change experiment includes the effects of both atmospheric greenhouse gases (which increase global surface temperatures) and sulfate aerosols (which reduce temperatures in regions with high aerosol loading). In this experiment, the carbon dioxide (CO_2) content of the atmosphere is increased by 1 percent per year over the 1990 values. The second model used in the MARA is from the Canadian Climate Centre (CCC). The CCC model simulates the global climate from 1850 to 1990 and then estimates the global climate from 1990 to 2100, including aerosols and a 1 percent annual increase in CO_2. Detailed descriptions of both models can be found in a number of publications. See, for example, Boer et al. (1992) for a discussion of the Canadian Climate Model, Cullen (1993) and Mitchell et al. (1995) for a description of the Hadley Centre model, and Doherty and Mearns (1999) for a comparison of the models.

Both models have done a reasonable job of reproducing U.S. climate trends. This is shown for the Mid-Atlantic Region in Table 3.2 which shows the similarity between observations and model results for a recent decade. We chose 1984-1993 to represent the current situation because of the wealth of socioeconomic, ecological and climate data available for this period.

Both models contain sophisticated representations of the physical processes that drive atmospheric dynamics, and both simulations are carried out with similar greenhouse gas and aerosol scenarios. Despite these similarities, the models produce significantly different results over the MARA region, which simply highlights the uncertainty involved in using global models to infer a regional response to changing climate. These differences are characterized in Figure 3.2. Here results for each model over the Mid-Atlantic Region for the coming century are compared to the model results for the baseline period 1960-1989 for maximum temperature and precipitation. The CCC model becomes increasingly warmer and drier than the Hadley model over the course of the 21st century. The CCC model lacks realistic-looking climate variations, while the Hadley model time series look more like observed climate variations (Figure 2.5). Global mean maximum temperature, minimum temperature, and precipitation for both models (not shown) are similar to the regional-scale generalizations.

Table 3.2. Mid-Atlantic Region observed and simulated temperature (ºF) and precipitation (inches) for 1984-93. Temperatures are daily maximum and minimum temperatures.

	Maximum Temperature		**Minimum Temperature**		**Precipitation**	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Observed	*63.7*	*16.5*	*41.4*	*15.2*	*43.1*	*4.4*
Hadley	*63.5*	*17.5*	*41.0*	*15.5*	*42.8*	*3.0*
CCC	*63.6*	*16.7*	*41.6*	*15.1*	*45.0*	*2.8*

Figure 3.3 shows the U.S. temperature change from both models, together with the resu1ts from several other models. The simulations tend to fall into two groups, one showing a more rapid temperature increase than the other. The CCC model falls into the former group and the Hadley model into the latter. At this point, there are no grounds for suggesting that any one model or simulation is more accurate or realistic than another, and both models produce climate changes that are possible given the projected changes in atmospheric composition. As is the case for the socioeconomic changes, the simulations produced by these models represent plausible ranges for possible climate change, rather than predictions of what actually will happen for any particular time or place.

In sum, at the scale of the Mid-Atlantic Region the two model scenarios depict very different climatic paths and therefore should generate distinct scenarios for associated impacts on ecosystems and societies. There is considerable uncertainty in the regional details of any global climate model and, in some respects these two models can be regarded as spanning the range of possible climate change scenarios for the Mid-Atlantic Region. Additional modeling studies (see

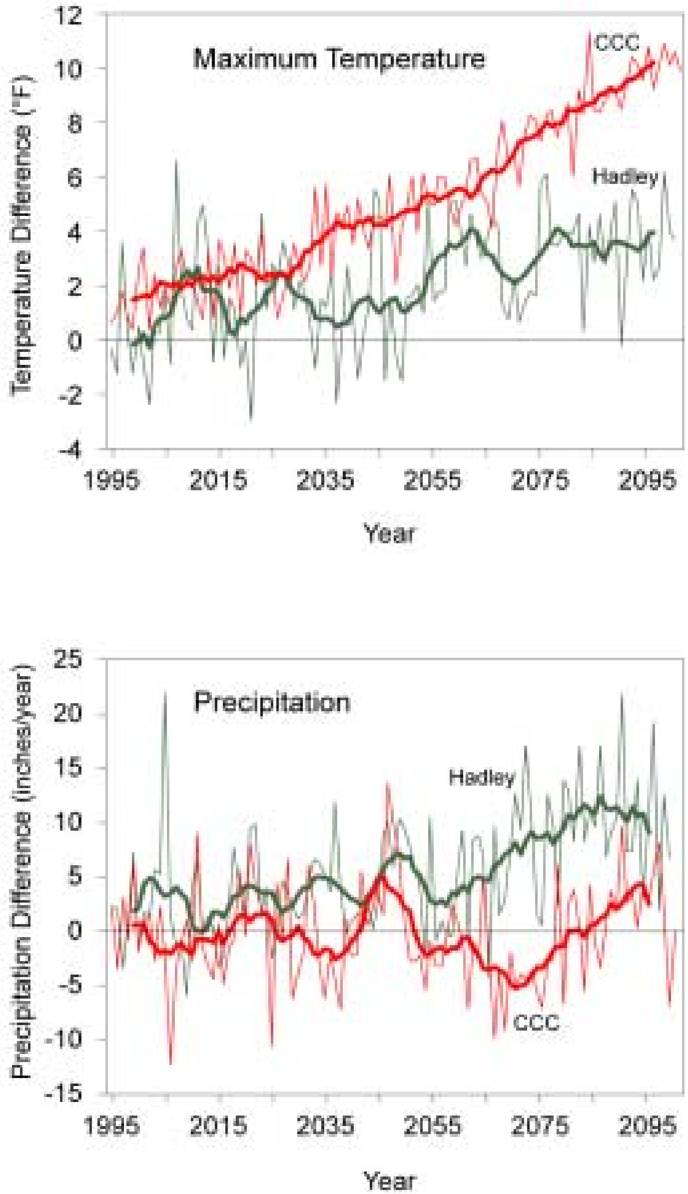


Figure 3.2. Hadley Centre and Canadian Climate Center model departures from the observed 1960-1989 base period, averaged over the MAR for (a) mean annual maximum temperature and (b) mean annual precipitation total. The smoothed lines represent nine-year running means.

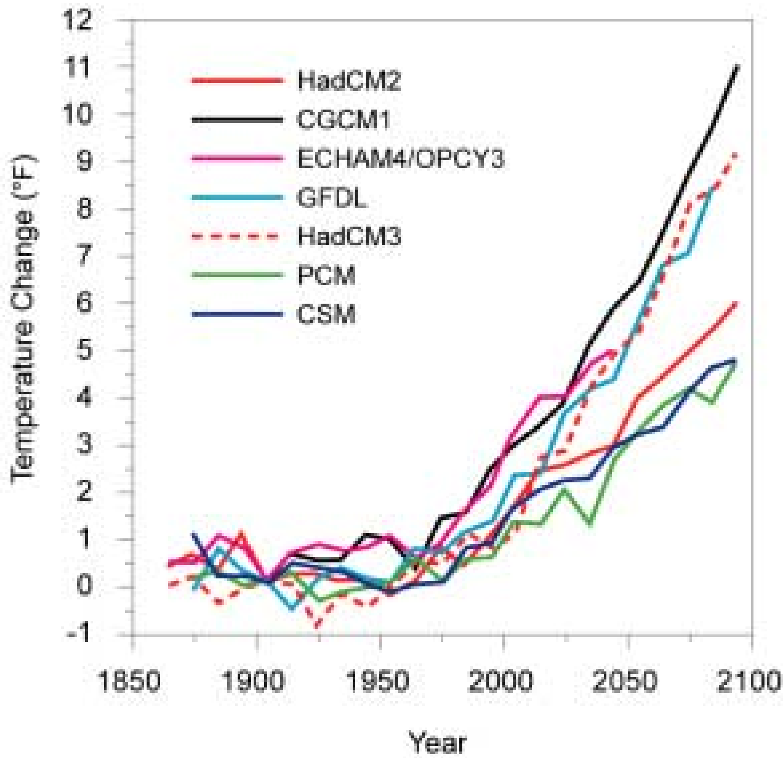


Figure 3.3. Simulations for the United States of average changes in temperature from leading climate models based on historic and projected changes of CO_2 and sulfate emissions. The red and black lines indicate the models chosen for use by the National Assessment.

below) are more consistent with the Hadley model results. Thus the Hadley results are used in the following discussion of likely climate change scenarios.

In nearly all of the analyses performed for the MARA, the decades 2025-2034 and 2090-2099 were extracted from the transient climate model runs to assess the regional impacts of potential climate change. We estimate the spatial distribution of climate change over the Mid-Atlantic Region by interpolating the model results ("future climate") to a finer regional spatial resolution using the VEMAP grid (Kittel et al. 1995; Rosenbloom and Kittel 1999), and noting the differences between these results and a measure of present climate. For purposes of illustration, Figure 3.4 shows the results of this procedure, for one model (Hadley) and one time slice (2025-2034) only, compared to the region's present climate represented by the years 1984-1993.

In particular, estimated climate changes (January and July mean maximum and minimum temperatures, and mean precipitation totals) are shown in Figure 3.4. The data in this figure are

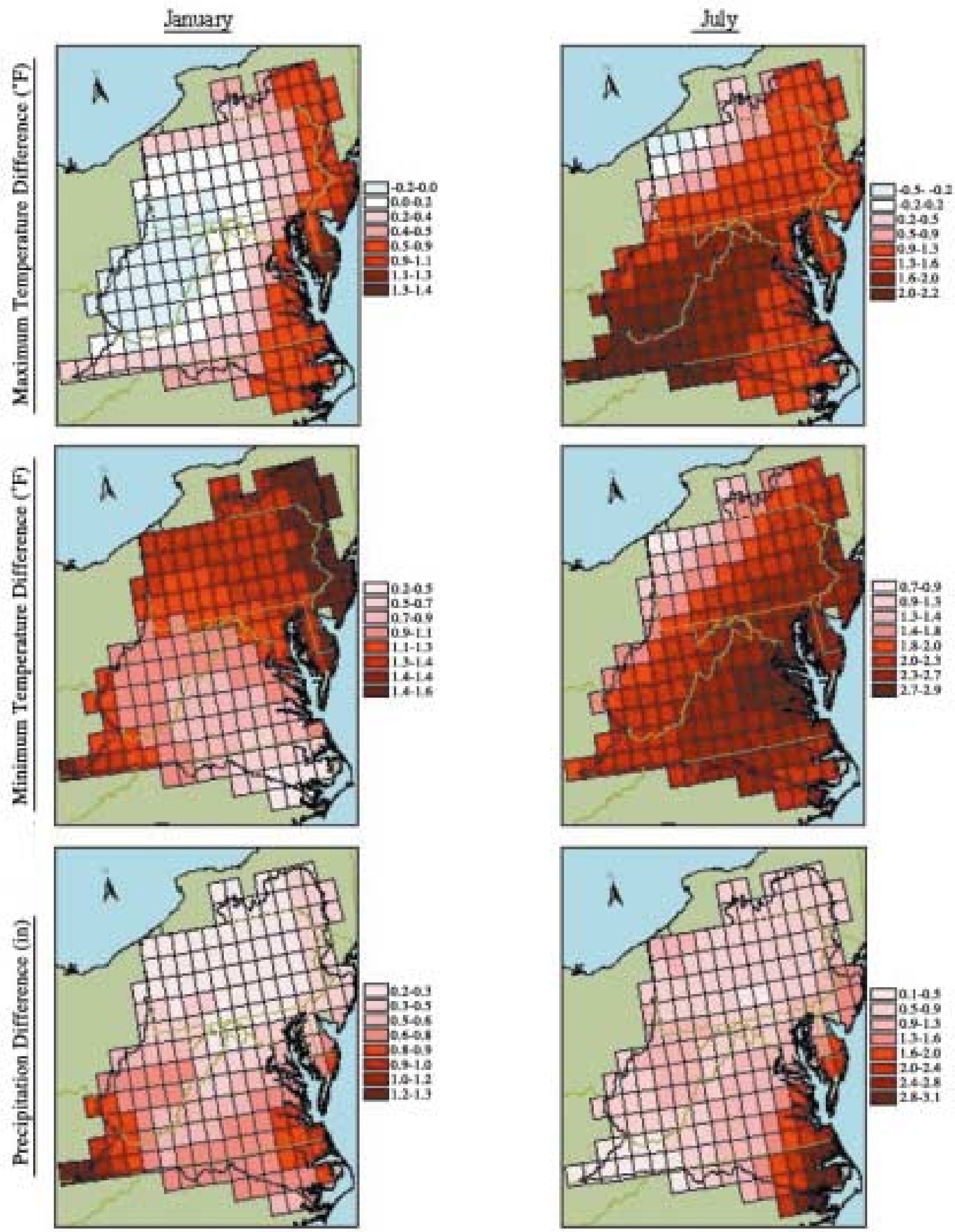


Figure 3.4. Difference between present (1984-1993) and future (2025-2034) January (left) and July (right) mean values for maximum temperature, minimum temperature, and precipitation (Hadley Centre model).

plotted at the VEMAP resolution, a 0.5° x 0.5° longitude-latitude grid. This figure suggests that much of the change in maximum temperatures will occur in the summer, with the greatest changes being in the southeast. The minimum temperature maps reveal a somewhat different pattern. Higher summer temperatures again occur in the southeast, but there are lower winter temperatures in the central and northern parts of the region. Comparing the model results for precipitation in 1984-1993 and 2025-2034 shows a slight uniform increase in January. Precipitation also increases across the whole region in July, but with the greatest increases being in the southeast.

These results are broadly consistent with two earlier climate downscaling studies that covered portions of the Mid-Atlantic Region, but used the GENESIS global climate model. Both GENESIS experiments were equilibrium experiments in which the atmospheric CO_2 concentration is doubled and the climate model reaches an equilibrium climate state. The results of the doubled CO_2 model are then compared to the results of the same model using late 20th century atmospheric CO_2 values. The models did not include the effects of sulfates. One study used a numerical regional climate model in conjunction with GENESIS (Jenkins and Barron 1997). Similar to the Hadley scenario, it produced an increase in annual precipitation, but the greater increase was in winter rather than summer. The second study employed a later version of GENESIS and used an empirical climate downscaling technique (Crane and Hewitson 1998). The results were very similar to the Hadley scenario, finding a large increase in precipitation that was concentrated in the summer months and that had the largest changes occurring to the south (but over the southwestern mountains instead of the southeastern coastal plain).

The CCC and Hadley simulations, when considered in the light of the additional downscaling results, suggest that the most likely MAR climate change scenario will show increasing temperatures and increased precipitation across the region. Temperature increases are likely to be on the order of 2°F by 2030 and may increase an additional 3°F to 8°F by the end of the 21st century. There is a high likelihood that average annual precipitation will increase, but the magnitude and seasonal distribution of the increased precipitation is uncertain. The MAR has experienced natural weather disasters and weather extremes at different times of the year. The current spatial resolution of global climate models is not fine enough to show thunderstorms or hurricanes, but both the CCC and Hadley models indicate slight increases in the frequency and intensity of winter storms with little change in storm track over the MAR. Because storm impacts can be substantial, Chapters 4-9 acknowledge the uncertainty and address the implications of more storminess.

It is also important to note that climate is highly variable from year to year and that some of this variability is due to features of the climate system (such as El Niño events) that are not well simulated by current global climate models. This variability will continue and may even increase in the future. On time scales of years-to-decades, the climate in any given period in the next century could be considerably warmer/colder or wetter/drier than indicated in Figure 3.2. Consequently, Figure 3.2 should be used only to infer the overall trend in regional climate change.

Table 3.3 summarizes the climate change scenarios for the MAR, together with projections of other important environmental parameters such as sea level and runoff. An indication also is given of our current confidence in these projections. The most likely change is the rise in atmospheric carbon dioxide (CO_2). (The great uncertainty in projections of storminess keeps this category from appearing in Table 3.3.) These environmental changes are linked with the socioeconomic scenarios to project potential impacts, challenges and opportunities in Chapters 4-9. The assessments in Chapters 4-9 use the scenario information in a variety of ways. Where a quantitative analysis is possible (in the case of stream flow, for example) the Hadley and CCC model projections are used to present a range of possible outcomes. Where only more qualitative assessments are possible, the judgment is based on the generalized trend of increasing temperatures and rainfall. In some cases the assessments use information from prior analyses utilizing different climate models, and details of these models are presented when relevant.

Table 3.3. Important projections for the years 2030 and 2095 with respect to 1990.

Parameter	**2030**	**2095**	**Confidence in projection**
CO_2 change *(%)*[a]	*+20 to +30*	*+50 to +120*	*Very high*
Sea level change *(inches)*[b]	*+4 to +12*	*+15 to +40*	*High*
Temperature change *(ºF)*[c]	*+1.8 to +2.7*	*+4.9 to +9.5*	*High*
Precipitation change *(%)*[c]	*-1 to +8*	*+6 to +24*	*Medium*
Runoff change *(%)*[d]	*-2 to +6*	*-4 to +27*	*Low*

a. Range reflects IS92d and IS92f CO_2 emission scenarios (Watson et al. 1996)

b. Low and high projections of Warrick et al. (1996) for IS92a scenario, plus a local component of 0.008 inches per year.

c. Range given by Hadley and CCC models for the Northeast US (Felzer et al. 1999)

d. For the Susquehanna River Basin, using a water balance model forced with the CCC and Hadley output (Neff et al. 2000)

References

Boer GJ, McFarlane NA, Lazare M (1992) Greenhouse gas-induced climate change simulated with the CCC second-generation general circulation model. *Journal of Climate* 5:1045-1077

Crane RG, Hewitson BC (1998) Doubled CO_2 precipitation changes for the Susquehanna Basin: Downscaling from the GENESIS general circulation model. *International Journal of Climatology* 18:65-76

Cullen MJP (1993) The Unified forecast/climate model. *The Meteorological Magazine* 122:81-95

Doherty ER, Mearns LO (1999) *A Comparison of Simulations of Current Climate from Two Coupled Atmosphere-Ocean Global Climate Models Against Observations and Evaluation of their Future Climates*. Report to the National Institute for Global Environmental Change (NIGEC), National Center for Atmospheric Research, Boulder, Colorado

Felzer B, Fisher H, Rosenbloom N, Kittel T, Schmiel D (1999) *VEMAP Phase 2 future climatology for the coterminus US (CGCMl and HADCM2)*. Unpublished manuscript prepared for the US National Climate Assessment

Jenkins GS, Barron EJ (1997) Global climate model and coupled regional climate model simulations over the eastern United States: GENESIS and RegCM2 simulations. *Global and Planetary Change* 15:3-32

Kittel TGF, Rosenbloom NA, Painter TH, Schirnel DS, VEMAP Modeling Participants (1995) The VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change. *Journal of Biogeography* 22:857-862

Mitchell JFB, Johns TC, Gregory JM, Tett S (1995) Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature* 376:501-504

Neff R, Chang H, Knight CG, Najjar RG, Yarnal B, Walker HA (2000) Impact of climate variation and change on Mid-Atlantic Region hydrology and water resources. *Climate Research* 14:207-218

NPA (1998) *Regional Economic Projection Series*. NPA Data Services, Inc., Washington, DC

Polsky C, Allard J, Curritt N, Crane R, Yarnal B (2000) The Mid-Atlantic Region and its climate: Past, present, and future. *Climate Research* 14:161-173

Rosenbloom N, Kittel TGF (1999) *A User's guide to the VEMAP Phase I Database*. http://www.cgd.ucar.edu/vemap/userspde.html, Climate System Modeling Program, University Corporation for Atmospheric Research, and the Ecosystem Dynamics and the Atmosphere Section, Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, August

Schwartz, P. (1991) *The Art of the Long View*. Doubleday, New York

Shortle J, Abler D, Fisher A (1999) Developing Socioeconomic Scenarios: Mid-Atlantic Case. *Acclimations* 7: July/August, 7-8.

Warrick RA, LeProvost C, Meier MF, Oerlemans J, Woodworth PL (1996) Changes in sea level. In: Hougton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A and Maskell K (eds). *Climate Change 1995: The Science of Climate Change*. Cambridge University Press: Cambridge, UK, p. 359-405

Watson RT, Zinyowera MC, Moss RH (eds.) (1996) *Climate Change 1995: Impacts, Adaptations, and Mitigations of Climate Change: Scientific- Technical Analysis*. Contributions of Working Group II to the Second Assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York

Box 3.1. The Potential Impacts of Extreme Weather Events in the Mid-Atlantic Region (Barron)

Severe weather clearly presents threats to both safety and property in the Mid-Atlantic Region (MAR). Of the 44 U.S. weather disasters causing in excess of one billion dollars in damage during the period from 1980 to 1999, 14 affected the MAR. Six of these events were major hurricanes. The largest hurricane impacts were in North Carolina and Virginia, but high rainfall and flooding commonly extended into Maryland and Pennsylvania. Three of the major mid-Atlantic weather disasters were heat and drought related. For example, the heat wave of 1988 had total U.S. damages of nearly 50 billion dollars. Each of the three droughts that resulted in at least one billion dollars in damage covered broad regions of the east, including the mid-Atlantic area. Four of the major disasters involved winter storms. These winter storms included major blizzards or nor'easters (primarily affecting the coastal zone), and an ice storm that caused significant damage in North Carolina and Virginia. The 1996 blizzard in the mid-Atlantic and New England region caused an estimated $3 billion in damages and 187 deaths. An additional billion-dollar storm, involving thunderstorms, tornadoes, and flooding, included West Virginia in its path. Each of the above weather disasters, catalogued by National Oceanic and Atmospheric Administration, are characterized by extreme conditions and impacts over broad geographic areas, including all or parts of the MAR. This catalogue of major weather disasters does not reflect the significant property damage associated with a range of smaller storm systems or less severe droughts. Changnon and Changnon (1992) have summarized storm damage for major regions of the country for the period of 1950-1989. In the eastern United States, hurricanes have caused the most damage, followed by thunderstorms, winter storms and wind.

Changnon and Changnon (1992) and Agee (1991) note some correlation between higher historical temperatures and increased cyclonic and anticyclonic activity when five-year averages from 1950 to 1989 are analyzed. The strongest relationships are between thunderstorm activity and winter storms. For example, the northeast had relatively few "weather disasters" during the cooler 1960's, followed by increased numbers of events during the warming trend that followed. This correlation suggests that the nature of severe weather events is likely to change significantly as climate evolves over the next century. However, changes in severe weather are widely regarded as one of the most uncertain aspects of future climate projection (USGCRP 1995; Barron 1995). Some of the tendencies in severe weather may reflect meteorological conditions associated with warmer climates. Other tendencies may be short term or transient features of a changing climate. For example, in the short term, warming may cause periods of more lake effect snows if ice free conditions for the Great Lakes extend further into the winter season. However, as warming continues, precipitation increasingly will fall as rain rather than as snow so that lake effect snows then are likely to decrease. The continuous changes expected over the next century present special challenges to adaptation.

As summarized below, an assessment of the future impact of severe weather in the MAR can *be guided by historical events with significant impact, including hurricanes and tropical storms, severe flooding, nor'easters, severe or persistent drought, and ice storms.*

Hurricanes

Major tropical storms remain a significant concern for future climate scenarios for several reasons:

- *Hurricanes have caused extensive coastal damage in the MAR due to storm surges and wind, and significant coastal and inland damage due to high precipitation. For example, damage from hurricane Floyd is estimated to be at least 6 billion dollars. This storm, moving inland and northward from its landfall in eastern North Carolina, produced historically high precipitation extremes in North Carolina, Virginia, Maryland, Delaware, New Jersey and Pennsylvania.*
- *On-going debate includes arguments for substantial increases in hurricane intensity associated with warmer tropical and extra-tropical temperatures, resulting in greater precipitation, higher winds or both (see for example Emanuel 1988; Idso et al. 1990; Lighthill et al. 1994; Bengtsson et al. 1996; Knutsen et al. 1998;).*
- *The debate about potential increases in the frequency of Atlantic hurricanes is also tied to whether warming will result in an increase or decrease in the tendency for El Niño-like conditions; historically El Niño events show a reduction in the probability of US land-falling hurricanes while La Niña events show an increase (Bove et al. 1998).*
- *Mid-Atlantic population growth in coastal regions substantially increases the potential health effects and property damage associated with hurricane events even if intensity or frequency remains unchanged.*
- *Higher sea level with global warming exacerbates the impact of hurricane storm surges even if the intensity or frequency of storms remains unchanged.*

In 1995, the Insurance Research Council estimated that a category 4 hurricane making land-fall in Asbury Park, NJ, New York City, or other regions with high property value, had the potential to cause insurance losses of $40 to $50 billion. Conservatively, total damages can easily exceed twice the level of insured damages. In short, the potential for hurricane damage in the mid-Atlantic from a single storm far exceeds the region's total damages from hurricanes over the last 40 years. Much of the vulnerability stems from a remarkable increase in coastal property values. A comparison of storm intensity, frequency, and damages during this century (Kunkel et al. 1999a, b) indicate that large increases in damages are associated with increasing value of property exposed to weather risk. Unfortunately, hurricanes' spatial scales prevent their simulation as features of most global climate models. This is because global models have insufficient spatial resolution to simulate the hurricane eye and eye wall winds required to have hurricanes form within the models. Currently we lack the computer resources to simulate the entire world at such a spatial scale. The Assessment climate models do not indicate any systematic change in the steering forces that might govern the path of future hurricanes compared to the present. Potential changes in *intensity and frequency remain highly uncertain.*

Severe flooding

The historical record from the MAR amply demonstrates the impact of severe flooding. Tropical storm Agnes (1972) and Hurricane Floyd (1999) were associated with high rates of rainfall over short time periods causing widespread flooding. The Blizzard of '96 produced very heavy snows (exceeding 1 to 4 feet) over broad areas of the MAR, which were then followed by severe flooding in the same area due to rain and rapid snowmelt. Records of severe floods reveal a diverse set of responsible meteorological conditions, including

- *rapid melting of snow with warming events following a major nor'easter or winter storm;*
- *spring snow melt following heavy winter snowfall;*
- *heavy rainfall (as opposed to snow) as warm air masses move over a frozen ground that limits percolation and drainage;*
- *major summer thunderstorm systems; and*
- *major precipitation events associated with hurricanes or tropical depressions.*

The frequency and occurrence of future flooding in the Northeast will depend on how this diverse set of meteorological conditions changes. Elements of the historical and model-derived future climate projections raise flooding as an increased concern. These elements are:

- *historical trends illustrate increases in extreme precipitation events through the latter half of the 20th century (Groisman et al. in press),*
- *global precipitation is likely to increase with warming, simply because of increased evaporation rates associated with higher temperatures,*
- *the Hadley model projects wetter conditions in summer and winter, and*
- *the intensity and frequency of major hurricanes may change, although current projections are highly uncertain as described earlier.*

Other elements of model-derived future climate projections suggest that winter and spring flooding increases may be transient in nature, or are likely to decline in the future. These elements are:

- *the Canadian model projects drier conditions in summer and winter,*
- *model simulations indicate milder winters and hence the potential for northward movement of warm air masses in winter producing rainfall over frozen ground as the climate warms, then decreased flooding as continued warming substantially reduces the length of time the ground is frozen, and*

- *seasonal warming may increase the potential for warming events during winter associated with higher snowfall creating rapid melting periods as a transient effect, followed by decreased snowmelt events as the climate continues to warm and precipitation tends to fall increasingly as rain.*

Nationally, annual flood damages increased steadily over the period 1903 to 1997, and flood-related fatalities have been high since the 1970s (Kunkel et al. 1999b). Although societal growth is certainly a factor in the increase in flood damages, it is an insufficient explanation. More heavy precipitation events (Karl and Knight 1998) have also been suggested as a factor in this increase. Since 1983, flood damages in the river-rich MAR total 4.7 billion dollars (US Army Corp of Engineers). Flooding also disrupts water supplies and is a significant health risk (Solley et al. 1998; Yarnal et al. 1997). Several water-borne diseases present risks even in wealthier countries when flood waters compromise water systems. These include viruses (e.g. rotovirus), and bacteria-borne (e.g. salmonella) or protozoan-borne (e.g. giardia and cryptosporidium) diseases.

Nor'easters

Major nor'easters produce significant precipitation and cause significant coastal damage, in terms of beach erosion and structural damage, and thus are of major interest to the MAR. This is particularly true because two of its states (New Jersey and Maryland) represent two of the top six states along the Atlantic and Gulf coasts in terms of value of insured coastal property (Insurance Research Council 1995). The climate model projections are divergent with regard to nor'easters. The shift to deeper winter cyclones in the western North Atlantic with stronger winds for doubled carbon dioxide concentrations found by Carnell et al. (1996) indicates the potential for increased property damage. In contrast, Stephenson and Held (1993) found little change in the North Atlantic using the NOAA Geophysical Fluid Dynamics Laboratory model, and thus future increases in storm damages would reflect development of coastal property more than climate change.

The climate models used in this assessment also provide different scenarios. The MAR is the only area of the east coast in which both the Canadian and the Hadley climate models indicate slight increases in the frequency and intensity of winter storms with little change in storm track. The differences are small, and therefore the statistical significance can be questioned. The increases are more significant in the Hadley model which projects a north-south shift of the jet stream under future carbon dioxide conditions, causing storms to track more strongly along the coast, as shown in Figure B.1. In contrast, the Canadian model suggests decreases in eastern storm counts with the exception of the mid-Atlantic.

A significant hazard to coastal areas stems from changes in flood levels superimposed on a more gradual rise in sea level. Return periods of coastal flood events will shorten considerably, even in the absence of any change in storm climatology, as sea level rises.

Interestingly, many of the severe winter weather conditions predicted for the region may seem counter-intuitive. For example, the Great Lakes will experience decreased ice cover or a shorter season of ice cover with climate warming, yet there is a good chance of an increase in the frequency and intensity of lake effect snows in the northwestern portion of the MAR. Specifically, the lack of ice cover will allow increased lake effect snows as cold polar air masses move southward. Hence, the lake effect snows in areas such as Erie, PA could break records even though the climate warms. This conclusion depends on the nature of cold air outbreaks, that initially may not be substantially different from today. As indicated earlier, the effect is likely to be temporary or transient, because precipitation increasingly will fall as rain as climate warms substantially. Both climate models used in the National Assessment project substantial reductions in snow cover by 2100.

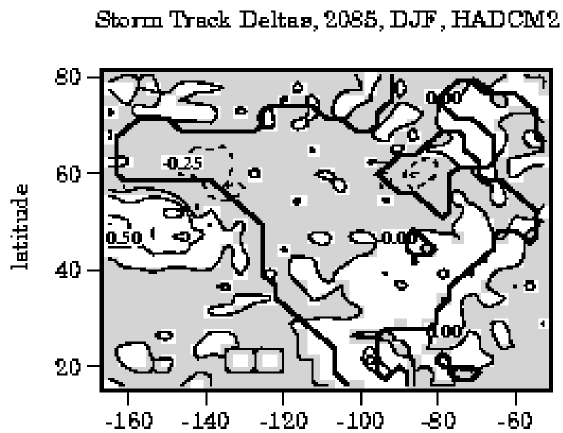


Figure B.1. *A storm track analysis from the Hadley climate model scenario projects a slightly strengthened storm track through the Northeast because the jet stream has a more north-to-south position along the east coast. This scenario projects a slightly stronger winter storm area (unshaded region). The Canadian climate scenario has a more east-west jet, and in general indicates slightly weaker storminess.*

Drought

Although the MAR is on average "water-rich" in comparison with precipitation levels for the rest of the nation, drought is a significant concern for three reasons:

- *Six of the last 20 years were characterized by drought in some part of the region and even a single year drought can result in water restrictions in many counties. Three of these droughts caused in excess of one billion dollars in damage.*
- *The increased warming associated with smaller precipitation changes in the Canadian model provides a scenario for the mid-Atlantic characterized by a strong tendency toward frequent extreme droughts.*

- *The lack of water storage in the MAR is a significant factor in producing vulnerability. In addition, the region's water withdrawals are highly dependent on surface flow. For example, in the MAR 90% of the water withdrawals are from surface flows (Chapter 6). Drought is a frequently cited potential impact of global warming because of increased evaporation rates associated with warming air temperatures.*

In contrast, drought tendencies could remain within historical limits or decrease given that:

- *The Hadley model, with a smaller temperature increase and increases in precipitation, yields a tendency toward neutral changes in drought severity or slightly decreased drought tendencies,*
- *Historical analyses indicate that the extent of area experiencing drought in the region has declined somewhat, and*
- *The differences in precipitation and temperature projected for the Northeast indicate substantial difficulty in determining how drought tendencies may change in the future.*

Ice storms

Severe ice storms have occurred to the north of the MAR (e.g. the extreme 1998 event across New York and northern New England) and a major event occurred across the southern states including North Carolina and Virginia in February of 1994. Whereas ice storms are not unusual in the MAR, the two storms just described were unusual in terms of persistence and extent.

The basis for arguing that such storms may become more frequent is limited to the cause of the ice storms:

- *Ice storms occur when warm moist air masses are uplifted over cold polar air masses or move over cold surfaces. Such conditions may be more common if the mild winters predicted by climate models increase the frequency of northern displacement of warm moist air masses as occurred in 1998.*

However, there are perhaps stronger reasons for considering little change or a decrease in the future occurrence of ice storms:

- *Changes in frequency, intensity or in the path of ice storms are not evident in the historical record.*
- *An increase in frequency, if it occurs at all, is likely to be transitory. In the Canadian scenario, winter precipitation decreases over much of the region and minimum winter temperatures eventually increase significantly (by 7 to more than 10^{o}F above present values) reducing the occurrence of subfreezing temperatures.*

Summary

The Mid-Atlantic Region is currently prone to weather-related natural disasters. Historical analysis and climate model projections present a range of possibilities, including the potential that such weather disasters could actually increase in both summer and winter. This is summarized in Figure B.2. The historical cases of large-scale damages associated with these events even under current climate conditions add a perspective of significant vulnerability. Designs for many human structures are based on historical climate records. If these structures are already vulnerable, then this argues for adaptation strategies that focus on "over-designing" critical structures to add margins of safety and more frequently reviewing design-criteria to account for updated climate projections. The potential for changes in frequency, path and intensity of hurricanes, and in the nature of severe winter storms, becomes a key uncertainty in assessing climate impacts. Coping with substantial increases in severe storms, or even a repeat of historical events coupled with higher sea level, might necessitate relocation of infrastructure away from high-risk zones. Historically, negative economic impacts of severe weather on forestry and agriculture resulted in different planting and harvesting methods. The impact of changes in severe weather on ecosystems is a significant unknown.

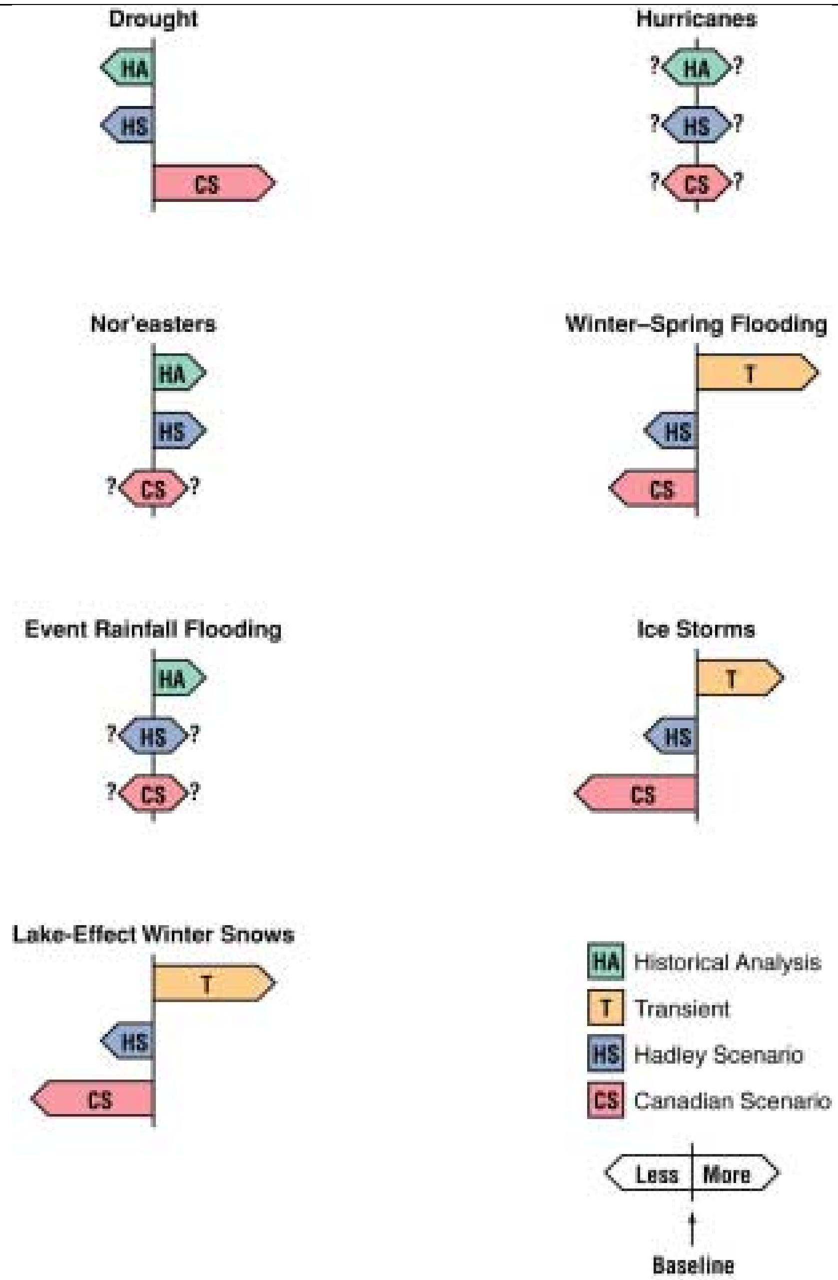


Figure B.2*.* *Schematic of the potential changes in severe weather for the Northeast based on historical data (HA), the Hadley model scenario (HS), the Canadian model scenario (CS) or an assessment of possible transient effects (T). The arrows indicate tendencies based on these data and model scenarios, with arrows to the right indicating increase and arrows to the left indicating decreases in extreme weather. Longer arrows indicate stronger tendencies. Question marks indicate greater uncertainty. The schematic summarizes the text description for each of the severe weather types.*

References

Agee EM (1991) Trends in cyclone and anticyclone frequency and comparison with periods of warming and cooling over North America. *Journal of Climate*. 4: 263-267.

Barron EJ (1995) Climate models: how reliable are their predictions? *Consequences* 1: 16-27.

Bengtsson L, Botzet M, and Esch M (1996) Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus* 48A: 57-73.

Bove MC, Elsner JB, Landsea CW, Niu X, and O'Brien JJ (1998) Effect of El Nino on U.S. Landfalling Hurricanes, Revisited. *Bull. Am. Meteo. Soc*. 79: 2477-2482.

Carnel0l RE, Senior CA, and Mitchell JFB (1996) An assessment of measures of storminess: simulated changes in northern hemisphere winter due to increasing CO_2. *Climate Dynamics* 12:467-476.

Changnon SA and Changnon JM (1992) Temporal Fluctuations in Weather Disasters: 1950-1989. *Climatic Change* 22: 191-208.

Emanuel KA (1988) The Maximum Intensity of Hurricanes. *J. Atmos. Sci*. 45: 1143-1154.

Groisman PY, Knight RW, Karl TR, and Lins HF (1999) Heavy precipitation and streamflow in the United States: Trends in the 20th Century. *Bull. Amer. Meteor. Soc.* in review.

Idso SB, Balling RC, Jr., and Cerveny RS (1990) Carbon Dioxide and Hurricanes: Implications of Northern Hemispheric Warming for Atlantic/Caribbean Storms. *Meteorol. Atmos. Phys.* 42:259-263.

Insurance Research Council (1995) *Coastal Exposure and Community Protection*. Insurance Research Council, Wheaton, Illinois, 45pp.

Karl TR and Knight RW (1998) Secular trends in precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.*, 79: 231-241.

Knutson TR, Tuleya RE, and Kurihara Y (1998) Simulated Increase of Hurricane Intensities in a CO_2-Warmed Climate. *Science* 279:1018-1020.

Kunkel KE, Andsager K, and Easterling DR (1999a) Long-Term Trends in Extreme Precipitation Events over the Conterminous United States. *J. Climate* 12:2515-2527.

Kunkel KE, Pielke Jr. RA, and Changnon SA (1999b) Temporal Fluctuations in Weather and

Extremes that Cause Economic and Human Health Impacts. *Bull. Am. Meteo. Soc*. 80: 1077-1098.

Lighthill J,. Holland G, Gray W, Landsea C, Craig G, Evans J, Kurihara Y, and Guard C (1994) Global Climate Change and Tropical Cyclones. *Bull. Am. Meteo. Soc*. 75: 2147-2157.

Solley WB, Pierce RR, and Perlman HA (1988) *Estimated Water Use in the United States in 1995*. U.S. Geological Survey Circular 1200. US Geological Survey: Washington, DC.

Stephenson DB and Held IM (1993) GCM Response of Northern Winter Stationary Waves and Storm Tracks to Increasing Amounts of Carbon Dioxide. *J. of Climate* 6: 1859-1870.

U.S. Army Corps of Engineers (1998) *Annual Flood Damage Report to Congress for Fiscal Year 1997*. Available on line at http:/www.usace.army.mil/inet/functions/cw/cecwe/flood.htm.

U.S.G.C.R.P. (1995) *Forum on Global Change Modeling*. USGCRP 95-02 Washington, D.C. 26pp.

Yarnal B, Johnson DL, Frakes B, Bowles GI, and Pascale P (1997) The flood of ’96 in the Susquehanna River Basin. *Journal of the American Water Resources Association*. 33: 1299-1312.

Impacts, Challenges and Opportunities

Chapter 2 briefly summarized the current status for the Mid-Atlantic Region in terms of its geography, economy, ecosystems, and climate. Chapter 3 sketched how the future might look, and the importance of considering how the MAR is likely to change even in the absence of climate change as well as adding the impacts from potential changes in climate and its variability.

Despite the many uncertainties in projecting future scenarios, planning for the future can be informed by assessment of what changes are most likely and what changes are likely to be largest. The six chapters in this section explore the potential future for each of the following sectors: agriculture, forests, fresh water quantity and quality, ecosystems, and human health. For each sector, potential future scenarios are considered as a starting point for assessing impacts from climate variability and climate change. A conscious effort is made to examine both the challenges posed by impacts that are likely to be negative, as well as the opportunities emanating from impacts that are likely to be positive. Each chapter is intended to provide detailed information for the reader especially interested in that topic.

The final section of this Foundations report, Planning for the 21st Century, pulls together the findings from the first nine chapters. This provides perspective about which potential impacts might be largest, as well as the relative uncertainties among impacts. Chapters 10 and 11 summarize what can be done now to improve resiliency in the MAR and take advantage of beneficial impacts, as well as what additional information and research are needed so that the region's citizens can make smarter decisions in the future.

Chapter 4. Agriculture*

Mid-Atlantic agriculture, like agriculture worldwide, has an intrinsic relationship with climate. Climate variability has strong impacts on Mid-Atlantic agriculture. Climate change potentially also could have significant impacts. This chapter reviews the current status and stresses on Mid-Atlantic agriculture and how climate variability affects the region's agriculture. It goes on to consider how climate change might affect future Mid-Atlantic agriculture, bearing in mind that the region's agriculture is likely to change dramatically independent of climate change. This chapter also considers some management and adaptation options for farmers, agribusinesses, and governments. It concludes with priorities for research and information that should be addressed in future assessments.

This assessment draws upon the literature as well as upon our analyses. It attempts to develop a more comprehensive picture for the region as a whole of the aggregate impacts on agricultural production and on the resulting environmental effects. To the extent feasible, quantitative analyses have been used. Gaps are filled with qualitative assessments that combine results from the literature and expert judgment. Results are reported using descriptors such as "substantial," because the models and data generally are not refined enough for statistical significance tests. Note that impacts can be substantial in the sense of being large enough to be noticeable, and yet small compared to the region's agricultural output or environmental status. The report (especially in the main section on Planning for the 21st Century) also distinguishes among the relative sizes of projected impacts; relatively large impacts can still be small in terms of the region's economy or environmental status.

Current Status and Stresses

Compared to many other parts of the United States, Mid-Atlantic agriculture is characterized by smaller farms and a wider range of crops and livestock products. Average farm size in the Mid-Atlantic region (MAR) is about 180 acres, compared with over 500 acres for the rest of the United States (USDA National Agricultural Statistics Service 1999a). However, poultry and hog operations within the region tend to be as large and intensive as those in other parts of the country.

The single largest source of cash receipts in most of Pennsylvania, upstate New York, and much of Maryland is dairy production. Mushrooms and other vegetables and nursery products are important in New Jersey, parts of Maryland, and parts of eastern Pennsylvania. Chicken and

* This chapter is based on Abler et al., (2000) "Climate Change and Agriculture in the Mid-Atlantic Region, *Climate Research*, 14:2. It appears with permission of Inter-Research.

eggs tend to dominate in the Delmarva Peninsula and in parts of Virginia and southern Pennsylvania. Significant production of apples, peaches, and other tree fruits occurs in certain areas of Maryland, New Jersey, Pennsylvania, and West Virginia. In western Virginia and West Virginia, cattle ranching is the most important agricultural activity. Tobacco production tends to predominate in southern Virginia and northern North Carolina.

Due to historically adequate supplies of rainfall in most years, crop production in the Mid-Atlantic region is overwhelming rainfed rather than irrigated. Less than 3 percent of crop acreage in the Mid-Atlantic is irrigated, compared with about 13 percent in the rest of the United States (USDA National Agricultural Statistics Service 1999a).

Present-day Mid-Atlantic agriculture can be illustrated using data for major land resource areas (MLRAs) within the region. MLRAs are areas characterized by common patterns of soil, climate, water resources, and land uses. MLRAs for the Mid-Atlantic region were obtained using geographic information systems (GIS) boundaries assembled by the U.S. Geological Survey (1999). Figure 4.1 shows MLRAs for the Mid-Atlantic region. Table 4.1 presents statistics for Mid-Atlantic agriculture at the MLRA level. Agricultural land use and sales data in Table 4.1 are from county-level data in the *1992 Census of Agriculture* (Government Information Sharing Project 1999). Employment data, which include full-time as well as part-time farmers, use 1996 county-level data from the U.S. Bureau of Labor Statistics (1999). In cases where a county spans two or more MLRAs, county data are apportioned among MLRAs according to the proportion of total county area in each MLRA.

Table 4.1 indicates that agriculture accounts for about one-fourth of total land area in the Mid-Atlantic region. Among MLRAs, this proportion varies from over one-half in the Mid-Atlantic Coastal Plain (153C) to less than 4 percent in the Cumberland Plateau and Mountains (125). Hay and pastureland are the predominant uses of agricultural land, accounting for nearly three-fourths of total agricultural land in the Mid-Atlantic region. The remainder, about one-fourth, is accounted for by cropland. Hay and pastureland are also the predominant uses of agricultural land in most MLRAs. Exceptions include the Atlantic Coastal Flatwoods (153A) and the Tidewater Area (153B) along the southern Virginia and northern North Carolina coasts, where producers grow a mixture of crops.

About three-fourths of the total value of farm production (including both sales and products consumed on the farm and not sold) in the Mid-Atlantic region is accounted for by crops rather than livestock or livestock products. Among MLRAs, crop production as a proportion of total farm production varies from about one-tenth in the Ontario Plain and Finger Lakes Region (101) to over 90 percent in the Northern Coastal Plain (149A) and the Tidewater Area (153B). The relative economic importance of livestock is larger as measured by farm sales. Livestock and livestock products account for about two-thirds of agricultural sales in the Mid-Atlantic region.

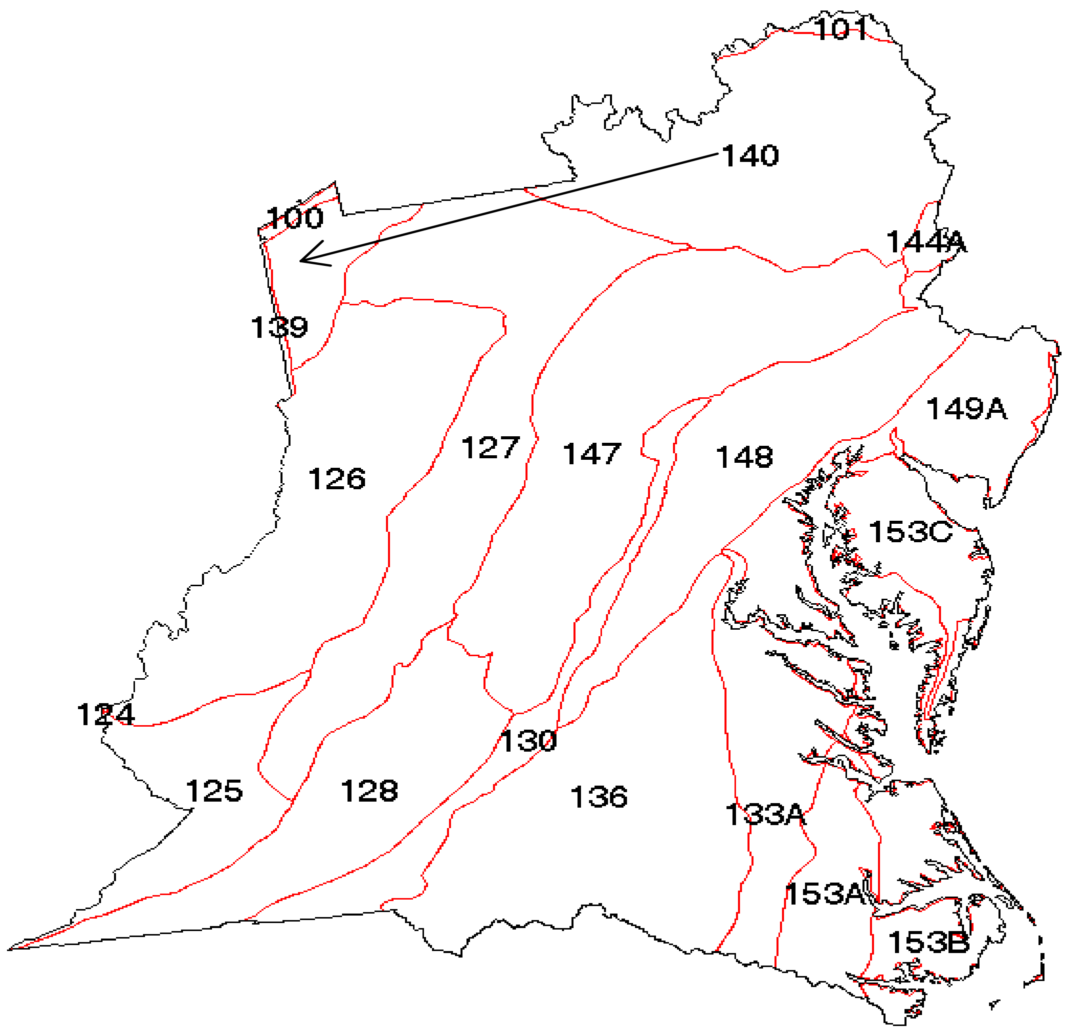


Figure 4.1. MLRA Map of the Mid-Atlantic Region.

Table 4.1. Mid-Atlantic Agriculture at the MLRA Level.

MLRA	MLRA Name	MLRA Area Lying in Mid-Atlantic Region (1000 Acres)	Percentage of Total Land in MLRA, 1992: Hay and Pastureland	Cropland	All Agricultural Land	Farm Labor Force as Percentage of Total Labor Force, 1996	Percentage of Total Value of Agricultural Production, 1992: Livestock and Livestock Products	Crops
100	Erie Fruit and Truck Area	426	25.0	9.3	34.3	1.1	45	55
101	Ontario Plain and Finger Lakes Region	835	29.6	6.9	36.6	3.7	89	11
124	Western Allegheny Plateau	7	13.5	2.5	16.0	1.3	31	69
125	Cumberland Plateau and Mountains	9,196	2.4	1.5	3.9	2.8	27	73
126	Central Allegheny Plateau	25,855	18.6	3.2	21.8	4.1	56	44
127	Eastern Allegheny Plateau and Mountains	25,935	8.3	1.7	10.0	3.2	78	22
128	Southern Appalachian Ridges and Valleys	16,105	18.2	2.9	21.1	10.9	79	21
130	Blue Ridge	7,106	20.9	2.2	23.1	10.1	78	22
133A	Southern Coastal Plain	10,888	12.7	12.8	25.5	4.9	14	86
136	Southern Piedmont	27,707	15.8	5.8	21.5	7.6	34	66
139	Eastern Ohio Till Plain	311	26.5	9.9	36.4	2.4	74	26
140	Glaciated Allegheny Plateau and Catskill Mountains	30,017	19.6	3.7	23.3	3.6	67	33
144A	New England and Eastern New York Upland, Southern Part	874	16.8	2.6	19.5	1.7	45	55
147	Northern Appalachian Ridges and Valleys	29,605	26.6	7.6	34.2	4.6	68	32
148	Northern Piedmont	16,586	37.9	10.8	48.7	2.6	43	57
149A	Northern Coastal Plain	11,557	13.4	6.7	20.0	1.1	5	95
153A	Atlantic Coastal Flatwoods	5,994	10.4	18.9	29.3	6.3	32	68
153B	Tidewater Area	9,082	12.0	19.5	31.5	6.7	8	92
153C	Mid-Atlantic Coastal Plain	6,458	30.0	21.8	51.8	3.4	35	65
Entire Mid-Atlantic Region		234,545	18.4	6.6	25.0	4.0	26	74

Agriculture accounts for about 4 percent of the total labor force in the Mid-Atlantic region (including both full-time and part-time farmers). This proportion ranges from over 10 percent in the Southern Appalachian Ridges and Valleys (128) and Blue Ridge (130) to less than 1 percent in the heavily urbanized Erie Fruit and Truck Area (100) and Northern Coastal Plain (149A). Agriculture's percentage of the labor force in the Mid-Atlantic drops to about 1 percent if only full-time farmers are included.

Agriculture's importance in the Mid-Atlantic region extends well beyond its role as a source of income and employment. Agriculture is the second largest land use after forests and the dominant land use in some areas. Its presence defines many rural landscapes. Rural and urban populations within and outside the region value the region's agricultural and rural land as open space and as a source of countryside amenities. Hunting, sightseeing, and other recreational activities on rural lands are important throughout the Mid-Atlantic. In 1997, over $1.5 billion was spent on hunting in the MAR, approximately three quarters of which took place on private land (U.S. Department of the Interior 1999). In the same year, over $1.6 billion was spent on wildlife viewing (U.S. Department of the Interior 1999). Agricultural land is an important habitat for some of the region's wildlife species.

These values are reflected in public programs to protect farmland from development and preserve agricultural landscapes in all eight states within the region (American Farmland Trust, 1997). Programs in place within the region include agricultural protection zoning, differential property assessment, and conservation easements, which cover over 400,000 acres in the MAR (American Farmland Trust 1997). This represents more than half of all conservation easements in the United States.

Agriculture in the Mid-Atlantic region is also a source of negative environmental impacts, particularly water pollution from nutrients, eroded soils, and pesticides. Of 2,105 watersheds (defined at the 8-digit hydrologic unit code level) in the 48 contiguous states, watersheds in southern New York, northern Pennsylvania, southeastern Pennsylvania, western Maryland, and western Virginia rank in the top 10 percent in terms of manure nitrogen runoff, manure nitrogen leaching, manure nitrogen loadings from confined livestock operations, and soil loss due to water erosion (Kellogg et al. 1997). Watersheds in southeastern Pennsylvania and along the southern Virginia/northern North Carolina coasts also rank in the top 10 percent in terms of nitrogen loadings from commercial fertilizer applications (Kellogg et al. 1997). Watersheds in the tobacco-growing areas of southern Virginia and northern North Carolina rank near the top as measured by potential threats to human drinking water supplies, fish, and other aquatic life from pesticide leaching and runoff (Kellogg et al. 1999).

Environmental impacts of agricultural production in the Mid-Atlantic are of concern for many reasons, but perhaps the most important is because of their impact on the Chesapeake Bay. The

64,000 square mile Chesapeake Bay watershed is the largest estuary in the United States and is one of the nation's most valuable natural resources (Chesapeake Bay Program 1999). It is a major source of seafood, particularly highly valued blue crab and striped bass. It is also a major recreational area, with boating, camping, crabbing, fishing, hunting, and swimming all being very popular and economically important. The Chesapeake Bay and its surrounding watersheds provide a summer or winter home for many birds, including tundra swans, Canada geese, bald eagles, ospreys, and a wide variety of ducks. In total, the Bay region is home to more than 3,000 species of plants and animals (Chesapeake Bay Program 1999).

Human activity within the Chesapeake Bay watershed during the last three centuries has had serious impacts on this ecologically rich area. Soil erosion and nutrient runoff from crop and livestock production have played major roles in the decline of the Chesapeake Bay. The Chesapeake Bay Program (1997) estimates that agriculture currently accounts for about 39% of nitrogen loadings and about 49% of phosphorus loadings in the Chesapeake Bay. This makes agriculture the single largest contributor to nutrient pollution in the Chesapeake Bay. Other contributors include point sources (e.g., wastewater), forests, urban areas, and atmospheric deposition.

Climate Variability and Mid-Atlantic Agriculture

Crop production in the Mid-Atlantic region historically has been sensitive to climatic variations. Extreme events such as heat waves, droughts, freezes, floods, hailstorms, and hurricanes have had strong impacts on crop yields over the years. For example, a drought and heat wave in the summer of 1980, as well as in the summer of 1991, significantly reduced crop yields in Maryland, Pennsylvania, Virginia, and other parts of the Mid-Atlantic region.

Among major crops within the MAR, yields of corn are perhaps the most climate-sensitive. Statistical analysis of crop yield data for 1980-1998 from the USDA National Agricultural Statistics Service (1999b) for states in the MAR indicates that corn yields tend to deviate significantly around their trend rates of growth – often more than 30 percent above or below trend. On the other hand, yields of crops such as hay and tobacco show much smaller deviations – generally on the order of 5-10 percent – around their trend rates of growth. The relatively high yield variability for corn could be due to the fact that virtually all corn is rainfed and the fact that water is a limiting input into corn production in many years.

In general, livestock production tends to be less sensitive to climate variability than crop production. This is particularly true for poultry production in the MAR, the vast majority of which occurs indoors under controlled climatic conditions. For outdoor livestock production, heat waves can lead to increased livestock mortality, lower livestock yields, and lower reproductive capacity (Klinedinst et al. 1993). Especially cold weather during the winter can also increase livestock mortality.

Future Agricultural Baseline Scenarios

This section examines future baseline scenarios for Mid-Atlantic agriculture – that is, what the region's agriculture might look like in the future because of influences other than climate change.

Mid-Atlantic agriculture, like U.S. agriculture as a whole, has changed radically during the last century. With the notable exception of the Amish, tractors and other farm machinery have virtually eliminated the use of draft animals and have made it possible for a single farmer to cultivate tracts of land orders of magnitude larger than a century ago. The introduction of synthetic organic pesticides in the 1940s revolutionized the control of weeds and insects. Similarly, there has been tremendous growth in the use of manufactured fertilizers and hybrid seeds. Farmers have become highly specialized in the livestock products and crops they produce, and they have become much more dependent on purchased inputs. Crops that were virtually unheard of 100 years ago, such as soybeans, are of major importance today. As agricultural productivity has risen, and as real (inflation-adjusted) prices of farm commodities have fallen, substantial acreage in the Mid-Atlantic region has been taken out of agriculture and either returned to forest or converted to urban uses.

There are few reasons to expect this rapid pace of change to slow down during the coming century. Biotechnology already is having significant impacts on agricultural production, and could lead to revolutionary changes in the types of crops and livestock produced and in the way that they are produced. Plant biotechnology has the potential to yield crops with significantly greater resistance to a whole host of pests, greater resilience during periods of temperature and precipitation extremes, and even cereal varieties that fix atmospheric nitrogen in the same manner as legumes (Plucknett and Winkelmann 1996; Huttner 1996). Work is also underway to engineer pest vectors into beneficial insects as part of integrated pest management (IPM) strategies. However, genetically modified organisms (GMOs) with tolerance to specific herbicides are also being developed and released, and concerns have been raised that these may promote herbicide usage (Rifkin 1998).

Precision agriculture and improved climate forecasts may give farmers much greater understanding of, and control over, growing conditions. Precision agriculture uses remote-sensing and information technologies in order to achieve very precise control over agricultural input applications (chemicals, fertilizers, seeds, etc.). This permits farmers to compensate for small-scale variations within a farm field in soil nutrients and crop pests, and to target agricultural inputs precisely to only those parts of a farm field where they are actually needed.

Biotechnology and precision agriculture could lead to substantial reductions in the negative environmental effects of agricultural production.

Future improvements in computer technology and in modeling smaller scale climatic processes such as thunderstorms can be expected to lead to improved weather forecasts (Tribbia 1997). Improved forecasts may lead farmers to make better choices about what crops to plant, when to plant and harvest, when to protect temperature-sensitive crops such as tree fruits, when to fertilize, and other farm management decisions (Johnson and Holt 1997; Mjelde et al. 1998). This can be expected to increase agricultural productivity.

At the same time, economic conditions facing Mid-Atlantic agriculture can be expected to continue changing for many other reasons, including changes in global agricultural commodity prices and continued conversion of agricultural land to urban uses. Analyses by the International Food Policy Research Institute (Islam 1995), the U.S. Department of Agriculture's Interagency Agricultural Projections Committee (1999), and Crosson and Anderson (1992) suggest that real prices for major agricultural commodities such as wheat, corn, other grains, soybeans, dairy products, beef, pork, chicken, and eggs are all likely to decline in coming decades, perhaps significantly. Others, such as Tweeten (1998) and Brown (1996), suggest that real prices of agricultural commodities could increase over the next few decades. However, as Johnson (1998) emphasizes, projections of rising agricultural prices have consistently been wrong in the past.

Future increases in population in the Mid-Atlantic region may lead to additional conversion of farmland to residential and commercial uses. Future increases in per capita income could manifest themselves in larger homes and lot sizes, and thus more residential land use, a tendency evident over the last 30 to 40 years. Studies of land use confirm that population and per capita income are important determinants of the conversion of farmland and forestland to urban uses (Hardie and Parks 1997; Bradshaw and Muller 1998). Probable futures for the spatial pattern of development within the Mid-Atlantic region are more difficult to assess than an overall tendency toward urbanization. One possible future involves a "fill in" of areas between existing major urban centers, such as the area between Baltimore and Washington, DC (Bockstael and Bell 1998).

These trends, when taken as a whole, suggest that there will be fewer commercial crop and livestock farms within the region in the future than there are today, and that some of the region's agricultural production will shift to other regions and countries. However, it is also probable that production per farm and yields per acre on the remaining commercial farms within the Mid-Atlantic region will be significantly higher than they are today. There may be growth in "weekend," "hobby," and other noncommercial farms within the region. However, such farms account for only a small fraction of total agricultural output; only 8% of total farm sales in 1997 were from farms with less than $50,000 in sales (USDA National Agricultural Statistics Service 1999a).

Another force for change in the region's agriculture in coming decades may be stricter regulatory control over nonpoint source water pollution. Agriculture accounts for the vast majority of nonpoint nitrogen and phosphorous pollution within the Chesapeake Bay region (Abler et al. 2000). There already have been moves on the part of the Environmental Protection Agency for stricter control of pollution from large-scale confined animal feeding operations. It is also possible that smaller agricultural producers may come under the purview of environmental regulations in coming decades.

With an eye toward establishing plausible upper and lower bounds on potential climate change impacts on Mid-Atlantic agriculture, along the lines discussed in Chapter 3, two baseline scenarios are considered here for the year 2030. These two scenarios, continuation of the status quo (SQ) and a smaller, more "environmentally friendly" agriculture (EFS), are detailed in Table 4.2. The EFS scenario is much more probable than any scenario approximating a continuation of

Table 4.2. Baseline Agricultural Scenarios for the Year 2030

Scenario	Scenario Assumptions
Status Quo (SQ)	• Agriculture as it exists today in the Mid-Atlantic region
Smaller, More "Environmentally Friendly" Agriculture (EFS)	• Major decline in field crop production in region • Significant decline in livestock production, perhaps smaller than decline in field crop production • Significant decrease in number of farms in region • Substantial increase in agricultural productivity due to biotechnology and precision agriculture • Major increase in agricultural production per farm on the remaining farms • Significant decrease in agriculture's sensitivity to climate variability due to biotechnology, precision agriculture, and improved climate forecasts • Some conversion of agricultural land to urban uses, with conversion slowed by farmland protection programs • Some reforestation of existing, economically marginal agricultural lands • Significant decrease in commercial fertilizer and pesticide usage due to biotechnology • Less runoff and leaching of agricultural nutrients and pesticides due to precision agriculture • Stricter environmental regulations facing agriculture, especially intensive livestock operations

the status quo, but both scenarios are needed to establish bounds on climate change impacts. The EFS scenario helps establish lower bounds on any negative impacts on agricultural production due to climate change, and upper bounds on any positive impacts on production. For example, the EFS scenario provides the upper bound on increased agricultural production because agriculture is much better equipped (even though smaller than under the SQ scenario) to take advantage of positive climate developments. The EFS also helps establish lower bounds on positive or negative impacts of climate change on environmental effects of agricultural production. The SQ scenario is the opposite of the EFS scenario, in that it helps establish upper bounds on negative production impacts, lower bounds on positive production impacts, and upper bounds on positive or negative environmental impacts. These are summarized in Table 4.3.

Table 4.3. Upper and Lower Bounds Established by the Two Agricultural Baseline Scenarios

	Negative Impacts on Production	**Positive Impacts on Production**	**Negative Environmental Impacts**	**Positive Environmental Impacts**
Upper Bound	SQ	EFS	SQ	SQ
Lower Bound	EFS	SQ	EFS	EFS

SQ = Status Quo Scenario
EFS = Smaller, More Environmentally Friendly Scenario

Using the SQ scenario alone (i.e., imposing future climate change on present-day agriculture) instead of using both scenarios could be misleading. The SQ scenario represents an extreme future, not a probable or likely future. Using the SQ scenario alone would lead to overestimation of negative impacts of climate change on production as well as overestimation of positive and negative environmental impacts. It would also lead to underestimation of positive impacts on production.

For the year 2100, the uncertainties are so overwhelming that it is very difficult to think about baseline agricultural scenarios. To illustrate this point, it would have been exceedingly difficult if not impossible for someone in 1900 to foresee the dramatic changes that would occur in Mid-Atlantic agriculture during the 20th century. It is probable that Mid-Atlantic agriculture in 2100 will bear only a faint resemblance to the region's agriculture today, but it is not possible to say with any confidence what the major changes between now and then might be.

Potential Climate Change Impacts on Mid-Atlantic Agriculture

This section assesses potential climate change impacts on four types of crops (corn, soybeans, tobacco, and tree fruits) and two types of livestock (dairy and poultry) that are currently important to Mid-Atlantic agriculture. The main tree fruits within the region are apples, cherries, peaches, and pears. This section also assesses potential climate change impacts on environmental effects from agricultural production within the region. Our assessment draws in part on previous assessments for U.S. and world agriculture (Adams et al. 1999; Adams et al. 1998; Darwin et al. 1995; IPCC 1996; Lewandrowski and Schimmelpfennig 1999; Rosenzweig and Hillel 1998; Schimmelpfennig et al. 1996).

Impacts on Agricultural Production

Carbon dioxide (CO_2) accumulation and climate change within the Mid-Atlantic are expected to have a number of direct and indirect effects on the region's agriculture (Adams et al. 1999). Elevated levels of CO_2 may increase photosynthesis and thus crop yields, a phenomenon known as the CO_2 fertilization effect. Carbon dioxide is indispensable in the process of photosynthesis. The balance of evidence to date suggests that higher atmospheric concentrations of CO_2, holding constant other climatic factors affecting crop yields, could lead to substantial increases in yields (Rosenzweig and Hillel 1998). Elevated levels of CO_2 also may decrease transpiration (evaporation from plant foliage), which would reduce water stress during periods with little or no rainfall (Rosenzweig and Hillel 1998).

Climate scenarios summarized in chapter 3 suggest that average daily minimum and maximum temperatures within the Mid-Atlantic Region may increase by about 2°F between now and the decade of 2025-2034, and that average annual precipitation may increase on the order of 3 inches per year between now and then. These increases in temperature and precipitation also could have substantial effects on crop yields. This is particularly true for corn, which is perhaps the most climate-sensitive crop in the Mid-Atlantic region because virtually all corn is rainfed and because water is a limiting input into corn production in many years.

For example, Table 4.4 presents estimates from Izaurralde et al. (1999) of percentage changes in crop yields due to CO_2 fertilization effects and climate change (using Hadley climate model results) for unirrigated corn, soybeans, and unirrigated alfalfa in three U.S. regions: Northeast, Appalachian, and Corn Belt. The Northeast and Appalachian regions overlap the Mid-Atlantic region, while the Corn Belt is shown because estimates for alfalfa are not available from Izaurralde et al. (1999) for the Northeast or Appalachian regions. The estimates suggest that CO_2 fertilization impacts on yields may be significant, while impacts of climate change on yields may be mixed. Other analyses (e.g., Rosenzweig et al. 1993) also suggest that CO_2 fertilization impacts on yields may be large, including impacts on crops important to the Mid-Atlantic Region such as soybeans and tobacco.

Table 4.4. Percentage Changes in Regional Crop Yields as Estimated by Izaurralde et al. (1999)

	50% Increase in CO_2 (365 to 560 ppm)			**Change from 1961-90 Climate to 2025-34 Climate**		
Crop	Northeast	Appalachian	Corn Belt	Northeast	Appalachian	Corn Belt
Unirrigated Corn	10.5*	11.1*	9.0*	14.3*	-1.7	5.6*
Soybeans	18.6*	18.5*	17.0*	4.6	-7.0	-7.4*
Unirrigated Alfalfa	—	—	19.2*	—	—	14.4*

*Change statistically significant at the 10% level.

Beyond these direct effects, climate change may have indirect effects on Mid-Atlantic agriculture (Adams et al. 1999; Schimmelpfennig et al. 1996). Climate change in other regions and countries may affect agricultural production in those areas. As national and global agricultural commodity markets adjust to these changes in production, commodity prices facing Mid-Atlantic farmers could change. Climate change may also have impacts on nonagricultural sectors of the Mid-Atlantic economy or economies of other regions and countries. These changes, which we refer to as economywide effects, might manifest themselves as changes in prices of purchased inputs used by Mid-Atlantic farmers, in competing demands for land within the region, or alternative employment opportunities available to Mid-Atlantic farmers.

For example, Table 4.5 presents estimates from Tsigas et al. (1997) of the impacts of climate change on prices of agricultural commodities and inputs into agricultural production, both with and without CO_2 fertilization effects. In general, many impacts on prices are large without CO_2 fertilization effects, but price changes become small to moderate once these impacts are taken into account. Other economic analyses (e.g., Darwin et al. 1995; Reilly et al. 1994) also find that changes in agricultural commodity prices are likely to be moderate.

Evidence on the potential impacts of climate change on weeds and on crop and livestock pests and diseases is much more limited. CO_2 fertilization effects may increase growth of many weed species (Rosenzweig and Hillel 1998). Warming can be expected to lead to a northern expansion of tropical and other warm-season weeds, plant parasitic nematodes, and insects, presenting Mid-Atlantic agriculture with a different set of pest challenges than it faces today (Main 1999). In the case of the European corn borer, warming can be expected to lead to an increase in the number of generations completed each year and an increase in the average population level (Calvin 1999). However, Mid-Atlantic agriculture is more diverse in terms of growing conditions and the types of crops and livestock produced than agriculture in many other parts of the U.S. or other countries, which should render it less vulnerable to devastating macro-scale disease or pest epidemics (Main 1999).

Table 4.5. Percentage Changes in U.S. Agricultural Commodity and Input Prices as Estimated by Tsigas et al. (1997)

Commodity or Input	**With CO_2 Fertilization Effect**	**Without CO_2 Fertilization Effect**
Commodity:		
Wheat	1.6	33.0
Other Grains	19.9	31.5
Non-Grain Crops	-13.4	27.5
Livestock	3.9	12.0
Input into Production:		
Land	-1.3	61.0
Labor	0.1	0.3
Capital	0.1	0.5

Potential climate change impacts on Mid-Atlantic agricultural production in the year 2030 are summarized in Table 4.6. Impacts are reported under our two alternative baseline scenarios – a smaller, more environmentally friendly agriculture (EFS), or a continuation of the status quo (SQ). Each impact in Table 4.6 is classified as either a substantial increase (+), substantial decrease (–), no noticeable impact in either direction (0), or unknown (?) based on currently available knowledge. Table 4.6 also reports our assessment of overall effects for each of the four crops and two livestock products.

Overall, the impacts of climate change on MAR crop production may be beneficial. Soybean and tree fruit production within the region may increase under both baseline scenarios due to CO_2 fertilization effects, increased precipitation, and reduced transpiration (for soybeans). Corn production should also increase, although CO_2 fertilization effects are not quite as strong for corn as for soybeans and tree fruits (Rosenzweig and Hillel 1998).

Of the four crops, tobacco appears to have the highest probability of suffering production losses because of climate change. Even here, the direct effects of climate change on production within the region may on the whole be beneficial. However, similar direct effects may be operating in other regions and countries, leading to an increase in global tobacco production and a decline in world tobacco prices. These declines could potentially be large enough to act as a disincentive to tobacco production within the MAR in spite of the fact that the direct effects of climate change on tobacco in the MAR are positive.

Table 4.6. Potential Climate Change Impacts on Agricultural Production in 2030.

	Impact Accounting for Adaptation by Producers* (Substantial Increase +, Substantial Decrease –, No Noticeable Impact 0, or Unknown ?)					
	Corn	**Soybeans**	**Tobacco**	**Tree Fruits**	**Dairy**	**Poultry**
Direct Effects**						
Increased Photosynthesis	+	+	?	+	0	0
Reduced Transpiration	+	+	+	0	0	0
Higher Temperatures	0 EFS – SQ	0	0 EFS – SQ	0 EFS – SQ	0	0
Increased Precipitation	+	+	+	+	0	0
Changes in Extreme Weather Events	?	?	?	?	0	0
Changes in Weeds, Insects, and Diseases	0 EFS ? SQ	0 EFS ? SQ	0 EFS ? SQ	0 EFS ? SQ	0 EFS ? SQ	0 EFS ? SQ
Indirect Effects**						
Changes in Farm Commodity Prices	0	0	–	?	0	0
Economywide Effects	0	0	0	0	0	0
OVERALL EFFECTS:						
EFS Scenario	+	+	0	+	0	0
SQ Scenario	0/+	+	–	+	0	0

* Accounting for actions taken by producers to minimize negative climate change impacts on production and exploit positive impacts on production.
** Unless otherwise noted, the effect (+, –, 0 or ?) is the same in the EFS and SQ scenarios.

We do not anticipate that the effects of climate change on livestock production within the MAR will be substantial in either a positive or negative direction. In general, livestock production tends to be less climate-sensitive than crop production. For outdoor livestock production, heat waves can lead to increased livestock mortality, lower livestock yields, and lower reproductive capacity (Klinedinst et al. 1993). However, increases in temperatures projected for the region will probably not be large enough to be a major detriment to livestock production. Furthermore, much livestock production in the Mid-Atlantic, especially poultry production, occurs indoors under controlled climatic conditions. Producers in these settings have several low-cost options for adapting to higher temperatures, including fans and improved ventilation. In principle, climate change can also affect livestock production through changes in the quality and availability of forage, or through changes in prices of purchased feeds. Here too, however, available evidence suggests that there may be no significant impacts one way or another.

The impacts in Table 4.6 take into account our assessment of adaptation by farmers to climate change. Farmers have a wide array of options at their disposal for minimizing negative impacts on production and exploiting positive impacts. For crops these options including changes in crop acreages, the types or varieties of crops grown, planting and harvesting dates, crop rotations, tillage practices, fertilization practices, and pest management practices. For livestock these options include changes in herd sizes, livestock types or breeds, feeding rations, and heating and cooling systems.

The question marks in Table 4.6 beside changes in extreme weather events and changes in weeds, insects, and diseases reflect our lack of knowledge of how these factors might change and how any changes that occur might impact the region's agriculture. It is very hard to predict whether extreme weather events will occur more or less often in the future. Likewise, climate change may affect pest-crop and pest-livestock relationships, but we have very little evidence on how these relationships might change (Rosenzweig and Hillel 1998).

Agriculture's Environmental Impacts

The potential effects of climate change on the environmental impacts of agricultural production in the Mid-Atlantic Region are difficult to assess. In part this is because we are unsure about how climate might change within the region. In particular, changes in extreme weather events such as floods or heavy downpours could easily overwhelm the impacts of other changes in the region's climate, but we lack good evidence on how these extreme events might change. Environmental impacts are also difficult to assess because of a lack of research on climate change, agriculture, and the environment. There have been some studies directed at impacts of climate change on agriculture's environmental effects (e.g., Favis-Mortlock and Savabi 1996; Follett 1995; Phillips et al. 1993; and Rosenzweig and Hillel 1998). However, these are all studies of regions with different soil, geological, climatic, and ecological conditions than the Mid-Atlantic Region. Furthermore, these studies were not designed to consider economic responses by farmers to climate change. Instead, they implicitly assume that farmers will continue to produce the same crops and livestock on the same land using the same management practices.

Recent simulation analyses by Abler et al. (2000) suggest that climate change in the Chesapeake Bay region could lead to increases in nonpoint nitrogen loadings in water supplies from corn production. However, the magnitude of the increase varies significantly depending on the baseline scenario (SQ or EFS) and on whether the predictions of the Hadley climate model or the Canadian Climate Centre model are used. Corn is a good case for study because it accounts for most nonpoint agricultural pollution in the Chesapeake Bay region as the majority of nonpoint pollution from all sources, agricultural and nonagricultural. The main driving force behind the simulation results in Abler et al. (2000) is that CO_2 fertilization effects make corn production in the region more economically attractive to farmers. Corn production increases as a result, and with it come increases in nonpoint pollution.

Bearing in mind this uncertainty, potential climate change impacts for the year 2030 on environmental effects from agricultural production are shown in Table 4.7. Impacts are reported in Table 4.7 under the two alternative baseline scenarios and are classified as either a substantial increase (+), substantial decrease (–), no noticeable impact in either direction (0), or unknown (?) based on currently available knowledge. A positive sign in Table 4.7 implies more environmental degradation, while a negative sign implies less environmental degradation. Table 4.7 first reports impacts assuming that farmers do not adapt in any way to climate change, and then brings farmer adaptation into the picture. Impacts assuming no farmer adaptation are based on the studies mentioned above (Favis-Mortlock and Savabi 1996; Follett 1995; Phillips et al. 1993; and Rosenzweig and Hillel 1998), bearing in mind the important caveat that these studies may have limited applicability to the Mid-Atlantic Region. Environmental effects of farmer adaptation are based on changes in crop acreages, crop management practices, and other factors that we anticipate might occur as a result of the production impacts reported in Table 4.6.

To the extent that elevated levels of atmospheric carbon dioxide lead to increased photosynthesis and reduced transpiration, nutrient leaching and runoff from crop and tree fruit production may decline because higher yielding plants tend to take up more nutrients, leaving fewer nutrients to run off or leach. On the other hand, to the extent that precipitation within the Mid-Atlantic Region increases, more nutrients may be washed into surface waters or groundwater before plants are able to take them up. Increased precipitation might also wash more pesticides and animal manure into surface waters or groundwater, and might wash more eroded soils into surface waters.

Whether these changes in nutrient leaching and runoff, pesticide leaching and runoff, and soil erosion will be large or small depends on what agriculture in the Mid-Atlantic Region will be like in the future. In the EFS scenario, where agriculture is significantly smaller than it is today, there may be fewer nutrients and pesticides to leach or run off simply because there is less agriculture. In addition, biotechnology and precision agriculture in the EFS scenario lead to livestock wastes with lower nutrient contents and more "environmentally friendly" crop and tree fruit farms that use significantly fewer commercial fertilizers and pesticides. Alternatively, under the SQ scenario, where agriculture does not shrink significantly and does not become more environmentally friendly, water quality impacts could be significant.

If climate change leads to an increase in soil erosion, farmers will have an incentive to take additional steps to counteract erosion in order to preserve the productivity of their own soils. These steps might involve planting less erodible crops, changing management practices for existing crops, or even removing some highly erodible cropland from production. Similarly, if climate change leads to an increase in runoff or leaching of crop nutrients or pesticides, farmers

Table 4.7 Potential Climate Change Impacts on Environmental Effects from Agriculture in 2030.

	Impact (Substantial Increase +, Substantial Decrease –, No Noticeable Impact 0, or Unknown ?)			
	Nutrient Leaching and Runoff from Crops	**Nutrient Leaching and Runoff from Livestock**	**Pesticide Leaching and Runoff**	**Water Erosion**
Effects Assuming Farmers Do Not Adapt to Climate Change*				
Increased Photosynthesis	–	0	0 EFS ? SQ	?
Reduced Transpiration	–	0	0 EFS ? SQ	?
Higher Temperatures	0	0	0	0
Increased Precipitation	+	0 EFS + SQ	0 EFS + SQ	+
Changes in Extreme Weather Events	?	?	?	?
Changes in Weeds, Insects, and Diseases	?	?	?	?
Effects of Farmer Adaptations to Climate Change*	0 EFS ? SQ	0	0 EFS – SQ	0 EFS ? SQ
OVERALL EFFECTS:**				
EFS Scenario	0	0	0	0
SQ Scenario	0	+	0	0

* Farmer adaptation is discussed in the text. Unless otherwise noted, the effect (+, –, 0 or ?) is the same in the EFS and SQ scenarios. Note that a positive sign implies more environmental degradation and a negative sign implies less environmental degradation.

** Effects assuming no significant changes in extreme weather events.

will have an incentive to take counteracting measures. From a farmer's perspective, nutrients or pesticides that do not reach their target represent lost income. However, farmers will only take counteracting measures to the extent that they themselves expect to benefit in some way. They may or may not take all counteracting measures that would be desirable from the point of view of society as a whole.

For the year 2100, the same overwhelming uncertainties that make it impossible to construct baseline scenarios also make it impossible for us to assess potential climate change impacts on agricultural production or its environmental effects.

Management and Adaptation Options

In their review of the literature on climate change and U.S. agriculture, Lewandrowski and Schimmelpfennig (1999) conclude that costly adaptation strategies are not warranted on the basis of available evidence. Our assessment for the Mid-Atlantic leads to the same conclusion. The impacts of climate change on Mid-Atlantic crop production may on the whole be beneficial, while impacts on Mid-Atlantic livestock production will probably not be large one way or the other.

Many adaptations to exploit opportunities created by climate change and minimize climate-related risks will occur more or less autonomously as farmers and agribusinesses react to experiences with climate change and evolving climate expectations. Farmers have a number of options for minimizing negative impacts of climate change on agricultural production as well as for exploiting positive impacts. For crops, these options include changes in crop acreages, the types or varieties of crops grown, planting and harvesting dates, crop rotations, tillage practices, fertilization practices, and pest management practices. For livestock, these options include changes in herd sizes, livestock types or breeds, feeding rations, and heating and cooling systems. Even in years with low yields or natural disasters, farmers can limit losses in income through crop insurance and disaster insurance. Agriculture is an industry already very familiar with continual, rapid, and often tumultuous change.

Nevertheless, there are actions that can be taken to facilitate adaptation. Our assessment of agriculture's adaptive abilities hinges in part on the development and adoption of new technologies, particularly biotechnology, precision agriculture, and improved climate forecasting. Farmers will need significant new skills, including computer skills, in order to understand and make profitable use of precision agriculture and biotechnology. Public- and private-sector agricultural and meteorological research organizations will need employees with the scientific skills to develop and implement these new technologies. This poses a major challenge for teaching and extension programs at the region's land grant institutions. Land-grant institutions will need to continue shifting their educational programs toward biotechnology, information technologies, and decision-making and business management skills. Because young farmers educated today will be in the labor force for the next forty or even fifty years, education belongs on today's agenda.

Federal and state governments can also support research on biotechnologies and precision agriculture technologies that lead to more environmentally friendly crop and livestock production systems. The vast majority of research on biotechnology and precision agriculture is occurring in the private sector rather than the public sector, but in some cases there may not be economic incentives for the private sector to focus research on improving the environment. Land grant institutions and federal agricultural research centers can help fill this gap. Because it can take years or even decades for research to yield commercially viable new products or technologies, agricultural research also belongs on today's agenda.

One potential threat to adaptation identified in previous assessments for other regions of the United States is access to additional irrigation water, particularly in the face of growing demands for water from other sectors (Lewandrowski and Schimmelpfennig 1999). Based on available evidence, this would not appear to be a major concern for the Mid-Atlantic at present. Less than 3 percent of Mid-Atlantic crop acreage is irrigated at the present time. Irrigation is currently uneconomic for most crops in most parts of the Mid-Atlantic, and projections suggest that regional precipitation may increase under climate change. However, the picture could be different if droughts were to increase significantly in frequency or severity.

Priorities for Research and Information

There are several areas where additional research and information would be useful. However, four areas stand out as priorities for agriculture in the Mid-Atlantic region and perhaps other US regions as well:

1. *Climate Change and Weeds, Insects, and Diseases*. Climate change is likely to affect pest-crop and pest-livestock relationships, but we have little evidence on how these relationships are likely to change (Rosenzweig and Hillel 1998). Additional research on these relationships is definitely needed at all levels – from the level of individual weed, insect, crop, and livestock species to the aggregate ecosystem level.

2. *Salt Water Incursion and Coastal Agriculture*. The Mid-Atlantic borders the Atlantic Ocean, and as such some agricultural activity takes place in low-lying coastal areas such as the Delmarva Peninsula. Saltwater incursion into coastal areas due to sea-level rise or storm surge could potentially threaten coastal agriculture. However, we currently lack evidence on the degree to which saltwater incursion might occur or what adaptation options might be available to the region's farmers.

3. *Extreme Weather Events and Agriculture*. Additional research is needed on the effects of climate change on extreme weather events and in turn on agricultural production and environmental effects from agricultural production. Current climate models do not adequately represent extreme weather events such as floods or heavy downpours, which can wash large amounts of fertilizers, pesticides, and animal manure into surface waters. For this reason, we did not incorporate extreme weather events into our analysis. However, changes in extreme events could easily overwhelm the production and environmental effects of changes in average levels of precipitation or temperature as well as the effects of changing atmospheric CO_2 levels.

4. *Climate Change and Environmental Effects from Agriculture*. The vast majority of research to date on climate change and agriculture has focused on agricultural production impacts. Very little work has been done on how climate change might lead to changes in the environmental effects of agricultural production and land use. To our knowledge, there is only limited research that considers how responses by farmers to climate change might mitigate or exacerbate environmental effects. Given the magnitudes of environmental effects in many areas, including the Chesapeake Bay, this should be a high priority for research.

References

Abler, D. G., J. S. Shortle, and J. Carmichael (2000), "Agriculture and the Chesapeake Bay," in *Agriculture and the Environment: Interactions with Climate*, U.S. National Climate Change Assessment, Agriculture Sector Assessment, http://www.nacc.usgcrp.gov/sectors/agriculture/draft-report/.

Adams, R. M., B. H. Hurd, and J. Reilly (1999), *Agriculture and Global Climate Change: A Review of Impacts to U.S. Agricultural Resources*, Arlington, Virginia: Pew Center on Global Climate Change, http://www.pewclimate.org/report4.html.

Adams, R. M., B. H. Hurd, S. Lenhart, and N. Leary (1998), "Effects of Global Climate Change on Agriculture: An Interpretative Review," *Climate Research*, 11:19-30.

American Farmland Trust (1997), *Saving American Farmland: What Works*, Washington, DC: American Farmland Trust.

Bockstael, N. E., and K. Bell (1998), "Land Use Patterns and Water Quality: The Effect of Differential Land Management Controls," *Conflict and Cooperation on Transboundary Water Resources*, ed. R. Just and S. Netanyahu, Norwell, Massachusetts: Kluwer Academic Publishers, pp. 169-191.

Bradshaw, T. K., and B. Muller (1998), "Impact of Rapid Urban Growth on Farmland Conversion: Application of New Regional Land Use Policy Models and Geographic Information Systems," *Rural Sociology*, 63:1-25.

Brown, L. R. (1996), *Tough Choices: Facing the Challenge of Food Scarcity*, New York: Norton.

Calvin, D. (1999), "Impact of Projected Climate Change on Insect Biology and Management in the Northeastern United States: A Case Study of the European Corn Borer, *Ostrinia Nubilalis* (Hubner)," Report for Mid-Atlantic Regional Assessment (MARA), Pennsylvania State University, University Park, Pennsylvania.

Chesapeake Bay Program (1997), *The State of the Chesapeake Bay, 1995*, http://www.chesapeakebay.net/pubs/state95/state.htm.

Chesapeake Bay Program (1999), *The State of the Chesapeake Bay*, EPA 903-R99-013 and CBP/TRS 222/108, http://www.chesapeakebay.net/pubs/sob/index.html.

Crosson, P., and J. R. Anderson (1992), *Resources and Global Food Prospects: Supply and Demand for Cereals to 2030*, Washington, DC: World Bank.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses (1995), *World Agriculture and Climate Change: Economic Adaptations*, U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 703.

Favis-Mortlock, D. T., and M. R. Savabi (1996), "Shifts in Rates and Spatial Distributions of Soil Erosion and Deposition under Climate Change," *Advances in Hillslope Processes*, vol. 1., ed. M. G. Anderson and S. M. Brooks, New York: Wiley, pp. 529-560.

Follett, R. F. (1995), "NLEAP Model Simulation of Climate and Management Effects on N Leaching for Corn Grown on Sandy Soil," *Journal of Contaminant Hydrology*, 20:241-252.

Government Information Sharing Project, Oregon State University, (1999), *1992 Census of Agriculture*, http://govinfo.kerr.orst.edu/ag-stateis.html.

Hardie, I. W., and P. J. Parks (1997), "Land Use in a Region with Heterogeneous Land Quality: An Application of an Area Base Model," *American Journal of Agricultural Economics*, 79:299-310.

Huttner, S. L. (1996), *Biotechnology and Food*, New York: American Council on Science and Health, New York.

IPCC (1996), "Agriculture," in *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, Cambridge, UK: Cambridge University Press, pp. 427-467.

Islam, N., ed. (1995), *Population and Food in the Early Twenty-First Century: Meeting Future Food Demand of an Increasing Population*, Washington, DC: International Food Policy Research Institute.

Izaurralde, R. C., R. A. Brown, and N. J. Rosenberg (1999), *U.S. Regional Agricultural Production in 2030 and 2095: Response to CO_2 Fertilization and Hadley Climate Model (HadCM2) Projections of Greenhouse-Forced Climatic Change*, Richland, Washington: Pacific Northwest National Laboratory.

Johnson, D. G. (1998), "Food Security and World Trade Prospects," *American Journal of Agricultural Economics*, 80:941-947.

Johnson, S. R., and M. T. Holt (1997), "The Value of Weather Information," *Economic Value of Weather and Climate Forecasts*, ed. R. W. Katz and A. H. Murphy, Cambridge, UK: Cambridge University Press, Cambridge, pp. 75-107.

Kellogg, R. L., R. Nehring, A. Grube, S. Plotkin, D. W. Goss, and S. Wallace (1999), "Trends in the Potential for Environmental Risk from Pesticide Loss from Farm Fields," Conference Presentation at *The State of North America's Private Land*, Chicago, Illinois.

Kellogg, R. L., S. Wallace, K. Alt, and D. W. Goss (1997), "Potential Priority Watersheds for Protection of Water Quality from Nonpoint Sources Related to Agriculture," Presentation at 52nd Annual Soil and Water Conservation Society Conference, Toronto, Ontario.

Klinedinst, P. L., D. A. Wilhite, G. L. Hahn, and K. G. Hubbard (1993), "The Potential Effects of Climate Change on Summer Season Dairy Cattle Milk Production and Reproduction," *Climatic Change*, 23:21-36.

Lewandrowski, J., and D. Schimmelpfennig (1999), "Economic Implications of Climate Change for U.S. Agriculture: Assessing Recent Evidence," *Land Economics*, 75:39-57.

Main, C. E. (1999), "Effects of Climate Change on Crop Diseases in the U.S. Mid-Atlantic Region," Report for Mid-Atlantic Regional Assessment (MARA), Pennsylvania State University, University Park, Pennsylvania.

Mjelde, J. W., H. S. J. Hill, and J. F. Griffiths (1998), "A Review of Current Evidence on Climate Forecasts and Their Economic Effects in Agriculture," *American Journal of Agricultural Economics*, 80:1089-1095.

Phillips, D. L., D. White, and B. Johnson (1993), "Implications of Climate Change Scenarios for Soil Erosion Potential in the USA," *Land Degradation & Rehabilitation*, 4:61-72.

Plucknett, D. L., and D. L. Winkelmann (1996), "Technology for Sustainable Agriculture." *Key Technologies for the 21st Century*, New York: Freeman, pp. 133-138.

Reilly, J., N. Hohmann, and S. Kane (1994), "Climate Change and Agricultural Trade: Who Benefits, Who Loses?" *Global Environmental Change*, 4:24-36.

Rifkin, J. (1998), *The Biotech Century: Harnessing the Gene and Remaking the World*, New York: Jeremy P. Tarcher/Putnam.

Rosenzweig, C., and D. Hillel (1998), *Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture*, New York: Oxford University Press.

Schimmelpfennig, D., J. Lewandrowski, J. Reilly, M. Tsigas, and I. Parry (1996), *Agricultural Adaptation to Climate Change: Issues of Longrun Sustainability*, U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 740, http://www.econ.ag.gov/epubs/pdf/aer740/.

Tribbia, J. J. (1997), "Weather Prediction," *Economic Value of Weather and Climate Forecasts*, ed. R. W. Katz and A. H. Murphy, Cambridge, UK: Cambridge University Press, Cambridge, pp. 1-18.

Tsigas, M. E., G. B. Frisvold, and B. Kuhn (1997), "Global Climate Change and Agriculture," *Global Trade Analysis: Modeling and Applications*, ed. T. W. Hertel, Cambridge, UK: Cambridge University Press, pp. 280-304.

Tweeten, L. (1998), "Dodging a Malthusian Bullet in the 21st Century," *Agribusiness*, 14:15-32.

U.S. Bureau of Labor Statistics (1999), *Labor Force Statistics*, http://stats.bls.gov/.

U.S. Department of Agriculture, Interagency Agricultural Projections Committee (1999), *USDA Agricultural Baseline Projections to 2008*, Staff Report WAOB-99-1, http://www.econ.ag.gov/epubs/pdf/baseline/index.htm.

U.S. Department of Agriculture, National Agricultural Statistics Service (1999a), *1997 Census of Agriculture*, http://www.nass.usda.gov/census/.

U.S. Department of Agriculture, National Agricultural Statistics Service (1999b), *Published Estimates Database*, http://www.nass.usda.gov/ipedb/.

U.S. Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, Bureau of the Census (1999), *1996 National Survey of Hunting, Fishing, and Wildlife-Associated Recreation*, http://www.census.gov/prod/www/abs/fishing.html.

U.S. Geological Survey (1999), *Major Land Resource Area*, http://edcwww.cr.usgs.gov/Webglis/glisbin/guide.pl/glis/hyper/guide/mlra.

Chapter 5. Forests*

Current Status and Stresses

Forests of the Mid-Atlantic Region

Forests are the dominant land cover of the Mid-Atlantic Region, accounting for about 65% of total land area (US EPA 1997). They support a rich mix of tree species, from the pine and coastal wetlands regions in the south to the northern upland hardwoods (Figure 5.1). In terms of current volumes of growing stock, dominant hardwood species are red oaks, white oak, yellow-poplar, red maple, sugar maple, black cherry, beech and sweetgum. Softwood forests are dominated by loblolly, shortleaf, and white pines and hemlock (Powell et al. 1994). Many other

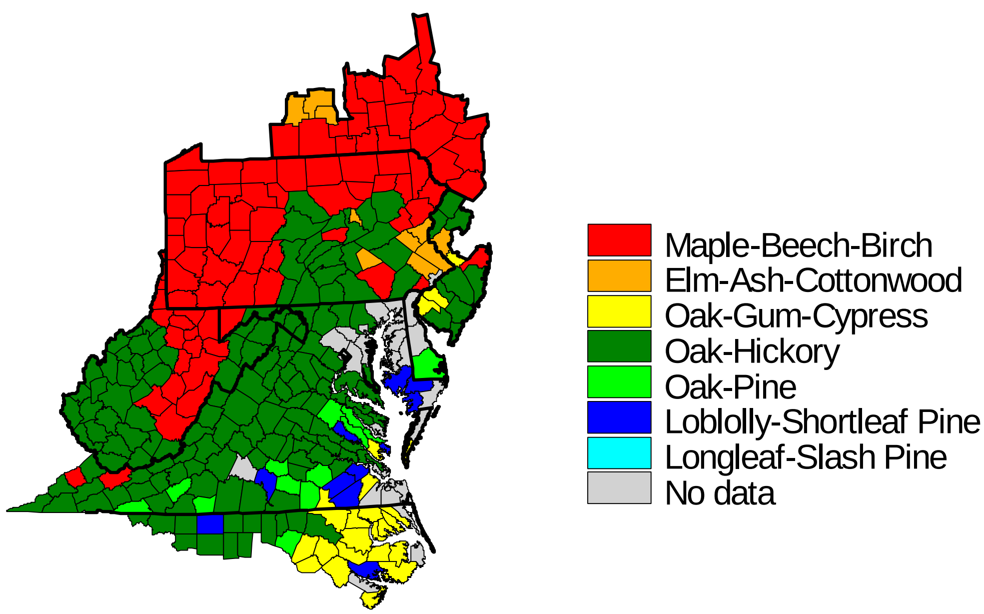


Figure 5.1. Distribution of major forest types in the Mid-Atlantic Region. (Based upon Forest Inventory and Analysis (FIA) data collected by USDA, Forest Service and compiled by Iverson et al. (1996).)

* This chapter is based on McKenney-Easterling et al., (2000) "The Potential Impacts of Climate Change and Variability on Forests and Forestry in the Mid-Atlantic Region," and Rose et al., "Simulating the Economic Impacts of Climate Change in the Mid-Atlantic Region," both in *Climate Research*, 14:2. The material appears with permission of Inter-Research.

species are locally abundant. The region's dominant forest types are oak-hickory (46% of forested area) and maple-beech-birch (37% of area), followed by pine and mixed pine-hardwood forests (8% of area).

Forests in the region were extensively cut for wood products in the early 1900s. Active management and protection from fire since then has resulted in second-growth forests that are rapidly approaching maturity. Trees in the region as a whole are primarily in 10-12 inch (25-30 cm) diameter classes, however substantial volumes of sawtimber (live trees that contain at least one 12-foot saw log or two noncontiguous 8-foot logs) exist in the larger diameter classes (Powell et al. 1994).

Recent survey data indicate that forest area in the Mid-Atlantic states has been relatively stable over the past 30 years, decreasing very slowly by about 1% per decade (Powell et al. 1994). Although forested area has changed little over this period, total standing biomass has increased due to an increase in biomass per unit area. Net volume (gross volume in cubic feet less deductions for rot, roughness, and poor form) of hardwood growing stock (live trees of commercial species meeting specific standards of quality and vigor) is steadily increasing, although growth rates are slowing as the forests approach maturity (Figure 5.2). Softwood growing stock volumes have leveled off somewhat and are expanding only very slowly. The ratio of net annual growth (the average annual net increase in the volume of trees during the period between inventories) to removals is 2.2 for hardwoods and 1.3 for softwoods (Powell et al. 1994). Mortality is only about 0.6 to 0.8% of growing stock annually. Most of the forests (88%) in the region are privately owned and management decisions rest largely with non-industrial private landowners.

Forests within the Mid-Atlantic region are extremely important from an ecosystem perspective. Forests help to control sediment erosion into streams and lakes. They cycle nutrients in the soil and act as a sink for carbon dioxide, nitrogen, and sulfur from the atmosphere. Wildlife utilize forests as a source of food and habitat. Forests mitigate against flooding, moderate streamflow, and help to maintain high water quality and aquatic habitats. (A more detailed discussion of the ecosystem benefits of Mid-Atlantic forests appears in Chapter 8 of this report.) Forests also enhance the human environment by providing recreational opportunities, visual buffers, and landscape diversity.

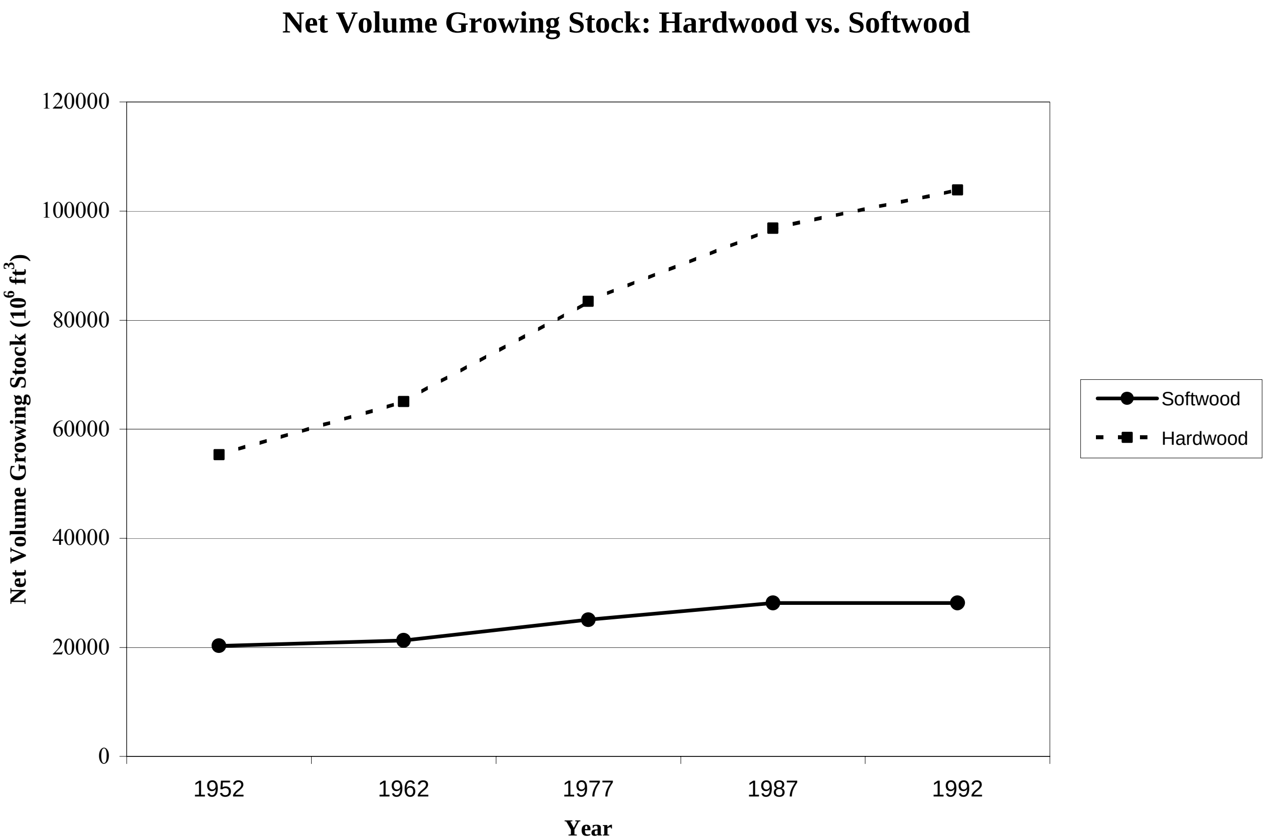


Figure 5.2. Trends in the Net Volume of Forest Growing Stock for States in the Mid-Atlantic Region (Powell et al. 1994).

Role of Mid-Atlantic Forests in the Regional Economy

Mid-Atlantic forests provide many important economic benefits to the Mid-Atlantic region. Forest products produced in the region are primarily sawlogs, pulpwood, fuelwood, and veneer logs. Several tree species are of particular economic importance: oaks (*Quercus spp.*) are used to produce construction materials and interior finishing to homes. Black cherry (*Prunus serotina*) is used for furniture, especially veneer. Pine (*Pinus spp.*) is a softwood species used for paper and plywood.

To assess the role of forests in the regional economy, forest-related economic activity was considered in 9 sectors: Forest Products, Forestry Products, Forestry/Services, Logging Camps & Contractors, Sawmills, Millwork & Plywood, Other Woodproducts, Wood Furniture & Fixtures, and Paper and Paper Products. The combined total gross output (sales revenue) of these sectors in 1995 was $41.8 billion, or 2.5% of the $1,671.1 billion total gross output in the Mid-Atlantic Region. This small percentage, however, understates the economic role of forest-related sectors. First, these sectors stimulate additional production and employment in supplier and customer sectors through backward and forward linkages, respectively. Second, forests provide a base for hunting, camping, hiking, birdwatching and fishing, which contribute to the service and other sectors of the economy. In addition, forests provide a range of non-market services such as carbon sequestration and wildlife habitat.

An input-output economic analysis for the forest-related sectors in the Mid-Atlantic Region yields insight into the interconnections among the individual forest-related sectors and their role in the regional economy (Table 5.1). The rows labeled R1 to R9 depict the sales of each of these products by businesses within the Region for intermediate demand, for consumer demand, and for export. Analogously, the rows labeled M1 to M9 depict imports of each of these products by each of the demand categories. Despite the Region's extensive forest resources, more than half of the value of forest-product inputs for several of the nine forest-related sector products is imported, most notably in Pulp & Paper Products. At the same time, the Region exports $21.3 billion of its $41.8 billion production of forest-related products, or over 50%.

Economic interdependency with the rest of the US stems from the fact that the Mid-Atlantic region borders regions with extensive forest resources as well. Hence many Mid-Atlantic businesses may be closer to suppliers and customers in other regions than to suppliers and customers within the region itself. It also stems from the uniqueness of some resources (e.g., hardwoods) that have a broad export market both domestically and internationally. Finally, the relatively high level of aggregation in Table 5.1 obscures the production of specialty products (e.g., wood furniture and newsprint) that are typically not self-contained within any one region.

The implications are that climate change effects on forests in the Mid-Atlantic region will have an economic ripple effect on other regions and vice versa.

Despite economic linkages to other regions, forest sectors within the Mid-Atlantic Region are also highly interdependent, as is evidenced by the large numbers in the sub-matrix of rows R1 to R9 and columns 1 to 9 in Table 5.1. For example, the inputs of Millwork & Plywood, Other Woodproducts, Wood Furniture & Fixtures, and Paper & Paper Products are mainly from Sawmills as indicated by the transaction from Sawmills to those four sectors of $246.3 million, $304.2 million, $130.1 million, and $220.1 million, respectively. Also, Regional Logging Camps & Contractors supplied the majority of inputs to Sawmills and Pulpmills in the region.

In the section "Economic Impacts of Extreme Weather Events" below, the Input-Output model is used to estimate the impacts of climate change on forest industries of the Mid-Atlantic region.

Table 5.1. Forest-related Sector Flows in the Mid-Atlantic Region Input-Output Table, 1995: Intra-Regional and Import Flows (in millions of 1995 dollars)

		Intermediate Sector Demand									**Total F-R Intermed Sales**	**Personal Consump-Tion**	**Exports**	**Other Final Demand**	**Total Gross Output**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**					
Forest-Related Subtotal Regional Inputs:		16.0	365.2	5.7	409.1	1046.5	580.7	604.0	348.6	601.9	3977.7	2267.4	21255.1	1357.8	41826.1
R1	Forest Products	0.0	14.4	0.5	80.7	59.4	16.8	0.0	0.2	0.0	171.9	70.4	38.3	1.8	292.2
R2	Forestry Products	0.0	45.6	1.5	256.3	188.6	53.2	0.0	0.8	0.0	546.1	218.2	118.7	5.6	906.3
R3	Agricultural, Forestry, Fishing Services	16.0	305.2	3.7	0.0	1.1	0.9	1.3	0.7	4.9	333.8	94.4	842.4	291.5	3453.8
R4	Logging Camps & Contractors	0.0	0.0	0.0	71.2	611.3	95.5	70.4	0.0	345.8	1194.2	0.0	78.2	17.7	1217.9
R5	Sawmills	0.0	0.0	0.0	0.9	182.4	246.3	304.2	130.1	220.1	1084.0	1.5	419.5	7.1	3720.0
R6	Millwork & Plywood	0.0	0.0	0.0	0.0	0.0	121.7	53.9	47.7	0.0	223.3	8.7	339.1	28.1	3206.0
R7	Other Woodproducts	0.0	0.0	0.0	0.0	3.7	46.3	156.3	50.6	9.3	266.2	178.0	2157.6	234.5	3846.1
R8	Wood Furniture & Fixtures	0.0	0.0	0.0	0.0	0.0	0.0	17.9	118.5	0.0	136.4	1658.8	1321.9	755.2	4212.5
R9	Paper & Paper Products	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.8	21.8	37.5	15939.2	16.4	20971.3
Total Regional Intermediate Inputs		160.1	581.2	214.8	580.3	1739.4	1130.8	1424.5	1376.2	6851.8	14059.1	491884.2	442053.7	261608.2	166005.4
Total Imported Inputs		69.7	186.2	108.4	222.1	813.5	687.6	1032.6	1226.1	6896.5	11242.7	154812.8	0.0	82337.0	495736.0
Forest-Related Subtotal Imports:		4.9	91.4	6.6	133.4	681.0	479.8	639.8	380.0	5061.7	7478.6	3791.3		1944.6	29998.3
M1	Forest Products	0.0	3.6	0.1	20.2	14.8	4.2	0.0	0.0	0.0	42.9	17.6		0.4	74.8
M2	Forestry Products	0.0	11.4	0.3	64.0	47.1	13.3	0.0	0.2	0.0	136.3	54.6		1.4	232.0
M3	Agricultural, Forestry, Fishing Services	4.1	76.2	1.0	0.1	0.2	0.1	0.2	0.3	1.3	83.5	23.6		72.9	702.2
M4	Logging Camps &	0.0	0.0	0.0	47.3	404.7	63.7	46.4	0.0	228.4	790.5	0.0		11.8	810.4
M5	Sawmills	0.0	0.0	0.0	1.4	207.0	278.8	345.4	147.7	249.9	1230.2	1.5		7.8	2225.6
M6	Millwork & Plywood	0.0	0.0	0.0	0.0	0.0	43.1	19.1	16.9	0.0	79.1	3.4		10.8	1071.6
M7	Other Woodproducts	0.8	0.0	0.0	0.0	4.8	59.9	204.6	67.3	11.4	348.8	233.3		307.3	2013.2
M8	Wood Furniture &	0.0	0.0	0.0	0.0	0.0	0.0	11.0	73.9	0.0	84.9	1034.5		471.0	1819.6
M9	Paper & Paper Products	0.0	0.2	5.2	0.4	2.4	16.7	13.1	73.7	4570.7	4682.4	2423.0		1061.2	21048.9
Total Value Added		62.4	138.9	3130.6	415.5	1167.1	1387.6	1389.0	1610.2	7223.0	16524.3	20904.7	13556.8	2468.4	1009396.4
Total Gross Outlay		292.2	906.3	3453.8	1217.9	3720.0	3206.0	3846.1	4212.5	20971.3	41826.1	667601.7	455610.5	346413.6	1671137.8

Each entry in the main body of the table represents a sale from the sector (in the MAR) indicated by the corresponding row label to the MAR sector indicated by the corresponding column label. (Computed from IMPLAN, 1997)

Current Stresses on Mid-Atlantic Forests

Forests in the Mid-Atlantic Region are currently stressed by factors that are natural or linked to human activities: loss of forest land to urban/suburban development, insects and diseases (especially gypsy moths), deer browsing, atmospheric pollution, and wildfire. Increased urban/suburban development contributes to increased fragmentation of forest tracts, reducing the ability of plants and animals to migrate (Malanson 1993, 1996, Malanson and Cairns 1997). Forests in the Mid-Atlantic Region periodically experience problems due to insects and diseases. In particular, gypsy moth larvae have caused extensive and locally heavy defoliation of hardwood (especially oak) forests over the past 1-2 decades in all Mid-Atlantic Region states except North Carolina. Successive years of defoliation have led to tree mortality in localized areas (Fajvan and Wood 1996). Fortunately, forests generally survive isolated defoliation events even though trees are undoubtedly weakened (Campbell and Sloan 1977). Another stress to MAR forests has been intense deer browsing, which has reduced forest stand development, forest regeneration, and wildlife habitat (Whitney 1984, Tilghman 1989).

Forests in the region are also stressed by atmospheric pollution, specifically high ground-level ozone and deposition of acidic compounds of nitrate and sulfate. Elevated ground-level ozone has been reported to cause leaf damage in some tree species, as well as reducing photosynthesis (Chappelka and Samuelson 1997). Acidic compounds can accelerate leaching losses of base cations from forest soils. Base cations such as calcium and magnesium are needed to maintain forest health and growth (Robarge and Johnson 1992). Atmospheric pollution is of specific concern in the Mid-Atlantic Region, due to the region's proximity to industry located in the Ohio Valley.

Wildfires are not a serious problem currently within most of the Mid-Atlantic Region states (Abrams 1992, Abrams and Nowacki 1992). However, occasionally in dry years wildfires damage many acres of forest land, especially in the south of the region (Little 1974; Komarek 1974).

Past Responses Of Forests To Climate Change

Changes in Forest Composition within the Mid-Atlantic Region

Mid-Atlantic forests have undergone many changes since the last glacial maximum 18,000 years ago. At that time, the Laurentide ice-sheet extended from the Great Lakes across northern Pennsylvania, and covered all of New York. To determine historical trends in vegetation, researchers have used radio-carbon techniques to date pollen uncovered from sediments in lakes and bogs (Jacobson, Jr. et al. 1987). Pollen records suggest Mid-Atlantic forests 18,000 years ago were dominated mostly by spruce (*Picea spp.*) and pine species (*Pinus spp.*) found in northern regions. Upon retreat of the ice-sheet around 12,000 years ago, spruce and pine forests migrated northward and were replaced by oaks (*Quercus spp.*) and firs (*Abies spp.*). In addition, hemlocks (*Tsuga spp.*) appeared in the higher elevations along the Appalachian Mountains. From 6,000 years ago until 500 years ago, northern pines moved out of the Mid-Atlantic region and were replaced by southern pine species. Oaks remained abundant while hemlocks were more prominent in the northern portion of the Mid-Atlantic region. Finally, maples (*Acer spp.*) migrated from the Great Lakes region to northern Pennsylvania and New York (Webb III 1988).

Forest Migration

Migration is the primary method by which tree species adapted to past climate changes. Major tree species and understory vegetation migrated at varying rates based primarily upon the mode of dispersal (e.g. animals, insects, wind, and water) (Pitelka et al. 1997). Migration rates for 20 tree taxa have been estimated to range from 5.4 to 25.7 miles (8.7 to 41.4 km) per century, with a mean of 12.7 miles (20.5 km) per century. More specifically, cottonwoods, poplars, and aspen (*Populus spp.*) migrated the fastest (approximately 20.5 miles (33 km) per century) followed by oaks (*Quercus spp.*) (approximately 8.7 miles (14 km) per century), walnuts (*Juglans spp.*) (approximately 5.6 miles (9 km) per century), and hickory (*Carya spp.*) (approximately 5 miles (8 km) per century) (Tallis 1991). Trees migrated much faster than understory plants. A study by Matlack (1994) found that understory vegetation could migrate anywhere between 0.014 miles (0.023 km) per century to 0.16 miles (0.25 km) per century. These slow rates suggest that understory vegetation is at a much greater risk to future climate changes than many tree species, which can migrate faster and more efficiently. Regardless, migration rates for tree species are limited and trees may not keep pace with changing climatic conditions. Considerable time lags could occur between climate change and establishment of forest adapted to that climate.

Potential Effects Of Future Climate Change

Overview of Key Impacts

Climate change may affect Mid-Atlantic forests both directly and indirectly. Higher temperatures and an altered precipitation regime will directly affect tree growth and survival. Increased concentrations of atmospheric CO_2 may cause enhanced growth and greater efficiency of water use, though it is uncertain whether these effects will persist under field conditions (Bazzaz 1990, Eamus 1996). Forests may be indirectly impacted by factors that are themselves affected by changes in climate and atmospheric constituents, such as the distribution and abundance of pests, fire frequency, and climate-sensitive soil processes such as erosion and decomposition (Watson et al. 1996). For example, pest species may expand their distributions northward and produce more generations annually if temperatures increase (Watson et al. 1996).

Fires may become more frequent if conditions become dryer. Decomposition of soil organic matter will be enhanced with warmer temperatures, increasing nutrient availability (Melillo et al. 1993). Increased temperatures may change the rates of emissions of atmospheric pollutants as well as the rates at which atmospheric constituents such as nitrogen and sulfur compounds are oxidized. Increases in precipitation amounts and frequency may dilute concentrations of atmospheric pollutants, thus reducing total wet deposition [(precipitation amount) x (concentration)] within the region; however, dry deposition of aerosols and particulates may increase. The net effect of these direct and indirect impacts on trees is difficult to predict, and will likely vary among species. This may alter competitive interactions and lead to shifts in species composition (Bazzaz et al. 1990). Impacts will be more severe if species are limited in their ability to migrate to a more climatically suitable habitat (Soloman and Kirilenko 1997, Pitelka et al. 1997).

Potential changes in the frequency of extreme weather events also may affect forests (Auclair et al. 1996), though relatively little attention has been given to these short-term phenomena in studies of climate change. The ways in which climate change may alter extreme events are poorly understood, though evidence suggests that "storminess" will increase in the Mid-Atlantic region with greenhouse warming (Fisher et al. 2000). These short-term and spatially variable events are difficult to incorporate using traditional forest modeling approaches.

There have been a variety of efforts to assess the impacts of climate change on forested ecosystems, though none has focused on the Mid-Atlantic region. Models--empirical and mechanistic, static and dynamic, and at global to local scales--have been used to predict changes that might occur in species composition and/or productivity of forests in response to climate change; some of these include the direct effects of CO_2. Significant uncertainties are associated with these models, and with the GCM-based climate change scenarios that are typically used to drive them (Watson et al. 1998)--thus their results must be viewed with some skepticism. Below we give an overview of some prior studies that include the Mid-Atlantic region, and describe one new analysis conducted as part of the MARA.

Prior Studies that Include the Mid-Atlantic Region

Impacts on Species Composition

The Forest Sector team of the National Assessment recently completed a comprehensive review of the literature on climate change impacts on forests (Aber et al., in press; NAST, in press). Rather than repeating their work here, we provide a brief overview of the general types of impacts thought to be important to forests, to provide context for subsequent discussion.

The VEMAP project-Phase 1 (VEMAP members 1995) compared the results of three biogeochemical (i.e. carbon and nutrient flux) models and three biogeographical (i.e. distributional) models under a range of GCM-based climate change scenarios for the conterminous U.S. The six models differ in their conceptual and mathematical formulations, including their representation of climatic effects and the direct effects of CO_2 on plant growth and water-use-efficiency. Under a 2xCO_2 climate and including the direct effects of a doubled CO_2 atmosphere, the three biogeography models show warm-temperate mixed forest/evergreen forest (WTM/E) type moving northward, displacing temperate deciduous forest in the southern part of the MARA region. Cool-temperate mixed forest disappears completely from the region. One of the models shows that some areas in western Virginia and central Pennsylvania become too dry to support forest and are converted to savanna-type vegetation.

In another study using one of the VEMAP1 biogeography models (MAPSS), Neilson and Drapek (1999) found the transient Hadley climate scenario to have relatively little impact on Mid-Atlantic forests. Small areas of temperate evergreen forest disappear from the MAR and only temperate mixed forest remains. However, the vegetation categories shown in this study are coarser than those in VEMAP1, reducing the chance that more subtle vegetation shifts can be detected.

Phase II of the VEMAP project, which is currently underway, has combined biogeochemical and biogeographical models to allow integrated simulation of changes in vegetation structure, productivity and carbon storage (Aber et al., in press). Two of these new "dynamic general vegetation models" (DGVMs) have been applied using the Canadian Climate Centre (CCC) and Hadley Centre (Hadley) transient climate scenarios developed for the National Assessment (see Chapter 3). The following results are drawn from Aber et al. (in press). Under the CCC scenario (the more severe of the two climate scenarios), one of the vegetation models (MC1) shows a large expansion of grassland into current temperate deciduous forest by 2030, but with most areas reverting to forest by 2095. Under the more benign Hadley scenario, the same model shows no conversion of southeastern forests to grassland. The other vegetation model (LPJ) also predicts a conversion of southeast forests to savanna under the CCC scenario, but no reversion to forest over time.

Forest succession (or "gap") models have been applied to simulate transient changes in forest composition and biomass on representative plots (e.g., Solomon 1986, Pastor and Post 1988, Shugart and Smith 1996). Although few of these studies have included sites in the MARA region, they have shown shifts in species composition with significant time lags between climate change and species response. The IPCC 2nd Assessment report (Watson et al. 1996) concluded that, although changes in the potential area of temperate forests (which includes the Mid-Atlantic) are projected to be less than for other latitudinal zones, they are likely to undergo significant changes in tree species composition. A northward shift in species' distributions and vegetation types is likely (Watson et al. 1998).

A key determinant of the adaptability of forests to climate change is the ability of trees to migrate in pace with climate change, as discussed above in the "Past Stressors" section. Assessments of the existing evidence, for the most part, have concluded that trees are unlikely to keep pace with climate (Watson et al. 1998; Soloman and Kirilenko, 1997). Even more optimistic assessments (e.g. Pitelka 1997) have cautioned that past rates may not necessarily be indicative of future rates due to increased habitat fragmentation (which will inhibit migration). Species have been shown to migrate in an individualistic manner in response to environmental change (Huntley 1995), suggesting that changes in species composition may occur. Results of simulation modeling have indicated that changes in the species composition of mature forests may lag environmental change by decades to centuries, due to the persistence and longevity of mature trees (Davis and Botkin 1985). If tree species' distributions are unable to keep pace with climate changes, forest dieback may occur, resulting in a net release of carbon to the atmosphere (Soloman and Kirilenko (1997)).

Impacts on Productivity and Carbon Storage

Previous studies of the impacts of climate change on forest productivity and carbon storage have produced varying estimates--influenced largely by the particular modeling approach used, climate scenarios applied, and whether the direct effects of CO2 on tree growth and water-use-efficiency are considered. Each modeling approach has its strengths and weaknesses. Below we briefly review the results of studies that have included all or parts of the Mid-Atlantic region.

Early studies using forest succession ("gap") models and relatively severe climate scenarios indicated the potential for extensive dieback of eastern forests (e.g., Solomon 1986, Pastor and Post 1988). More recent results with improved gap models and revised climate scenarios have suggested that the earlier estimates of dieback may be too extreme (Watson et al. 1998). For the most part, the gap models do not include the potential direct effects of CO_2 (Shugart and Smith 1996).

Studies using a regional forest ecosystem model (Aber and Federer 1992) to estimate climate change impacts on net primary productivity (NPP - the increase in plant biomass per unit area) have suggested that forests in the northeastern U.S. might increase in biomass (Aber et al. 1995), while southeastern forests could experience dieback (McNulty et al. 1996). However, the northeastern study included the direct effects of CO_2, while the southeastern one did not. This approach does not consider possible shifts in species' distributions.

When the three VEMAP Phase 1 biogeochemical models (discussed above) were run with input from the biogeography models, there was considerable variation in NPP estimates among models and among GCM scenarios, although the net change in annual NPP appears to be positive for the Mid-Atlantic region in all cases. Total carbon storage, on the other hand, decreases for one of the three models, but generally increases for the other two models under each of the climate change scenarios.

Predictions by the entire suite of VEMAP Phase 2 models show that changes in carbon storage are generally positive under the Hadley scenario. However, under the CCC scenario, severe reductions in carbon storage are predicted in the eastern and southeastern U.S. One of the VEMAP 2 models that is capable of simulating the impacts of fire suggests that, under the CCC scenario, fire could become a more significant feature of southeastern forests, and enhance carbon loss in areas already impacted by increased drought (Aber et al., in press).

Modeling Conducted for the MARA

Approach

None of these prior assessments focused on the Mid-Atlantic Region in particular, nor did they include regional estimates of species-specific changes. To fill this gap, we expanded upon a previous study of trees in the eastern U.S. (Iverson and Prasad 1998) and applied our approach to the Mid-Atlantic region using five GCM scenarios. The modeling approach uses a statistical procedure to relate current environmental conditions to current tree species' abundance at the county level, and then projects potential future abundance based on potential future climatic conditions. A statistical approach is justified based on the observation that environmental factors, modified by disturbance and competitive processes, generally control the overall range and abundance of tree species (Woodward 1987).

USDA Forest Service Forest Inventory and Analysis (FIA) data for over 100,000 plots in the eastern U.S. (Hansen et al. 1992) provided tree species range and abundance information. The data were summarized for individual forest plots to create general importance values (IV) for each species (x):

$$IV(x) = \frac{100BA(x)}{BA(all\ species)} + \frac{100NS(x)}{NS(all\ species)},$$

where BA = basal area and NS = number of stems. In single-species stands, the IV could thus reach the maximum of 200. The plots were averaged for each county to yield that county's IV score. Only those species that were found in at least 100 counties were modeled. Further details are given in Iverson et al. (1996).

Values of thirty-three environmental variables were obtained for each county in the United States east of the 100th meridian. Climate data--monthly means of precipitation, temperature, and potential evapotranspiration (PET)--were obtained for current conditions, and from the output of five GCMs as specified below. These climate data were used to generate annual means of temperature and precipitation, mean monthly values of PET, and two derived attributes based on their physiological importance to tree growth for this region: July-August (the time most prone to drought stress) ratio of precipitation to potential evapotranspiration (JARPPET), and May to September (i.e., growing season) mean temperature (MAYSEPT). Additional environmental variables used in the models include 18 soils factors, four land use/ cover variables, three elevation variables, and a measure of landscape fragmentation. Details and data sources for the environmental variables can be found in Iverson and Prasad (1998).

Climate scenarios from five GCMs, based on equilibrium conditions and an increase in greenhouse gases equivalent to a doubling of CO_2, were used to evaluate possible future species distributions: (1) the Geophysical Fluid Dynamics Laboratory (GFDL) model (Wetherald & Manabe 1988); (2) the Goddard Institute of Space Studies (GISS) model (Hansen et al. 1988); (3) the Hadley Center for Climate Prediction and Research (Hadley) model (Mitchell et al. 1995); (4) the United Kingdom Meteorological Office (UKMO) model (Wilson & Mitchell 1987); and (5) the Canadian Climate Center (CCC) model (Laprise et al. 1998). Current climate, GFDL, and GISS data were obtained in 10 x 10 km format (U.S. Environmental Protection Agency 1993). Hadley, CCC, and UKMO data were obtained from the USDA Forest Service Laboratory in Corvallis, Oregon in 0.5 x 0.5° format (Neilson and Drapek, personal communication).[1]

These "2 x CO_2" climate scenarios differ from the "transient" climate scenarios used in other parts of the MARA. The transient scenarios were not used for the forest analysis because the data were not available at a sufficient level of detail in time to complete the analysis. To allow comparison between the two types of scenarios, we computed the regional average change in mean annual temperature and total precipitation for the CCC and Hadley scenarios as shown in Table 5.2. For the 2 x CO_2 scenarios, we compared "current" (= measured) values of these

[1] Importantly, the latter three data sets had relatively high PET values as compared to the first three data sets (Table 5.3), because the method of PET computation differed between the two sources of data (Neilson, personal communication). This inconsistency could potentially affect our results for the Hadley, CCC, and UKMO models for the species that use the variables PET or JARPPET in their models (these species are flagged in Table 5.5). However, we believe the impact is minimal because, in most of the models, the PET-related variable comes out low in the binary regression tree and, even for the eight species where the PET-variable comes out high in the regression tree, there appears to be consistency across the five GCM scenarios (see Table 5.5).

variables with the 2 x CO_2 values; for the "transient" scenarios, we compared average values for the "current" time slice (1990-1999) with those for each of the future time slices (2025-2034 and 2090-2099). As can be seen in Table 5.2, the *changes* predicted by the 2 x CO_2 scenarios are very similar to those for the 2090-2099 transient scenarios, for both GCMs. (Note, however, that the absolute values differ.) Because of these similarities we view the climate scenarios used in the forest analysis as comparable to the 2090-2099 time slice of the transient climate scenarios.

Table 5.2. Comparison between 2 x CO_2 equilibrium climate scenarios used in the forest analysis and transient climate scenarios used in other parts of the MARA.

Variable*	**2xCO_2 equilibrium scenarios**			**transient scenarios**					
	"current" (actual)	**2xCO_2**		**"current" (modeled)**		**2025-2034**		**2090-2099**	
		CCC	**Hadley**	**CCC**	**Hadley**	**CCC**	**Hadley**	**CCC**	**Hadley**
TAVG (°F)	50.5	60.3	55.2	52.5	52.3	55.0	53.8	61.8	56.7
PPT (inches)	42.2	43.6	53.1	45.0	42.8	43.2	46.9	46.5	53.6
Δ TAVG (°F)		9.7	4.7			2.5	1.4	9.4	4.3
Δ PPT (%)		3	26			-4	9	3	25

*Legend

TAVG = mean annual temperature
PPT = total annual precipitation
Δ TAVG = change in mean annual temperature relative to "current"
Δ PPT = change in total annual precipitation relative to "current"

The five 2 x CO_2 scenarios give a range of possible outcomes for the Mid-Atlantic region (Table 5.3). The Hadley scenario has the least severe change in temperature, both on a mean annual basis (+4.7°F or +2.6°C) and for July and January. The UKMO model predicts the most extreme change in mean annual and January temperature (+14.2° F or +7.9°C and +16° F or +8.9°C, respectively), while July temperatures are highest under the GFDL scenario (+15.1°F or +8.4°C). Precipitation shows little change under the GISS, GFDL and CCC scenarios, while the Hadley model calls for a 26% increase in precipitation, and the GISS model for a 15% increase. Conditions become much dryer relative to current conditions under all scenarios during the warmest months, as evidenced by the reduction in the ratio of July-August precipitation to PET from the current condition of JARPPET = 1.34.

Individual tree species models were generated using DISTRIB, a statistical model predicting the distribution and importance value of most of the common tree species in the Eastern United States (Iverson & Prasad 1998). DISTRIB uses Regression Tree Analysis (RTA) to capture spatial variation in the environmental variables that determine species' influence. RTA uses a recursive partitioning approach to first split a data set using a single variable. It then splits the remaining data into increasingly smaller, homogeneous subsets until a termination is reached (Clark and Pregibon 1992). The variables that operate at larger scales (e.g., many climate variables) usually split the data early in the model, while variables that influence the response variable at more local scales operate closer to the terminal nodes of the regression tree (Michaelsen et al. 1994). Further details on model development and validation can be found in Iverson and Prasad (1998). Species' maps and data on environmental relationships are available in an atlas (Iverson et al. 1999a) and on the web (Prasad and Iverson, ongoing). Models for 75 tree species in the Mid-Atlantic Region were used in our analysis.

To project potential future suitable habitat for each species, the predictive models were applied. Values of current climate were replaced by those computed from each of the five GCM scenarios. (Climate variables in the models are those shown in Table 5.3). The output obtained was the average importance value for each species, for each county, and for each GCM scenario. These values were used to calculate a ∑ IV x area score (hereafter, IV x area score) for each species and GCM scenario, calculated as the sum of the IV x county area for each county in which the species was present (i.e., IV above a minimum level of 3.0). We converted these data outcomes to estimates of potential change from current condition.

Table 5.3. Change from current climate conditions as predicted by five GCMs (2 x CO_2 equilibrium runs) for each climate variable in the Iverson-Prasad tree models (area-weighted averages for the MAR); actual value is shown for JARPPET. For reference, values for current climate are shown in last row.

	JANT (°F)	JULT (°F)	AVGT (°F)	MAYSEPT (°F)	PPT (%)	PET (%)	JARPPET
GISS	8.5	6.7	7.6	7.0	+ 4	+ 67	1.06
GFDL	9.9	15.1	9.9	10.8	- 3	+ 125	0.25
Hadley	3.2	4.7	4.7	4.7	+ 26	+ 201	0.57
UKMO	16.0	11.9	14.2	12.6	+ 15	+ 347	0.34
CCC	9.0	8.5	9.7	9.2	+ 3	+ 253	0.29
Current	28.4	71.2	50.5	66.0	42.2 inches	2.13 inches	1.34

Legend:

AVGT	Mean annual temperature (°F)
JANT	Mean January temperature (°F)
JULT	Mean July temperature (°F)
PPT	Annual precipitation (inches)
PET	Potential evapotranspiration (inches/mo)
MAYSEPT	Mean May-September temperature (°F)
JARPPET	July-August ratio of precipitation to PET

Using these predicted importance values, forest type maps were constructed for current conditions and for each GCM scenario, based on rules developed to sum importance values (IV) for key species associated with particular forest types. Species were assigned to a forest type based on the USDA Forest Service classification according to Hansen et al. (1992), as shown in Table 5.4. Each county was scored for each forest type, and assigned to the type receiving the highest score. Seven forest types are presently recorded from the Mid-Atlantic region (see Fig. 5.1).

The methods used here assume that species will be able to colonize all suitable sites. Time lags in species' migration are not accounted for, nor are competitive interactions among species. Since the models are not physiologically based, they cannot account for enhanced growth or gains in water use efficiency with increased CO2. Neither can the models address potential changes in other aspects of forest dynamics, such as silviculture, insects and disease, invasion of exotics, or land use change.

Table 5.4. Classification scheme used for assigning tree species to a forest type (follows Hansen et al., 1992).

Longleaf/Slash Pine	slash pine, longleaf pine
Loblolly/Shortleaf	shortleaf pine, loblolly pine, Virginia pine
Oak/Pine *	eastern white pine, shortleaf pine, Virginia pine, northern red oak, southern red oak, loblolly pine, water oak, willow oak, post oak, scarlet oak
Oak/Hickory	hickory, bitternut hickory, pignut hickory, shagbark hickory, mockernut hickory, white oak, scarlet oak, chestnut oak, northern red oak, post oak, black oak, sweetgum, tulip tree
Oak/Gum/Cypress	swamp red oak, willow oak, sweetgum, American elm, baldcypress, pond cypress, red maple, water tupelo, swamp tupelo
Elm/Ash/Cottonwood	red maple, American elm, black ash, white ash, sycamore, eastern cottonwood, willow, black willow
Maple/Beech/Birch	red maple, sugar maple, American beech, yellow birch, black cherry, black walnut

* An additional rule set was needed for the oak/pine forest type, because it was a sum of many major oaks and pines, yet the class was intended for counties with mixtures of at least 50% oak and 25-50% pine species (Merz 1978). For this, if the above algorithm determined the class to be oak/pine, the following statements were applied: (1) if the loblolly/shortleaf class was greater than the oak/hickory class 6, the county was reclassified to loblolly/shortleaf, because the pine component is >50%; (2) if the oak/hickory class was greater than twice that of the loblolly/shortleaf class, the county was reclassified to oak/hickory, because there was likely less than a 25% pine component; (3) if neither of the above applied, the county remained classed as oak/pine.

Potential Changes in Species' Importance

The IV x area score incorporates the effect of changing importance and area simultaneously, and thus may be the best metric of potential change for species. Table 5.5 shows the percent change in the IV x area score for 42 of the most important species in the Mid-Atlantic region, ranked according to the average (across all five GCMs) percent change. The species shown here are ones whose current or future IV x area score (average across GCMs) exceeds an arbitrary threshold of 0.47. The current IV x area scores, based on FIA data, are also presented to allow better interpretation of the data, since some of the species that undergo potentially large percentage changes are currently uncommon.

There is general agreement among GCMs in the direction of change and, in many cases, the magnitude of change in IV x area scores (Table 5.5). If the absolute values of the predicted changes are summed by GCM, the Hadley and GISS scenarios cause the least amount of change in tree species importance values, while the UKMO, GFDL and CCC scenarios cause larger changes. (This is true even if some of the largest percent changes are excluded from the computation.) This is in general agreement with the relative magnitude of the climate changes shown in Table 5.3. For some species, IV x area scores are remarkably similar across GCM scenarios. In these cases, climate variables appear early in the RTA models to distinguish coarsely between suitable and unsuitable habitat. The RTA technique forces continuous data to follow one of two discrete branches. Variables that operate at large scales (e.g., climate) are often used in decision rules early in the RTA models, while variables that operate locally (e.g., soils) appear later in the models. Thus, relatively small variations in future climate among scenarios do not always mean they will follow different branches.

Of the total 75 tree species that were considered from the Mid-Atlantic region, 37 species could be reduced in overall importance under climate change. Of these, 20 species could be reduced by at least 50% in importance, and 8 could be reduced by at least 90%. On the other hand, 33 species could be enhanced in importance, with 22 increasing at least 50% including 15 species that could at least double in importance. Seven species could increase by more than 20-fold.

Many of the species showing a large percentage increase in their IV x area score (e.g., *Carya tomentosa* (mockernut hickory, +6388%), *Quercus laurifolia* (laurel oak, +5565%)) are currently uncommon in the Mid-Atlantic region (see current IV x area score in Table 5.5). Percentages alone can therefore be misleading if not interpreted in conjunction with the current status of the species. Species potentially undergoing the largest absolute increases in IV score include *Quercus stellata, Pinus taeda, Ulmus alata, Quercus falcata var. falcata, Pinus palustris, and P. ellotti*. These species tend to thrive in warmer climates currently, and their predicted increase in importance represents a potential northward migration. Species potentially undergoing large absolute decreases in IV score are more representative of species preferring cooler, moister habitats, and include *Acer rubrum, A. saccharum, Prunus serotina, Fraxinus americana, Quercus rubra, and Fagus grandifolia*.

Of the species that are of economic significance to the region, most could see significant changes in importance values. Species that could be enhanced (with their potential percentage change) include *Pinus palustris* (longleaf pine, +2893%), *P. taeda* (loblolly pine, +177%), *P. echinata*

Table 5.5. Current IV x area score[1], percent change in the IV x area score under each of five GCM scenarios, and average percent change in the IV x area score across GCM scenarios for the 42 most important (current or future IV x area score above an arbitrary cut-off value) tree species in the MAR.

Species	Common Name	Current IV x area score (÷10⁶)	Percent change in IV x area score GISS	GFDL	Hadley	CCC	UKMO	Average GCM
Populus tremuloides	quaking aspen	0.50	-100	-100	-96	-100	-100	-99
*Acer saccharum***	sugar maple	4.18	-95	-100	-100	-100	-100	-99
Betula alleghaniensis	yellow birch	0.52	-92	-100	-86	-100	-100	-96
*Fagus grandifolia***	Am. beech	3.15	-84	-84	-84	-84	-84	-84
*Crataegus sp.**	hawthorn	1.05	-77	-78	-83	-78	-78	-79
*Prunus serotina***	black cherry	3.84	-77	-78	-78	-78	-78	-77
Acer rubrum	red maple	10.40	-50	-82	-85	-82	-84	-77
Acer pensylvanicum	striped maple	0.65	-73	-78	-39	-72	-79	-68
Tsuga canadensis	Eastern hemlock	1.36	-65	-65	-57	-65	-65	-63
Fraxinus americana	white ash	2.88	-62	-80	-13	-61	-97	-63
*Pinus strobus**	eastern white pine	1.37	-61	-68	-42	-63	-68	-60
Quercus rubra	Northern red oak	2.89	-48	-62	-26	-59	-95	-58
*Pinus virginiana**	Virginia pine	1.69	-10	-89	-39	-39	-80	-51
Juglans nigra	black walnut	0.47	-49	-57	-19	-46	-62	-46
*Sassafras albidum**	sassafras	1.49	-41	-51	-35	-44	-59	-46
Ilex opaca	American holly	0.64	-47	-49	-23	-47	-48	-43
Betula lenta	sweet birch	1.53	-53	-53	-15	-51	-42	-43
Robinia psuedoacacia	black locust	1.01	-38	-49	-26	-49	-52	-43
*Ostrya virginiana**	E. hophornbeam	0.65	-53	-59	-5	-49	-33	-40
Quercus coccinea	scarlet oak	1.19	-0	-65	0	-32	-57	-31
Fraxinus sp.	ash	0.48	-29	-0	-40	1	-21	-18
*Liriodendron tulipifera**	yellow-poplar	3.15	-18	-24	-15	-15	-15	-17
Quercus prinus	chestnut oak	3.60	-3	5	-24	-12	-24	-12
*Carpinus caroliniana**	Am. hornbeam	0.81	4	15	-4	9	10	7
Nyssa sylvatica	black tupelo	1.89	8	-14	42	-8	19	9
*Ulmus sp.**	elm	0.59	10	10	10	10	10	10
Oxydendrum arboreum	sourwood	0.78	48	40	-28	55	58	34
*Carya sp.**	hickory	2.36	32	41	14	41	46	35
Cornus florida	flowering dogwood	2.20	47	53	24	50	51	45
*Quercus alba***	white oak	3.50	25	72	98	64	6	53
Nyssa biflora	swamp tupelo	0.38	68	70	21	56	68	57
Liquidambar styraciflua	sweetgum	2.10	63	79	10	69	91	63
*Quercus velutina**	black oak	1.59	53	122	207	101	-55	86
Pinus echinata	shortleaf pine	0.37	156	159	130	160	166	154
Pinus taeda	loblolly pine	3.05	138	219	20	185	324	177
Q. falcata var. falcata	Southern red oak	0.44	176	251	47	229	436	228
*Diospyros virginiana**	persimmon	0.15	247	407	247	406	488	359
Quercus nigra	water oak	0.19	862	1161	336	1053	1551	992
Quercus muehlenbergii	chinkapin oak	0.08	1281	2439	770	2403	3359	2051
*Quercus stellata***	post oak	0.18	418	4329	2965	4412	4427	3310
Quercus laurifolia	laurel oak	0.05	4107	4623	899	3316	14881	5565
*Carya tomentosa***	mockernut hickory	0.05	2289	7412	7412	7412	7412	6388

[1] Computed from Forest Inventory and Analysis (FIA) data. * Species used PET or JARPPET in the regression tree model ** Species used PET or JARPPET early in the regression tree model.

(shortleaf pine, +154%), and *Quercus alba* (white oak, +53%). Important species subject to reduction include *Acer saccharum* (sugar maple, -99%), *Prunus serotina* (black cherry, -77%), *Quercus rubra* (red oak, -58%), and *Liriodendron tulipifera* (tuliptree, -17%) (Table 5.5). These changes could significantly alter the economic and aesthetic resources of the region. For example, the large decrease in black cherry would adversely impact the local furniture industry.

The severe reduction in sugar maple would affect autumn color (with implications for tourism), and the production of maple sugar products. On the other hand, the predicted increase in southern pines may provide expanded opportunities for pulp and paper manufacture in the region.

Potential Changes in Forest Type

Forest type maps for each of the climate scenarios (Fig. 5.3) suggest that dramatic changes could occur following climate change. The potential large increases in three species of pine--*Pinus echinata, P. taeda, and P. palustris*--greatly influence the potential forest type outcomes by enhancing the longleaf-slash pine, loblolly-shortleaf pine, and oak-pine types under most GCM scenarios. Compared to today, large increases could also occur within the oak-hickory type (and the oak-pine type) as 10 species of oak could increase by at least 50% (Table 5.5).

On the other hand, two forest types could be severely reduced or eliminated following climate change: the elm-ash-cottonwood type and the maple-beech-birch (Fig. 5.3). Though most individual tree species from these forest types would remain, their importance could be greatly diminished relative to the pines and oaks. For example, the primary elements (and their potential changes from Table 5.5) in the maple/beech/birch type are *Acer rubrum* (-77%), *A. saccharum* (-99%), *Fagus grandifolia* (-84%), *Betula alleghaniensis* (yellow birch, -96%), *Prunus serotina* (-77%), and *Juglans nigra* (black walnut, -46%).

The GCM scenarios with the most severe temperature change (UKMO, GFDL, CCC) show the oak-pine forest type advancing farther to the north and east than the two more benign climate scenarios (Hadley and GISS) (Fig. 5.3). The intrusion of the oak-pine type is most pronounced for UKMO--the climate scenario with the highest temperatures during the growing season and on a mean annual basis. Small areas of maple-beech-birch and elm-ash-cottonwood forest remain under the GISS scenario only, most likely a reflection of the fact that one of the constituent species of both of these forest types, *Acer rubrum* (Table 5.5), is less severely affected by the GISS scenario. Loblolly-shortleaf pine forest is most abundant under the GISS scenario. In this case, the oak species generally show proportionately less increase as compared to the other GCM scenarios, and pines more often dominate in a particular county.

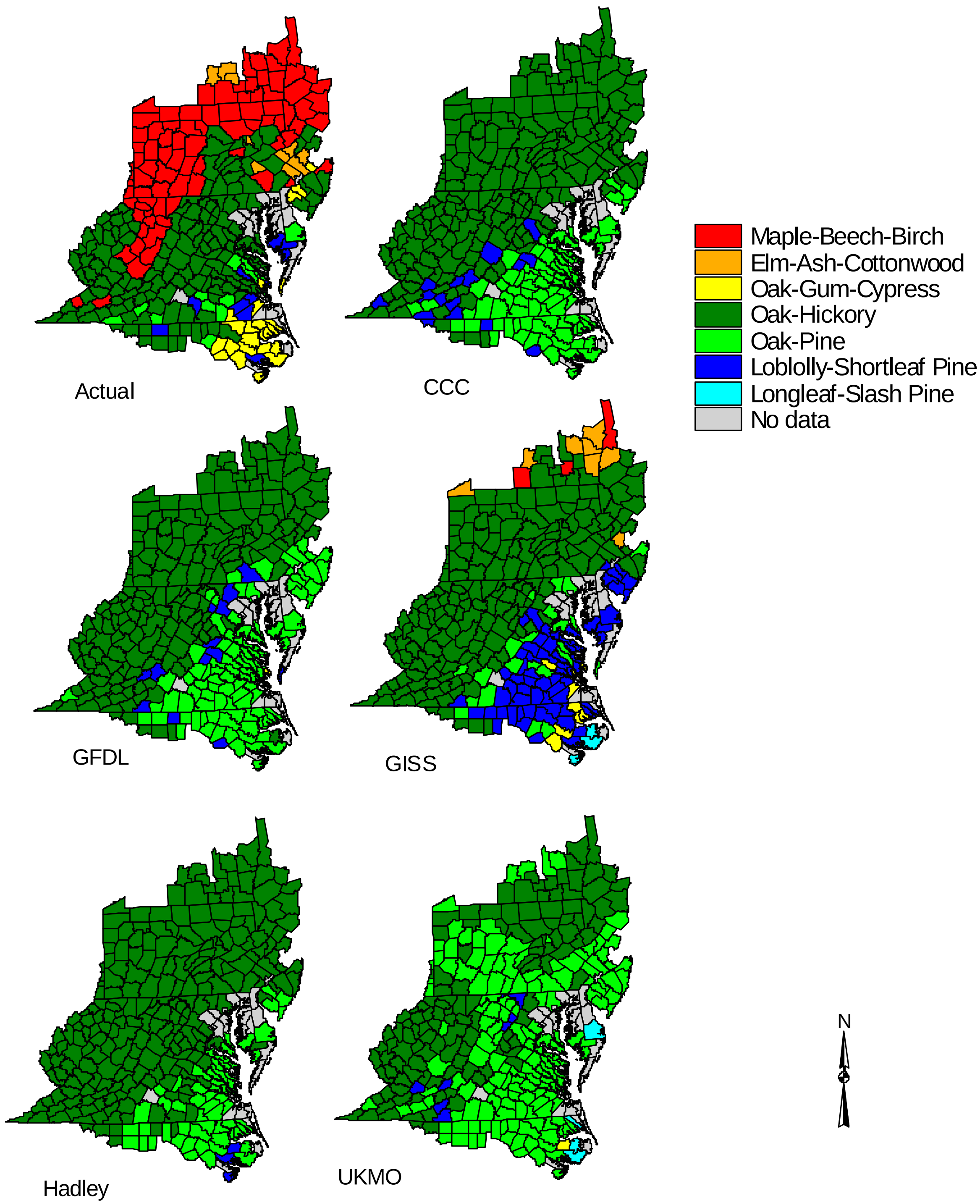


Figure 5.3. Dominant forest types for current climate, and potential forest type distribution for CCC, GFDL, GISS, Hadley, and UKMO 2 x CO_2 equilibrium scenarios.

The changes in forest type predicted by this analysis are broadly consistent with those of the VEMAP Phase 1 study (VEMAP members 1995), where results generally show warm-temperate mixed forest/ evergreen forest moving northward, displacing temperate deciduous forest in the southern part of the MAR, and cool-temperate mixed forest (such as maple-beech-birch) disappearing completely from the region. Results from VEMAP Phase II and from one of the Phase 1 models suggest the possibility that some MAR forests will be converted to savanna-type vegetation. Since our analysis only considers forest tree species, it is unable to support or argue against these sorts of predictions.

Impacts Of Extreme Weather Events On Forest Land Management

Survey Purpose and Methodology

Most past research has focused on the long-term impacts of changing temperature and precipitation regimes on forests based on GCM predictions expressed as mean monthly or annual values. Daily values also were used but were created by applying monthly differentials to daily climatology (e.g., VEMAP members 1995, Shugart and Smith 1996, McNulty et al. 1996). Much less attention has been given to how climate change will affect the frequency and intensity of extreme events and how these changes in turn will affect forest land management. Examining the impacts of current climate variations can provide insight into the types of climatic events that are most problematic in the Mid-Atlantic Region now, and help us to anticipate the impacts of future climate change.

Because little specific information was available on how climate variability currently affects forestry activities in the Mid-Atlantic Region, we developed, pre-tested, and revised a questionnaire to investigate how extreme weather affects day-to-day forestry operations. The questionnaire was largely targeted to government agencies (federal and state) and private firms (consulting foresters, loggers, and industrial foresters), but some urban and municipal foresters were included. The questions were designed to obtain information about effects of extreme weather on specific aspects of forestry operations, coping mechanisms currently being employed or contemplated, and effects on costs of operation and income. The results presented here focus on the impacts of various types of severe weather events, and differences in weather impacts between upland hardwoods versus Southern pine forestry operations. We then relate these impacts to projections of potential shifts in species composition due to long-term changes in climate.

Questionnaires were sent to government and private forestry offices/agencies/firms in the Mid-Atlantic region based upon lists compiled from contacts with management agencies in each state. All government and large industrial forestry offices/agencies/firms identified were sent questionnaires. To make the sample size more manageable (yet still yield useful data), questionnaires also were mailed to a random sample of the loggers, sawmill operators and consulting foresters in the region. A preliminary survey of 30 firms was used to help determine the size of the random sample needed and to improve the questionnaire.

A total of 592 surveys were mailed in late November 1998 followed by a second mailing to non-respondents in January 1999. A total of 322 surveys were returned, yielding an overall response rate of 57% after correction for erroneous addresses. Most respondents represented private forestry firms (159 consulting foresters, logging companies, and industrial foresters) or public forestry agencies (114 state and federal agencies/offices). Of the total respondents, 66% operate in the hardwood forest types, while 22% operate only within the Southern pine types. Chi-square tests using two-way classifications and an $\alpha = 0.05$ (Noether 1991) were used to test for significant differences in the distributions of responses (1 = no impact to 5 = major impact) for upland hardwoods vs. Southern pine groups.

Survey Results

Overall, extreme weather events have had a low to moderate impact on forestry activities in the Mid-Atlantic region over the past ten years (Fig. 5.4). Respondents rated events with heavy rainfall, ice storms and high winds as causing the most problems over the past decade. More than 20% of the respondents ranked these three types of severe weather events as having a major impact (rank = 5) on their operations. This is consistent with the occurrence of major hurricane/tropical depression events (Hugo, Bertha, and Fran) and associated high winds and heavy rain in the southern portion of the region over the past ten years, and a major ice storm in the northern portion of the region in 1998 (USDA Forest Service 1998). Lesser impacts were associated with low rainfall, heavy snow, and periods with extreme high and low temperatures, but all types of events showed mean impacts well above zero (mean rank > 2).

The impacts of severe weather on forest land management were generally similar for Southern pine and hardwood regions (Fig. 5.4), with one exception. Heavy snows--which are quite uncommon in the southern part of the region--were obviously not as great a problem for the Southern pine operations. Other differences between hardwood and Southern pine operations were not statistically significant. Despite the fact that hurricane or tropical depression impacts are more likely in the Southern pine areas, high winds were rated similarly for both hardwood and pine operations. Impacts of severe weather were primarily related to effects on accessibility to forest land, direct damage to trees, and increased problems with insects, disease and fire (Table 5.6). The rankings of the types of impacts were remarkably consistent between the hardwood and Southern pine region, again except for obvious differences related to geography and snow.

Climate change could increase the occurrence of severe weather events in the Mid-Atlantic Region, but the specific nature and magnitude of these changes are difficult to predict at this time. Several studies have suggested that climate change might increase the frequency of extreme events (Mitchell and Ingram 1990, Noda and Tokiola 1989, Changnon and Changnon 1992, Karl et al. 1995), but the certainty of the predictions is quite low and they are not specific to the Mid-Atlantic Region. By 2095, based on transient runs of two general circulation models (GCMs), the region's air temperatures are predicted to increase by 5 to 10°F and precipitation is expected to increase by about 6 to 24% (Fisher et al. 2000). Such warming suggests that heavy

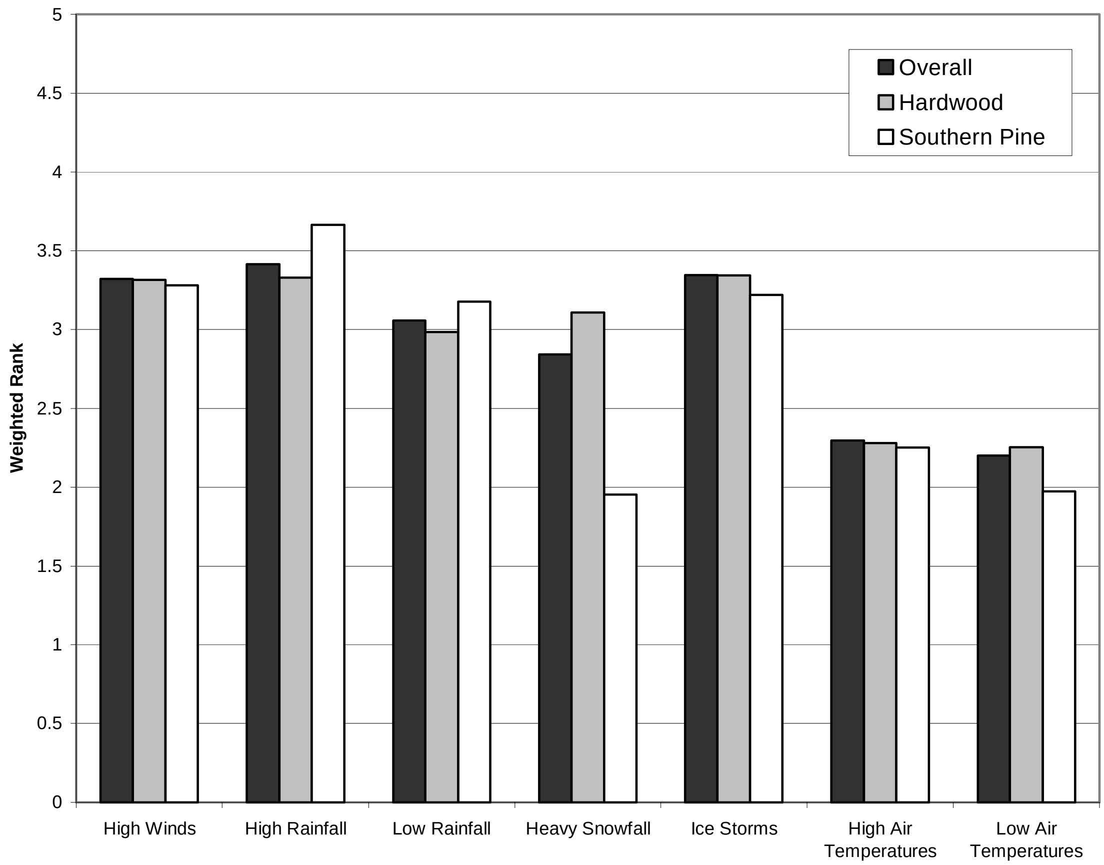


Figure 5.4. Weighted mean rank of the impact of various types of extreme weather events on forest land management in the Mid-Atlantic Region for all, for hardwood, and for Southern pine forestry operations based upon a 1999 questionnaire survey (rank 1 = no impact, 3 = moderate impact, 5 = major impact).

Table 5.6. Major forestry problems caused by various types of severe weather in the Mid-Atlantic Region over the past decade.

Weather Type	Highest Ranked Impact	Second-Highest Ranked Impact
High winds	Direct damage to trees	Creating unsafe work environment
High rainfall	Limited access due to flooding and muddy conditions	Increased maintenance costs for roads, yards, landings
Low rainfall	Improved access	Tree mortality
Heavy snow and ice	Direct damage to trees by ice and snow loading	Limited access by deep snow
Extreme temperatures	Increased insect and disease problems	Tree mortality or increased fires

snowfall events will decrease in the Mid-Atlantic Region, and that the geographic distribution of ice storms may migrate northward. Increased storminess would likely generate more high rainfall and high wind events. The impact of climate change on the occurrence of hurricanes, which can have major impacts on forestry in the Mid-Atlantic region, is very poorly understood (Walsh and Pittock 1998).

The types of impacts experienced currently by forest land managers in the Mid-Atlantic Region, coupled with the expected changes in climate, can be used to make preliminary estimates of climate change impacts on forestry operations. Increased air temperatures suggest that the frequency of limited access due to deep snow and tree damage due to severe icing events would decrease in the region. However, increases in rainfall and storminess suggest greater problems with forest land access due to muddy roads and flooding, and increased maintenance costs. General increases in storminess could also increase direct wind damage to forests and create related problems with periodic variations in market prices for timber products (Quine et al. 1995). Higher temperatures combined with low rainfall would cause more frequent drought, which may lead to more problems with insects, disease and fire in the region than currently experienced. The similarity of responses from Southern pine and hardwood sectors of the Mid-Atlantic Region suggest that changes in species distributions due to climate change would not lead to major changes in the importance of severe weather. One possible exception is that expansion of southern pine species in the region would likely increase problems associated with direct wind and ice damage to trees due to persistent foliage on conifers.

Overall, given that extreme weather is currently having only a low to moderate impact on forest land management in the region, the net effect of future changes in extreme weather is likely to be modest, on average. However, impacts are likely to vary spatially, so that some areas may be severely affected while others escape harm. Since climate change may affect the magnitude, periodicity, duration and co-occurrence of extreme events, our ability to extrapolate from past experience is somewhat limited. Results also will be influenced by the extent to which the last decade provides a representative sample of extreme weather events. In spite of these limitations, the survey approach has provided a means of making a relatively rapid assessment of the impacts of extreme weather events, based on past experience, that can be used to provide insight into possible future impacts.

Illustrative economic impacts of climate variability

Basic Considerations

To illustrate the strengths and limitations of the Input-Output (I-O) modeling approach, we simulate some of the potential economic impacts from climate variability affecting mid-Atlantic forests. Two prerequisites are needed to perform such an analysis: 1) a more detailed characterization of the impacted sectors than is presented in Table 5.1, and 2) a set of direct sectoral impact estimates.

The full-scale MAR I-O model consists of fifty-five sectors with a high degree of resolution for climate-sensitive ones. Forest-related sectors are not limited to those primary activities within SIC 1 (Agriculture and Forestry) but also include downstream processing components within SIC 4 (Manufacturing). The nine 4-digit SIC Forest-related subsectors are presented in Table 5.7. The group is dominated by Paper and Paper Products, whose gross output of $20.973 billion comprises 50 percent of the $41.827 billion total gross output of the entire group. Note also that the Forest-related sectors have a stronger economic linkage with the rest of the U.S. and foreign countries than the average of sectors within MAR. The $29.9 billion of exports amounts to 71 percent of these sectors' production, and the $25.7 billion of imports amounts to 61 percent of their production.[2]

Estimates of direct climate impacts variability were obtained from the survey discussed above of over 300 forest managers in the MAR. The questionnaire focused on the forest impacts of extreme weather events, such as high winds, high and low rainfall, heavy snowfall, and ice storms. The results indicated average production cost increases for the primary stages of the

[2] Economic interdependency with the rest of the U.S. stems from the fact that the MAR borders other regions with extensive forest resources, and hence many mid-Atlantic businesses may be closer to suppliers and customers in other regions than to suppliers and customers within MAR itself. It also stems from the uniqueness of some resources, e.g., hardwoods that have a broad export market both domestically and internationally. Finally, although disaggregated to the 4-digit level, the classification still obscures the production of specialty products, found, e.g., in wood furniture and printing, which are typically not self-contained with any one region.

forest product chain (Forest Products, Forestry Products, and Logging & Contractors) of 5.2 percent for just the extreme instances that took place one or more times over the past 10 years.[3] Our simulations are based on a projection that such extreme events could potentially become commonplace, i.e., take place on an annual basis in the future, admittedly a high-end estimate.

Region-Wide Impacts

We calculated three types of impacts using the MAR I-O model:

1. Demand-Driven Multiplier Impacts. These are the standard I-O multipliers that measure the upstream stimulus to the MAR economy through the chain of suppliers to each affected forest-related subsector.

2. Supply-Driven Multiplier Impacts. These measure the downstream stimulus to the MAR economy through the chain of customers of each affected subsector

3. Price Impacts. These measure the cost-push inflation for the MAR economy as a result of productivity losses in each affected sector.

This analysis represents an advance over the MINK I-O study of forest impacts in that it more fully analyzes the upstream impacts of decreased forest exports and considers a more extensive set of downstream supply impacts within the region.

Before presenting the results, we note two important considerations. First, while demand-driven multipliers are well-established, the supply-driven counterpart is a subject of some controversy because it is based on the premise that supply creates its own demand (see, e.g., Oosterhaven, 1988; Rose and Allison, 1989). In our context, a literal interpretation would be that businesses using forest-related products would reduce their own production somewhat for lack of availability of these inputs. Of course, there is always the possibility of utilizing imports if other regions are not affected as greatly as the MAR. To a lesser extent, it may be possible to substitute other inputs for Forest-related ones. Hence the supply-driven multipliers are likely to overstate the impacts. Second, both the quantity and price multipliers fail to take into account

[3] Forest Products and Forestry Products both relate to timber growth, but differ in that the former pertains to traditional forests, while the later refers to large scale business cultivation. Note that the direct impacts differed by tree species and by sub-region, information that can be incorporated in analyses at a higher degree of resolution.

Table 5.7. Forested-Related Sector Flows in the Mid-Atlantic Region Input-Output Table, 1995: Intraregional Flows (in millions of 1995 dollars)

	1	2	3	4	5	6	7	8	9	Total F-R Intermediate Inputs	Exports	Other Final Demand	Total [a] Gross Output
1. Forest Products	0	14	*	81	59	17	0	*	0	172	38	71	293
2. Forestry Products	0	46	2	256	189	53	0	1	0	546	119	225	906
3. Agri, Forestry, Fishing Services	16	305	4	*	1	1	1	1	5	334	842	392	3453
4. Logging Camps & Contractors	0	0	0	71	611	96	70	0	345	1193	78	19	1219
5. Sawmills	0	0	0	1	182	246	304	130	220	1083	420	12	3720
6. Millwork & Plywood	0	0	0	0	0	122	54	48	0	224	339	32	3206
7. Other Wood Products	0	0	0	0	4	46	156	51	9	266	2158	180	3846
8. Wood Furniture & Fixtures	*	0	0	0	0	0	18	119	0	137	1322	2497	4212
9. Paper & Paper Products	0	*	*	*	*	*	*	*	22	22	15939	224	20972
Forest-Related Subtotal	16	365	6	409	1046	581	603	350	601	3977	21296	3652	41827
Total Regional Intermediate Inputs	160	581	215	580	1739	1131	1425	1376	6852	14059	0	797291	
Forest-Related Imports	5	91	6	131	670	464	639	379	5260	7645	0	5336	
Total Imported Inputs	71	186	108	223	814	687	1032	1226	6897	11244	0	292607	
Total Value Added	62	139	3130	416	1167	1388	1389	1610	7223	0	0	0	(16635)[b]
Total Gross Outlay	293	906	3453	1219	3720	3206	3846	4212	20972	41827			1671138

Source: Computed by the authors using the IMPLAN System (1997).
[*] Less than $0.5 million
[a] Total Gross Output also includes non-forest-related intermediate inputs (not shown).
[b] Forest-Related Sectors only.

the negative impacts on other regions of the U.S., which in total could be equal in magnitude, though far lower in percentage terms, than the impacts in MAR.[4]

Economic impacts of climate change depend on a range of considerations relating to supply and demand elasticities and the ability to shift production changes backward onto factor markets or forward onto other product markets. Estimates of these considerations vary, and, in the complete analysis (Cao, 1999), sensitivity tests are performed for groups of lower-bound, upper-bound and mid-range values. Here we present a set of upper-bound estimates, which are useful in deciding whether further study or policy-making is warranted, i.e., if the upper-bound estimates do not pass the threshold of significance, then it is not necessary to fine-tune the analysis or to take action. These upper-bound estimates are based on a price elasticity of supply equal to 1.0 and a price elasticity of demand equal to –1.0 for the directly affected sectors. We also assume that half of the 5.2 percent cost increase is absorbed by producers and half is passed on to customers.[5]

These factors translate into a direct output decrease of $62.9 million (see Table 5.8, Column 1). The total (direct, indirect, and induced) demand-driven impacts are projected to result in a $98.3 million decrease in gross output for the MAR economy as a whole. Only 45 percent of the indirect impacts (the difference between entries in Column 2 and Column 1 of Table 5.8) fall on the Forest-related sectors. The major impacted sectors are Finance and Services, Manufacturing, and Wholesale and Retail Trade.[6]

The supply-driven analysis involves the same basic assumptions and direct impacts but yields significantly larger total impacts amounting to -$150.1 million (see Column 3 of Table 5.8). Here, however, most of the impacts are contained within the grouping of forest-related sectors themselves—these are the sectors in which a restriction in timber supply is most severe. With respect to other sectors, Construction suffers the majority of the indirect impacts. Note also that the supply-driven impacts can be muted by an increase in imports (in fact the percentage offset in the direct and indirect impacts would be equal to the percentage level of the import replacement). Although a greater reliance on imports would appear to be an obvious adaptation, this may be

[4] This conclusion concerning magnitudes is based on comparison of MAR output multipliers with U.S. National I-O multipliers in the IMPLAN System.

[5] The higher prices are modeled by adjusting forest-related input coefficients, and the absorbed costs are modeled by adjusting value-added coefficients to reflect lower profits.

[6] The relationship between total and direct impacts yields an implicit multiplier of 1.34. The output multipliers of the three forest-related sectors is in fact a weighted average of 1.7. The difference stems from the fact that forest sector input and value-added coefficients have been changed as well (see the previous footnote).

difficult if other supplying regions are impacted by climate variability at a level equal to or greater than the MAR.

Recall that, based on the survey results, we assigned half of the weather-induced cost increases to the three affected sub-sectors, which translated into 2.6 percent direct price increases. Total price impacts for the MAR economy are presented in Column 4, Table 5.8, and indicate that

Table 5.8. MAR economy-wide upper bound impacts of direct climate variability damage to forest-related sectors.

Sector	Direct Impacts (thousand $1995)	Demand-Driven Total Impacts (thousand $1995)	Supply-Driven Total Impacts (thousand $1995)	Price Change Total Impacts (percentage)
Forest-Related Sectors				
Forest Products	-7,604	-10,002	-7,607	2.6
Forestry Products	-23,590	-31,495	-25,008	2.8
Ag, Forestry, Fishing Services	0	-3,765	-30	*
Logging Camps & Contractors	-31,694	-33,529	-41,870	3.5
Sawmills	0	-156	-26,766	0.7
Millwork & Plywood	0	-48	-6,828	0.2
Other Woodproducts	0	-40	-4,783	0.1
Wood Furniture & Fixtures	0	-36	-1,156	*
Paper & Paper Products	0	-12	-12,811	0.1
Subtotal	-62,888	-79,083	-126,859	0.6
Other Sectors				
Agriculture	0	-403	-125	*
Mining	0	-38	-165	*
Construction	0	-1,304	-12,302	*
Manufacturing (except F-R)	0	-3,092	-6,405	*
Transport & Communication	0	-1,424	-297	*
Utilities	0	-468	-288	*
Wholesale & Retail Trade	0	-2,749	-649	*
Finance & Services	0	-8,375	-2,036	*
Government	(	-1,449	-1,007	*
Subtotal	0	-19,302	-23,274	*
MAR Total	-62,888	-98,385	-150,133	*

*Less than 0.05%

cost-push inflation is minimal for them and for the Forest-related grouping as a whole. The highest indirect impact is projected to be sustained by Sawmills at 0.7 percent, almost as high, e.g., as the indirect impacts for Logging of 0.8 percent (3.4 percent total price increase minus the 2.6 percent direct price increase). Moreover, the price impacts for every sector outside the Forest group are less than 0.05 percent.[7]

The output impacts appear significant in absolute terms, but might appear insignificant in relative terms, since they represent a gross output reduction for the Region of only 0.0055 percent and 0.0083 percent for the demand and supply cases, respectively. Moreover, the demand-driven and supply-driven impacts are not purely additive since they both include the same direct impacts, and thus $62.9 million, or .0035 percent, must be subtracted to avoid double-counting. However, the direct effect of a 5.2 percent output reduction (productivity loss) in Forest-related sectors is likely to eat substantially into profit margins, thus forcing business closures beyond those estimated by the I-O model. On the supply-side, not only are several Forest-related sectors impacted significantly, but so are sectors, such as Construction, whose output is projected to decrease if it could not import replacements or if wood substitutes were not feasible or not available. Moreover, given the fact that forestry activity is not spread uniformly throughout the region, the relative impacts for some sub-regions are likely to be several times those presented above.[8]

Recall that the results presented here represent an upper bound on possible region-wide economic impacts of forest productivity losses due to short-run climate variability. They overstate impacts on the supply side if input and import substitution possibilities are extensive,

[7] These percentages are based on a projection of the MAR economy total and sectoral output levels for the year 2010 based on data supplied by National Planning Associates (see NPA, 1998 and Chapter 3). The percentage impacts are likely to decrease over time, as forestry activities are projected to be an increasingly smaller portion of the MAR economy under baseline conditions. Of course, the structure (i.e., the technical coefficients) of an I-O table would change in addition to the shifts in the relative prominence of sectors. However, without an adequate basis for estimating such changes we rely on the base year (1995) I-O table. Moreover, several studies have shown that despite technical coefficient change, I-O multipliers are reasonably stable for several years (Miller and Blair, 1985).

[8] Again, we emphasize that the results presented here represent only a small portion of the possible impacts on the forest sector and an even much smaller portion of impacts for the economy as a whole (e.g., we have omitted several non-market impacts of forest growth, such as amenity values in sustaining wildlife, see, e.g., Oladosu, 1999). Unfortunately, accurate estimates of direct climate change impacts for most sectors are not yet available for the MAR region. Moreover, their presentation and analysis in the context of a region-wide model cannot be adequately addressed within the confines of this chapter.

though the former is limited in the short run and the latter in the long run (if forests in other regions are damaged). The demand-side impacts should, however, be reasonably accurate since decreased forest production (either through direct damage or higher prices) will result in decreased production of upstream inputs directly and indirectly.

Ongoing Research on Economic Impact Analysis

Partly because of the limitations of the I-O approach, a computable general equilibrium (CGE) model has been developed for the MAR. This model builds on the one developed for the Susquehanna River Basin (Oladosu 1999). CGE models are the state-of-the-art and preferred technique in regional impact and policy modeling; they retain the favorable features of the I-O model, while simultaneously capturing the optimizing behaviors of producers and consumers in a market setting.

The MAR/CGE model is disaggregated into 51 producing sectors (9 of which are forest-related), using a constant elasticity of substitution (CES) specification of technology, and 3 income-based household types, having Cobb-Douglas (C-D) utility functions. Trade is modeled consistent with the Armington assumption that domestic and foreign goods are imperfect substitutes; investment is based on an exogenous fixed share; there are 2 levels of government (Federal, State/Local) with balanced budgets; and the labor market has 2 alternate closure rules – allowing unemployment or forcing full-employment. Appendix F presents the details of this illustrative application of the MAR/CGE model.

Conclusions And Priorities For Research

The results of the work presented here, and those of previous studies, suggest that the potential species composition of Mid-Atlantic forests is likely to shift as a result of climate change, favoring species that prefer warmer, drier conditions than those that currently prevail. The extent to which these potential distributions will be realized is uncertain, though evidence suggests that the rate of climate change may exceed the rate at which species can migrate through a fragmented habitat. Temporary or long-term conversion of forest to grassland/savanna in parts of the east/southeast U.S. has been suggested by some recent modeling efforts using transient climate scenarios. Forest productivity and carbon storage may increase or decrease depending on the particular climate scenario used, and other factors such as the direct effects of CO_2 and other atmospheric constituents (ozone and compounds of nitrogen and sulfur), fire, and species' migration rates.

Further research is needed to determine the extent to which the potential changes in distribution predicted here will be realized. This will be influenced by species' ability to migrate through a fragmented habitat. Work in this area is underway (Iverson et al. 1999b). Other factors that warrant further investigation are the potential secondary impacts of climate change, such as the increased incidence of insects, disease and fire--factors that were identified as important by our survey respondents. Current MARA research is addressing some of these secondary impacts. The impacts of climate change on atmospheric deposition (acid rain) also need to be established.

Answers to some of the above research questions also can shed light on how climate change might affect diverse functions provided by forests in the Mid-Atlantic region. For example, little currently is known about how changes in the dominant tree species will affect a forest’s capacity to filter water, or the timing of water flows through the forest to groundwater or streams. Similarly, changes in dominant tree species will affect other components of the forest ecosystem; an example would be a change in habitat that affects biodiversity.

Results of our forest manager survey indicate that high winds and precipitation-related events have been more problematic for forest management than extreme temperatures alone, based on experiences over the past decade. Types of major impacts include operational impacts (in particular, altered access to forest areas) as well as structural impacts (direct damage to trees) and biological impacts (mortality, and increased problems with insects, disease and fire). Although our survey results suggest that the net effect of future changes in extreme weather is likely to be modest on average, better predictions are needed of future changes in the frequency, severity and duration of extreme events.

There is a significant need for analyzing economic and policy responses using integrated ecological and economic modeling approaches. This type of modeling can be used to gain insight into economic consequences of changes in species mix and primary productivity. It can also be used to analyze and evaluate adaptation policy options, and the interaction between biological and economic adaptation. Finally, because of the central role of forests as a source of non-market goods, research on non-market impacts of climate induced change in the regions’ forests is crucial. Some of these issues are being addressed in the economic analysis currently underway.

References

Aber JD and Federer CA (1992) A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. *Oecologia* 92:463-474.

Aber JD, Neilson R, McNulty S, Lenihan J, Bachelet D, Drapek R (in press) Forest processes and global environmental change: predicting the effects of individual and multiple stressors. *Bioscience*.

Aber JD, Ollinger SV, Federer CA, Reich PB, Goulden ML, Kicklighter DW, Melillo JM and Lathrop RG (1995) Predicting the effects of climate change on water yield and forest production in the northeastern US. *Clim Res* 5:207-222.

Abrams MD (1992) Fire and the development of oak forests. *BioScience* 42(5):346-353.

Abrams MD and Nowacki GJ (1992) Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania. *Bulletin of the Torrey Botanical Club* 119(1):19-28.

Auclair AND, Lill JT, Revenga C (1996) The role of climate variability and global warming in the dieback of northern hardwoods. *Water Air Soil Pollut* 91: 163-186.

Bazzaz FA (1990) The response of natural ecosystems to the rising global CO_2 levels. Ann Rev *Ecol Syst* 21: 167-196.

Bazzaz FA, Coleman JS, Morse SR (1990) Growth responses of seven major co-occurring tree species of the northeastern United States to elevated CO_2. *Can J For Res* 20: 1479-1484.

Campbell RW and Sloan RJ (1977) Forest stand responses to defoliation by the gypsy moth. *For. Sci. Monogr*. 19. 34p.

Changnon SA, Changnon JM (1992) Temporal fluctuations in weather disasters: 1950-1989. Clim Change 22: 191-208. Chappelka AH and Samuelson LJ (1997) Ambient ozone effects on forest trees of the eastern United States: a review. *New Phytologist* 139:91-108.

Chappelka AH and Samuelson LY (1997) Ambient ozone effects on forest trees of the eastern United States: a review. *New Phytologist* 139:91-108.

Clark LA, Pergibon D (1992) Tree-based models. In: Chambers JM, Hastie TJ (eds) *Statistical models*. S Wadsworth, Pacific Grove, California, p 377-419.

Cao Y (1999) *An economic input-output analysis of forest-related sector vulnerability to climate change in the Mid-Atlantic region*. Unpublished MS Thesis, Department of Energy, Environmental, and Mineral Economics, The Pennsylvania State University, University Park, PA.

Davis MB and Botkin DB (1985) Sensitivity of cool-temperate forests and their pollen record to rapid temperature change. *Quaternary Res* 23: 327-340.

Eamus D (1996) Responses of field grown trees to CO_2 enrichment. *Commonwealth Forestry* Rev 75: 39-47.

Fajvan MA and Wood JM (1996) Stand structure and development after gypsy moth defoliation in the Appalachian Plateau. *Forest Ecology and Management* 89:79-88.

Fisher A et al. (2000) *Preparing for a Changing Climate: The Potenntial Consequences of Climate Variability and Change -- Mid-Atlantic Overview*, prepared for USGCRP First National Assessment, sponsored by U.S. Environmental Protection Agency, Cooperative Agreement No. CR 826554.

Hansen J, Fung I, Lacis A, Rind D, Lebedeff S, Ruedy R (1988) Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *J Geophys Res* 93:9341-9364.

Hansen MH, Frieswyk T, Glover JF, Kelly JF (1992) *The Eastwide Forest Inventory data base: users manual*. General Technical Report NC-151, US Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Huntley B (1995) How vegetation responds to climate change: evidence from palaeovegetation studies. In: Pernetta J (ed) *Impact of climate change on ecosystems and species: environmental context*. Proceedings of symposium on the impacts of climate change on ecosystems and species, December 1991, Amersfoort, the Netherlands. IUCN in collaboration with WWF, US-EPA, SIDA and RIVM, Gland, Switzerland.

IMPLAN (1997) *Impact analysis for planning system*. Stilwater, MN, Minnesota IMPLAN Group.

Iverson LR, Prasad AM, Hale BJ, Sutherland EK (1999a) *An atlas of current and potential future distributions of common trees of the eastern United States*. General Technical Report NE-265, Northeastern Research Station, USDA Forest Service, 245 p.

Iverson LR, Prasad AM, Schwartz MW (1999b) Modeling potential future individual tree-species distributions in the Eastern United States under a climate change scenario: a case study with *Pinus virginiana*. *Ecol Modelling* 115:77-93.

Iverson LR, Prasad AM, Scott CT (1996) Preparation of forest inventory and analysis (FIA) and state soil geographic data base (STATSGO) data for global change research in the eastern United States. In: Hom J, Birdsey R and O'Brian K (eds) *Proceedings, 1995 meeting of the Northern*

Global Change Program. General Technical Report NE-214, US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor PA, p 209-214 .

Iverson, LR, Prasad AM (1998) Predicting abundance of 80 tree species following climate change in the eastern United States. *Ecol Monogr* 68 (4): 465-485.

Jacobson, Jr. GL, T Webb III, and EC Grimm (1987) Patterns and rates of vegetation change during the deglaciation of eastern North America. in: Ruddiman, WF *North America and Adjacent Oceans during the Last Deglaciation*. Geological Society of America. Boulder, CO. 277-288.

Karl RK, Knight RW, Plummer N (1995) Trends in high-frequency climate variability in the twentieth century. *Nature* 377: 217-220.

Komarek, EV (1974) Effects of fire on temperate forests and related ecosystems: Southeastern United States. IN: Kozlowski, TT and Ahlgren, CE. *Fire and Ecosystems*. Academic Press. New York, NY. 225-250

Laprise R, Caya D, Giguère M, Bergeron G, Côté H, Blanchet JP, Boer GJ, McFarlane N (1998) Climate and climate change in Western Canada as simulated by the Canadian Regional Climate Model. *Atmos-Ocean* 36:119-167.

Little, S (1974) Effects of fire on temperate forests: Northeastern United States. IN: Kozlowski, TT and Ahlgren, CE. *Fire and Ecosystems*. Academic Press. New York, NY. 225-250.

Malanson GP (1993) Comment on modeling ecological response to climatic change. *Climatic Chang*e 23:95-109.

Malanson GP (1996) Effects of dispersal and mortality on diversity in a forest in a forest stand model. *Ecological Modeling* 87:103-110.

Malanson GP, Cairns, DM (1997) Effects of dispersal, population delays, and forest fragmentation on tree migration rates. *Plant Ecology* 131:67-79.

Matlack G (1994) Plant species migration in a mixed-history forest landscape in eastern North America. *Ecology* 75(5):1491-1502.

McKenney-Easterling M, DeWalle DR, Iverson LR, Prasad AM, Buda AR (2000) The potential impacts of climate change and variability on forests and forestry in the Mid-Atlantic Region. *Climate Research* 14: 195-206.

McNulty SG, Vose JM, Swank WT (1996) Potential climate change effects on loblolly pine forest productivity and drainage across the southern United States. *Ambio* 25(7): 449-453.

Melillo JFB, McGuire AD, Kicklighter DW, Moore III B, Vorosmorty CJ, Schloss AL (1993) Global climate change and terrestrial net primary production. *Nature* 363: 234-240.

Merz RW, compiler (1978) *Forest atlas of the Midwest*. North Central Forest Experiment Station, USDA Forest Service, St. Paul, MN.

Michaelsen J, Schimel DS, Friedl MA, Davis FW, Dubayah RC (1994) Regression tree analysis of satellite and terrain data to guide vegetation sampling and surveys. *J Vegetation Sci* 5: 673-686.

Miller R and Blair P (1985) *Input-output analysis: foundations and extensions*. Prentice-Hall, Englewood Cliffs, NJ.

Mitchell JFB, Ingram WJ (1990) Mechanisms of changes in cloud. *J Climate* 5: 5-21.

Mitchell JFB, Johns TC, Gregory JM, Tett S (1995) Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature* 376:501-504.

National Assessment Synthesis Team (in press) http://www.gcrio.org/NationalAssment/ (public comment draft, accessed 7-12-00).

National Planning Associates (NPA) (1998) *Regional economic projection series*. NPA Data Service Inc., Washington DC.

Neilson R, Drapek R. Personal communication with Louis Iverson, February 1999.

Neilson R. Personal communication with Louis Iverson, May 1999.

Noda A, Tokiola T (1989) The effect of doubling CO_2 concentration on convective and nonconvective precipitation in a general circulation model coupled with a simple mixed layer ocean. *J Meteor Soc Japan* 67: 95-110.

Noether GE (1991) *Introduction to statistics, the nonparametric way*. Springer-Verlag, New York.

Oladosu GA (1999) *A non-market computable general equilibrium model for evaluating the economic impacts of climate change in the Susquehanna River Basin*. PhD thesis, The Pennsylvania State University, University Park, PA.

Oosterhaven J (1988) On the plausibility of the supply-driven input-output model. *J Regional Science* 27: 203-17.

Pastor J, Post WM (1988) Response of northern forests to CO2-inducted climate change. *Nature* 334: 55-58.

Pitelka LF and the Plant Migration Workshop Group (1997) Plant migration and climate change. *Am Sci* 85: 464-473.

Polsky C, Allard J, Crane R and Yarnal B (2000) The Mid-Atlantic region and its climate: past, present, and future. *Clim Res*, 14(3):161-173.

Powell, DS, Faulkner JL, Darr DR, Zhu Z, MacCleery DW (1994) Forest resources of the United States, 1992. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, *General Tech. Report*, RM-234 (Revised). 133 p.

Prasad AM, Iverson LR (ongoing) *A climate change atlas for 80 forest tree species of the eastern United States* [database]. www.fs.fed.us/ne/delaware/4153/atlas.html

Quine C, Coutts M, Gardiner B, Pyatt G (1995) *Forests and wind: management to minimize damage*. HMSO, Bull 114, London. 27 p.

Robarge WP and Johnson DW (1992) The effects of acidic deposition on forested soils. *Adv. Agron*. 47:1-83.

Rose A, Allison T (1989) On the plausibility of the supply-driven input-output model: Some empirical evidence. *J Regional Science* 29: 451-58.

Rose A, Cao Y, Oladosu G (2000) Simulating the economic impacts of climate change in the Mid-Atlantic Region. *Climate Research* 14(3):175-183.

Rosenberg N (ed.) (1993) *Towards an integrated impact assessment of climate change: The MINK study*. Kluwer, Boston, MA.

Shugart HH, Smith TM (1996) A review of forest patch models and their application to global change research. *Clim Change* 34(2): 131-153.

Soloman AM (1986) Transient response of forests to CO2-induced climate change: simulation modeling experiments in eastern North America. *Oecologia* 68: 567-579.

Solomon AM, Kirilenko AP (1997) Climate change and terrestrial biomass: what if trees do not migrate? *Global Ecol Biogeog Letters* 6: 139-148.

Tallis JH (1991) *Plant Community History*. Chapman and Hall. New York, NY. 118-149.

Tilghman, NG (1989) Impacts of White-tailed deer on forest regeneration in northwestern Pennsylvania. *J. Wildl. Manage*. 53(3):524-533.

US EPA (1993) EPA-Corvallis model-derived climate database and 2xCO_2 predictions for long-term mean monthly temperature, vapor pressure, wind velocity and potential evapotranspiration from the Regional Water Balance Model and precipitation from the PRISM model, for the conterminous United States. Digital raster data on a 10 x 10 km, 470 x 295 Albers Equal Area grid, in "Image Processing Workbench" format. US Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

US EPA (1997) *An Ecological Assessment of the United States Mid-Atlantic Region: a landscape atlas*. US Environmental Protection Agency, Office of Research and Development, Washington DC. Document #EPA/600/R-97/130.

USDA Forest Service (1998) *Ice storm 1998: cooperating for forest recovery*. USDA Forest Service, Northeastern Area and Private Forestry. 35 p.

VEMAP Members (1995) Vegetation/ecosystem modeling and analysis project: Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochem* Cycles 9(4): 407-437.

Walsh K, Pittock AB (1998) Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. *Clim Change* 39: 119-213.

Watson RT, Zinyowera MC and Moss RH, eds. (1996) *Climate change 1995: Impacts, adaptations, and mitigation of climate change: Scientific-technical analysis*. Contribution of Working Group II to the second assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Watson RT, Zinyowera MC and Moss RH, eds. (1998) *The regional impacts of climate change: an assessment of vulnerability*. A special report of the Intergovernmental Panel on Climate Change Working Group II. Cambridge University Press, New York.

Webb III T (1988) Glacial and Holocene vegetation history – 20ky to present: Eastern North America. IN: Huntley B and T Webb III (1987) *Vegetation History.* Kluwer Academic Publishers. Norwell, MA. 385-414.

Wetherald RT, Manabe S (1988) Cloud feedback processes in a general circulation model. *J Atmos Sci* 45:1397-1415.

Whitney, GG (1984) Fifty years of change in the aboreal vegetation of heart's content, an old-growth hemlock-white pine-northern hardwood stand. *Ecology*. 65(2):403-408.

Wilson CA, Mitchell JFB (1987) A doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean. *J Geophys Res* 92 (D11):13315-13343.

Woodward FI (1987) *Climate and plant distribution*. Cambridge University Press, Cambridge, England.

Chapter 6. Fresh Water Quantity and Quality*

Introduction

The Mid-Atlantic Region (MAR, Figure 6.1) has abundant freshwater resources, on average. The mean annual rainfall total is approximately 39.71 inches (1009 mm); annual rainfall has ranged from 25.47 inches to 50.71 inches (647 mm to 1288 mm) over the historical record. Rainfall is distributed somewhat evenly throughout the year, which suggests that there generally might be ample quantities of water available to use in all seasons. Nevertheless, streamflow is reduced in late summer and early fall largely because of evapotranspiration during the growing season. Water resources are used for a variety of purposes including power generation, public and private water supply, industry, agriculture, waste discharges from an assortment of point and non-point sources, and for support of diverse and valued aquatic habitats. Climate variation has many effects on competing needs for finite water resources. Water and watershed management concerns include measures to conserve water supply during periods of drought, to minimize adverse impacts of periodic flooding, and to protect and restore the quality of the region's surface and groundwater resources.

Climate change projections from General Circulation Models (GCMs) for regions the size of the MAR are highly uncertain. Still, there are a number of practical planning activities that could help mitigate adverse consequences of future shifts in hydrologic variability (Lins & Stakhiv 1998), in demand for water resources, and in changes in sources of pollution to freshwater and coastal estuaries and bays.

This chapter presents research on the physical impacts of climate variability and change on fresh water quality and quantity and on how community water system managers perceive the risks posed by these impacts. It characterizes the historical relationships between MAR precipitation and freshwater hydrology and illustrates possible changes in regional streamflow, groundwater, and water quality resulting from climate change in the 21st century. We use the Susquehanna River Basin (SRB; Figure 6.1) to meet this goal for streamflow and water quality and five climate-based regions of Pennsylvania to meet this goal for groundwater. Similar hydroclimatic studies have been conducted for two other MAR basins — the Delaware River (McCabe & Ayers 1989, Ayers et al. 1994) and Potomac River (Steiner et al. 1997). We have conducted updated

*This chapter is based on Neff et al. (2000) "Impact of climate variation and change on Mid-Atlantic Region hydrology and water resources," *Climate Research*, 14:2. It appears with permission of Inter-Research. William Pike also contributed to this chapter.

analyses for these two watersheds; these results will be reported in our Phase 2 report and support our results for the Susquehanna. Before presenting results and discussing their implications, we review freshwater uses, demands, and stresses in the MAR. We then present results from a survey of community water system managers in the Pennsylvania portion of the SRB, followed by conclusions.

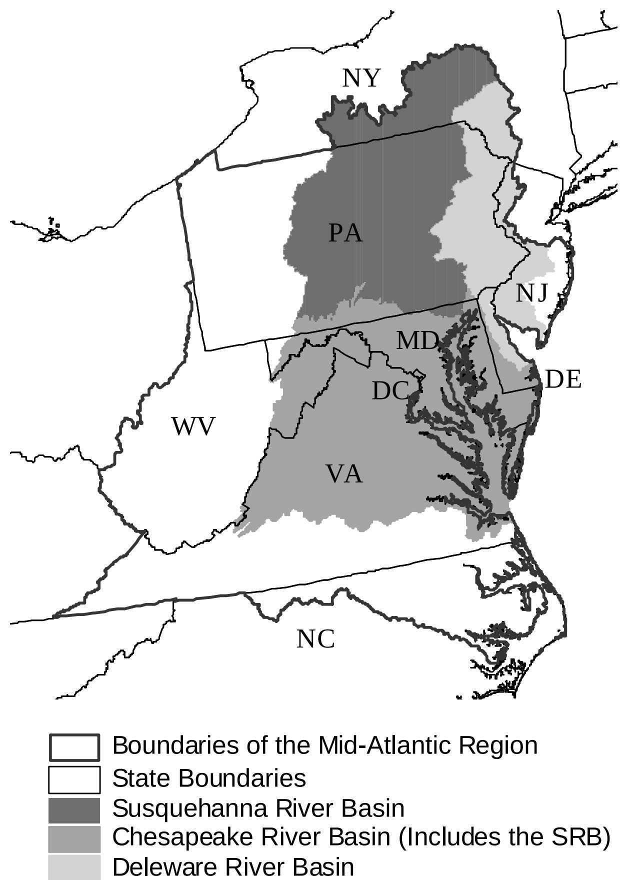


Figure 6.1. Boundaries of the Mid-Atlantic Region, and sub-basins of the Chesapeake River Basin. First-year assessment of water impacts concentrated on these sub-basins; stream-flow and water-quality results for the Susquehanna River Basin (SRB) are presented in this chapter.

Freshwater quality and quantity

Freshwater use

Water use is commonly characterized in terms of groundwater withdrawals and in-stream and off-stream water uses. In the MAR, however, the dominance of forests and agricultural lands means that evapotranspiration from these land-cover types accounts for the greatest water consumption. Approximately two thirds of all precipitation returns to the atmosphere via evapotranspiration. The remaining one third of precipitation moves as groundwater or surface water to streams, where both flows provide a valuable resource for human use. In this chapter, the term "water use" and data pertaining to it refer to both consumptive and non-consumptive withdrawals of water from ground or surface sources. Non-consumptive withdrawals include such uses as once-through cooling for power plants, where water is withdrawn but returned to the watershed. Consumptive use includes irrigation and evaporative cooling towers for power plants. The term "water use" and associated data do not include instream uses such as recreation or wildlife habitat, where water is not removed from the source (Solley et al. 1998).

Freshwater resources and withdrawals can be divided between surface water (lakes, reservoirs, and streams) and groundwater (wells). In 1995, approximately 90 percent of all MAR withdrawals were from surface water and 10 percent were from groundwater (Table 6.1). Delaware and Maryland used proportionally more groundwater than other Mid-Atlantic states (15 percent and 17 percent of their withdrawals, respectively). In contrast, West Virginia used much less groundwater than other political units in the region (3 percent of total withdrawals) and therefore relied heavily on surface water.

Pennsylvania withdrew more freshwater in 1995 than any state in the MAR — one third of total regional withdrawals. This large quantity resulted from a combination of moderate per capita water use and the largest population in the region. West Virginia had by far the largest per capita water use, which ranged from roughly 2.5 to nearly 9 times that of the other states. This occurred because West Virginia demand for water includes large withdrawals by industry and thermoelectric production that are disproportionate with its population, though much of the withdrawals by thermoelectric production are returned to the watershed rather than consumed (Table 6.2).

Three categories dominated 1995 freshwater withdrawals in the region (Table 6.2): thermoelectric power generation, including both fossil fuel and nuclear power (60 percent of all withdrawals), public supply (20 percent), and industry (14 percent). Domestic supplies used only 2 percent of the freshwater supply, while all other uses were smaller. Of special interest is water for irrigation, which was less than 2 percent of the total freshwater withdrawal. Thus, unlike many other areas in the United States, irrigated agriculture is only a minor user of water in the MAR.

Despite the relatively small proportion that groundwater contributes to overall regional water withdrawals, wells are important to domestic water supplies. Twenty-four percent of the region's domestic supply comes from privately owned wells. In the SRB, 34 percent of all households are self-supplied. Nationally, the MAR ranks second only to the southeastern United States in self-supplied domestic water use, while Pennsylvania and North Carolina rank third and fourth, respectively, among the 50 states in their population depending on privately owned wells (Solley et al. 1998).

Table 6.1. Per capita water withdrawal and total freshwater withdrawals in the MAR by source type, 1995

State	Per capita water withdrawal	Groundwater	% groundwater of total	Surface water	% surface water of total	Total freshwater withdrawals	% contribution to total withdrawals
Delaware	1,050	110	15	642	85	752	3
Maryland	289	246	17	1,210	83	1,456	5
Pennsylvania	802	860	9	8,820	91	9,680	33
Virginia	826	358	7	5,110	93	5,468	19
West Virginia	2,530	146	3	4,470	97	4,616	16
Rest of Region	—	1,130	15	6,426	85	7,556	26
Total	**—**	**2,850**	**10**	**26,678**	**90**	**29,528**	**—**

All figures in million gallons per day, except for per capita water use (gallons per day) and percentage tabulations.

Note that these figures are calculated from United States Geological Survey county data for the MAR as defined by Fisher et al. (2000) and do not correspond to the MAR of Solley et al. (1998). “Rest of Region” refers to Washington, DC and the relatively few New York and North Carolina counties in the MAR; they are combined and treated as a residual here.

Table 6.2. As in Table 6.1, but for total freshwater withdrawals by water-use category and state. (Row sums may differ from row totals because of rounding.)

State	Public supply	Domestic	Commercial	Irrigation	Livestock	Industry	Mining	Thermo-electric	Total	% total MAR
Delaware	89	12	3	48	4	61	0	534	752	3
Maryland	834	73	24	62	35	65	5	360	1,460	5
Pennsylvania	1,550	181	30	16	55	1,680	252	5,920	9,680	33
Virginia	786	125	41	30	36	516	39	3,890	5,470	19
West Virginia	176	41	46	0	18	1,320	11	3,010	4,620	16
Rest of Region	2,309	249	74	358	15	357	132	4,012	7,496	25
TOTAL	**5,744**	**681**	**218**	**514**	**163**	**3,999**	**439**	**17,726**	**29,484**	**--**
% Sector Total	20	2	1	2	1	14	2	60	--	--

All figures in million gallons per day.

In summary, the MAR relies upon dependable supplies of both surface and sub-surface freshwater. Because of the high average precipitation totals, supply currently meets demand in most instances (Solly et al. 1998). The exceptions include periodic droughts and occasional disruption or contamination by floods, pathogen outbreaks, and other anthropogenic or natural disasters (e.g., Yarnal et al. 1997, 1999). If climate change were to bring increased climate variation with more droughts, floods, and water-borne pathogen outbreaks, then the ability of future supply to meet future demand is uncertain. Adding to this uncertainty, the ability of future supply to meet demand is indeterminate because of the large uncertainty surrounding future demand.

Climate Variation and Water

As noted, climate variation has a large effect on hydrology and, consequently, on water available for human and ecosystem use in the MAR. This section relates climate to streamflow, groundwater, and water quality on various temporal and spatial scales. Much of the work uses the SRB to represent region-wide processes, relationships, and trends. The Susquehanna is the largest river basin in the region and covers over 21,200 square miles (55,000 km^2), including all four physiographic regions of the MAR (Chapter 2). The basin contributes over 60 percent of the freshwater input to the Chesapeake Bay (Miller 1995), and provides 90 percent of the freshwater to the northern part of the bay (Schubel & Pritchard 1986). Thus, the SRB can be considered representative of the hydrology and water resources of the broader MAR.

Streamflow

There is a close association between streamflow and climate in the region. Figure 6.2 shows the relationship between smoothed precipitation and smoothed streamflow from the SRB for a recent 11-year period. The adjusted R^2 for the *unsmoothed* values of the entire historical record (1895-1997) is 28 percent; the most recent 11 years are presented alone in Figure 6.2 for clarity. Note the slight lead of precipitation ahead of streamflow. During this decade, there is an upward trend in both precipitation and streamflow. The monthly, unsmoothed curves illustrate that high streamflow results from basin-wide weather and climate events, such as the March 1993 "superstorm," the spring melt after the record snow year of 1993-94, the January 1996 flood (Yarnal et al. 1997), and the record wet year of 1996 (Yarnal et al. 1999). In contrast, drought periods, such as the 1991 and 1995 basin-wide droughts are more difficult to discern in the monthly data, but are readily apparent in the smoothed curves.

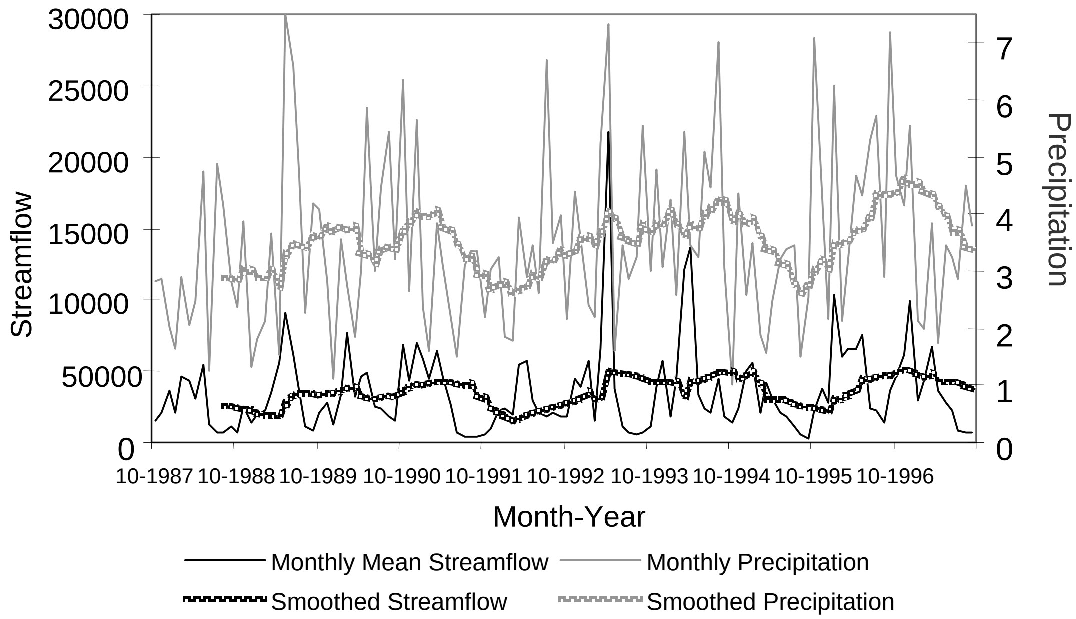


Figure 6.2. Monthly streamflow (cubic feet per second) for the Susquehanna River at Harrisburg, Pennsylvania, and mean monthly precipitation (inches) over the SRB, 1988-1997. Smoothed values use an eleven-month running mean.

Long-term flow in the SRB (Figure 6.3) also suggests the influence of climate. For instance, the rain-on-snow flood of March 1936 (Lichtenwalner 1936) and the Hurricane Agnes flood of June 1972 (Bailey et al. 1975) are evident in the unsmoothed data. Similarly, the decade-long drought of the 1960s (Cook & Jacoby 1983) and the very wet decade of the 1970s (Yarnal & Leathers 1988) appear in the smoothed curve. Despite the record snowfalls of the 1990s and the record wet year of 1996, from this perspective the 1990s were not outstandingly wet in the SRB.

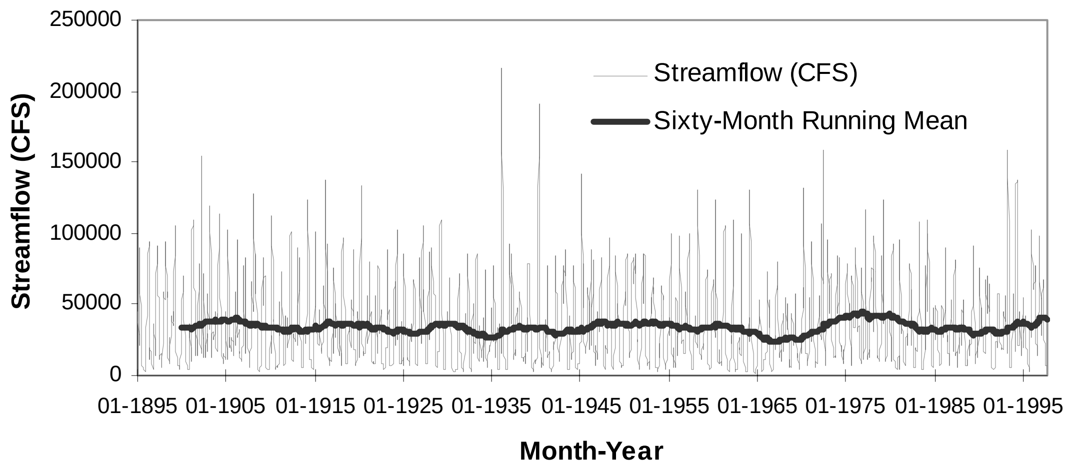


Figure 6.3. Monthly Susquehanna River flow at Harrisburg, Pennsylvania, 1895-1997

Groundwater

Groundwater provides 10 percent of the freshwater withdrawn for human activities in the MAR (Table 6.1). It is especially important to public, domestic, and commercial water supplies. The Pennsylvania Department of Environmental Protection uses a 49-site network of monitoring wells established and maintained by the United States Geological Survey as part of the state's drought management system (Smith 1998). Data from this network can be used to show the close association between groundwater level and climate variation.

Since these data are only available for Pennsylvania, we could not conduct our groundwater analysis for the SRB (see Figure 6.1). Instead, we assigned each well to one of five precipitation-based regions (White et al. 1991; Figure 6.4). Because the geology of these regions is not homogeneous, the groundwater levels for each station were normalized, thus negating the effects of geology on the mean and variance of any individual station. These normalized values were then averaged for each of the five regions shown in Figure 6.4. The result was a time series of normalized regional mean groundwater levels. Unlike streamflow records, reliable groundwater records are only available for more recent decades. While some stations do provide records as far back as the 1940s, others only contributed data for the 1970s or later through the present. Generally, using records earlier than 1970 resulted in biased estimates of regional average groundwater levels; thus, the historical records for each region were truncated at a point in time that provided consistent estimates of regional groundwater levels before they were normalized. This varied from region to region; Central Pennsylvania had the longest reliable historical records, dating back to 1970, while Northeast Pennsylvania had the shortest reliable data set, dating back only as far as 1982 (Figures 6.5-6.9).

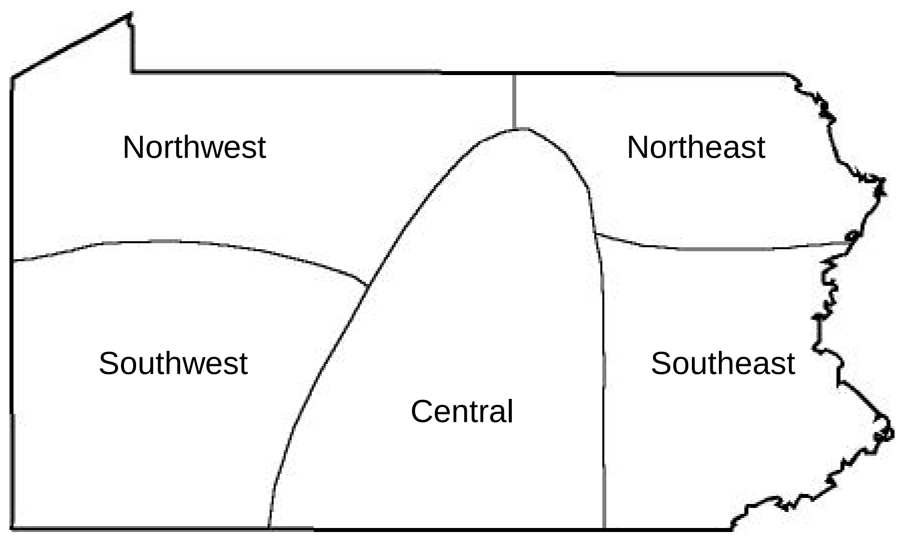


Figure 6.4. Precipitation-based regions of PA from White, et al. (1991).

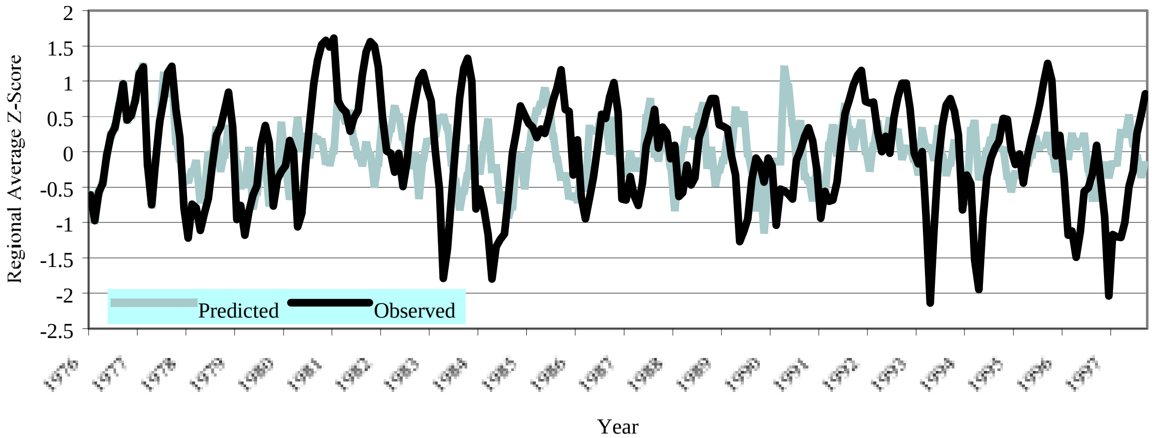


Figure 6.5. Predicted vs. observed groundwater levels for Southeast Pennsylvania.

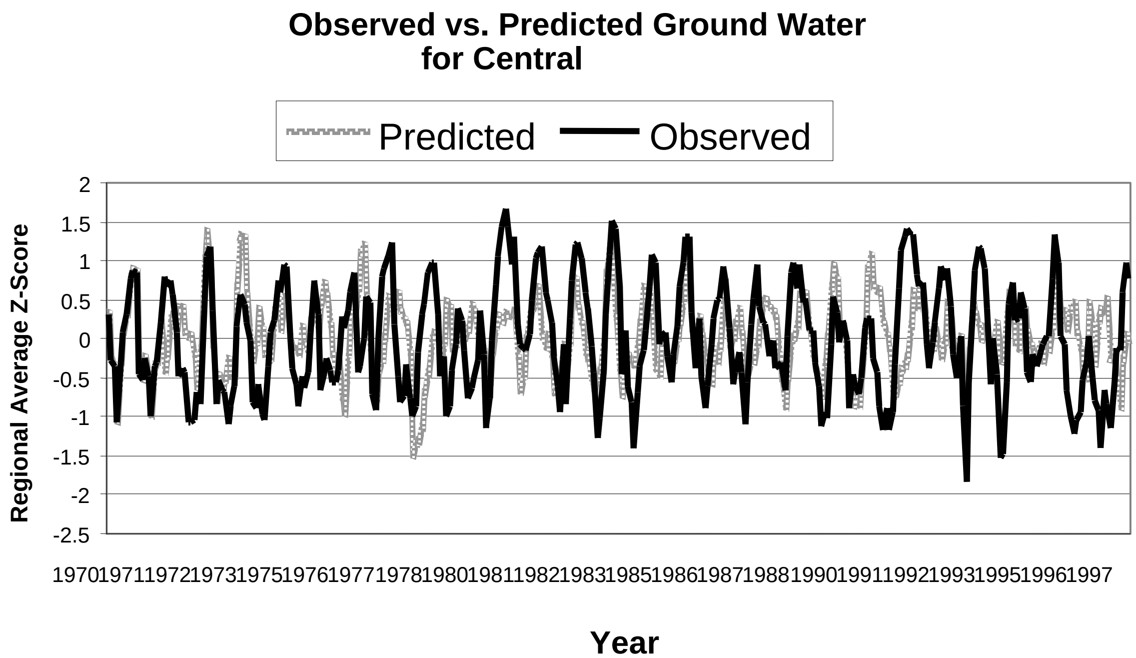


Figure 6.6. Predicted vs. observed groundwater levels for Central Pennsylvania.

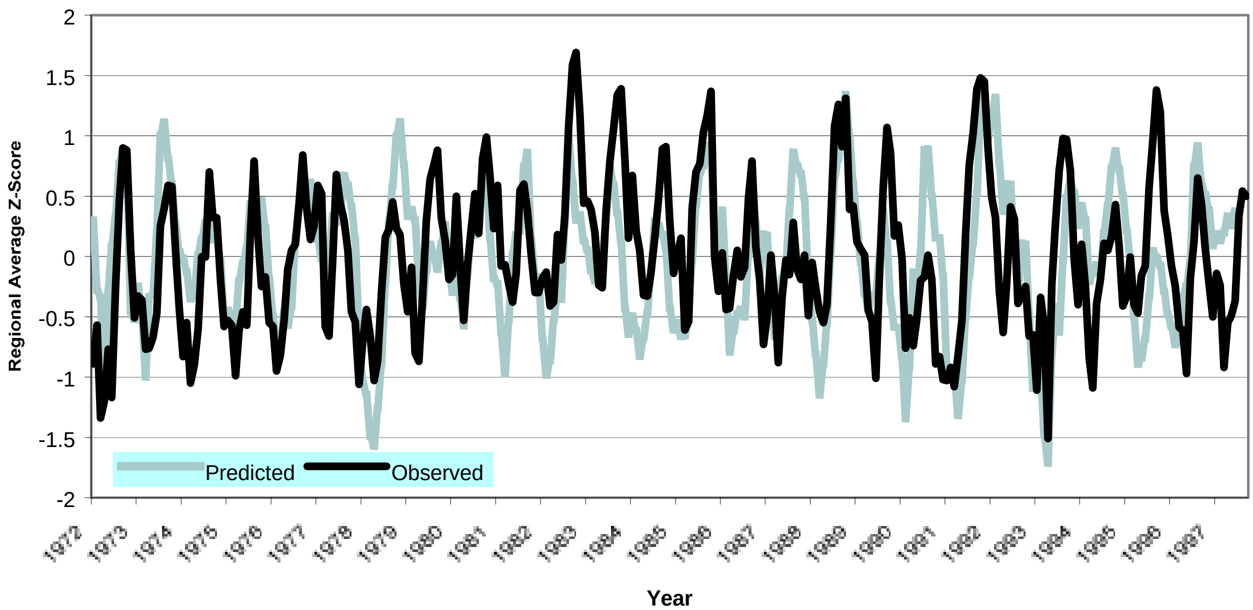


Figure 6.7. Predicted vs. observed groundwater levels for Northwest Pennsylvania.

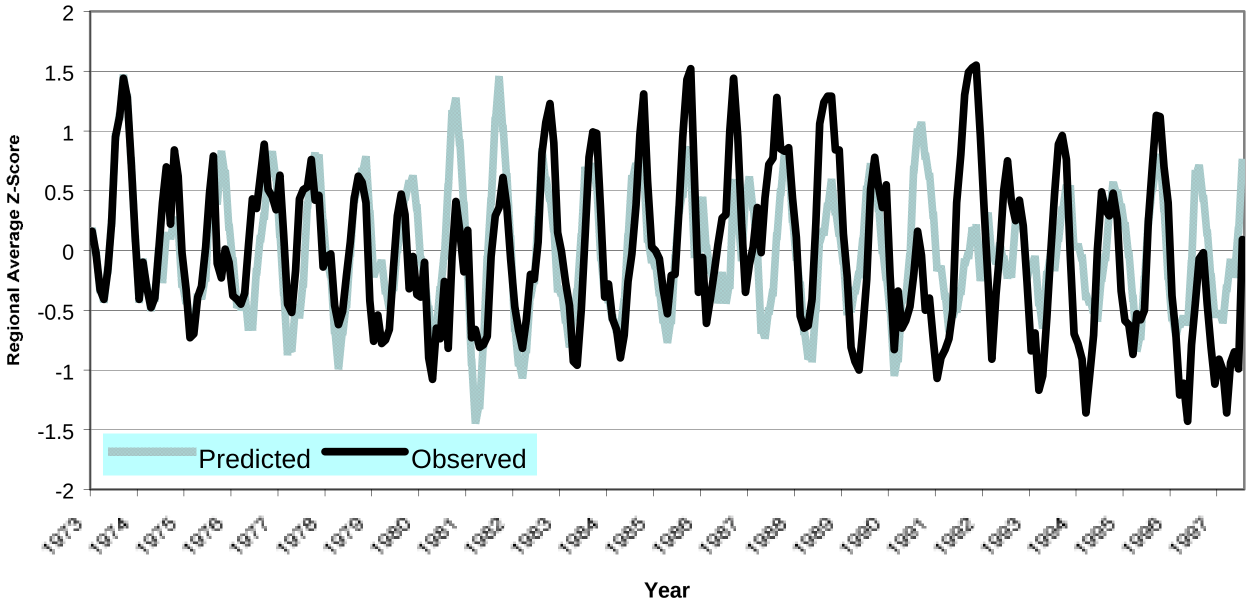


Figure 6.8. Predicted vs. observed groundwater levels for Southwest Pennsylvania.

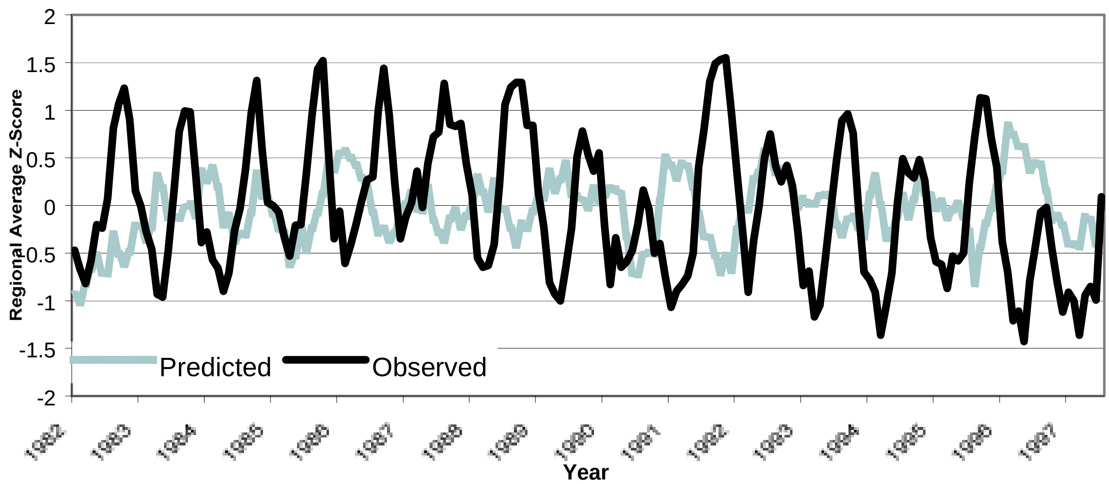


Figure 6.9. Predicted vs. observed groundwater levels for Northeast Pennsylvania.

The next task was to relate the time series of regional average z-scores (variations around the mean) to historical climate data. A stepwise regression suggested a relationship between groundwater levels and precipitation as far back as an 18-month lag. This presented a statistical challenge due to multicolinearity among lagged precipitation values. To alleviate this problem, a temporal principal components analysis was performed on the precipitation data to reduce the number of lagged precipitation values to a more manageable number of principal components. These components then were regressed as independent variables against the normalized regional mean groundwater levels. Because precipitation is used as the sole determining factor of groundwater levels in this model, evapotranspiration is not accounted for. However, regressions using temperature and the Palmer Drought Severity Index (PDSI; see Alley 1984) did not yield significant results, so we concluded that evapotranspiration historically has not been an important determining factor of groundwater levels in Pennsylvania. However, we cannot rule out the possibility that evapotranspiration may become a more important determining factor of groundwater levels as temperatures and CO_2 levels increase. See Neff and Yarnal (2000) for more detail on this procedure.

Using this statistical model, climate data can predict contemporary groundwater fluctuations, albeit with varying success between regions (Figures 6.5-6.9). In general, predicted water-table height showed good agreement with historical values in the western and central regions of Pennsylvania, while the eastern regions showed a relatively poor fit. Thus, as further discussed in the section on climate change, our projections for Southwestern and Northeastern Pennsylvania should be treated with caution. Phase 2 activities will examine determine whether this is a result of the different geological features of the eastern part of the state, human influence, or both. Nevertheless, Figures 6.6-6.8 demonstrate a clear relationship between temporally factored precipitation values and groundwater levels, thus showing there is an influence of climate variability on the water table. In the regions where this relationship is a good predictor of historical water-table levels, it also can be used to project future groundwater levels. These projections are presented in the section on climate change impacts.

Water quality

Contemporary climate variation affects both the quantity and quality of available water resources; similarly, climate change will influence future water quality. Although climate can directly affect water quality, for instance by increasing sedimentation or water temperature, more commonly climate exacerbates water quality problems caused by human activity. Therefore, to understand the influence of future climate variation and change on regional water quality, it is important to understand how humans have affected Mid-Atlantic region water quality in the past.

Before European settlement, the native peoples of the region had little impact on water resources (e.g., Cooper & Brush 1993; Walker et al. 1999a). Early European settlers also had minimal influence, but by the late 18th century rapid population growth and associated land clearing, agriculture, and construction produced severe sedimentation of the region's water bodies. Although land clearing, agriculture, and therefore sedimentation declined rapidly after the Civil War, industrialization and strong population growth resulted in other forms of water pollution. Many of the most severe problems associated with point-source discharges into streams and rivers have been cleaned up in the last few decades. Nevertheless, since World War II, extensive development around and between urban centers, increased fertilizer use, increased intensity of animal husbandry operations, and increased atmospheric nitrogen deposition further degraded the waters of the region in many ways (Walker et al. 1999a).

For example, increased nutrient loading is associated with increased occurrence of hypoxic and anoxic conditions, excessive algal growth, blooms of undesirable algae, and declines in submerged aquatic vegetation. For phosphorous, estimated fluxes from the land, through the rivers, and into the estuaries and bays increased slowly between 1900 and 1945, then began a sharp increase that lasted until 1971. The majority of this increase was due to wastewater inputs. The Federal Water Pollution Control Act of 1972 and the Clean Water Act amendment of 1977 provided the basic legislative structures and authorities for regulating discharges of pollutants to waters of the United States. Removal of phosphorus from detergents and improvements in wastewater treatment resulted in a precipitous decline in phosphorus inputs from wastewater. For nitrogen, agricultural inputs to the MAR's estuaries and bays have risen steadily since World War II. Estimated nitrogen inputs attributable to atmospheric deposition also rose steadily until 1970 (except for a slight dip in the depression years), and have fallen somewhat since then. Direct wastewater contributions of nitrogen have risen systematically throughout the century. The net effect has been a dramatic increase in the nitrogen flowing from land to coastal receiving waters.

Water quality in the regional rivers and streams, lakes, groundwater, and wetlands are documented in water quality reports from the states as required by the Clean Water Act. These documents assess various uses including aquatic life support, swimming use support, and fish consumption. Current water quality problems that compromise designated uses have various causes: abandoned mine drainage, agriculture, siltation, nutrients, metals pollution, organic enrichment/low dissolved oxygen, municipal point sources, and other forms of habitat alteration. Major causes of degradation vary from state to state.

For example, the State of Pennsylvania (1998) indicates that 66.4% of rivers and streams support aquatic life. Acid mine drainage from coal mines accounts for the largest proportion (41%) of assessed waters not meeting overall designated use support, while agricultural operations account for the second largest impact (30%) on assessed waters. Pennsylvania does not have a coast and does not report impacts on estuarine water quality. Nevertheless, the SRB and Delaware River Basin drain eastern Pennsylvania, and nutrient fluxes from these watersheds affect estuarine water quality in Maryland and Delaware. State of Maryland (1998) reports that 50% of estuarine waters are considered impaired, with the principal causes being eutrophication/low oxygen, bacterial indicators, pesticides, and pathogenic algae. Similarly, State of Delaware (1998) reports that 50% of the Delaware Bay, while currently meeting aquatic life support standards, is threatened. Nutrients are a major contributor to these problems.

The major urban areas of the MAR coast have serious water quality concerns. Drinking water is supplied from upstream rivers and reservoirs and therefore is affected by the nutrient and other water quality problems noted above. Storm-water management in urban areas also is a major worry. As a result of these and other water quality issues, for instance, 95.3% of the rivers and streams in the District of Columbia (DC) do not support use designations (DC 1998). In DC lakes and reservoirs, 43.1% do not meet aquatic life support criteria. The most serious estuarine problem is the accumulation of nutrients; none of DC estuarine waters supports overall use designations.

To overcome some problems related to regional characterization of surface water conditions and to differences in reporting across state boundaries, new probability-based sampling designs are being used to obtain unbiased estimates of current conditions in the MAR streams, rivers, and estuaries (U.S. EPA 1998 1999). These methods show that, in general, problems associated with industrial and municipal point sources (metals, pH, biological oxygen demand) impair a much smaller portion of the region's surface waters than nonpoint sources of pollution and other forms of habitat alteration. Most nonpoint sources of excessive nutrients (nitrogen and phosphorus) to fresh water bodies in the region originate from fertilizer and manure application in widespread agricultural areas of this region, from wastes from animal husbandry operations, and from fossil fuel combustion resulting in atmospheric deposition of reactive nitrogen. Land-use changes, including elimination of wetlands and modification to riparian zones, degrade water quality by diminishing the nutrient-retentive capacities of the landscape (U.S. EPA 1997). Along the MAR coast, urban centers further pollute surface waters by dumping wastewater into tidal estuaries.

Thus, these and other studies (e.g., USGS 1999) indicate that the MAR's water pollution problems are closely related to nutrients. Nitrogen and phosphorus concentrations in streams and groundwater tend to be well above the national average. In the southeastern part of the lower SRB and the northeastern part of the Potomac River Basin, for example, many small shallow aquifers with carbonate bedrock have elevated nitrate concentrations, exceeding the EPA drinking water standard of 10 milligram per liter (mg/l). The concentration of phosphorus in the DC area also exceeds the EPA standard of 0.1 mg/l. In addition, the estimated nitrogen deposition from the atmosphere is higher in the MAR than in other parts of the nation, accounting for as much as 25% of the nitrogen entering the Chesapeake Bay (Fisher and Oppenheimer 1991).

Water pollution can be examined by three indices – concentration, load, and yield. Climate variability and change influence these indices mainly through changes in streamflow. Although nutrient concentrations reflect nutrient control strategies for a particular water body, changes in streamflow also affect nutrient concentrations. When a nonpoint source is the dominant nutrient source, nutrient concentrations increase as streamflow increases because runoff from agricultural land or storm runoff from urban areas washes away more nutrients to streams. For example, in Muddy Creek at Mount Clinton, VA, nitrate concentrations are typically higher during periods of high flow than during drier periods (Langland and Hainly 1997). Best management practices undertaken to decrease nutrient concentrations could end up being offset by higher streamflows. However, it is not easy to project future nutrient concentrations because the relative effect of management practices on nutrient concentrations is hard to quantify.

Load, the mass of nutrient transported by streamflow over time, increases as streamflow increases. Thus, the Susquehanna, the Potomac, and the James Rivers, having the highest flow in the MAR, contribute the largest nutrient loads to the Chesapeake Bay. The Susquehanna River contributed about 60 % of the total streamflow and 62 percent of the total nitrogen load from the nontidal part of the Chesapeake Bay Basin during 1985-98 (Belval and Sprague 1999). In 1996, during the January Susquehanna flood, the Susquehanna contributed about one-half of the annual phosphorus and one-quarter of the annual nitrogen transported into the Bay (Zynjuk and Majedi 1996). Although nitrate concentrations at Harrisburg are generally lower than the EPA standard, these concentrations contribute a large amount of nitrate to the Bay when accompanied by high flows. If such a flood would occur in spring or summer under altered climate, the impacts could increase algal growth and subsequently decrease dissolved oxygen levels in the Chesapeake Bay. In addition, without changes in climate, future nutrient loads of the Bay could be increased as the reservoirs fill with sediment, resulting in faster transport to the coast and consequently less nutrient removal (Langland and Hainly 1997).

Thus, there are reasons to believe that with present nitrogen loads on the Mid-Atlantic Region land surface, nutrient fluxes to the coasts could increase with higher precipitation totals (Alexander et al. 1996). This hypothesis was tested by using a statistical model to estimate future water quality. Based on a five-year period (1990-1994) of nitrate loads measured in the Susquehanna River at Harrisburg, contemporary relationships between monthly spot samples of nitrate loads and daily streamflow were calculated (Mattikalli 1996, Webb et al. 1997). Our results (not shown) verify that the nitrate loads have a strong positive relationship with corresponding streamflow ($R^2 = 0.8$), thus suggesting that nitrate loads can be estimated from streamflow projections. Although changes in atmospheric deposition, agricultural practices, wastewater discharges, and urbanization could alter nutrient flux flow relationships in the future, these factors are held constant. Projections of nutrient loadings using both the CCC and Hadley models are presented in the next section.

As demonstrated above, dissolved oxygen (DO) also is of great concern in the Chesapeake Bay. The amount of oxygen in a stream, measured as a concentration of DO, is an indicator of the ecological health of the stream. Four controlling factors influence DO concentrations. They are "the volume of water, the temperature of water, the consumption of oxygen during the decay of organic matter, and the amount of oxygen removed during the nitrification of ammonium" (Arnell 1996). The last two factors, which make up biochemical oxygen demand (BOD), are determined by the quantity and quality of organic materials including point source pollutants.

Changes in catchment vegetation as a consequence of increased CO_2 also could alter the amount of organic materials in the river. However, modeling these processes is complex and no studies have modeled them yet. In contrast, there is a fairly straightforward relationship between water temperature and DO concentration. The higher the water temperature, the lower the amount of oxygen that can be held in water (because of Henry's Law), so a rise in temperature would lead to a reduction in DO. As with nutrient fluxes, several factors outlined above are held constant.

Relating DO levels to climate variability, and projecting it under future climate change scenarios, requires several steps. First, the relationship between air temperature and water temperature has to be determined.[1] Once the relationship between them is determined, DO levels can be estimated based on the association between water temperature and DO levels.

To develop these relationships, empirical data for air temperature, water temperature, and DO concentrations were employed. A water quality monitoring station near Harrisburg (#WQN201) was chosen because of data availability. Ten-year (1987-1996) records of DO concentration levels and water temperature were extracted from the USEPA STORET CD. A meteorological station (#3699) near the monitoring station provided air temperature for the same day when the water samples were taken. This station was chosen because it is located in the middle of the Susquehanna River Basin (SRB) and thus can be used as indicative of the whole basin. We were able to use water and air temperatures for the same day, rather than using time lags to account for the delayed effect of air temperature on water temperature, because such lags are not needed when dealing with mean monthly air and water temperatures (Erickson and Stefan 1996). The data were obtained from the NCDC Summary of the Day CD.

Linear regression models were used for determining the relationships between variables. As Figure 6.10 shows, the linear regression model explains about 90% of the variations.[2] Figure 6.11 also demonstrates a strong association between water temperature and DO concentrations, with a correlation coefficient of 0.87. Because linear models provide good results, using these

[1] Using the temperature variable has a benefit because temperature is one of the most reliable climatic variables from General Circulation Model (GCM) outputs (Lau et al. 1996).

[2] It is questionable whether the linear relationship developed under current climatic conditions will hold under global warming. In a recent study based on weekly samples, Mohseni and Stefan (1999) showed the non-linearity of water temperature/air temperature relationship at high and low temperature zones, suggesting an S-shaped relationship between them. This study, however, found that the summer air temperature/water temperature relationship from the 15-year (1977-1991) monthly spot samples does not change significantly.

equations with air temperatures from the climate models seems to be useful for producing possible changes in water temperature and finally DO levels.

The effects of changes in streamflow on temperature are not taken into account for the analysis, because there is almost no relationship between streamflow and temperature and between streamflow and DO level (see Figures 6.12 and 6.13). However, increased flows, predicted by both GCM scenarios (see climate change projections, next section), might increase BOD and thus exacerbate the decline in DO, by flushing more nutrients into the streams (even in the absence of more extreme events).

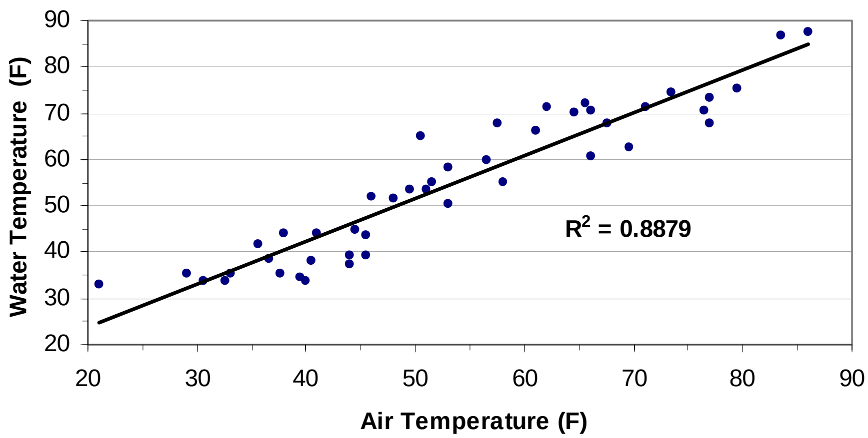


Figure 6.10. Water Temperature vs. Air Temperature for the Susquehanna River at Harrisburg, 1987-1991.

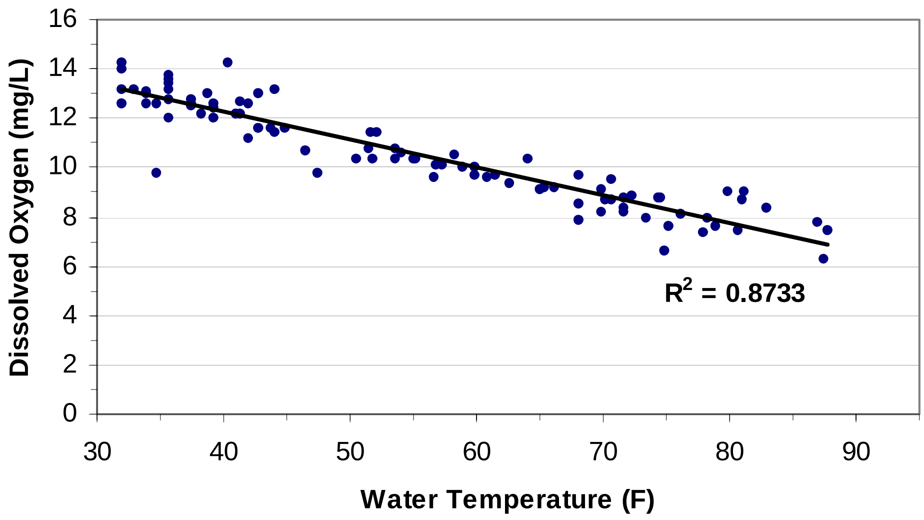


Figure 6.11. Dissolved Oxygen Concentration vs. Temperature, WQN201, Susquehanna River at Harrisburg, 1987-1996.

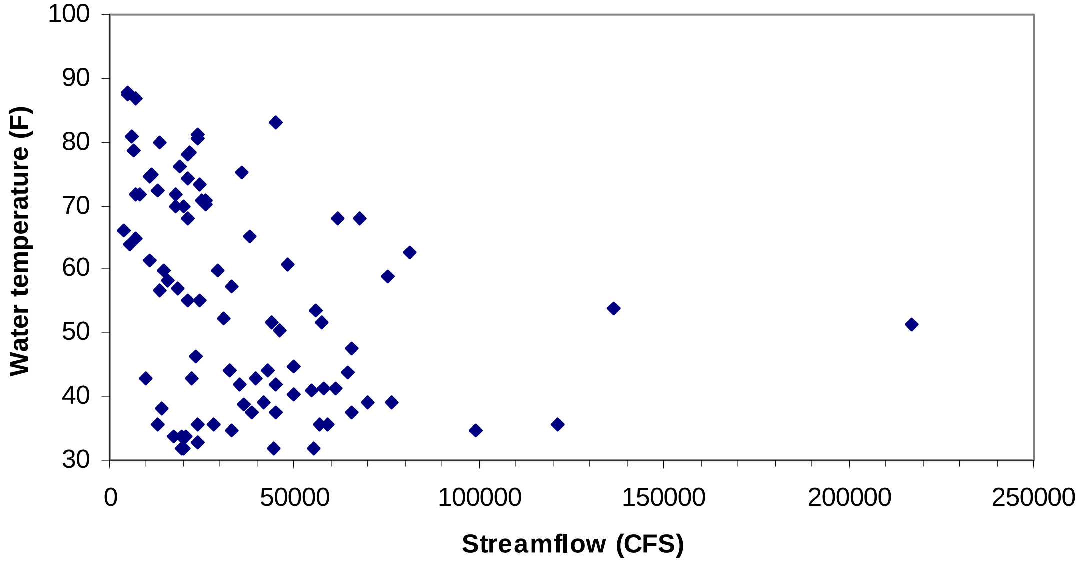


Figure 6.12. Correlation between streamflow and temperature, Susquehanna River at Harrisburg, 1987-1996.

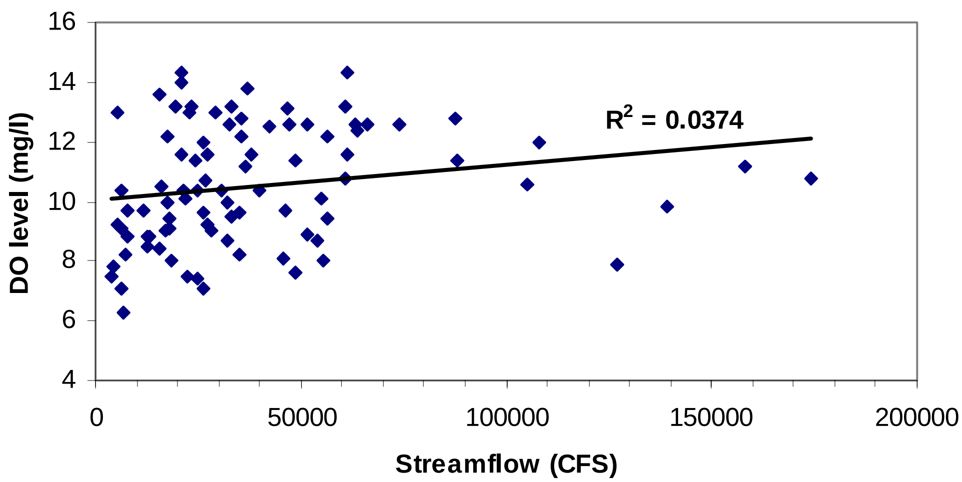


Figure 6.13. Correlation between streamflow and DO level, Susquehanna River at Harrisburg, 1987-1996

Climate Change and Water

The climate change scenarios provided by the Canadian Climate Centre (CGCMI) and the British Hadley Centre (HADCM2; see Chapter 3 for more detailed comparison of these models) are used here to project future streamflow, groundwater, and water quality in the MAR. To be consistent with other regional assessments, we used two 10-year time slices from the model outputs (2025-2034 and 2090-2099), which were selected by the National Assessment Synthesis Team (NAST; see Chapter 1 and Appendix B for more details about the National Assessment process). It is important to note that despite several similarities (e.g., both models are coupled with ocean circulation models, incorporate aerosols in their formulation, and produce transient runs based on an assumed 1 percent annual increase in CO_2 concentrations), they produce very different projections of future climate. For instance, the CCC model projects an increasingly warmer and drier climate than does the Hadley model. As we demonstrate below, this results in a range of projected hydrological conditions; thus, our results should be interpreted as plausible scenarios rather than an attempt at accurate prediction of future conditions.

Streamflow

To estimate streamflow changes in response to climate change, we use the water balance model of Najjar (1999), which simulates flow at the mouth of the Susquehanna River given mean monthly air temperature and monthly precipitation total over the SRB. The model is run to steady state using the mean annual cycle for three periods: 1900-1987, 2025-2034, and 2090-2099. Najjar (1999) provided details for the computation of the mean annual cycle in temperature and precipitation for 1900-1987. The corresponding mean annual cycles for the latter two periods were derived as follows. Outputs from the CCC and Hadley models were interpolated to a one-degree grid covering the SRB for the 1985-1994 base period, for 2025-2034, and for 2090-2099. Spatially averaged mean annual cycles were computed for each period and differences for temperature and precipitation were computed for the latter two periods with respect to the base period. These differences were added to the mean annual cycle for 1900-1987 (Polsky et al. 2000).

The simulation for 1900-1987 captures 99 percent of the variability in the observed mean annual cycle (not shown). The model projects modest change in annual streamflow for 2025-2034 (Figure 6.14); i.e., +7 percent for the Hadley scenario and -2 percent for the CCC scenario. By 2090-2099, the model projects substantially larger annual changes of +24 percent for the Hadley scenario and -4 percent for the CCC scenario. Although both scenarios indicate future increases in precipitation and temperature, the CCC model projects much larger temperature changes and much smaller precipitation changes than the Hadley model. Consequently, the water-balance model projects different directions in streamflow change for each scenario, both annually and for most seasons. Winter, when both scenarios suggest increased flows because of the warming-induced decreases in snow pack, is an exception. The large differences between the two projections highlight the difficulty of predicting future streamflow.

An important result of these projections is the shift in the seasonality of streamflow (Figure 6.14). In both periods, the models accurately capture the observed double peak in streamflow. The late autumn-early winter peak comes one month earlier in the Hadley scenario for 2025-2034 and the late winter-early spring peak comes one month earlier in the CCC scenario for that period. Much more dramatic changes take place in 2090-2099: both peaks come one month sooner in the Hadley scenario, while the CCC scenario appears to shift the early peak to a later date and the late peak to an earlier date. In all cases, these changes in the timing of average peak flows have important implications for water resource availability and management.

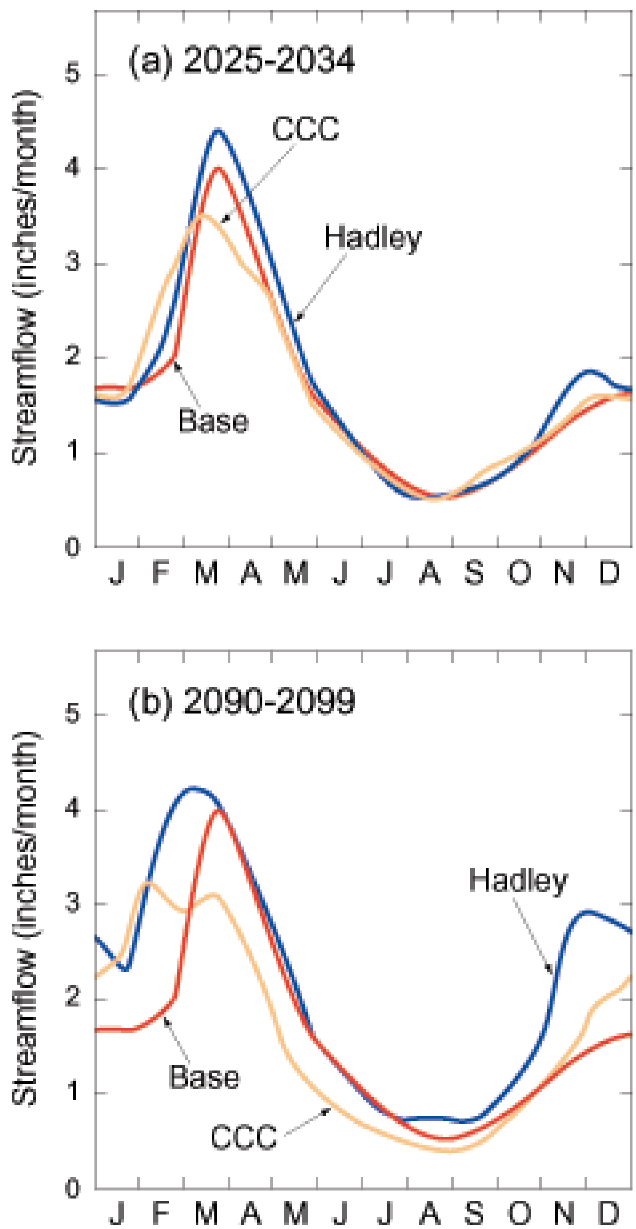


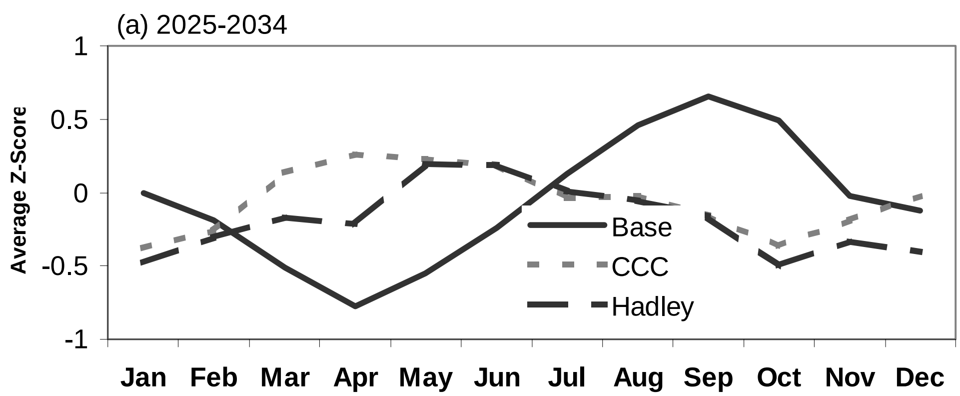
Figure 6.14. Simulated flow at the mouth of the Susquehanna River for the 1985-1994 base period and for the Hadley and CCC models for two time periods: (a) 2025-2034, and (b) 2090-2099.

Groundwater

To project future groundwater levels, we applied the association between contemporary water table height and climate variation to the climate change scenarios. These projections are presented for all 5 climate-based regions of Pennsylvania (Figure 6.4) in Figures 6.15-6.19. These figures demonstrate that the impact of climate change on groundwater levels depends on the climate-change scenario used. Figures 6.15 and 6.19 also demonstrate the dangers of placing too much faith in models that demonstrate poor fits with historical data. Recall that the model predictions for Northeastern and Southeastern Pennsylvania demonstrated dampened variability compared to historical data, and in some cases predicted the incorrect sign of the historical normalized data. It is not surprising, then, that the projections for these regions based on this model exhibit similar characteristics. Thus, the results for these two regions demonstrate more about the inappropriateness of this method for projecting groundwater levels *in these particular regions of Pennsylvania* than they demonstrate anything about the potential impacts of climate change there. Nevertheless, the statistical relationship between groundwater levels and temporal factors of precipitation *do* prove useful in generating believable projections for Northwest, Southwest, and Central Pennsylvania, as evidenced by the strong relationship between temporal factors of precipitation and groundwater levels in those regions.

For the first sample period (2025-2034), both models project earlier seasonal recharge and drawdown of groundwater for all three of these regions. The Hadley model projects no significant change in the annual highs and lows in water table height, while the CCC model projects less extreme annual lows and highs for Southwest and Northwest Pennsylvania. This suggests that in the medium term, availability of groundwater may improve in winter. However, a shift in seasonal fluctuations predicted by both models suggests there may be still be problems in water availability, particularly in late spring and early fall.

In the long term (2090-2099), the projected groundwater levels diverge. The CCC model projects even earlier seasonal recharge and drawdown of groundwater, and less interannual variation in levels; these results suggest greater groundwater availability in winter but less groundwater availability in summer for all three regions. The Hadley model, however, now projects slightly later seasonal recharge and drawdown and, therefore, lower groundwater levels in the winter but higher levels in the summer. Thus, while these results demonstrate that climate change can be expected to affect groundwater levels, it also highlights the uncertainty inherent in projecting that impact into the distant future. Still, the results presented here suggest a possible range of impacts on groundwater levels that could be of interest to water-resource planners. Phase 2 activities will examine the relevance of the projected changes through spatial analysis of community water systems relying on groundwater and projected changes in water-table levels.



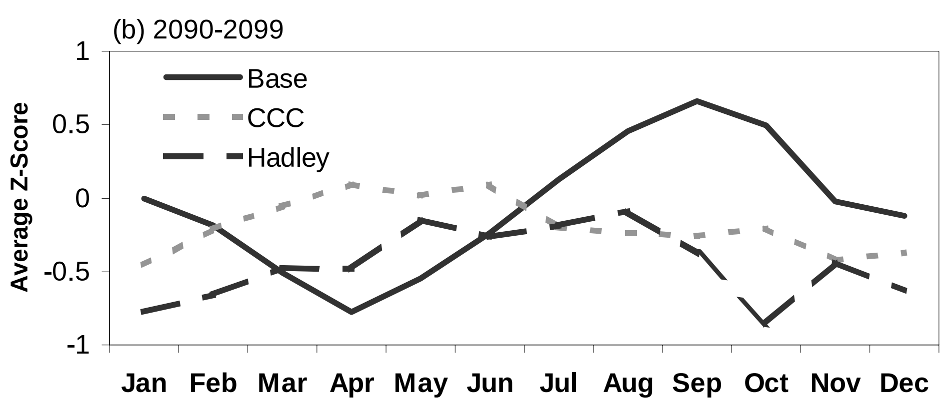


Figure 6.15. Projected groundwater levels for Southeast Pennsylvania using the CCC and Hadley GCM precipitation projections, a) 2025-2034, and b) 2090-2999.

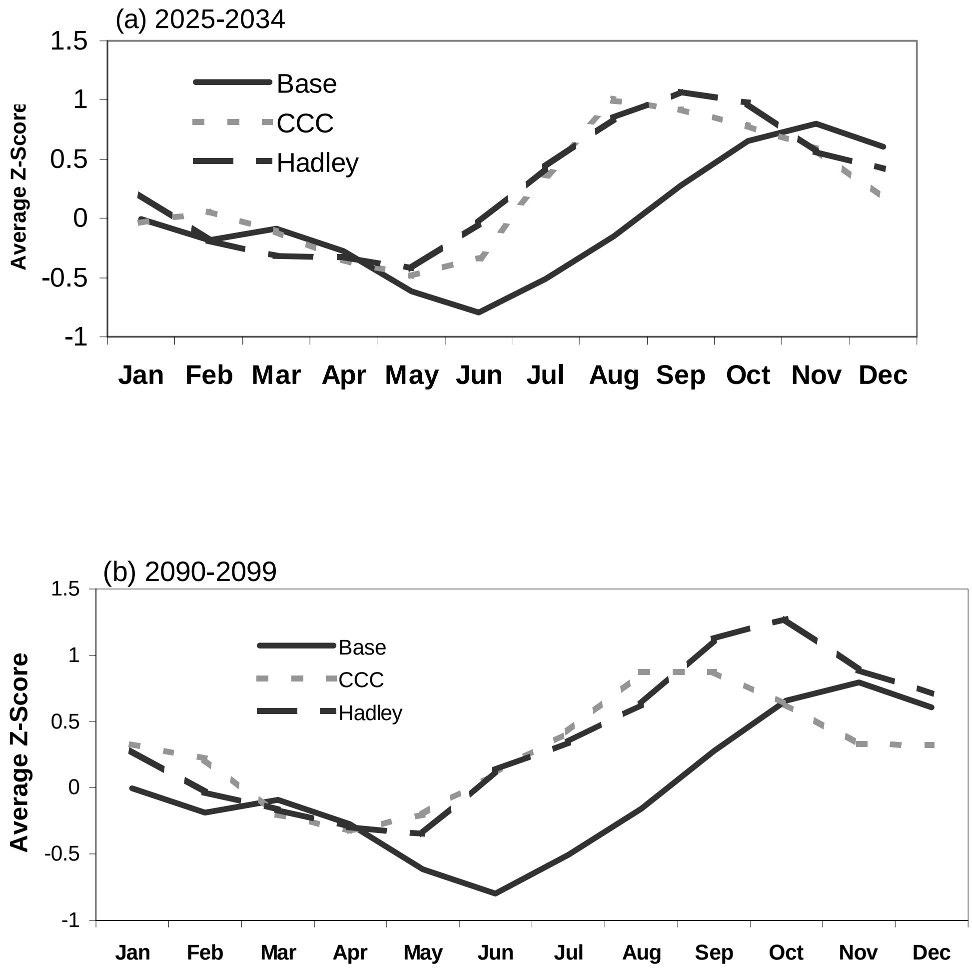
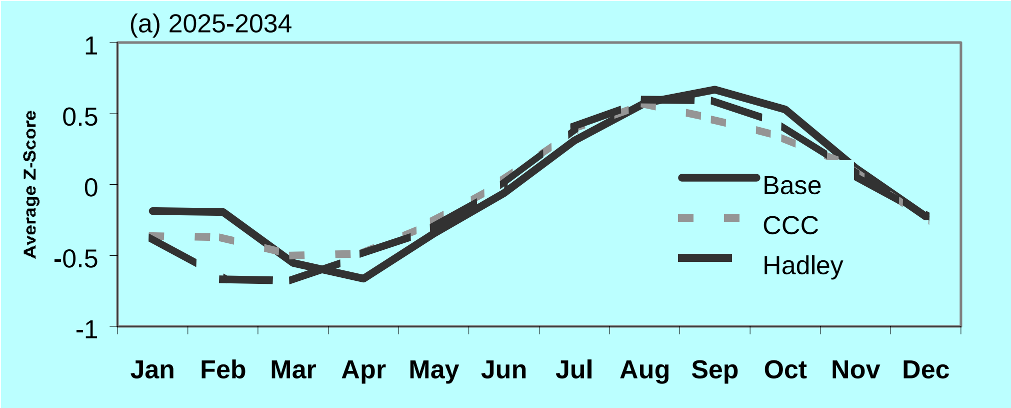


Figure 6.16. As in Figure 6.15, for Central Pennsylvania



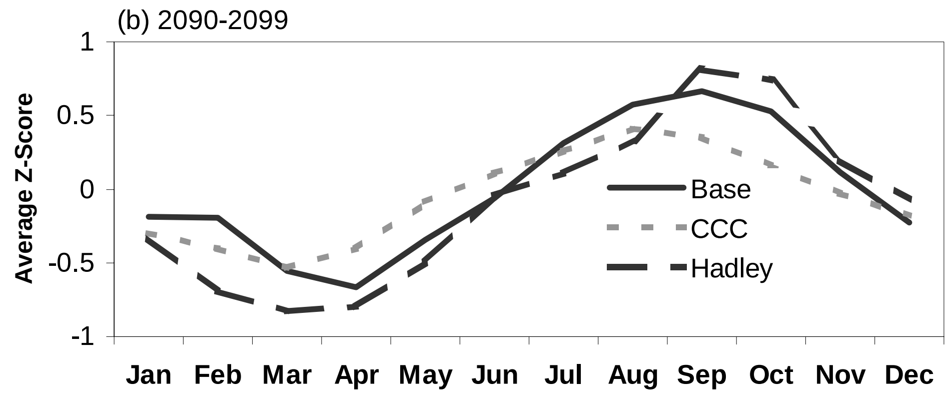
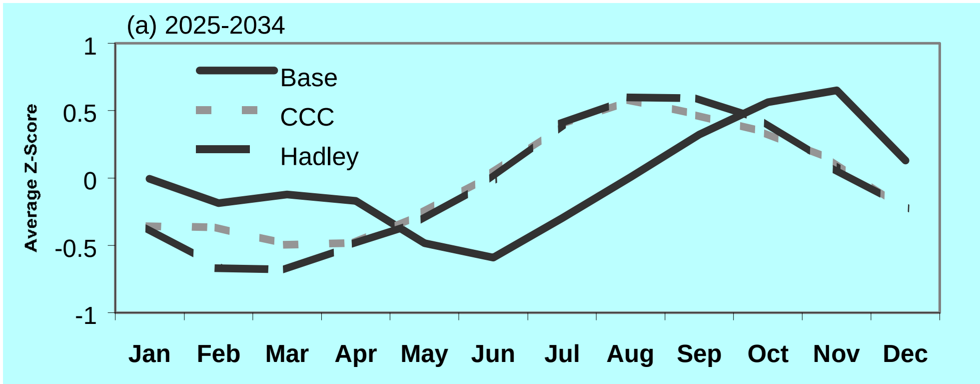


Figure 6.17. As in Figure 6.15, for Southwest Pennsylvania



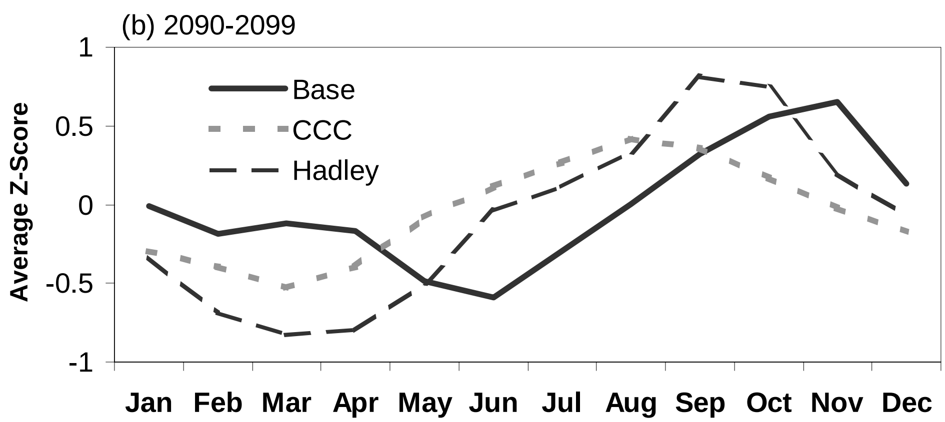


Figure 6.18. As in Figure 6.15, for Northwest Pennsylvania.

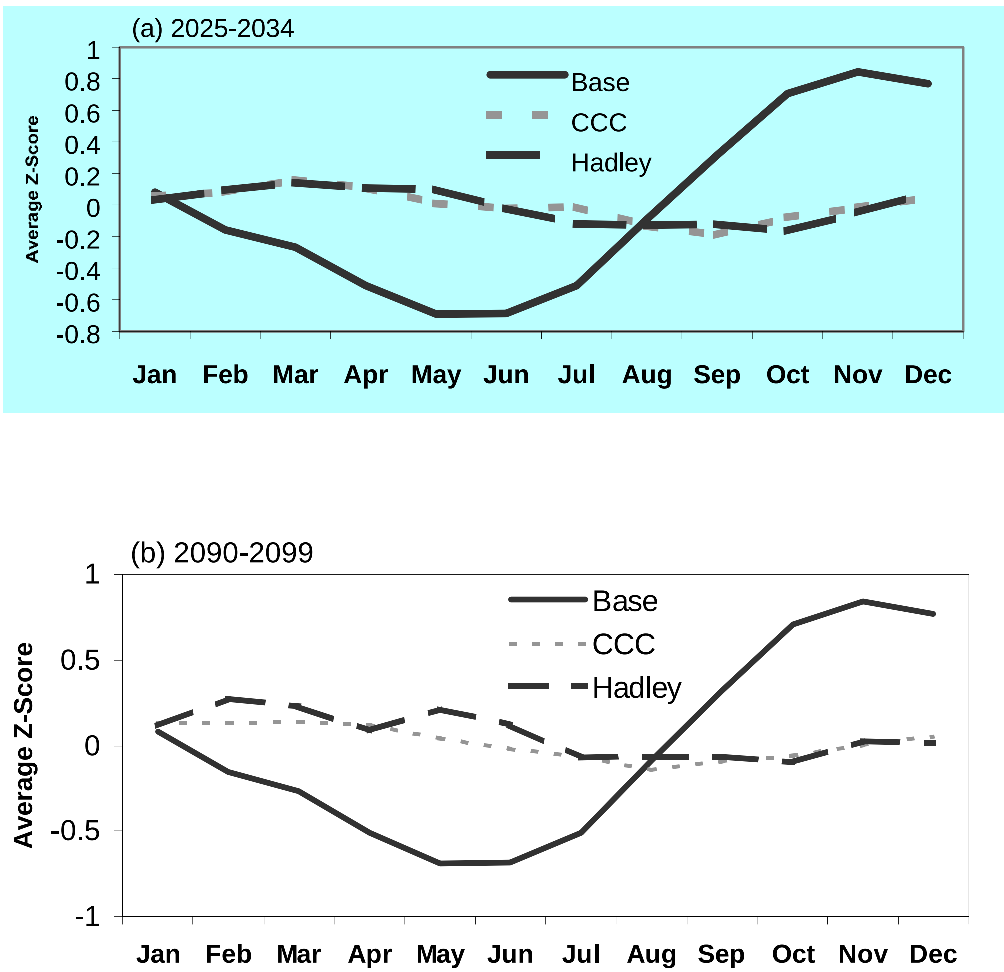
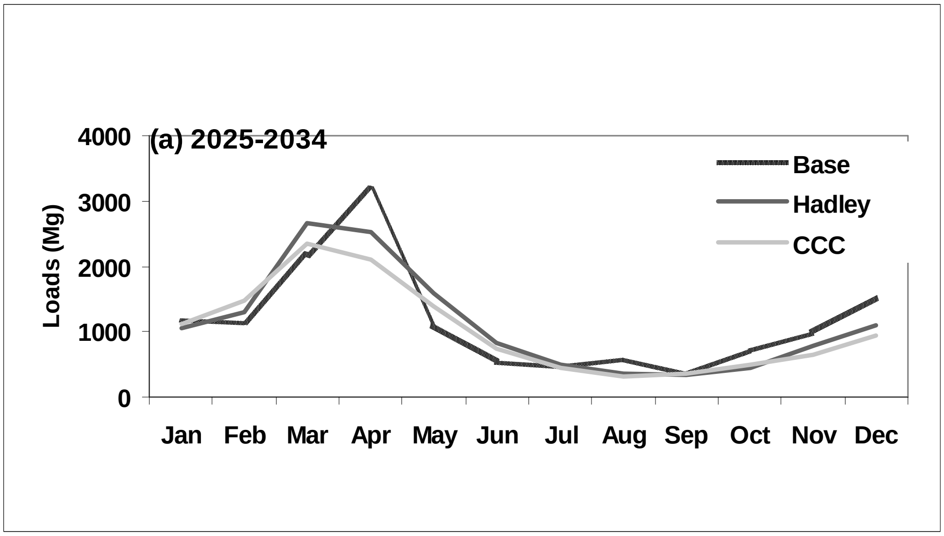


Figure 6.19. As in Figure 6.15, for Northeast Pennsylvania.

Water quality

Projections of future water quality in the Susquehanna River at Harrisburg are presented in Figure 6.20. Under the Hadley and CCC scenarios, nitrate loads can be expected to increase in winter and late spring because of the expected increase in streamflow, especially under the Hadley model. An interesting result is that both scenarios show decreases in streamflow and associated nitrate loads in July and August, which could ameliorate problems associated with estuarine stratification and eutrophication in late summer. This finding is the same as the results of Moore et al. (1997) on future water quality in the MAR. However, decreases in summer streamflow as accompanied by increases in water temperature might increase other water quality problems such as increased contaminant concentration levels. In addition, it is not clear whether the human sources of nutrients and pollutants (eg, land use, pollution policies) will continue on the same trajectories into the future.

Figures 6.21 and 6.22 show monthly DO concentrations under the CCC and the Hadley scenarios for 2030 and 2095. Ten-year monthly mean air temperatures (2025-34; 2090-99) were first calculated from the outputs of the two models. The temperature data represent the whole SRB rather than a single station. As the figures show, both models project slight reductions of DO concentrations for most months except winter months. Because air temperature is expected to increase steadily in the future, the long-term projection is for rather significant decreases in DO concentrations in 2095, especially in summer (see Figure 6.22). The CCC model produces larger reductions compared with the Hadley model, which is expected due to the warmer, drier scenario generated by that model. The reductions in summer might cause ecosystem problems, affecting plants and fish communities, and may severely impact the Chesepeake Bay (as suggested above). Further, because Figures 6.21 and 6.22 merely show mean conditions, they provide no information on the effects of extreme weather conditions on DO concentrations, which might be more frequent under global warming.



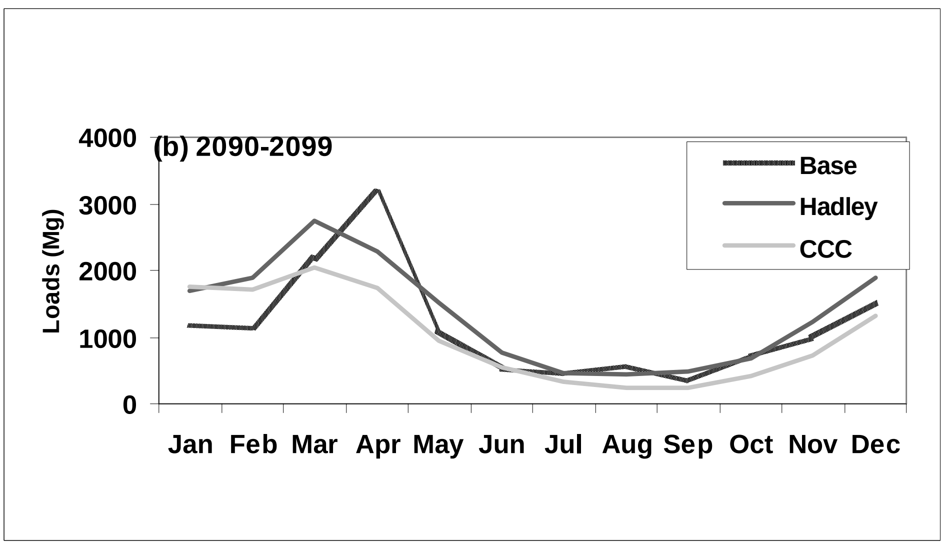


Figure 6.20. Simulated nitrate loads at the Harrisburg monitoring station of the Susquehanna River for the 1980-1994 base period and for the Hadley and CCC models for two time periods: (a) 2025-2034, and (b) 2090-2099.

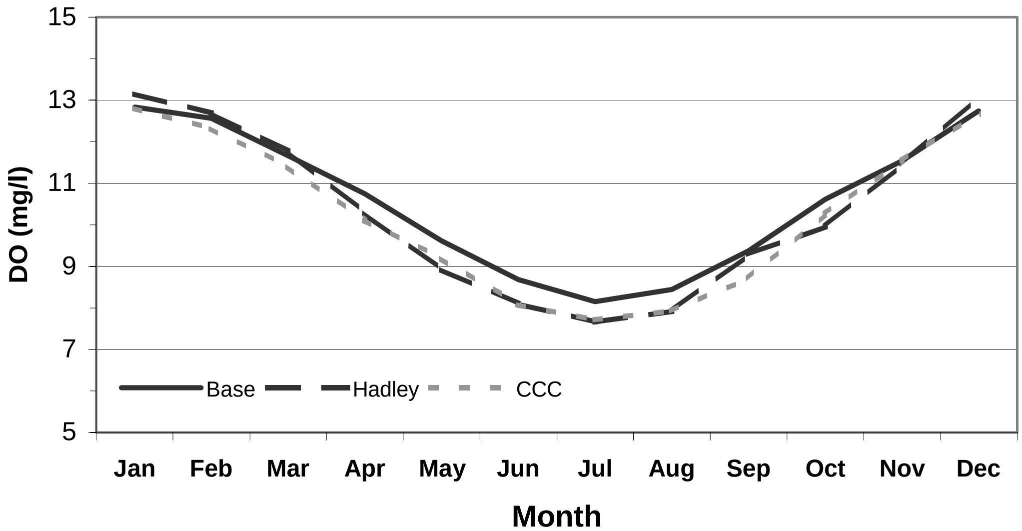


Figure 6.21. Monthly DO concentrations, Susquehanna River at Harrisburg, 2025-2034.

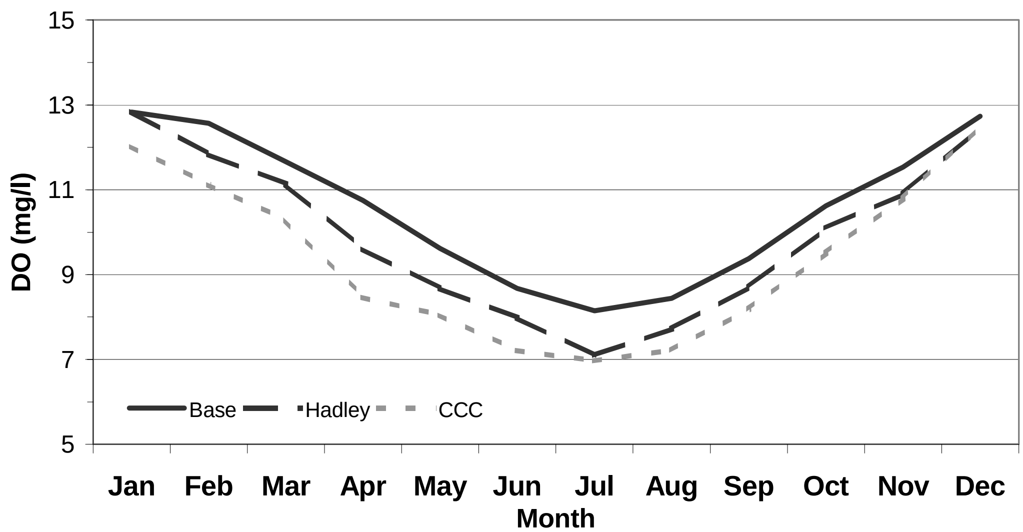


Figure 6.22. As in Figure 6.21, for 2090-2099.

Vulnerabilty of community water sytems to climate variation and change

In discussing the potential effects of climate change and vulnerability on human and ecological systems, the Intergovernmental Panel on Climate Change (IPCC; Watson *et al*. 1996: pp. 23-25) uses three terms: *sensitivity*, *vulnerability*, and *adaptability*. *Sensitivity* indicates the degree to which a system responds to weather and climate, while *vulnerability* denotes the extent to which weather and climate may harm a system in the future. *Adaptability* represents the degree to which it is possible to adjust the practices, processes, or structures of systems in response to past weather and climate or in anticipation of future weather and climate. Vulnerability is a function of both current sensitivity and adaptability. The previous section of this chapter examined the sensitivity of natural freshwater systems to climate variability and change. This section examines the current sensitivity of community water systems (CWSs)—systems that serve at least 25 residents year round—to weather and climate, and then relates these sensitivities to how CWS managers plan (i.e., adapt). The purpose is to gain an understanding of the vulnerability, both real and perceived, of CWSs to climate change and variation.

From what we learned from previous case studies, we hypothesized that smaller systems (i.e., those that serve fewer people) and systems relying on surface water will have greater sensitivity to contemporary weather and climate variation than larger systems and systems relying on groundwater. To test these hypotheses, we surveyed CWS managers in the Susquehanna River Basin of Pennsylvania, asking them about the current impact of weather and climate on their systems. Then, we explored how these water managers perceive climate change and how they think about planning for climate variation and change.

Case Studies

Safe Drinking Water Act (SDWA)

Case studies of CWSs in Centre County, PA suggest that the SDWA has had a significant impact on the composition of those water systems. The Surface Water Treatment Rule (SWTR), a regulation imposed as a result of the SDWA, requires filtration of all surface water sources. Further, the SWTR includes provisions for the Surface Water Influence Protocol (SWIP), which requires testing to determine whether groundwater sources are under the influence of surface-water hydrology. The goal is to ensure that all water drawn from surface water or surface-influenced groundwater is filtered before it is delivered for human consumption. Nearly 50 percent of all CWSs in Centre County have switched to groundwater or pursued regionalization of water services because of SWDA regulations (Table 6.3). Case studies of these systems demonstrate that systems switching to groundwater were more insulated from climate impacts due to the nature of their new source, since the response of groundwater levels to dry periods is delayed and depends on the severity of the drought. Systems relying on both ground and surface sources may be the most insulated. Systems choosing to regionalize their water services took advantage of economies of scale, which allowed them to improve their storage and treatment facilities. For instance, during the 1980 drought, seven water systems in Centre County, PA experienced severe water shortages, and all had to ration water (Pennsylvania DER 1981). When drought struck in 1995, however, only three systems experienced severe shortages and there was no water rationing (Pascale 1997). Nonetheless, contemporary resilience to drought cannot be extrapolated directly to future climate change – areas presently experiencing drought of only minor duration may need to adopt water-saving innovations now used in areas that are more permanently dry.

Table 6.3. Centre County CWS Response to SWTR.

Option Chosen	Number of Systems	Percent of System
Switched to Groundwater	13	25
Regionalized	7	14
Considering Regionalization	6	11
Filtration	3	6
Passed SWIP test	3	6
Awaiting SWIP test results	10	20
Non-Compliance	4	8
NA	5	10

Pennsylvania Infrastructure Investment Authority

Another case study (Jocoy 2000) examined the allocation practices of the Pennsylvania Infrastructure Investment Authority (PENNVEST). Findings demonstrate that smaller CWSs are less likely to apply for funding to improve water-treatment facilities and, of those that do apply, fewer small water systems actually receive the funding they need (Table 6.4). Because severe events such as flooding, which could change in frequency under climate change, can result in changes in water quality, this has an effect on the vulnerability of these systems (Yarnal et al. 1997; Yarnal et al. 1999).

Thus, we expected smaller systems and those on surface water to display higher vulnerability to climate variability, and therefore to climate change. However, our survey results suggest there may be more complex and evasive issues contributing to CWS vulnerability to climate phenomena.

Table 6.4. Percent of Pennsylvania CWS applying to and funded by PENNVEST.

EPA Size Category	Number of systems submitting at least one application	Percent of total systems	Percent of systems applying	Percent of applications funded
Small (< 3,300)	239	85	12	75
Medium (3,301 – 50,000)	121	13	41	85
Large (>50,000)	15	2	42	83

The CWS Managers' Survey

The Survey Instrument

The methodology for the survey followed a modified Dillman (1978) approach. In Pennsylvania, managers of large systems most often affiliate with the American Water Resources Association, while managers of small systems most often affiliate with the Pennsylvania Rural Water Association. In August of 1998, we sent letters urging managers to cooperate from the American Water Resources Association to managers of systems with under 10,000 users (letters to managers of systems with 10,000 or more users were from the Pennsylvania Rural Water Association). In September we sent the questionnaire with a stamped pre-addressed return envelope to 830 CWS managers. One week later we sent postcards reminding respondents to fill out the questionnaire. In October we mailed a second questionnaire to all respondents who had not returned the first questionnaire. By the end of the fall we had received 506 completed questionnaires, a 61 percent response rate.

The survey instrument itself is a booklet with ten pages of questions divided into three sections. The first four pages ask about experiences with and expectations about extreme climate and weather events. Then, four pages deal with operating characteristics, and the questionnaire concludes with two pages about finances and planning.

Sensitivity of CWS to Weather and Climate

The problems that CWS managers say they have from weather and climate events in a typical year are summarized in Table 6.5. The most common problems (69 percent) involve the inability to pump water because of power outages caused by electrical storms. Problems with pumping water because of wet snows and because of heavy winds are also common. The next most common type of problem occurs when drought or heat strains the supply of water. Finally, a quarter of the systems - mostly those relying on surface water - experience problems from flash floods. In summary, most CWS managers report problems from weather and climate events in a typical year. It is not surprising that most managers say that they expect disruptions caused by weather and climate in daily operations in the next five years (Bord et al. 1999).

Table 6.6 exhibits three regression equations designed to explore the correlates of sensitivity. These sensitivity measures emerged from a factor analysis of the weather and climate items of Table 6.5:

- Drought factor combines items a, b, c, and h of Table 6.5. Cronbach's alpha statistic for these items is .77. The measure ranges from 4 (1 on each measure) to 12 (3 on each measure).
- Flooding factor combines items d, e, and f of Table 6.5. Cronbach's alpha is .61. The measure ranges from 3 (1 on each measure) to 9 (3 on each measure).
- Outages factor combines items j, k, and l of Table 6.5. Cronbach's alpha is .79. The measure ranges from 3 (1 on each measure) to 9 (3 on each measure).

The independent variables of Table 6.6 are straightforward measures. "Population" is the number of people served by the CWS, as reported by the Pennsylvania Department of Environmental Protection. The "number of sources" is the number of different ground water or surface water intakes for the CWS. "Surface water" is a dummy variable for systems that have at least one surface water intake.

Contrary to our hypothesis, small systems are not more sensitive than large ones. In none of the three equations are smaller systems more sensitive. In the case of flooding, larger systems have more problems, even after controlling for variance accounted for by the surface-water dummy variable. Perhaps these larger systems entail greater complexity that makes them more likely to suffer turbidity and recharge problems from flash floods and storm water runoff (Perrow 1984). In other words, because smaller systems may be simpler, they may have fewer problems. It is also possible that larger systems are operating closer to their capacity, and thus feel the effects more than smaller systems, which may have more excess capacity. However, we do not have data at an acceptable resolution to test either hypothesis. Follow-up interviews may be the best way to understand these results, and would be part of future work in this area.

Table 6.5. CWS Difficulties due to Weather Events* (O'Connor et al. 1999).

	% never	% 1-2 times per year	% 3 or more times per year
a. Drought conditions lowered the supply of water in the system	59	37	5
b. Drought conditions forced us to seek out another source	88	10	2
c. Drought conditions led to significant increased demand on our system	58	3	9
d. (Ground water systems) Flash floods have overloaded our recharge area's ability to filter surface water naturally	94	6	1
e. Flash floods have increased the turbidity in our surface water systems	75	14	12
f. Storm water runoff has threatened our recharge areas	90	9	2
g. Extremely high air temperatures have overloaded electrical circuits and knocked out pumping stations	90	9	1
h. Extremely high air temperatures have increased demand and thus strained our supply of water	72	23	5
i. Extremely low air temperatures have frozen water in the pipes that expanded and broke water lines	67	28	6
j. Electrical storms have led to power outages that have affected our ability to pump water	32	58	11
k. Heavy, wet snows have led to power outages that have affected our ability to pump water	55	42	2
l. Heavy winds have led to power outages that have affected our ability to pump water	56	42	3

* The question is, "For each of the items below, indicate how many time **in a typical year** your **current system** has suffered some form of difficulty due to the types of events listed below."

N's range from 497 to 459.

The impact of surface water is strong and as expected. Surface water systems are much more sensitive to droughts and floods. Flooding rarely causes problems for groundwater systems in the Susquehanna River Basin. Thus, the encouragement of the SDWA to CWSs that they adopt groundwater systems would seem to reduce the impacts from droughts and floods.

Our data show that CWSs with drought problems have more sources than do systems without drought problems. We suspect that CWSs with drought problems have sought out additional sources to increase their capacity; we doubt that having more sources increases drought impacts.

In summary, droughts are less likely to cause difficulties for systems that rely wholly on ground water. Flooding is primarily a problem in surface water systems, although larger systems also are more likely to have problems with flooding regardless of whether they are surface, ground, or mixed systems. Power outages are the most common problem, but are not related to the system size, the number of sources, or the type of source.

Table 6.6. Sensitivity Measures Regressed on Size, Number and Type of Source (O'Connor et al. 1999).

	Drought Factor	Flooding Factor	Outages Factor
Population served	-.000012	.000026***	.000012
	(.00)	(.00)	(.00)
Number of Sources	.18***	-.03	.03
	(.05)	(.03)	(.04)
Surface Water	1.37***	1.42***	.11
	(.20)	(.10)	(.17)
Constant	4.76	3.19	4.68
Adjusted R^2	.14	.40	.00
N	425	383	430

Cell entries are unstandardized regression coefficients, with standard errors in parentheses.
* Significant at .05
** Significant at .01
*** Significant at .001, all two-tailed tests.

Climate Change and Planning

Forty-one percent of CWS managers report they are "not concerned at all" about global warming influencing their water systems. A more probing question reveals that 50 percent of the sample admits they do not know what to believe about global warming, and 19 percent think global warming may happen, but is too far in the future to warrant worry now. Of the remaining 31 percent, managers who think, "global warming is real" (22 percent) outnumber managers who think that global warming is unlikely (9 percent). Other results from the survey suggest that CWS managers also are open to planning based on projected future availability; 38 % stated that they plan for possible future events, with only 15% stating they plan based only on actual past events. The remaining 47% responded in between these extremes (O'Connor et al. 1999). Overall, managers are mostly ambivalent about global warming, neither certain that it is a hoax nor a serious concern to their water systems. However, the results do suggest that CWS managers may be interested in, and possibly even pursuaded by, regional assessments of climate change, particularly if researchers take care to identify issues of interest to them.

Conclusions

Many CWSs in the Susquehanna River Basin of Pennsylvania are sensitive to extreme weather and climate. Early case studies suggested that smaller systems may be sensitive and vulnerable to weather and climate. A subsequent survey of the region's CWS managers indicates, however, that larger systems have more problems with flooding and that size is not a significant determinant of outages from storms or disruptions from droughts. Instead, the source of the system's water is important for disruptions from both droughts and flooding. CWSs that rely on groundwater have lower sensitivity, while systems that rely partly or wholly on surface water face more disruptions from weather and climate.

Although weather and climate are critical to their daily operations, CWS managers are unsure about global warming. An important finding is that few managers dismiss global warming as an irrelevant concern; most think global warming could be a problem but are unwilling to consider it in their planning activities until there is greater scientific certainty.

Uncertainties and challenges of climate variation and change

While it would be ideal, particularly from the point of view of CWS managers, to predict the impacts of climate change on water resources accurately, no methodology currently can achieve that goal. Due to the confounding factors discussed below, it is highly dubious that any method will emerge in the near future that can predict these impacts with confidence. Thus, we contend that the goal of climate change impacts research should be the generation of plausible impact scenarios. That is precisely the goal of this chapter. The approach taken here is to generate impact scenarios using state-of-the-art GCM runs and historical relationships between climate and the available quantity and quality of water. By using these GCMs, our impact scenarios are also directly comparable with those used in other regions of the United States as part of the National Assessment process. The results presented here thus provide a range of plausible impacts that could occur under a set of plausible future climatic conditions, but should not be misinterpreted as predictions. There are many feedback processes and relationships, for example human systems involved in adaptation, that cannot be modeled deterministically over the long term. Still, further research in areas such as land-use change, improved climate scenarios, and better surface and ground water models, could improve our understanding of the potential effects of climate change and suggest possible adaptive strategies.

Despite the uncertainty involved in projecting the impacts of climate change, our research demonstrates that contemporary climate *variation* influences streamflow, groundwater, and water quality in the MAR and, consequently, the essential water resources needed by industries, municipalities, and individuals. Relationships between climate, streamflow, and groundwater are somewhat uncomplicated and reasonably well understood, but the relationship between water quality and climate is not as simple. Dry periods decrease nutrient fluxes from the land to the waters. Even modest wet periods immediately following dry periods result in the flushing of accumulated nutrients from the land and large nutrient spikes in regional waters; subsequent very wet periods may not flush as many nutrients because fewer nutrients are available. In the Piedmont and Coastal Plain provinces of the Chesapeake Bay watershed, discharges of nitrate can be promoted by increased surface runoff and groundwater flow, but phosphorous concentrations in streams are more highly correlated with suspended solids concentrations (Jordan et al. 1997). Despite such complexities, research has demonstrated strong associations between climate variability and water quality in the MAR. For example, Walker et al. (1999b) found a chain of associations linking elements of the global-scale atmospheric circulation, MAR climate, regional streamflow, nutrient fluxes to the region’s estuaries and bays, and oxygen conditions in these water bodies. Cronin and collaborators (personal communication) have found similar linkages among the global-scale circulation, regional climate, streamflow, and sedimentation in the Chesapeake Bay.

This study also has shown that climate *change* will influence streamflow, groundwater, and water quality. The two climate change scenarios used here both found that water quantity and quality will vary in the future with the climate. These scenarios and others (i.e., Jenkins and Barron 1997, Crane and Hewitson 1998) suggest that future climate may be wetter in the MAR. Other factors being equal, this finding means that streamflow and groundwater could provide more water for human and ecosystem use.

Nevertheless, other factors are not necessarily equal. Streamflow is difficult to project because of the offsetting effects of increased temperature and precipitation. Our results (see Figure 6.14) show that the sign of the change cannot be estimated because one climate model scenario is much warmer and drier than the other. Three published studies on the streamflow response to climate change in the MAR highlight this uncertainty. All use water balance models combined with climate model scenarios for a doubling of CO_2. McCabe & Ayers (1989) estimated streamflow changes in the Delaware River Basin of -36 percent, -7 percent, and +4 percent, depending on the particular climate model used. Moore et al. (1997) calculated streamflow decreases of 21-31 percent for the Northeast United States. Najjar (1999) computed a 24±13 percent increase in flow at the mouth of the Susquehanna River. Yang et al. (1999), using a suite of regression-based models with doubled CO_2 scenarios, found similar results for the SRB. Increased precipitation variation will likely be reflected in increased streamflow variation, making the delivery of freshwater and nutrients much more variable in the future.

Other factors not accounted for here also may affect the amount of MAR streamflow in the future. Elevated CO_2 may decrease evapotranspiration on land, thereby increasing streamflow. For example, Wigley and Jones (1985) estimated that a doubling of CO_2 could increase streamflow as much as 20 percent for watersheds in which half of the precipitation runs off (recall that one third of MAR precipitation contributes to ground water and surface water flow and is available for human use). Increased urbanization will increase the fraction of land that is impervious, resulting in increased streamflow. In their comprehensive analysis of long-term streamflow variations in the United States, DeWalle et al. (1999) saw a significant urbanization signal, suggesting that future impacts of urbanization on streamflow are likely to be as large as climate change impacts. Moreover, these and other land cover changes resulting from urbanization (such as the removal of riparian vegetation or the storage of storm water in holding ponds) may increase stream temperatures. The combined uncertainty of the effects of precipitation, temperature, CO_2, and urbanization on streamflow makes projections extremely uncertain.

Similarly, recall that our groundwater model does not account for evapotranspiration. While this shortcoming does not affect the predictive power of the model when simulating historical groundwater levels in most of Pennsylvania, it is possible that as temperatures and CO_2 levels increase in the region, evapotranspiration could become an increasingly important determinant of groundwater levels in the region. Plants may respond to elevated CO_2 by reducing the transpiration of water vapor in leaf stomata, which could reduce the amount of groundwater uptake. Our projections suggest that groundwater levels will be affected by future climate change, even if we cannot pinpoint the exact effect.

Wetter future conditions have clearer implications for the potential impacts of climate change on water quality. Walker et al. (1999a & 1999b) show that increased precipitation could increase nutrient fluxes to the region's rivers, estuaries, and bays. Thus, reducing water quality problems in a wetter world will require policy changes to influence the human sources of the nutrients that affect the waters of the MAR, such as land-use and atmospheric deposition.

Although there are threats from non-point source pollutants with higher runoff, the prospect of additional water resources would appear to be attractive. For example, there could be fewer occurrences of drought watches, warnings, and emergencies. However, favorable situations may not always be the case. Four examples illustrate the management challenges that could come with additional water in the context of higher temperatures. First, dam managers would have to provide for low water levels in anticipation of a longer period of high runoff at the same time that demands for a high and stable water level for freshwater recreation could increase. Second, water and sewage treatment facilities are often located in floodplains. A greater frequency of high runoff events would require protection of these facilities to avoid harmful health impacts from their failure. Third, higher rates of groundwater recharge could lead to greater frequencies of groundwater surcharge in low-lying areas of karst landscapes, as well as to failure of septic disposal systems. Finally, even with greater flow in general, there would still be seasonal and episodic occurrence of low river-flow levels, most likely when temperatures tend to be highest in the summer and early fall. During these periods, peak power demands for air conditioning would require greater consumptive (evaporative) water loss in cooling towers or would stimulate greater evaporation from higher stream temperatures in energy-production systems that use once-through cooling. Either process — diminished flows or elevated stream temperatures — would negatively effect the ability of streams to dilute and process pollutants, thus exacerbating water pollution during low-flow periods.

In sum, this work suggests that most conceivable variations and changes in climate will influence the availability and quality of water in the MAR. Although present climate models may not be able to project future climate change with accuracy or certainty, it is clear that the region's water is sensitive to climate variation. The fact that the impacts of future climate change cannot be predicted accurately should not be construed to mean that nothing can or should be done about climate change impacts on water resources. Instead, considering the rather dramatic range of projections, climate change can and should be considered a significant risk to the MAR's water resources. The sensitivities demonstrated in this paper should be a clarion call for decision-makers to ensure a secure water supply in the face of a varying — and possibly changing — climate.

References

Alexander RB, Murdoch PS, and Smith RA (1996) Streamflow-induced variations in nitrate flux in tributaries to the Atlantic Coastal Zone. *Biogeochemistry* 33:149-177.

Alley W (1984) The Palmer Drought Severity Index: limitations and assumptions. *Journal of Climate and Applied Meteorology* 23:1100-1109.

Arnell, N. (1996) *Global Warming, River Flows and Water Resources*. John Wiley & Sons, New York.

Ayers, MA, Wolock DM, McCabe GJ, Hay LE, Tasker GD (1994) *Sensitivity of water resources in the Delaware River Basin to climate variability and change*. US Geological Survey Water-Supply Paper 2422, US Geological Survey, Reston, VA.

Bailey JF, Patterson JL, Haulhus JLH (1975) *Hurricane Agnes rainfall and floods, June-Jul*y 1972. Geological Survey Professional Paper 924, US Geological Survey and National Oceanic and Atmospheric Administration, Washington, DC.

Belval DL, Sprague LA (1999) *Monitoring Nutrients in the Major Rivers Draining to Chesapeake Bay*. USGS Water-Resources Investigations Report 99-4238, Reston, VA.

Bord RJ, O'Connor R., Yarnal B, Fisher A, Shudak R., Reenock C (1999) Factors Influencing Community Water System Managers' Perceived Vulnerability to System Disruption. Science into Policy: Water in the Public Realm, *Proceedings of the AWRA Summer Specialty Conference*, Bozeman, MT, June 30-July 2, 1999, American Water Resources Association.

Cook ER, Jacoby GC (1983) Potomac River streamflow since 1730 as reconstructed from tree rings. *Journal of Climate and Applied Meteorology* 22:1659-1672.

Cooper SR, Brush GS (1993) A 2,500-year history of anoxia and eutrophication in Chesapeake Bay. *Estuaries* 16:617-626.

Crane RG, Hewitson BC (1998) Doubled CO_2 precipitation changes for the Susquehanna basin: Down-scaling from the GENESIS general circulation model. *International Journal of Climatology* 18:65-76.

DeWalle DR, Swistock BR, Johnson TE, McGuire KJ (1999) Potential effects of urbanization on sensitivity of mean annual streamflow to climate change in the United States. *Water Resources Research* (submitted).

Dillman D (1978) *Mail and telephone surveys: The total design method*. John Wiley & Sons, New York.

District of Columbia (1998) *1998 Report to the Environmental Protection Agency and U.S. Congress Pursuant to Section 305(b) Clean Water Act (P.L. 97-117).* Environmental Health Administration, Government of the District of Columbia, Washington DC

Erickson TR and Stefan HG (1996) *Correlation of Oklahoma stream temperatures with air temperatures*. University of Minnesota, St. Anthony Falls Laboratory, Project report No. 398, Minneapolis, MN

Fisher A, Neff R, Barron EJ (2000) The Mid-Atlantic Regional Assessment: Motivation and approach. *Climate Research* 14:153-159.

Fisher DC, Oppenheimer M (1991) Atmospheric nitrogen deposition and the Chesapeake Bay Estuary. *AMBIO* 20:102-108.

Jenkins GS, Barron EJ (1997) Global climate model and coupled regional climate model simulations over the eastern US: GENESIS and RegCM2 simulations. *Global and Planetary Change* 15:3-32.

Jocoy, CL (2000) Who gets clean water? Aid allocation to small water systems in Pennsylvania. *Journal of American Water Resources Association* (in press).

Jordan TE, Correll DL, Weller DE (1997) Relating nutrient discharges from watersheds to land use and streamflow variability. *Water Resources Research* 33:2579-2590.

Langland, MJ, Hainly RA (1997) *Changes in bottom-surface elevations in three reservoirs on the lower Susquehanna River, Pennsylvania and Maryland, following the January 1996 flood-Implications for nutrient and sediment loads to Chesapeake Bay*. U.S. Geological Survey, Reston VA.

Lau KM, Kim JH, Sud Y (1996) Comparison of hydrologic processes in AMIP GCMs. *Bulletin of the American Meteorological Society* 77:2209-2227.

Lichtenwalner NL (1936) *Report of loss and damage: The March 1936 flood in Pennsylvania*. State Director for the National Emergency Council, Philadelphia, PA.

Lins HF, Stakhiv EZ (1998) Managing the nation's water in a changing climate. *Journal of the American Water Resources Association* 34:1255-1264.

Mattikalli NM (1996) Prediction of river discharge and surface water quality using an integrated geographical information system approach. *International Journal of Remote Sensing* 17:683-701.

McCabe GJ, Ayers MA (1989) Hydrologic effects of climate change in the Delaware River basin. *Water Resources Bulletin* 25:1231-1242.

Miller EW (1995) Water resources. In: Miller EW (ed) *A Geography of Pennsylvania*. The Pennsylvania State University Press, University Park, PA, p 56-66.

Mohseni O, Stefan HG (1999) Stream temperature/air temperature relationship: A physical interpretation. *Journal of Hydrology* 218:128-141.

Moore MV, Pace ML, Mather JR, Murdoch PS, Howarth RW, Folt CL, Chen CY, Hemond HF, Flebbe PA, and Driscoll CT (1997) Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic Region. *Hydrological Processes* 11:925-947.

Najjar, RG (1999) The water balance of the Susquehanna River Basin and its response to climate change. *Journal of Hydrology* 219:7-19.

Neff R, Yarnal B (2000) Projections of climate change impacts on Pennsylvania groundwater levels. *Journal of the American Water Resource Association* (in preparation).

O'Connor RE, Yarnal B, Neff R, Bord R, Wiefek N, Reenock C, Shudak R, Jocoy CL, Pascale P, Knight CG (1999) Weather and climate extremes, climate change, and planning: Views of Community Water Sytem managers in Pennsylvania's Susquehanna River Basin. *Journal of the American Water Resources Association* 35:1411-1419.

Pascale P (1997) *The Impacts of the Safe Drinking Water Act on Community Water Systems and Changes in Drought Vulnerability*. Master's Thesis, Pennsylvania State University, University Park, PA.

Pennsylvania Department of Environmental Resources (1991) *Water Systems and Drought Restrictions for the 1980 Drought*. Department of Environmental Resources, Harrisburg, PA.

Perrow C (1984) *Normal Accidents: Living with High-risk Technologies*. Basic Books, New York.

Schubel JR, Pritchard DW (1986) Responses of the upper Chesapeake Bay to variation in discharge of the Susquehana River. *Estuaries* 9:236-249.

Smith EE (1998) *An expert system approach to regional drought monitoring in Pennsylvania*.

Unpublished MS thesis, Department of Civil and Environmental Engineering, Pennsylvania State University, University Park, PA.

Solley WB, Pierce RR, Perlman HA (1998) *Estimated use of water in the US in 1995*. US Geological Survey Circular 1200, US Geological Survey, Washington, DC.

State of Delaware (1998) *1998 Watershed Assessment Report (305(b)).* Department of Natural Resources and Environmental Control, Dover DE.

State of Maryland (1998) *1998 Maryland Section 305(b) Water Quality Report*. Resource Assessment Service, Maryland Department of Natural Resources, Annapolis MD.

State of Pennsylvania (1998) *1998 Pennsylvania Water Quality Assessment*. Bureau of Watershed Conservation, Pennsylvania Department of Environmental Protection, Harrisburg, PA.

Steiner RC, Ehrlich NN, Boland JJ, Choudhury GS, Teitz W, McCusker S, Yamamoto A (1997) *Water resources management in the Potomac River Basin under climate uncertainty*. ICPRB Report 94-3, Interstate Commission on the Potomac River Basin, Rockville, MD.

U.S. EPA (1997) *An Ecological Assessment of the United states mid-Atlantic Region: A Landscape Atlas*. Jones KB, Ritters KH, Wickham JD, Tankersley RD, O'Neill RV, Challoud DJ, Smith ER, Neale AC (eds.) EPA/600/r-97/130. U.S. Environmetal Protection Agency, Office of Research and Development, Washington, DC.

U.S. EPA (1998) *Condition of the Mid-Atlantic Estuaries*, EPA 600-R-98-1 47, U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

U.S. EPA (1999) *Mid Atlantic Highlands: State of the Streams Report*, EPA/620/R-99/002. U.S. Environmental Protection Agency, Washington, DC.

USGS (1999). *The quality of our nation's waters-nutrients and pesticides*. U.S. Geological Survey Circular 1225, U.S. Geological Survey, Reston, VA.

Walker HA, Latimer JS, Dettmann, EH (1999a) Assessing the effects of natural and anthropogenic stressors in the Potomac Estuary: implications for long-term monitoring. *Environmental Monitoring and Assessment* (in press).

Walker HA, Najjar RG, Yarnal B (1999b). Historical changes in global scale circulation patterns, Mid-Atlantic climate, streamflow, and nutrient fluxes to Chesapeake Bay. *Climate Research* (in preparation).

Watson RT et al (1996) Technical summary: Impacts, adaptations, and mitigation options. In: Watson RT, Zinyowera MC, Moss RH, (eds) *Climate change 1995 — Impacts, adaptations and mitigation of climate change*. Cambridge University Press, New York, p. 19-53.

Webb BW, Phillips JM, Walling DE, Littlewood IG, Watts CD, Leeks GJL (1997) Load estimation methodologies for British rivers and their relevance to the LOIS RACS(R) programme. *The Science of the Total Environment* 194/195:379-389.

White DA, Richman M, Yarnal B (1991) Climate regionalization and rotation of principal components. *International Journal of Climatology* 11:1-25.

Wigley TML, Jones PD (1985) Influences of precipitation changes and direct CO_2 effects on streamflow. *Nature* 314:149-152.

Yang GW, Najjar RG, Evans BM, Shortle JS (1999) *Climate change effects on streamflow in the Susquehanna River Basin, Pennsylvania*. Unpublished manuscript, Department of Agricultural Economics and Rural Sociology, Pennsylvania State University, University Park, PA.

Yarnal B, Leathers, DJ (1988) Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate. *Annals of the Association of American Geographers* 78:624-641.

Yarnal B, Johnson DL, Frakes B, Bowles GI, Pascale P (1997) The flood of ‘96 in the Susquehanna River Basin. *Journal of the American Water Resources Association* 33:1299-1312.

Yarnal B, Frakes B, Bowles I, Johnson D, Pascale P (1999) Severe convective storms, flash floods, and global warming in Pennsylvania. *Weather* 54:19-25.

Zynjuk LD, Majedi BF (1996) *January 1996 floods deliver large loads of nutrients and sediment to the Chesapeake Bay*: U.S. Geological Survey Fact Sheet 140-96, U.S. Geological Survey, Reston, VA.

Box 6.1. Potential Effects of Climate Change on Recreational Fishing in the Mid-Atlantic Region

Introduction

Global climate change is unique among environmental stressors on ecological systems because it represents changes in one of the fundamental forces controlling the distribution of life forms on earth - energy. Previous and current stressors, even those with large scale effects such as acidic deposition or organic and heavy metal contamination, affect selected subsets of species and ecosystems. Climate change, or the change in the distribution of heat energy, affects processes from the molecular level (i.e, chemical reaction rates) to the global scale (patterns in water distribution, vegetative land cover and human land use). It is these larger scale effects rather than local or site specific effects that are of greater concern.

Potential large scale effects on the Mid-Atlantic Region stream ecosystems will be assessed by analyzing current and potential changes in the distribution of trout populations in the Mid-Atlantic Highlands. Prior to addressing potential changes in the regional trout fisheries, the current status and extent of regional fisheries is benchmarked.

Regional population estimates

To determine the current status and extent of the Highland stream trout fisheries, information on stream quality was obtained from the US Environmental Protection Agency Environmental Monitoring and Assessment Program (EMAP) Mid-Atlantic Highlands stream monitoring program. About 360 stream reaches, selected as probability samples using the EMAP sample survey design (Paulsen et al. 1996, Stevens 1998), were sampled once during the 1993–1994 spring season. Stream attributes were measured on riparian and instream habitat, chemistry, fish, benthos, periphyton, and stream metabolism for Highland streams. The location of these Highland sites is shown in Figure B4.1. All of the EMAP streams sampled in the Mid-Atlantic Highlands were first through third Strahler order streams (Strahler 1964) so very few streams were gaged. These sites represent over 110,000 stream km in the Highlands or about 90% of the total stream kilometers in the Highlands based on a 1:100,000 scale map. Most of the streams were located in Pennsylvania and West Virginia. In addition to stream measurements, general watershed characteristics (e.g., area, slope, land use/land cover, disturbance, etc.) for the watershed upstream from the corresponding stream reach were determined for each stream segment sampled. Forest land cover dominated the stream watersheds throughout the Highlands with 95% of first order streams, 80% of second order streams, and 75% of third order stream watersheds forested. Agriculture represented 2% of the land use in first order stream watersheds and 20% of the land use in second and third order stream watersheds, respectively, throughout the Highlands.

Additional information on the Mid-Atlantic Highland and the Mid-Atlantic Integrated Assessment (MAIA) Programs can be obtained by visiting the MAIA web site, http://www.epa.gov/owowwtr1/ecoplaces/part1/site15.html and the EMAP site, http://www.epa.gov/emap/

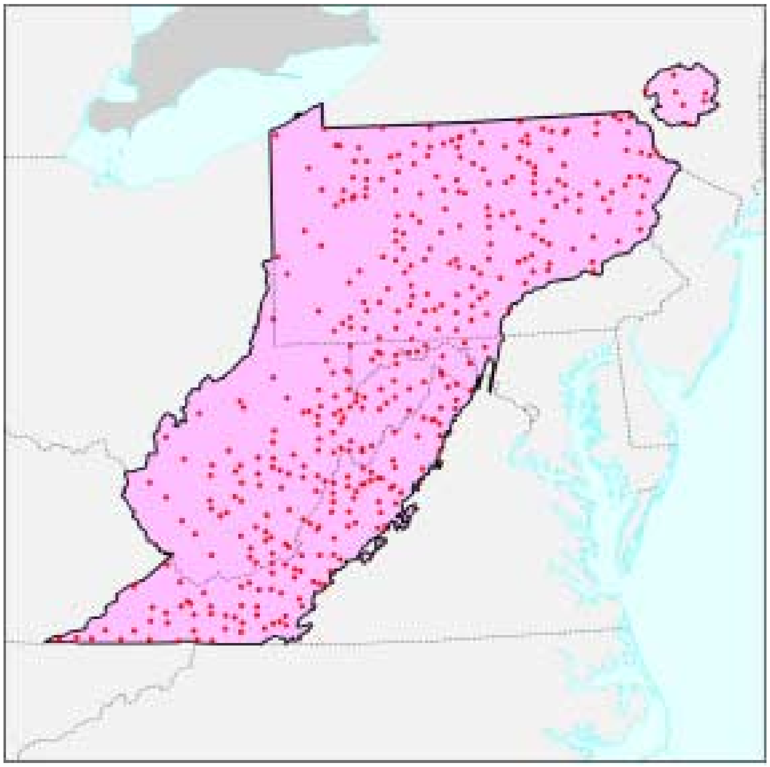


Figure B6.1.1. *Location of Highland stream trout fisheries in this assessment*.

Trout populations - current status

While many fisheries management agencies emphasize the importance of third order and higher streams for sportfishing, first and second order streams also are important in maintaining and sustaining these fisheries. In the Mid-Atlantic Highlands, almost 75% of the first order stream miles contained fish and over 25% of the first order streams had gamefish (Figure B4.2). Over 90% of the second order stream miles had fish and 66% of all the second order stream miles had game fish. Over 90% of the third order stream miles had gamefish and less than 2% of third order streams had no fish. First and second order streams are important for sustaining fisheries within the Highlands so even small watersheds with lower order streams can play a significant role in sustaining higher order stream fisheries.

Three trout species were considered in this evaluation - brook trout (Salvelinus fontinalis), brown trout (Salmo Trutta) and rainbow trout (Salmo gairdneri).

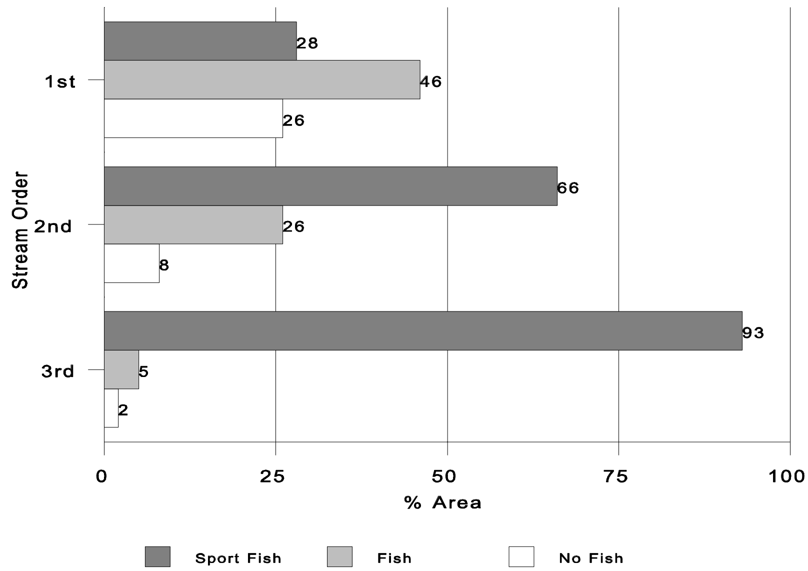


Figure B6.1.2. *Percent of streams containing fish.*

The Mid-Atlantic Highlands have some of the finest trout fishing in the continental US. Brook trout are native to the Mid-Atlantic Highlands but the brown and rainbow trout are non-native species managed as sport fisheries.

The rainbow trout is native to the western US and Alaska, but not the eastern US. The brown trout is not native to North America; it is a native of Europe and western Asia.

Brook trout were found in about 14% of the stream kilometers in the Highland Region while brown and rainbow trout were found in about 10 and 2%, of the stream kilometers, respectively, in Highland streams. Brook and brown trout were found predominately in the smaller first and second order streams while rainbow trout were found primarily in second and third order streams. These trout species were found most frequently in the North-Central and Central Appalachian ecoregion followed by the Ridge and Blue Ridge ecoregion. These ecoregions are described by Omernik (1995). The Valley and Western Appalachian ecoregions, with warmer, slower moving streams contained few cold-water trout species.

In general, the brown and rainbow trout compete with the brook trout for food and habitat and prey on the brook trout. Brook trout prefer cold, clear small streams and have a *relatively narrow temperature tolerance, preferring temperatures of 68°F (20°C) or lower. The brook trout is native to the Appalachian Mountains, but the Highland region represents the southern margin of its distribution in North America (Bivens et al. 1985, Meisner 1990). Summer temperatures restrict brook trout in the Appalachian region to cold waters found at higher elevations, which are found in the headwater or first order streams of watersheds (Bivens et. al. 1985, Meisner et al. 1988). This is consistent with the observed distribution of brook trout in Mid-Atlantic Highland streams noted above. Brown trout also prefer cooler water, but have a greater temperature tolerance than brook trout. Only the rainbow trout exceeds the brown trout in temperature tolerance. The rainbow trout has the greatest temperature tolerance of nearly any trout species, tolerating a temperature range from 32 to 82.9 (0-28.3°C) (Becker 1983). The distribution of these species in the Mid-Atlantic Highland streams and ecoregions is consistent with the temperature and habitat tolerances of these species. The smaller first order streams are found primarily in watersheds with steep slopes, forested land cover, and cold to cool temperatures in the Highland region. The second order streams have a greater proportion of agricultural land use, shallower slopes, and slightly warmer temperatures. Because of the narrower temperature tolerances of the brook trout, it has been a target species to illustrate the potential effects of climate change on coldwater fishes (Meisner 1990, Meisner et.al. 1988, Reis and Perry 1995).*

Other stressors in the two Highland ecoregions in which trout are prevalent include alteration of riparian and instream habitat, acidic deposition and mine drainage, and nitrogen enrichment (EPA 1999). The Ridge and Blue Ridge ecoregion, in general, has the highest quality streams in the Highlands. This ecoregion is heavily forested, with low population density and limited agriculture. Nitrogen enrichment, however, appears to be increasing in this ecoregion as well as recreational use (e.g., hiking, camping). Over 30% of the stream miles in the North-Central and Central Appalachian ecoregion have altered riparian habitat. In addition, stream channel sedimentation, acid rain, mine drainage, nitrogen enrichment, and mercury contamination of fish are in ranges of concern in this ecoregion (EPA 1999). Over 20% of the stream miles are affected by acid rain and mine drainage. Acidic deposition effects occur primarily in the first and second order streams, further reducing potential habitat for brook trout.

Possible future changes and impacts of climate change on mid-atlantic highland trout populations

Climate change directly affects the energy budget of streams resulting in changes in stream temperatures. Possible climate change scenarios for the Mid-Atlantic Highland region indicate there might be an increase in air temperature of about 1.8°F (1°C) by 2030 and 4.5°F (2.5°C) by 2100. In addition, increased precipitation of about 0.2 inch (0.6 cm)per month and 10 inch (2.5 cm) per month might be anticipated by 2030 and 2100, respectively.

These air temperature increases represent the annual increase in average temperatures are for the region, not the seasonal or daily increases, which will likely be larger. For example, Meisner et. al. (1988) indicate that the mean annual temperature range at latitude 40°N is about 70°F (21°C) around a mean annual air temperature of about 67°F (17°C). Mesiner et. al. (1988) investigated the relation of air temperature to groundwater temperature and its role in affecting the survival and distribution of stream salmonines. Average annual changes in temperature of 4.5°F (2.5°C) could easily translate into increases in the temperature range of 7.9 to 9°F (4 to 5°C). The brook trout is currently near the edge of its range because of temperature constraints and is less tolerant to increased temperature ranges than either the brown or rainbow trout. Under ideal conditions, maximum brook trout growth rates are reported at temperatures between 55 (13) and 61° F (16°C) (Baldwin 1956, McCormick et. al. 1972) with mortality increasing at 64°F (18°C) and above (Peterson et al. 1979). Increasing stream temperatures by 4 (2) to 7°F (4°C) could increase the mortality rate for brook trout and increase the competitive advantage of both brown and rainbow trout over brook trout.

Direct influences of temperature on coldwater species are obvious, but there are other, less direct, effects of climate change and altered energy budget on stream ecosystems and fish populations. Dissolved oxygen (DO) concentrations are inversely proportional to water temperature; the higher the temperature, the lower the solubility and concentration of dissolved oxygen in water. DO concentrations in the stream gravels are critical during egg and larval fish development incubation period. All three trout species deposit their eggs in gravel where interstitial DO concentrations have a significant influence on egg survival and development (Sowden and Power 1985). Decreased DO concentrations with increased temperature can affect trout populations by decreasing egg survival. Increased temperatures will also affect microbial respiration and decomposition rates. Increased microbial decomposition of organic matter will increase stream oxygen demand and can lead to pockets of anoxia in stream sediments. Increased precipitation would be expected to increase both organic and nutrient loads to the stream ecosystems, which provides additional substrate for microbial decomposition and stream oxygen demand, but also increased stream production. However, respiration tends to increase faster than production with increased temperatures (Busch and Fisher 1981). The type, size, composition, and quantity of organic matter plays a significant role in structuring the stream biological community (Wallace et. al. 1997). Changes in the composition and quantity of leaf litter and woody debris to streams will also change the composition of the benthic community and trophic structure in the stream (Carpenter et. al. 1992; Wallace et. al. 1997). Subtle changes in the benthic community can also affect the stream fisheries.

Stream communities have evolved and adapted to the stream flow regime. Trout spawning periods, insect emergence, and other biotic processes are triggered both by stream flow and *stream temperature. Altering this flow regime would be expected to affect the stream ecosystem and fisheries.*

Regier and Meisner (1990) argued that fish populations should follow changes in stream flow (one measure of fish habitat space). The projected drier summers are likely to reduce stream flow and lake levels in the mid-latitudes, which will cause a reduction in trout habitat. Therefore, a reduction of stream flow from a change in precipitation patterns will hurt the brook trout population. In fact, Meisner (1990) concluded that southern areas in Pennsylvania, New York, and states northeast of Long Island, New York could become too warm to support any brook trout.

However, not all fish species will be hurt by decreases in stream flow. In a thesis examining the factors affecting the survival of young-of-the-year smallmouth bass, McCosh (1993) suggest that instream habitat features, such as stream flow, affect the population and distribution of smallmouth bass. Looking specifically at the Susquehanna River, McCosh concluded that low flows actually benefit smallmouth bass populations while above normal stream flows produced the weakest year classes of smallmouth bass. Currently, smallmouth bass were found in about 6% of the stream kilometers in the Mid-Atlantic Highlands, primarily in third order streams. The two predominant ecoregions for smallmouth bass streams were the North-Central and Central Appalachian and the Valley ecoregions.

Management/adaptation options

The brown and rainbow trout populations currently are, and will continue to be, managed fisheries. There are reproducing populations of brown and rainbow trout in some of the Highland streams, but put-and-take fisheries can be established on streams where climate change might eliminate the reproducing populations. The brook trout populations, however, are currently near the edge of their temperature range, have been eliminated from some of their previous habitat by brown and rainbow trout populations, are sensitive to both instream and riparian habitat alterations, and are the least tolerant of the three trout species to temperature fluctuations. Brook trout might be lost from many of the Highland streams with the temperature increases projected through climate change scenarios. Remnant populations are likely to continue to exist, but these remnant populations will likely be genetically isolated from the current gene pool.

Riparian and instream habitat restoration in upper reaches of some watersheds could help maintain brook trout habitat, but two factors could offset the effectiveness of this management option. First, increased temperatures will likely continue to favor brown trout, which are likely to migrate into these improved habitats and continue to compete with the brook trout population. Second, recent evidence indicates that past land use, particularly agricultural *land use, continues to have a present day influence on stream invertebrates and fish (Harding et. al. 1998). Past land use can result in long-term modification to the stream habitat that is not restored with reforestation of the riparian habitat. Instream sedimentation and loss of gravel spawning areas are difficult to restore, regardless of the restoration of the terrestrial watershed to more forested land cover. Poor forest management practices that resulted in significant instream sedimentation of headwater streams also might not provide suitable habitat for reproducing trout populations even with reforestation.*

Other management alternatives for stream fisheries are to consider moving toward more cool water species such as smallmouth bass instead of cold water species. Smallmouth bass also are managed fisheries throughout the Highland area. These, and similar game fish, species would provide opportunities for recreational fishing, similar to trout fishing. Habitat restoration would also benefit these species.

Recreational anglers, along with participants in most other recreational water activities, will be affected by global climate change because of the effects it has on freshwater resources. Waters where anglers fish are likely to be altered by changes in the three linkages described earlier. Some fish habitats will expand while others will contract. If fishermen have preferences for different species, then their welfare may be affected as a result of expansion or contraction of habitat for their preferred species.

The Michaels et al. research (1995) on anglers' welfare uses an economic model that estimates changes in fishing days for each type of fishing habitat, multiplied by a value per fishing day (for each type of fish). The value of the loss of fishing depends on the general circulation models (GCMs) because each GCM gives different estimates of temperature changes. In general, the results show that cold-water habitat will decrease causing economic damages to recreational fishing while warm and rough fish habitat will increase, leading to economic benefits.

Remaining uncertainties affecting trout populations

Fish species represent a logical target species for considering climate change impacts on Mid-Atlantic stream ecosystems. Fish are at the top of the food web, are valued by the public, provide recreational opportunities, and are integrators of stream quality. However, fish are part of an intricate stream ecosystem. Some of the factors influencing decisions that remain uncertain are:

1. *The ecosystem responses to climate change on a regional basis are not well understood. Subtle changes in the organic inputs to the stream, small changes in interstitial DO concentrations in stream gravel beds, altered stream*

metabolism as a function of temperature will all affect the stream ecosystem and its responses.

2. *Information on the ecological interactions within stream systems are not well understood, particularly the cumulative impacts of multiple stressors and the cascading effects of these changes from headwater streams to higher order streams.*

3. *Decisions are required on the value of endemic species versus introduced species, sustainable versus replacement management practices, and the importance of habitat restoration as a management and policy option for protection and management of stream ecosystems before specific management and policy alternatives can be formulated.*

4. *Better understanding of the watershed-stream interactions and the stream continuum interactions are needed to be able to evaluate the feasibility of any specific management and policy options for adapting to climate change.*

5. *Consideration might be given to substitution of space for time. Is it likely the change in the precipitation and temperature regime will result in the Mid-Atlantic Highland region becoming more like the Southern Appalachian region in NC, TN, and GA? If so, it might be possible to use the Southern Appalachians as a surrogate for the changes anticipated in the Mid-Atlantic region in 2100.*

References

Baldwin NS (1956) Food consumption and growth of brook trout at different temperatures. *Trans. Am. Fish. Soc*. 68:323–328.

Bivens RD, Strange RJ, and Peterson DC (1985) Current distribution of the native brook trout in the Appalachian region of Tennessee. *J. Tenn. Acad. Sci*. 60:101–105.

Busch DE and Fisher SG (1981) Metabolism of a desert stream. *Freshwat. Biol*. 11:301–7.

Carpenter SR, Fisher SG, Grimm NB, and Kitchell JF (1992) Global change and freshwater ecosystems. *Ann. Rev. Ecol. Syst*. 23:119–39.

EPA. (1999) Mid-Atlantic Highlands. State of the Streams Draft Report. Office of Research and Development, US Environmental Protection Agency, Washington, DC.

Harding JS, Benfield EF, Bolstad PV, Heffman GS, and James III, EBD (1998) Stream biodiversity: the ghost of land use past. *Proc. Nat. Acad. Sci*. 95:14843–14847.

McCormick JH, Hokanson KEF, and Jones BR (1972) Effects of temperature on growth and survival of young brook trout, Salvelinus fontinalis. *J. Fish. Res. Bd. Can*. 29:1107–1112.

McCosh ML (1993) Abiotic Factors Affecting Survival of Young-of-the-Year Smallmouth Bass. State College: The Pennsylvania State University. Thesis. 1–40.

Meisner JD (1990) Effect of climate warming on the southern margins of the native range of brook trout, Salvelinus fontinalis. *Can. J. Fish. Aquat. Sci*. 47:1065–1070.

Meisner JD, Rosenfeld JS, and Regier HA (1988) The role of groundwater in the impact of climate warming on stream salmonines. *Fisheries*. 13:2–8.

Michaels G, O'Neal K, Humphrey J, Bell K, Camacho R, and Funk R (1995) Ecological Impacts from Climate Change: An economic analysis of freshwater recreational fishing. A report for the US EPA, EPA 230-R-95-004, by ABT Associates Inc.

Omernik JM (1995) Ecoregions: A spatial framework for environmental management. In Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Davis W. and T. Simon (eds). Lewis Publishers. Boca Raton, FL. pp. 49–62.

Peterson, R.H., A.M. Sutterlin, and J.L. Metcalf. 1979. Temperature preference of several species of Salmo and Salvelinus and some of their hybrids. *J. Fish. Res. Bd. Can*. 36:1137–1140.

Regier HA, and Meisner JD (1990) Anticipated Effects of Climate Change on Freshwater Fishes and their Habitat. *Fisheries*. 15(6):10–15.

Ries, R.D. and S.A. Perry. 1995. Potential effects of global climate warming on brook trout growth and prey consumption in central Appalachian streams, USA. Clim. Res. 5:197–206.

Sowden TK and Power G (1985) Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. *Trans. Amer. Fish. Soc*. 114:804–812.

Strahler AN (1964) Geology - Part II. Handbook of Applied Hydrology. V.T. Chow (ed.) McGraw-Hill Book Company, NY.

Wallace JB, Eggert SL, Meyer JL, and Webster JB (1997). Multiple trophic levels of a forest stream linked to terrestrial litter inputs. *Science* 277:102-104.

Chapter 7. Coastal Zones*

Introduction

Impacts of climate change on coastal areas can be expected to have a regional signature that depends on the local climate change and the local geomorphological, biogeochemical, ecological and social factors that affect the sensitivity to climate. Here we present an assessment of the potential impacts of climate change on one of the most populated and ecologically important areas of the United States, the mid-Atlantic coastal (MAC) region, as part of a "National Assessment" process mandated by the US Global Change Research Program (Fisher et al. 2000). For this assessment, the MAC region extends from central New Jersey (near Toms River) to central North Carolina (near Cape Lookout), and includes several large estuaries: Delaware Bay, Chesapeake Bay and Albemarle-Pamlico Sound (see Chapter 2 for a map of the region).

Our assessment is based partly on output from coupled ocean-atmosphere models developed at the Hadley Centre for Climate Prediction and Research and the Canadian Climate Centre (CCC) (presented in Chapter 3). These models were run in a transient mode from the middle of the 19th century to the end of the 21st century with gradual increases in greenhouse gases (1% per year carbon dioxide (CO_2) equivalent) and sulfate aerosols (the "IS92a" scenario, Houghton et al. 1996). For more details on the models, see Johns et al. (1997), Mitchell et al. (1995), Mitchell and Johns (1997), Boer et al. (1984, 1992, 2000a, b), Flato et al. (2000) and McFarlane et al. (1992). Following National Assessment guidelines, we base our assessment on output from these models averaged over 10 year periods centered on 2030 and 2095, referenced to the climate of the 10 year period centered on 1990, except where noted.

This chapter summarizes how climate change is likely to affect the physical environment in the MAC region. We consider how sea level will change, as well as changes in atmospheric CO_2, temperature, precipitation and streamflow. Then we discuss the results from our assessment of possible ecological and societal responses to such changes. We conclude by identifying priorities for climate-change research in the MAC region.

Climate-related Changes in the Physical State of the MAC Region

Table 7.1 presents a summary of the predicted climate-related changes in the MAC region for 2030 and 2095. Included are predictions for atmospheric CO_2, sea level, temperature,

---

* This chapter is based on Najjar et al., (2000) "The potential impacts of climate change on the mid-Atlantic coastal region" *Climate Research*, 14:2. It appears with permission of Inter-Research.

precipitation and streamflow. Also included is our subjective assessment of the reliability of each mean prediction, based on our understanding of the limitations of the models used to make the predictions. Some important climate-related changes are not included in Table 7.1 because they are very poorly known. Extreme weather events, such as hurricanes and Nor'easters, both of which may cause severe flooding, are good examples.

Atmospheric CO_2 Concentration

Of the possible global changes in the physical environment of coastal regions, a rise in atmospheric CO_2 is the most likely (Table 7.1). Though there is active debate about the necessity and feasibility of reducing CO_2 emissions, the long lifetime of CO_2 in the atmosphere means that CO_2 levels will likely rise even in the face of the most stringent emission reductions (Houghton et al. 1996). The best estimate is that atmospheric CO_2 concentration will be approximately double its 1990 value by 2095. CO_2 is rarely discussed as a direct effect on coastal waters but, as we show below, it may affect wetlands.

Table 7.1. **MAC region climate projections for 2030 and 2095 with respect to 1990.**

Parameter		2030 mean	(range)	2095 mean	(range)	Reliability of mean prediction
CO_2	(%)[1]	+25	(+20 to +30)	+92	(+52 to +118)	Very high
	(ppm)	+90	(+70 to +105)	+325	(+185 to +420)	
Sea level[2]	(in)	+7.5	(+4.3 to +12.2)	+26.0	(+20.5 to +40.2)	High
	(cm)	+19	(+11 to +31)	+66	(+39 to +102)	
Temperature[3]	(˚F)	+2.3	(+1.8 to +2.7)	+72	(+4.9 to +9.5)	High
	(˚C)	+1.0	(+0.7 to +1.4)	+3.8	(+2.3 to +5.2)	
Precipitation	(%)[c]	+ 4	(-1 to +8)	+15	(-6 to + 24)	Medium
Streamflow[4]	(%)[1]	+2	(-2 to +6)	+11	(-4 to +27)	Low

[1]Mean reflects IS92a and range reflects IS92d and IS92f CO_2 emission scenarios; see Fig. 5b from technical summary of Houghton et al. (1996). 1990 CO_2 concentration was 355 ppm.
[2]Low, middle and high projections of Warrick et al. (1996) for IS92a scenario with varying aerosols (see their Fig. 7.7), plus a local component of 0.08 inch per year (2 mm yr^{-1}).
[3]Range is given by Hadley Centre and Canadian Climate Centre (CCC) models for the mid-Atlantic region (Polsky et al., 2000). Mean is average of two models. Changes are with respect to 1983-1994 model output.
[4]For the Susquehanna River Basin, using a water balance model forced with the CCC and Hadley output (see Chapter 6).

Sea-Level Rise and Coastal Flooding

Sea-level variations on time scales of a decade or more have two components: a global component that reflects thermal expansion of the ocean, decreases in surface water and groundwater storage, and glacial melting (eustatic sea-level rise (SLR)); and a local component that reflects vertical land movements (resulting, for example, from regional tectonics, post-glacial isostatic adjustment, compaction and surface subsidence). The sum of the two components is known as relative sea-level rise (RSLR), which, over the past 100 years, has been measured mainly from tide gauges. By avoiding regions of significant tectonic SLR impacts and by accounting for post-glacial isostatic adjustment, Douglas (1991) estimated a global eustatic sea-level rise of 0.071 $\pm$ 0.003 inch per year(1.8 $\pm$ 0.1 mm yr^{-1}) between 1880 and 1980. By considering other studies, Warrick et al. (1996) gave a range of 0.039 to 0.098 inch per year (1.0 to 2.5 mm yr^{-1}) for eustatic sea-level rise over the past century. In the mid-Atlantic region, RSLR is between 0.12 to 0.16 inch per year (3 and 4 mm yr^{-1}) (Titus and Narayanan, 1995), suggesting a local component of RSLR of about 0.08 in per year (2 mm yr^{-1}), which may be due to variations in the accumulations of Holocene sediments and their subsequent compaction (Psuty 1992; Nicholls and Leatherman 1996), regional differential crustal warping (Walker and Coleman 1987) and possibly removal of groundwater by humans (Leatherman et al. 1995). Kearney and Stevenson (1991) noted that around Chesapeake Bay, rapid RSLR during the 19th Century contrasts with slower RSLR during the 17th and 18th Centuries, a period of cooler global conditions. They also note that 19th-Century global warming and eustasy are insufficient to account for the magnitude of the recent acceleration in RSLR around Chesapeake Bay. The effects of groundwater withdrawals and recent alterations in sediment loading need to be evaluated to fully understand local changes (Kearney and Stevenson 1991).

The rate of eustatic sea-level rise is likely to increase in the future because of CO_2-induced warming, which will cause expansion of the ocean and possibly glacial melting. The best estimate of Warrick et al. (1996) is that, by 2030 and 2095, global sea level will be about 4.3 and 18 inches (11 and 45 cm) higher, respectively, than in 1990. Adding in a local RSLR of 0.8 inch per year (2 mm yr^{-1}), these figures increase to 7.5 and 26.0 inches (19 and 66 cm), respectively, for MAC waters (Table 7.1). For the MAC region, therefore, global climate change, as opposed to local effects, is predicted to account for about 60% and 70% of the sea-level change from 1990 to 2030 and 2095, respectively.

How much land will be lost as a result of sea-level rise in the MAC region? We are using digital elevation models (DEMs) to assess this; here we present the results for Delaware. A simple inundation model was used in which all land with an elevation less than 2 feet (ft) (61 cm) is assumed to be flooded.[1] We acquired DEMs in 7.5-minute maps with a horizontal resolution of 100 feet (30 m) from the United States Geological Survey [USGS, detailed information on the data set is available from USGS (1999a)]. We estimate that 22,000 acres (91 km^2) would be inundated, or about 1.6% of the total land area of the Delaware (Figure 7.1). However, this is

Figure 7.1 Inunation of the shoreline of Delaware due to a rise in sea level of 2 feet (61 cm). See text for details of calcuation.

[1] The DEM data used for this analysis give elevation in integral feet above the National Geodetic Vertical Datum of 1929. A value of 1 foot, for example, is assumed to represent land between 0.5 and 1.5 feet above mean sea level. For the calculation, we chose a sea-level rise of 2 feet (61 cm), which is the value closest to 26 inches (66 cm), the projected rise for 2095.

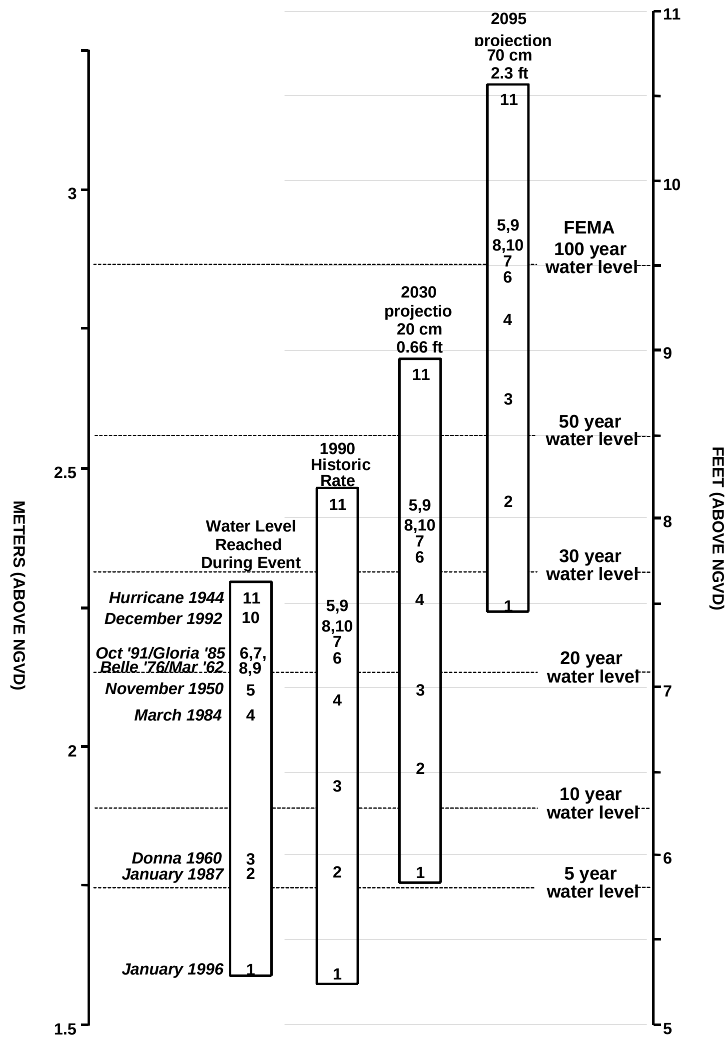


Figure 7.2. Impact of sea-level rise on storm-surge-level recurrence intervals at Atlantic City, New Jersey.

Recurrence-interval values (horizontal lines) are current Federal Emergency Management Agency (FEMA) determinations for Atlantic City. The vertical axis is height above the fixed elevation known as the National Geodetic Vertical Datum (NGVD). The first column on the left is the storm-surge level achieved during the specific event. Each event has a corresponding number repeated in the remaining columns. The second column shows the flood levels these storms would have produced had they occurred in 1990, using a sea-level rise of 0.15 inches per year (3.85 mm yr^{-1}). The third and fourth columns show the expected flood level of these storms given a sea-level increase of 8 inches (20 cm) and 26 inches (70 cm), the best estimates for 2030 and 2095, respectively.

only a rough estimation. On the one hand, two factors make this calculation an underestimate. First, the DEMs are derived by digitizing topographic maps with coarse contour intervals, normally around 10 feet (3 m), using linear interpolation to fill in values between contour lines. Because shorelines in the MAC region are typically concave-up (i.e., the slope increases in the inland direction), the DEMs underestimate the amount of low-lying land nearshore. Second, we have completely ignored erosion at the shoreface, which will increase the amount of inundation (Bruun 1988). On the other hand, there are factors that could lead to over estimation, such as the delivery of sediment from rivers, organic matter accumulation in the root zone of marshes, and shoreline protection schemes. These are discussed in later sections. Storm-surge levels will be affected by sea-level rise, even if the frequency and intensity of storms do not change. To illustrate this, past storm events in Atlantic City, NJ are adjusted to the 1990 sea level and projected to 2030 and 2095 (Figure 7.2). Consider the 1962 storm, which had probability slightly greater than 1-in-20 years. If that storm occurred in 1990, its flood level would be 4.3 inches (11 cm) higher, assuming a 0.15 inch per year (3.85 mm yr^{-1}) rate of sea-level rise, the average over the past 85 years (Psuty and Collins, 1996). Such a flood currently has nearly a 1-in-30 year probability. If the storm were to occur in 2030, when sea level is expected to be about 8 inches (20 cm) higher than in 1990, it would produce a flood considered to have a 1-in-40 years probability. For 2095, when sea level is expected to be about 26 inches (70 cm) higher than in 1990, it would produce a flood currently considered to have a 1-in-120 years probability. These calculations suggest that coastal flooding due to storms will be much more severe by the end of the 21st Century than it is today, though the severity of the flooding also will depend on the local geomorphological characteristics and the degree of human alteration of the coast.

Temperature

Chapter 2 summarizs MAR temperature and precipitation trends for the past 100 years. Chapter 3 summarizes the model projections for the next 100 years, which are the basis for MAC scenarios. Over the last century the MAR has experienced an upward temperature trends of nearly 1 degree Fahrenheit.

The prediction of rising air temperature in the MAC region is less certain than the sea-level rise prediction because regional responses of climate are harder to predict and the cooling impact of aerosols may offset the CO_2-induced warming. This cooling impact is likely to be significant in the mid-Atlantic region because of its high industrial activity (Taylor and Penner 1994), though the implementation of new environmental regulations would reduce the impact. Uncertainties are reflected in the range of the predictions of the two climate models used for the National Assessment (Table 7.1; see also Chapter 3).

How will MAC water temperatures respond? Using data from the Chesapeake Bay Program, we computed monthly mean temperature from 1949 to 1994 in 23 regions of the main-stem

Chesapeake Bay, using techniques described by Gibson and Najjar (2000). We found Bay temperature to be highly correlated (r^2 from 0.68 to 0.93) with the estimation of mean surface air temperature over the Susquehanna River Basin (Najjar 1999). The slopes of the linear fits vary from 0.99 in shallow waters to 0.68 in deep waters, showing that water temperatures in Chesapeake Bay, and probably in most estuaries and coastal bays in the region, closely track air temperature. This suggests that the warming of surface air masses in the northeastern US will be tracked by near-shore MAC waters. During the summer, water temperatures in shallow areas may increase less than air temperatures as a result of evaporative cooling. In deeper, less-restricted MAC waters, the temperature change is likely to be smaller because of the greater volume to be heated and the larger influence of ocean circulation and mixing (Williams and Godshall 1977).

Precipitation

Chapter 2 showed that precipitatio has increased about 10 percent over the last century. As described in Chapter 3 and summarized in Table 7.1, the two National Assessment models predict increases in mean precipitation over the northeastern US by 2095. Such predictions are supported by other climate model studies in the mid-Atlantic (Hodny 1992; Crane and Hewitson 1998; Najjar 1999). Estimates of the magnitude and seasonal timing of the precipitation increase vary considerably among models, suggesting significant uncertainty in these predictions. The combined effect of higher sea level and more precipitation would very likely result in greater coastal flooding.

Streamflow

Figure 6.3 (p. 127) shows considerable inter annual variability in streamflow in the Mid-Atlantic Region, but no clear long-term trend. Similarly, Najjar (1999) found no long-term trend in the Susquehanna River flow for the 20th century. Streamflow into coastal waters is an extremely important driver of variability in the physical, chemical and biological characteristics of mid-Atlantic estuaries. Streamflow at the outlet of a watershed will respond to the meteorological conditions of the watershed, such as air temperature and precipitation. Streamflow increases with greater precipitation for obvious reasons and decreases with higher temperature because of higher rates of evapotranspiration. Chapter 6 shows that very different changes in streamflow are predicted by a water balance model when forced by the output of the two National Assessment climate models; this is because of the counteracting effects of increasing temperature and precipitation (Table 7.1). Three published studies on the response of mid-Atlantic streamflow to a doubling of atmospheric CO_2 reinforce this uncertainty (McCabe and Ayers 1989; Moore et al. 1997; Najjar 1999). In the future, other factors may also affect the amount of streamflow into coastal waters. Elevated CO_2 may decrease evapotranspiration on land, thereby increasing streamflow (Wigley and Jones, 1985). Increased urbanization will increase the fraction of land that is impervious to water infiltration, resulting in increased runoff and streamflow (DeWalle et al., 2000). The combined uncertainty of the effects of precipitation, temperature, CO_2, and urbanization on streamflow makes prediction extremely uncertain.

Ecological Responses

We now address the response of MAC ecosystems to climate. Our discussion is structured to move "downstream," from coastal wetlands to coastal bays and estuaries, as well as "up the food chain," from plankton and submerged aquatic vegetation to fish, shellfish and birds.

Coastal Wetlands

Coastal wetlands include wetland forests, salt-water marshes and fresh-water marshes. These wetlands serve several important functions: wildlife habitats; spawning grounds; filtration systems for excess nutrients (from agricultural runoff and acid rain), heavy metals, and organic toxic substances (e.g., pesticides); and recreational open space. Sea-level rise is likely to cause the most important climate-related impacts on coastal wetlands. To evaluate the potential for these impacts, we return to the Delaware case study (Figure 7.1). To characterize land use, we use maps from the Multi-Resolution Land Characteristics (MRLC) Consortium, which are based on Landsat Thematic Mapper data (USGS, 1999b). The data are available at the same resolution as the DEMs described earlier and are based on the land use characteristics of 1993. We find that most of the affected area is wetlands—95% marsh and 1% forest—and estimate that 21% of all marsh land in Delaware is at risk of being permanently flooded. However, this potential risk of wetland loss is moderated if wetlands can migrate horizontally and accrete vertically.

The potential for future horizontal migration inland by wetland plant species is limited primarily by human barriers, such as urban and suburban development and the construction of seawalls and bulkheads. The area ajacent to the area at the risk of flooding from sea level is largely undeveloped, suggesting that future horizontal migration may be possible in Delaware if urbanization is controlled. However, direct anthropogenic modifications, including causeway construction, which alters tidal flushing, and creation and maintenance of mosquito ditches, can alter salt marsh vegetation patterns and processes (Niering and Warren 1980).

Wetlands can accrete vertically, depending on the availability of sediment and the rate of organic matter accumulation within the root zone, potentially reducing the flooding effect of sea-level rise. The amount of land lost for a given length of shoreline will be a reflection of the deficit of sediment and organic matter inputs with respect to the increased volume of water associated with sea-level rise. As noted earlier, Chesapeake Bay salt marshes currently do not receive sufficient sediment and organic matter to keep up with current rates of sea-level rise (Stevenson et al. 1988;

Kearney and Stevenson 1991). It seems likely that the current imbalance will grow in the future because sea-level rise rates are projected to increase and because the decreasing trend in sediment yields of major mid-Atlantic rivers over the past few decades is likely to continue. The latter is largely a result of farmland abandonment, dam construction and reduced soil erosion (Trimble 1974; Meade 1982).

Because of the importance of sediment inputs, MAC wetlands will not respond uniformly to sea-level rise. Thus, wetlands lacking inputs of riverine sediments will be most vulnerable to sea-level rise. These wetlands include microtidal marshes of the Chesapeake Bay, extensive non-tidal wetlands of the Albermarle-Pamlico Peninsula (Moorhead and Brinson 1995), and upland and marsh islands in Chesapeake Bay. Wray et al. (1995) noted that upland islands along the main stem of Chesapeake Bay are rapidly eroding, due to wave action against low silt/clay cliffs, and are expected to totally disappear in fewer than 20 years. Marsh islands in Chesapeake Bay are shrinking due to perimeter edge erosion and interior marsh loss, and are likely to be greatly reduced in size or totally lost in the coming century (Wray et al. 1995).

On the other end of the spectrum are tidal fresh-water marshes, which receive large influxes of riverine sediments, and so are likely to be less vulnerable to sea-level rise than their salt-water counterparts. However, horizontal migration of these wetlands will be limited by the steep valley slopes that characterize the upper reaches of such river systems, and up-river migration will be limited by increasingly narrow channels. Conversely, an increase in freshwater flow would shift tidal freshwater wetlands downstream, potentially increasing their area.

Climate-related changes in the environment may affect the material balance in wetlands, thereby affecting the degree of flooding due to sea-level rise. This could happen in at least three ways. First, carbon storage in wetlands may be altered by elevated CO_2. A Maryland salt marsh exposed to experimentally doubled levels of CO_2 (with respect to ambient) since 1987 has responded with an increase in carbon storage, mainly below ground (Drake et al*.*, 1996). Because the marsh in this study is isolated from a number of geophysical and biogeochemical processes that affect soil aggregation on regional scales, it is uncertain whether these results can be applied regionally. Second, regional warming may influence carbon storage in marsh sediments. A trend for higher levels of soil organic matter in Gulf-of-Mexico marshes compared to northern marshes (Callaway et al*.*, 1996) suggested that the net effect of regional warming will be to increase accretion rates. Also, the effect of elevated CO_2 on net ecosystem production increases with temperature by about 4% per ˚F (2% per ˚C) (Drake et al. 1996). Third, and finally, if streamflow increases [as a result of an increases in precipitation (Table 7.1)], then riverine inputs of sediments to marshes would likely increase.

Thus, all three of these climate-related changes (CO_2, temperature and hydrology) have the potential to reduce some of the flooding effect of sea-level rise in coastal wetlands. Quantifying these effects, however, is extremely difficult. With regard to the impacts of hydrology, they are difficult to quantify mainly because of the uncertainty in the precipitation predictions. With regard to organic matter accumulation rates, very little is known about their theoretical maximum upper limits and to what extent accretion results in an increase in surface elevation. For example, Bricker-Urso et al. (1989) suggested a maximum theoretical accretion rate of 0.63 inch per year (16 mm yr^{-1}), a rate that exceeds even the highest projections for the mid-Atlantic. On the other hand, Cahoon et al. (1995) found that surface elevation changes in microtidal marshes in the southeastern US were significantly less than vertical accretion rates, the difference being due to shallow subsidence. Clearly more work is needed on the potential for increased accretion in the root zone as a function of CO_2 and temperature increases, particularly in the context of local elevation changes due to subsurface subsidence.

In addition to RSLR and resulting changes in vegetation patterns, Drake et al. (1996) examined the effects of elevated CO_2 on marsh plants. C3 plants use sunlight to make sugar starting with three carbon atoms, and are well suited to climates that are not too hot or too dry. Plants that originated in drier, hotter climates are called C4 plants because their first product from photosynthesis has 4 carbon atoms. C4 plants (such as corn, sugar cane, and lawn grasses) grow rapidly in conditions of high sunlight and use CO_2 efficiently. Increasing atmospheric CO_2 is likely to benefit C3 plants more than the already efficient C4 plant. Drake et al. (1996) found that elevated CO_2 significantly increased the density of C3 species (e.g., sedge *Scirpus olneyi*) at the expense of C4 species (e.g., grasses *Spartina patens* and *Distichlis spicata*). Thus, elevated CO_2 may change plant species composition in coastal marshes. The cumulative consequences of such changes on ecosystem functioning are uncertain.

Coastal Bays and Estuaries

Salinity

As sea level rises, the ocean will encroach landward and estuarine salinity will increase. Hull and Titus (1986) suggest that such a salinity change could have significant negative impacts on drinking water quality and estuarine ecosystems in and around Delaware Bay during the 21st Century. They used a one-dimensional numerical model to evaluate the impact of a 29 inch (73 cm) sea-level rise (expected near the end of the 21st century, Table 7.1) on salinity above a 1965 baseline. The maximum 30-day average chloride concentration increased from 135 mg per liter to 305 mg per liter (average seawater is about 20,000 mg per liter) at one location in the upper Bay. The salt front (a rapid change in salinity in the horizontal direction, which is indicated by a chloride concentration of 250 mg per liter in this Bay), was predicted to move upstream by 6.8 miles (11 km). These changes would have direct social impacts. An increasing number of water supplies in coastal area, particularly cities such as Philadelphia and New York, are at the risk of salt water intrusion in their surface- or groundwater supplies. Salty aquifers could become a more serious problem in New Jersey.

In addition to sea-level variations, streamflow affects estuarine salinity on interannual timescales. Drought conditions in late 1964 caused the Delaware Bay salt front to advance up to 30 miles (50 km) upstream with respect to its average position (Hull and Titus 1986). To investigate streamflow impacts on Chesapeake Bay salinity, Gibson and Najjar (2000) developed an autoregressive statistical model with monthly resolution. They found that annual mean salinity decreases by 0.8% in the upper Bay to 0.1% in the lower Bay for every 1% increase in annual mean streamflow. We applied the Gibson and Najjar (2000) model to the streamflow projections in Chapter 6, which were derived using output from the National Assessment climate models. For the CCC model, the mid-Bay salt front is projected to migrate upstream by 2 miles (3 km, 0.94% of the Bay's length) by 2030 and 4.4 miles (7 km, 2.2% of the Bay's length) by 2095. For the Hadley model, the mid-Bay salt front is projected to migrate downstream by 6.8 miles (11 km, 3.4% of the Bay's length) and 30 miles (48 km, 15% of the Bay's length) by 2095. Clearly, streamflow changes could either offset or compound the effects of sea-level rise on the salinity of MAC waters.

Water Quality, Plankton and Submerged Aquatic Vegetation

Current water quality conditions in mid-Atlantic estuaries are typically poor. According to NOAA (1997a, b) and US EPA (1998), mid-Atlantic estuaries are generally characterized as high in chlorophyll concentration (a measure of phytoplankton abundance), nutrients and turbidity, and low in submerged aquatic vegetation (SAV) and dissolved oxygen. A significant increase of phytoplankton biomass has occurred during the last 40 to 50 years in MAC waters; the increase in Chesapeake Bay has been particularly well documented (Harding and Perry 1997). Nuisance algae are reported for half of the mid-Atlantic estuaries and toxic algal blooms have had resource impacts in four bays, three of which are in North Carolina (NOAA 1997a, b). US EPA (1998) identified Chesapeake Bay as the most hypoxic estuary in the region, with low dissolved oxygen levels associated with stratification and nutrient overenrichment.

How will climate change influence mid-Atlantic estuarine water quality, plankton, and SAV? The single most important climatic influence on estuarine water quality is streamflow. For several reasons, water quality degrades as streamflow increases (Hurley 1991). First, the vertical stability of the water column increases as fresher water overrides denser saltier water, decreasing the ability of winds and tides to vertically mix water, thereby decreasing the replenishment of oxygen from the atmosphere to deeper waters of the estuary (Seliger and Boggs 1988). Second, nutrient inputs from associated watersheds increase, increasing plankton production (Harding and Perry 1997; Malone 1992) and the rain of organic debris to deeper levels, causing additional oxygen consumption as bacteria and other fauna degrade the debris. Third, increased particle loads in shallow areas may hinder filter feeding by invertebrates and cause water clarity and photosynthesis by SAV to decrease. Fourth, increased nutrient loading (and warming) stimulates growth in epiphytic algae on the blades of the SAV, reducing the light available to the SAV. Losses in SAV and their physical buffering of wave action along shorelines can contribute to increases in coastal erosion, which may further decrease water clarity.

Because of its impact on mid-Atlantic fisheries, the degree of anoxia in Chesapeake Bay is an important water-quality indicator. Seliger and Boggs (1988) found that summertime anoxic volume in Chesapeake Bay in recent decades was highly correlated with April-May flow of the Susquehanna River, a major source of fresh water to the Bay. Their analysis suggests that a 10% increase in flow above the mean results in a 26% increase in summertime anoxic volume. The fact that anoxia depends on the timing, as well as the magnitude, of streamflow makes prediction under climate change difficult. Table 7.2 highlights this point by summarizing how climate-induced changes in streamflow may change Chesapeake Bay anoxia in the future. In addition to the two National Assessment models, results from two regional climate models are used. The results show that anoxia changes could be very large but the direction of the change varies among the different climate models. Walker et al. (2000) documented how anthropogenic activity has dramatically altered the relationship between nutrient flux and streamflow during the last century. They suggested that the relationship between Chesapeake Bay anoxia and streamflow documented by Seliger and Boggs (1988) was much stronger in the past few decades than it was in previous centuries. If nutrient loads to the coast continue to increase as coastal populations grow, it seems that anoxia will become even more sensitive to streamflow in many mid-Atlantic estuaries.

The oxygenation of estuarine waters will be affected by warming. Oxygen solubility (the capacity to dissolve oxygen) decreases as water temperature increases at a rate of 1% per °F (2% per °C). Changes in oxygen concentration also depend on biotic factors. Higher temperature increases bacterial production and raises the metabolism of cold-blooded aquatic animals (invertebrates, amphibians, fish and reptiles), thereby increasing the metabolic need for oxygen. Thus, warming will increase anoxia in MAC waters, but the magnitude of the effect is not known.

Table 7.2. Change in April-May flow of the Susquehanna River and Chesapeake Bay summertime anoxic volume estimated from climate model output. CCC = Canadian Climate Centre

Change	Hadley 2030	CCC 2030	Hadley 2095	CCC 2095	Nested model[1] $2xCO_2$	Empirical downscaling[1,2] $2xCO_2$
April-May flow (%)[3]	+12	-4	+4	-25	+43	-0.2
Anoxic volume (%)[4]	+31	-10	+10	-65	+112	-0.5

[1]Details of these models are given in Crane and Hewitson (1998) and Najjar (1999).
[2]See Crane and Hewitson (1998) for details of precipitation calculation. Temperature taken from Hadley 2095.
[3]Computed from water balance model of Najjar (1999). Also see Chapter 6.
[4]Uses linear relationship of Seliger and Boggs (1988).

Increases in water temperature are likely to have important effects on phytoplankton species composition, their geographic range, and grazing rates of their zooplankton and benthic filter-feeding predators. Several species of toxic phytoplankton enjoy wider distribution during warmer periods (Tester, 1996). Keller et al. (1999) demonstrated that increases in winter temperature can result in increased cropping of phytoplankton by zooplankton in the water column, reducing the supply of detrital material for benthic organisms. This could negatively impact benthic food chains, but have a positive effect on the oxygenation of bottom waters.

Fish and Shellfish

Variations in the abundance of many fish and shellfish are correlated with environmental conditions during early larval stages that affect natural mortality. Such variations subsequently affect variations in fishing mortality. Wood and Austin (personal communication) summarized fluctuations in recruitment patterns of Chesapeake Bay fish in relation to variations in weather and climate during the past several decades. Recruitment success in anadromous species was associated with variations in river discharge, whereas recruitment in bay-spawned species was influenced by wind, river discharge and temperature. Shallow-water spawners were sensitive to variability in precipitation and sea level during critical periods. Recruitment in many shelf-spawned species was associated with variability in winds on the coastal shelf. Thus, a combination of heavy fishing pressure and a series of climatically unfavorable years for recruitment can result in dramatic reductions in the abundance of valued fish stocks.

There is a historical basis for expecting warming to have significant impacts on estuarine and marine fish and shellfish in the mid-Atlantic. For example, Murawski (1993) found that marine temperature variation on the North American east coast explained changes in the north-south distribution of 12 of 36 species of fish. On the west coast from the early 1930s to the mid 1990s, annual mean shoreline temperature increased by 1.4˚F (0.75˚C) while abundances of 63% of northern species of rocky intertidal invertebrates decreased and 89% of southern species increased (Barry et al., 1995). Species whose southern range ends in the MAC region, such as the soft clam, *Mya arenaria*, in Chesapeake Bay, could be eliminated if water temperatures reach levels that are lethal or that inhibit successful reproduction.

The prediction for soft clams is based on the species' geographic limits and on laboratory data on its upper temperature tolerances (Kennedy and Mihursky 1971). There are few data on temperature tolerances for other animal species in the MAC region. However, data on geographic ranges can be used to project shifts in distribution related to warming (recognizing that factors other than temperature tolerances may be involved in limiting distributions). Distribution information in Murdy et al. (1997) provides examples of cooler-water fish species whose southern limits within MAC may shift northward. These include cunner (*Tautogolabrus adspersus*; ranges from Labrador to Virginia, but is more common north of New Jersey), lumpfish (*Cyclopterus lumpus*; North Atlantic to Chesapeake Bay), and threespine stickleback (*Gasterosteus aculeatus*; Labrador to Chesapeake Bay). Similar predictions can be made for some invertebrates (e.g., copepods; see Table 21.5 in Gosner 1971).

On the other hand, warming could cause the northern distribution limits of some warm-water species to shift even further north. Fish species include Atlantic stingray (*Dasyatis sabina*; Chesapeake Bay to Mexico), southern flounder (*Paralichthys lethostigma*; Chesapeake Bay to Texas), black drum (*Pogonias cromis*; uncommon north of Delaware Bay), and spotted seatrout (*Cynoscion nebulosus*; rare north of Delaware Bay). The range of southern kingfish (*Menticirrhus americanus*; most common from Chesapeake Bay to Mexico) could expand northward, perhaps overlapping even more with that of northern kingfish (*Menticirrhus saxatilis*; most common from New York to North Carolina). Similar predictions can be made for some invertebrates. For example, southerly species of swimming crabs (*Callinectes ornatus* and *C. similis*) could range further northward, thereby overlapping with the blue crab *Callinectes sapidus* in the MAC. Three species of the genus *Farfantepenaeus* (pink, white, and brown shrimp) support commercial fisheries in the North Carolina region and range north of Cape Hatteras in non-commercial abundances. If temperature is the factor limiting their northward distribution, climate warming might allow them to become established in Chesapeake Bay in numbers that would support a fishery.

Northward retreat of warm-intolerant species (caused by heat-related mortality or unsuccessful reproduction) has the potential to reduce species diversity in MAC coastal habitats, depending on the immigration rates of warm-tolerant species. This is especially true of estuarine-dependent species that have limited abilities to disperse or that are intolerant of marine conditions that represent physiological barriers between estuaries (Kennedy 1990). The fish, swimming crabs, and shrimp mentioned above are mobile organisms that are able to migrate northward along the coast to colonize new estuarine and marine habitat. However, sessile or relatively immobile invertebrates (e.g., many molluscs, annelids, echinoderms, and arthropods) will migrate north more slowly unless aided (either deliberately or inadvertently) by human activities.

Finally, a positive effect of warming might be less frequent severe winters like those of 1997 and 1981 that are thought to have resulted in low blue crab catches in the Delaware estuary (US EPA 1998).

Parasitic and predatory relationships among organisms in MAC waters are also sensitive to temperature. The parasite that causes Dermo disease in eastern oysters, *Crassostrea virginica*, was restricted to locations south of Delaware Bay before 1990. Since then, a rapid range expansion of this parasite to the north has occurred in association with warmer winters (Cook et al. 1998). Links between climate change and other marine diseases have been reviewed by Harvell et al. (1999). Experiments in Oregon have shown that small changes in sublethal temperatures interfere with the controlling effect of a starfish on its mussel prey, thereby potentially altering species compositions and dynamics of the intertidal community (Sanford 1999). Thus small, nonlethal temperature changes can indirectly cause large ecological changes.

The interactions between higher temperatures and depleted oxygen noted earlier could constrict the available habitat for a variety of species along the North American east coast, including striped bass, *Morone saxatilis*, in Chesapeake Bay, an important spawning center for this species (Coutant 1990). Laboratory studies have shown that organisms under stress pay a metabolic cost in the form of a continued expenditure of energy that may preclude survival if the stress does not abate (e.g., Parsons, 1990). Examples of this in Chesapeake bay are shellfish mortalities that have occurred due to low-oxygen conditions (Seliger et al. 1985; Officer et al. 1984).

Climate-related salinity changes also could affect mid-Atlantic estuarine ecosystems. Sea-level rise will enable mobile estuarine species to migrate upstream where potential impacts from pollution and other human influences will be greater. Higher salinities could result in the invasion of salinity-tolerant pests, such as two lethal oyster diseases and two species of predatory snails of eastern oysters that are inhibited by salinities below about 12 and 20, respectively (Kennedy and Breisch 1981). During the mid-1980s, for example, low riverine flows resulting from low precipitation over the watersheds of mid-Atlantic states caused estuarine salinities to be higher than nomal. Oyster diseases responded positively to these saltier waters and decimated the oyster population in much of the region (US EPA 1998). The predicted increases in streamflow (Table 7.1), on the other hand, may benefit oysters by making estuarine waters fresher and a poorer environment for disease. But if precipitation variability increases as suggested by Crane and Hewitson (1998) oysters and organisms with similar salinity thresholds may suffer. For example, the tremendous freshening of Chesapeake Bay associated with Tropical Storm Agnes in 1972 caused massive oyster mortality (Leatherman et al. 1995).

Finally, wetland and SAV loss due to sea-level rise and water quality degradation will affect the many fish and shellfish that utilize these habitats. For example, loss of estuarre beaches will likely lead to a decrease in the abundance of horseshoe crabs.

Birds

The bays and estuaries of the mid-Atlantic region provide important habitat for a variety of resident and migratory birds including the osprey, bald eagle, six species of colonially nesting waders (such as the great blue heron and snowy egret), and dozens of shorebird and waterfowl species. Chesapeake and Delaware Bays harbor the largest concentrations of migratory shorebirds in the Western Hemisphere. Approximately 70% of the entire North American population of the red knot, *Calidris canutus*, is in Delaware Bay at one time (Sutton et al. 1996). Chesapeake Bay is also used by nearly one million ducks, geese and swans to feed and rest during the winter months and thousands more use it as a migration stopover point. MAC birds utilize a diversity of wetland habitats within the region for feeding, consuming fish, amphibians, invertebrates, and SAV. Habitat loss and the effects of contaminants and declines in water quality on food resources have caused population declines of many of these species (Funderbunk et al., 1991). Changes in water temperature and quality under climate change will have mostly indirect effects on these species, primarily through changes in the distribution and abundance of food resources.

Waterfowl use of Chesapeake Bay has changed tremendously in the last 45 years. Wintering population sizes of most duck species have declined steadily since the 1950s while population sizes of Canada geese and snow geese have increased (Perry and Deller 1995). Most of these changes are attributed to changes in waterfowl food resources in and around the Bay, particularly the wide-spread decline of SAV (Perry and Deller 1996). Projections of warming Bay waters, possible streamflow increases, and increasing coastal populations suggest that water quality and therefore SAV will continue to decline, leading to further declines in SAV-dependent waterfowl. Diving ducks and many other birds also could be affected negatively by the anoxia-induced declines in shellfish noted earlier. Finally, losses in wetlands and estuarre beaches could negatively impact shellfish, such as horseshoe crabs, and the birds that feed on them.

Factors outside the mid-Atlantic will likely play a role as well. For example, Sorenson et al. (1998; personal communication) used the warmer and drier projections for the prairie pothole region of the north-central United States and south-central Canada (the continent's "duck factory") to infer that the number of pothole wetlands and, correspondingly, the number of ducks breeding in the region would be reduced. In turn, this could reduce waterfowl abundance in MAC waters because many of the ducks that winter there breed in the pothole region. Band recovery data for one of the most abundant ducks, the canvasback, *Aythya valisineria*, show that approximately 40% (346/875) of canvasbacks breeding in the prairie pothole region winter in the Atlantic Flyway. Ninety-one percent (316/346) of the Atlantic Flyway population are found in MAC waters, 75% (236/316) of these on Chesapeake Bay. Declines in breeding population sizes of ducks in Prairie Canada ranging from 19% to 39% and 7% to 70% are projected for the 2030s and 2090s, respectively (See Box 7.1). Declining breeding population sizes and fewer young produced under increasing drought conditions on the prairies coupled with likely declines in wintering habitat quality due to climate change bode poorly for future duck populations on MAC waters.

Societal Responses

The coastal areas of the mid-Atlantic region have aesthetic and economic values. The shore is a tourist destination, inviting investment in facilities to serve the tourist population. For many coastal areas, visitors and temporary residents exceed the resident population by an order of magnitude or more. The annual flux of visitors to the coast is concentrated during the peak summer holiday but extends to the shoulder seasons in late spring and early fall, as well as weekends and holidays. Loss of coastal areas would result in a loss of tourist revenues as well as other overlooked nonmonetary benefits, such as cultural and aesthetic uses.

American society has, in general, subsidized coastal development with federal activities such as shoreline protection, beach replenishment, federal disaster assistance, and the National Flood Insurance Program (NFIP). Coastal counties of four mid-Atlantic states (New Jersey, Delaware, Maryland, and Virginia) had 177,758 NFIP policies in effect with $21 billion in coverage from 1978 to 1998 (H. John Heinz III Center, 1999). During that time, $81 million in premium revenues were collected and $327 million were paid in 46,670 thousand claims, $138 million (42%) of which were repetitive. The Coastal Zone Management Act of 1972, in cooperation with state coastal agencies, encourages control of development, and NFIP has strengthened regulations regarding the elevation of new or reconstructed buildings. However, NFIP regulations are enforced poorly in many areas (H. John Heinz III Center 1999). Furthermore, federal declarations of emergency, which make people eligible for financial assistance after storms, may only serve to encourage development.

Potential Impacts

The potential impacts on development and use in the MAC region are positive and negative. On the positive side, the warming projected in Table 7.1 would extend the season of coastal recreation, giving seasons to the northerly areas that are as long as those now occurring in North Carolina and Virginia. On the negative side, there appear to be greater risks. Although the MAC region is not particularly vulnerable to hurricanes (with the exception of the Outer Banks of North Carolina), September is the most common period of direct hits (Jarrell et al. 1992). Thus, an extension of the tourist season would result in a greater number of people potentially affected by hurricanes even if hurricane frequency does not change (which is a matter of considerable debate). The threats to the coasts from sea-level rise include long-term and sometimes subtle threats from coastal inundation and erosion. Such gradual change may eventually cause the loss of relatively unique cultures, for example on Smithand Tangier Islands, which are likely to erode away. Immediate threats may occur from storms and tidal surges either greater in frequency and severity than in the past or imposed on higher water levels (Figure 7.2). Wetlands loss due to sea-level rise and increased anoxia and habitat squeeze due to warming would negatively affect waterfowl hunting and sport and commercial fishing. If warming increases toxic algal blooms, decreased coastal tourism and fishing would likely result.

Management and Adaptation Options

Sea-level rise poses an important challenge to desirable coastal environments and beach-front developments. In estuaries, it is likely that protection from submergence will be accepted only for socially significant locations, and values of land development will largely determine areas to be protected by dikes or walls. Dry land will yield to wetlands and water where economic or cultural importance, or both, are not established. In Chesapeake Bay, with its numerous small cliffs, sea-level rise will directly increase erosion rates if other changes (e.g., increased bulkheading) do not occur. Response strategies will vary from state to state. North Carolina prohibits armoring of the open shoreline, while other states allow a wider range of responses. Titus (1998) documented rapidly increasing armoring of Maryland’s bay shores. Some communities will identify ecologically important areas and protect them, as is being tried in parts of the Blackwater Refuge in Maryland. Both protection and abandonment will exact a cost from society that will increase through time.

In general, we anticipate that in the ocean coastal areas, society will continue to support structural approaches such as beach replenishment, groins, and sea walls to maintain the status quo. Titus et al. (1985) estimated that the costs of maintaining the beachfront should be negligible over the next 40 years, given the large amount of revenue that local tourism generates. Their calculations were based on sea-level rise scenarios close to the middle and high projections shown in Table 7.1. From these scenarios, sand requirements and their associated costs were computed. More recent studies using similar methods support the economic benefit of beach nourishment in Delaware (Parsons and Powell 1998; Faucett Associates 1998). Nevertheless, Delaware has taken the stance of allowing strategic retreat for state-owned coastal lands. An emerging policy of beach replenishment in New Jersey has a potential cost of $60 million per mile and a 50-yr total cost of $9 billion (Grunwald 1999).

There are important legal dimensions to the process of beach retreat in coastal areas (Titus 1998). For example, along estuarine shores where people erect bulkheads and revetments, the margin between high and low tide eventually erodes away, thereby eliminating public access to the shore. Titus (1998) argued for a rolling easement concept that would maintain public access to tidal lands as shorelines retreat, by preventing shores from being armored in lightly developed areas and by ensuring a right to access immediately landward of the bulkhead in those areas where shores are armored. Such a policy can be implemented through the purchase of rolling easements from private property owners, by modifying existing bulkhead permit guidelines, or through legislation. States that have adopted such policies in other regions generally have allowed property owners to use beach nourishment, which also retains public access.

Inland flood losses and flood control investments in the United States have increased with time. Settlement history and the development of federally-subsidized transport systems and flood mitigation measures have encouraged floodplain occupancy. It has taken a century for US flood control policy to begin moving from structural approaches to non-structural approaches. Only in the last decade has there been serious consideration of relocating flood-prone communities and abandoning breached levees to re-establish normal river-floodplain relations. On the mid-Atlantic coast, if not elsewhere, one can foresee coastal management repeating the inland floodplain experience: federal subsidies for occupation of dynamic and sometimes hazardous coastal zones; structural answers to control coastal hazards and the impact of sea-level rise; and ever-increasing vulnerability with losses increasing along with investments in protection.

Conclusions and Recommendations for Further Research

Expectations of how climate change may affect the mid-Atlantic coastal region can be informed by based on information about past climate impacts on the region and climate model projections. Sea level, temperature, storminess and streamflow have had significant effects on the MAC region. Climate change has caused a progressive and significant increase in sea level over the past century, eroding shores and increasing storm-related coastal flooding (Figure 7.2). Temperature variations have affected coastal ecosystems and fisheries by changing parasite-host relationships, and may also affect predator-prey relationships among other things. Streamflow variations have effectively dictated the seasonal and interannual variations in estuarine water quality. Past experience strongly suggests that mid-Atlantic climate change will significantly affect coastal waters. Table 7.3 presents a qualitative summary of what the impacts might be and how certain the predictions are. The first row of this table gives the best estimates for expected changes in climate and population. If these changes occur, the rest of the table shows our best estimate (and their uncertainties) of what those impacts might be. The ecological, and hence societal, impacts are largely negative. The only direct positive societal benefit is the potential for increased coastal tourism in some areas due to the warmer climate. Indirectly, however, society may benefit if, for example, wetland accretion increases due to increased streamflow and shellfish fare better with less harsh winters. Table 7.3 also presents the potential impacts on the MAC region of future population growth. These impacts tend to be in the same direction as the climate change impacts.

The high human population density of the MAC region has increased the sensitivity of the region to climate variability. For example, coastal inundation due to sea-level rise is exacerbated by human activities, such as dam building and bulkheading, that reduce the supply of sediment.

Coastal anoxia has probably always been sensitive to streamflow in many mid-Atlantic estuaries, like Chesapeake Bay (Cooper and Brush 1991), but nutrient inputs due to human activity have probably heightened this sensitivity (Walker et al, 2000). Thus, climatic and human influences act synergistically on the MAC region. We speculate that climate may indirectly impact the MAC region in the future through warming-induced human migration to the coast. In other words, the more moderate climate found in coastal regions may become more attractive to people in the future. This could compound effects on water quality and sea-level rise, as suggested in Figure 7.3. One management implication of our study, therefore, is that policies designed to reduce adverse environmental impacts of local human activities could help mitigate some of the risks associated with climate change.

The capability of predicting the environmental impacts of future climate change on the MAC region is influenced by two factors: (1) our ability to predict how the regional climate will change and (2) our understanding of the sensitivity of the region to climate change. Predictions for sea-level rise and temperature change have much greater certainty than predictions for other aspects of climate variability. There is a large body of work published on global sea-level rise (Warrick et al. 1996, and references therein), and on RSLR in Chesapeake Bay and its likely consequences (Kearney and Stevenson 1991; Downs et al. 1994; Wray et al, 1995). There is much greater uncertainty concerning past and future changes in extreme weather events, variability in regional precipitation, and streamflow, all of which have the potential for substantial impacts in the coastal zone. More research is clearly needed in these areas

Table 7.3. Summary of potential impacts of climate and population change in the mid-Atlantic coastal region.

	Best estimate of change:				
Impacts on:	**Near certain CO_2 increase**	**Very likely sea level increase**	**Likely temperature increase**	**Possible precipitation increase**	**Very likely population increase**
Wetlands	Possible increase in accretion	Likely flooding; elimination of estuarine wetlands	Possible increase in accretion	Possible increase in accretion due to increased sediment input	Decrease in area due to: human development, decreased sediment supply (due to dams), and increased groundwater withdrawals
Water quality	Slight pH decrease	Very likely higher turbidity	Possible increase in anoxia and nuisance blooms; possible phytoplankton decreases	Very likely increase in turbidity and anoxia	Likely increase in toxic substances, nutrients and anoxia; possible turbidity decrease due to dams and bulkheads
SAV	Small	Likely decrease due to increased turbidity	Likely species distribution changes	Very likely decrease due to increased turbidity and nutrients	Likely decrease due to water quality decrease, but possible increase due to lower turbidity
Fish and Shellfish	Small (calcification decrease?)	Possible species distribution changes due to salinity changes; possible oyster disease increase	Likely species distribution changes; likely oyster disease increase; possible population increases due to less harsh winters	Likely decrease due to decreased water quality; possible species distribution changes due to salinity changes; possible oyster disease decrease	Likely decrease due to water quality decrease and overfishing
Birds	None	Likely loss to intertidal habitat and decrease in food for SAV-dependent species	Possible species distribution change	Likely decrease in food for SAV-dependent species	Likely decrease in food for SAV-dependent species
Society	None	Very likely increased costs of coastal flooding Reduction in beaches along developed and bulkheaded shores	Likely increased tourism and possible migration to the coast	Possible increased cost of coastal flooding; likely decrease in recreational and commercial fishing	Increased tourism

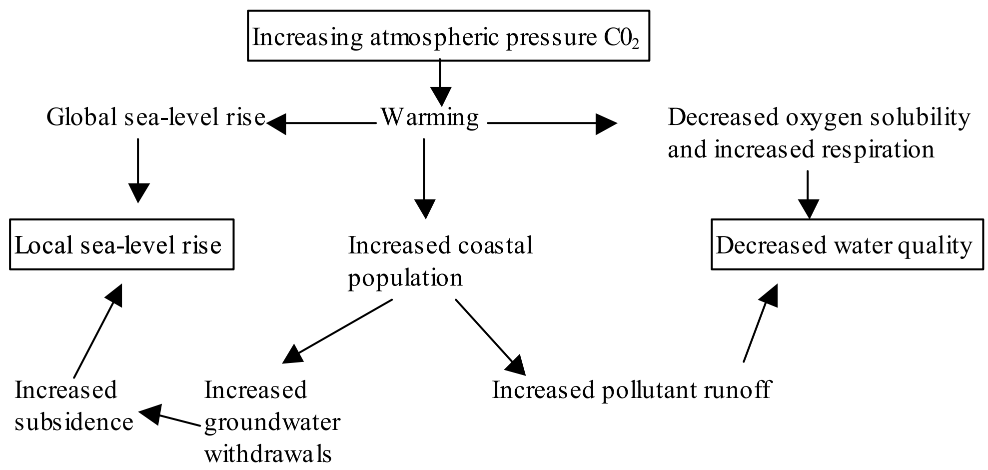


Figure 7.3. Schematic for possible synergistic impacts of climate change and coastal development on sea-level rise and water quality.

Though there is abundant evidence that ecosystems in the MAC region are sensitive to climate, the mechanisms are not well understood; this makes prediction of the impacts of climate change uncertain, even if the future climate could be predicted with certainty. We recommend a four-pronged approach to understanding the sensitivity of MAC ecosystems to climate, and to help distinguish between effects of climate variability and other anthropogenic components of change: (1) increased monitoring and historical data analysis; (2) experimental manipulation of the environment (temperature, salinity, CO_2, etc.) in the laboratory and field (including large-scale manipulation) to test specific hypothesis concerning ecosystem sensitivity; (3) measurement and analysis of paleo-climate variability (from caves, tree rings, marine sediment cores, etc.) to increase our understanding of decadal-scale changes in regional climate, in the context of larger spatial-scale variability in the Northern Hemisphere during the Holocene; and (4) numerical modeling of the impact of climate on physical, chemical and biological processes.

There are a number of important unknowns with regard to the societal impacts of climate change in the MAC region. Research attempting to quantify the effect of increased temperatures on human migration to the coast would be extremely helpful. Mapping is needed of coastal regions that are most economically vulnerable to climate change, particularly to sea-level rise. Finally, research into the long term costs and benefits of federal subsidies and shoreline protection methods would be most helpful in guiding future public policy for the mid-Atlantic coastal region.

References

Barry JP, Baxter CH, Sagarin RD, Gilman SE (1995) Climate-related, long-term faunal changes in a California rocky intertidal community. *Science* 267:672-675.

Boer GJ, McFarlane NA, Laprise R, Henderson JD, Blanchet J-P (1984) The Canadian Climate Centre spectral atmospheric general circulation model. *Atmosphere-Ocean* 22:397-429.

Boer GJ, McFarlane N, Lazare M (1992) Greenhouse gas induced climate change simulated with the CCC second generation GCM. *Journal of Climate* 5:1045-1077.

Boer GJ, Flato GM, Reader MC, Ramsden D (2000a) A transient climate change simulation with greenhouse gas and aerosol forcing: Experimental design and comparison with the instrumental record for the 20th century, *Climate Dynamics* 16:405-425.

Boer GJ, Flato GM, Ramsden D (2000b) A transient climate change simulation with greenhouse gas and aerosol forcing: Projected climate for the 21st century, *Climate Dynamics* 16:427-450.

Bricker-Urso S, Nixon SW, Cochran JK, Hirschberg DJ, Hunt C (1989) Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries* 12:300-317.

Bruun P (1988) The Bruun Rule of erosion by sea-level rise: A discussion on large-scale two- and three-dimensional usages. *Journal of Coastal Research* 4:627-648.

Cahoon DR, Reed JW, Day JW Jr (1995) Estimating shallow subsidence in microtidal saltmarshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology* 128:1-9.

Callaway JC, Nyman JA, DeLaune RD (1996) Sediment accretion in coastal wetlands: A review and a simulation model of processes. *Current Topics in Wetland Biogeochemistry* 2:2-23.

Cargo D.G. and Schultz LP. (1966) Notes on the biology of the sea nettle, *Chrysaora quinquecirrha*, in Chesapeake Bay. *Chesapeake Science* 7: 95-100.

Cook T, Folli M, Klinck J, Ford S, Miller J (1998) The relationship between increasing sea-surface temperature and the northward spread of Perkinsus marinus (Dermo) disease epizootics in oysters. *Estuarine, Coastal and Shelf Science* 46:587-597.

Cooper SR, Brush GS (1991) Long-term history of Chesapeake Bay anoxia. *Science* 254:992-996.

Coutant CC (1990) Temperature-oxygen habitat for freshwater and coastal striped bass in a changing climate. *Transactions of the American Fisheries Society* 119:240-253.

Crane RG, Hewitson BC (1998) Doubled CO_2 precipitation changes for the Susquehanna Basin: Downscaling from the Genesis general circulation model. *International Journal of Climatology* 18:65-76.

DeWalle DR, Swistock BR, Johnson TE, McGuire KJ (2000) Potential effects of urbanization on sensitivity of mean annual streamflow to climate change in the United States. *Water Resources Research* (in press).

Douglas BC (1991) Global sea-level rise. *Journal of Geophysical Research* 96:6981-6992.

Downs LL, Nicholls RJ, Leatherman SP, Hautzenroder J (1994) Historic evolution of a marsh island: Bloodsworth Island, Maryland. *Journal of Coastal Research* 10:1031-1044.

Drake BG, Peresta G, Beugeling E, Matamala R (1996) Long-term elevated CO_2 exposure in a Chesapeake Bay wetland: Ecosystem gas exchange, primary production, and tissue nitrogen. In: Koch GW, Mooney HA (eds) *Carbon Dioxide and Terrestrial Ecosystems*. Academic Press, San Diego, CA, p 197-214.

Faucett Associates (1998) *The economic effects of a five-year nourishment program for the ocean beaches of Delaware*, Report for The Beach Replenishment Task Force, State of Delaware.

Fisher A, Neff R, Barron EJ (2000) The mid-Atlantic regional assessment: Motivation and approach. *Climate Research* 4:153-159.

Flato GM, Boer GJ, Lee WG, McFarlane NA, Ramsden D, Weaver AJ (2000) The Canadian Center for Climate Modeling and Analysis global coupled model and its climate, *Climate Dynamics 16*:451-467.

Funderbunk SL, Jordan SJ, Mihursky JA, Riley D (eds) (1991) *Habitat requirements for Chesapeake Bay living resources*, 2nd edition. Chesapeake Research Consortium, Inc., Solomons, MD.

Gibson J, Najjar RG (2000) The response of Chesapeake Bay salinity to climate-induced changes in streamflow. *Limnology and Oceanography*, in press.

Gosner KL (1971) Guide to Identification of Marine and Estuarine Invertebrates. Cape Hatteras to the Bay of Fundy. Wiley-Interscience, New York. 693 pages.

Grunwald M (1999) Fixing the Beach, for $60 Million a Mile, *Washington Post*, April 19, p A3.

H. John Heinz III Center for Science, Economics and the Environment (1999) *The Hidden Costs of Coastal Hazards: Implications for Risk Assessment and Mitigation*. Island Press, Covelo, CA.

Harding LW, Perry ES (1997) *Long-term increase of phytoplankton biomass in Chesapeake Bay, 1950-1994*. Marine Ecology Progress Series 157:39-52.

Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes DJ, Hofmann EE, Lipp EK, Osterhaus ADME, Overstreet RM, Porter JW, Smith GW, Vasta GR (1999) Emerging marine diseases—Climate links and anthropogenic factors. *Science* 285:1505-1510.

Hodny JW (1992) *Climate Change and Water Resources Within the Delaware River and Delmarva Regions*. Masters thesis, Department of Geography, University of Delaware, Newark, DE.

Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (1996) *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge, United Kingdom.

Hull CHJ, Titus JG (1986) *Greenhouse Effect, Sea-level Rise, and Salinity in the Delaware Estuary*. Washington, DC: US Environmental Protection Agency and the Delaware River Basin Commission. US EPA 230-05-86-010.

Hurley LM (1991) Submerged aquatic vegetation. In: Funderbunk SL, Jordan SJ, Mihursky JA, Riley D (eds), *Habitat requirements for Chesapeake Bay living resources*, 2nd edition. Chesapeake Research Consortium, Inc., Solomons, MD, p 2-1 to 2-19.

Jarrell J D, Hebert PJ, Mayfield M (1992) *Hurricane Experience Levels of Coastal County Populations From Texas to Maine*. NOAA Technical Memorandum NWS NHC-46 (August). National Hurricane Center, Coral Gables, FL.

Johns TC, Carnell RE, Crossley JF, Gregory JM, Mitchell JFB, Senior CA, Tett SFB, Wood RA (1997) The second Hadley Centre coupled ocean-atmosphere GCM: Model description, spinup and validation. *Climate Dynamics* 13:103-134.

Kearney MS, Stevenson JC (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. *Journal of Coastal Research* 7:403-415.

Keller AA, Oviatt CA, Walker HA, Hawk JD (1999) Predicted impacts of elevated temperature on the magnitude of the winter-spring phytoplankton bloom in temperate coastal waters: A mesocosm study. *Limnol Oceanogr* 44:344-356.

Kennedy V.S. and Mihursky JA (1971) Upper temperature tolerances of some estuarine bivalves. *Chesapeake Sci*. 12:193-204.

Kennedy VS (1990) Anticipated effects of climate change on estuarine and coastal fisheries. *Fisheries* 15(6):16-24.

Kennedy VS, Breisch LL (1981) *Maryland's oysters: Research and management*. Maryland Sea Grant Publications UM-SG-TS-81-04, University of Maryland, College Park, MD.

Leatherman SP, Chalfont R, Pendleton EC, McCandless TL, Funderburk S (1995) *Vanishing Lands: Sea Level, Society and Chesapeake Bay*. University of Maryland and US Fish and Wildlife Service, Annapolis, MD.

Malone TC (1992) Effects of water column processes on dissolved oxygen, nutrients, phytoplankton and zooplankton. In: Smith DE, Leffler M, and Mackiernan G (eds.) *Oxygen dynamics in the Chesapeake Bay*, pp 61-112. Maryland Sea Grant, College Park, MD.

McCabe GJ, Ayers MA (1989) Hydrologic effects of climate change in the Delaware River Basin. *Water Resources Bulletin* 25:1231-1242.

McFarlane NA, Boer GJ, Blanchet JP, Lazare M (1992) The Canadian Climate Centre second-generation general circulation model and its equilibrium climate. *Journal of Climate* 5:1013-1044.

Meade RH (1982) Sources, sinks, and storage of river sediment in the drainage of the United States. *Journal of Geology* 90:235-252.

Mitchell JFB, Johns TC, Gregory JM, Tett S (1995) Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature* 376:501-504.

Mitchell JFB, Johns TC (1997) On modification of global warming by sulfate aerosols. *Journal of Climate* 10:245-267.

Moore MV, Pace ML, Mather JR, Murdoch PS, Howarth RW, Folt CL, Chen CY, Hemond HF, Flebbe PA, Driscoll CT (1997) Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic Region. *Hydrological Processes* 11:925-947.

Moorhead KK, Brinson MM (1995) Response of wetlands to rising sea level in the lower coastal plain of North Carolina. *Ecological Applications* 5:261-271.

Murawski SA (1993) Climate change and marine fish distributions: Forecasting from historical analogy. *Transactions of the American Fisheries Society* 122:647-658.

Murdy E.O, Birdsong RS, and Musick JA (1997) Fishes of Chesapeake Bay. Smithsonian Institution Press, Washington DC. 324 pages.

Najjar RG (1999) The water balance of the Susquehanna River Basin and its response to climate change. *Journal of Hydrology* 219:7-19.

Najjar RG, Walker HA, Anderson PJ, Barron EJ, Bord RJ, Gibson JR, Kennedy VS, Knight CG, Megonigal JP, O'Connor RE, Polsky CD, Psuty NP, Richards BA, Sorenson LG, Steele EM, Swanson RS (2000) The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research* 14: 219-233.

Nicholls RJ, Leatherman SP (1996) Adapting to sea-level rise: Relative sea-level trends to 2100 for the United States. *Coastal Management* 24:301-324.

Niering WA, Warren RS (1980) Vegetation patterns and processes in New England salt marshes. *BioScience* 30:301-307.

NOAA (1997a) *NOAA's Estuarine Eutrophication Survey. Volume 1: South Atlantic Region*. Silver Spring, MD: Office of Ocean Resources Conservation and Assessment, National Oceanic and Atmospheric Administration.

NOAA (1997b) *NOAA's Estuarine Eutrophication Survey. Volume 2: Mid-Atlantic Region*. Silver Spring, MD: Office of Ocean Resources Conservation and Assessment, National Oceanic and Atmospheric Administration.

Officer CB, Biggs RB, Taft JL, Cronin LE, Tyler MA, Boynton WR (1984) Chesapeake Bay anoxia: Origin, development and significance. *Science* 223:22-27.

Parsons GR, Powell M (1998) *The cost of beach retreat: A hedonic price analysis of Delaware beaches*. University of Delaware, Department of Economics Working Paper 98-14.

Parsons, PA (1990) The metabolic cost of multiple environmental stresses: Implications for climatic change and conservation. *Trends in Ecology and Evolution* 5:315-317.

Perry MC, Deller AS (1996) Review of factors affecting the distribution and abundance of waterfowl in shallow-water habitats of Chesapeake Bay. *Estuaries* 19: 272-278.

Perry MC, Deller AS (1995) Waterfowl population trends in the Chesapeake Bay area. Hill P, Nelson W (eds). *Toward a Sustainable Coastal Watershed: The Chesapeake Experiment*. Chesapeake Research Consortium Publication No. 149, Edgewater, MD.

Psuty NP (1992) Estuaries: Challenges for coastal management. In: Fabbri P (ed) *Ocean Management in Global Change*. Elsevier Applied Science, London, p 502-518.

Psuty NP, Collins D (1996) *Sea-level rise: A white paper on the measurements of sea-level rise and a perspective on the implications for management*, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, 20 p.

Sanford E (1999) Regulation of keystone predation by small changes in ocean temperature. *Science* 283:2095-2097

Seliger HH, Boggs JA, Biggley WH (1985) Catastrophic anoxia in the Chesapeake Bay in 1984. *Science* 228:70-73.

Seliger HH, Boggs JA (1988) Long term pattern of anoxia in the Chesapeake Bay. In: Lynch MP, Kronme EC (eds) *Understanding the Estuary: Advances in Chesapeake Bay Research*. Publication 129. Ref. CBP/TRS 24/88, Chesapeake Research Consortium, Gloucester Point, VA, p 570-583.

Sorenson LG, Goldberg R, Anderson MG, Root TL (personal communication) Potential consequences of global warming for wetlands and ducks breeding in the Canadian Prairie Pothole Region.

Sorenson LG, Goldberg R, Root TL, Anderson MG (1998) Potential effects of global warming on waterfowl populations breeding in the Northern Great Plains. *Climatic Change* 40:343-369.

Stevenson JC, Ward LG, Kearney MS (1988) Sediment transport and trapping in marsh systems: Implications of tidal flux studies. *Marine Geology* 80:37-59.

Sutton CC, O Herron JC II, Zappalorti RT (1996) *The Scientific Characterization of the Delaware Estuary*. The Delaware Estuary Program (DRBC Project No. 321; HA File No. 93.21).

Taylor KE, Penner Je (1994) Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature* 369, 734-737.

Tester PA (1996) Climate change and marine phytoplankton. *Ecosystem Health* 2(3):191-197.

Titus JG, Leatherman SP, Everts C, Kriebel D, Dean R (1985) *Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland*. US EPA document EPA 230-10-85-01. (accessed November 15, 1999), available at http://www.epa.gov/globalwarming/reports/pubs/sealevel/ oceancity/index.html

Titus JG (1998) Rising seas, coastal erosion, and the takings clause: How to save wetlands and beaches without hurting property owners. *Maryland Law Review* 57:1279-1399.

Titus JG, Narayanan V (1995) *The Probability of Sea-level Rise*. US Environmental Protection Agency, Office of Policy, Planning, and Evaluation, Climate Change Division. US EPA 230-R-95-008. US EPA, Washington, DC.

Trimble SW (1974) *Man-induced soil erosion on the southern Piedmont 1700-1970*. Soil Conservation Society of America, Ankeny, IA.

US EPA (1998) *Condition of the Mid-Atlantic Estuaries*. US EPA 600-R-98-147, Environmental Protection Agency, Office of Research and Development, Washington, DC.

USGS (1999a) *7.5-Minute Digital Elevation Model Data*. United States Geological Survey, Reston, VA (accessed 15 November 1999); available at http://edc.usgs.gov/glis/hyper/guide/ 7_min_dem#7m11

USGS (1999b) *Multi-Resolution Land Characteristics (MRLC)*. United States Geological Survey, Reston, VA (accessed 15 November 1999); available at http://edc.usgs.gov/glis/hyper/guide/ mrlc

Walker HA, Latimer JS, Dettmann EH (2000) Assessing the effects of natural and anthropogenic stressors in the Potomac estuary: Implications for long-term monitoring. *Environmental Monitoring and Assessment* 63:237-251.

Walker HJ, Coleman JM (1987) Atlantic and Gulf coastal province. In: Graf WL (ed), *Geomorphic Systems of North America, Centennial Special Volume 2*. Geological Society of America, Boulder, Colorado, p 51-110.

Warrick RA, Le Provost C, Meier MF, Oerlemans J, Woodworth PL (1996) Changes in sea level In: Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds) *Climate Change 1995: The Science of Climate Change*, Cambridge University Press, Cambridge, United Kingdom, p 359-405.

Wigley TML, Jones PD (1985) Influences of precipitation changes and direct CO_2 effects on streamflow. *Nature* 314:149-152.

Williams RG, Godshall FA (1977) *Summarization and interpretation of historical physical oceanographic and meteorological information for the mid-Atlantic region*. Washington, DC: US Department of Commerce.

Wood RJ, Austin H (personal communication) Climate forcing of a multispecies recruitment pattern in Chesapeake Bay.

Wray RD, Leatherman SP, Nicholls RJ (1995) Historic and future land loss for upland and marsh islands in the Chesapeake Bay, Maryland, US. *Journal of Coastal Research* 11:1195-1203

Box 7.1. Impacts of Global Warming on Waterfowl Wintering in the Chesapeake Bay *(Sorenson)*

The Chesapeake Bay is one of the most famous sites for wintering waterfowl in North America (Perry and Deller 1995). Early explorers to the area wrote of the vast numbers of waterfowl using this estuary. John James Audubon (1840) observed that "innumerable ducks fed in beds of thousands, or filled the air of Chesapeake Bay; and that great flocks of swans, looking like banks of snow, rested near the shores." Unlimited sport and market hunting during the 1700s and 1800s nearly decimated the once seemingly inexhaustible flocks. Further declines resulted from the drainage of millions of acres of wetlands on the prairie breeding grounds for agriculture in the 1900s along with the continental drought of the 1930s. Since this period, the advent of wetland conservation programs, hunting regulations and careful monitoring have led to a general recovery of waterfowl populations in North America. Presently, nearly one million ducks, geese and swans use Chesapeake Bay to feed and rest during the winter months and thousands more use it as a migration stopover point (Perry 1987). Both recreational hunting and waterfowl watching provide important sources of income to the MAR economy (Aiken 1999). Good water quality in the Bay's various wetland habitats is essential for maintaining healthy waterfowl populations (Funderbunk et al. 1991).

Waterfowl use of Chesapeake Bay has changed tremendously in the last 50 years. Wintering populations of most duck species have declined markedly since the 1950s (when systematic aerial surveys began) while population sizes of Canada Geese, Snow Geese, and Brant have increased (see table below, Perry and Deller 1995). Most of these changes are attributed to dramatic changes in waterfowl food resources in and around the Bay, particularly the wide-spread decline of submerged aquatic vegetation (SAV), a prime waterfowl food (Perry and Deller 1996). Loss of SAV is attributed to degradation of Bay water quality caused by pollution from the surrounding watershed. Excessive runoff of nutrients and sediments cause algal blooms and high turbidity that shade SAV and limit its growth (Hurley 1991). Also contributing to the destruction of major aquatic habitats for waterfowl has been the loss of oyster rock (Haramis 1999). Oysters filter water for food, improving water clarity conditions for SAV and other species. The ability of the Bay's biological systems to buffer nutrient enrichment has been greatly reduced by the decline of the oyster. An additional tax on waterfowl food resources are increasing summer populations of Canada Geese and exotic Mute Swans in recent years. A serious problem for managers, these birds consume what few SAV resources are left in the Bay as well as waterfowl foods grown in managed impoundments, food sources that are critical to migrating and wintering birds (Haramis, pers. comm).

A few species have adapted to the loss of SAV meadows by changing their diet. For example, *wintering swans and geese now feed largely in upland agricultural areas on waste corn and winter cover crops (Munro 1980, Perry 1987). Canvasbacks have switched from a diet of wild celery and sago pondweed to Baltic clams, an invertebrate that has become more plentiful in recent years (Perry and Uhler 1988, Haramis 1991a). Although populations of many duck species have rebounded in recent years due to excellent breeding ground conditions (e.g. Wilkins and Cooch 1999), numbers of Canvasbacks and other ducks wintering on the Bay have changed little, underscoring the influence of SAV on waterfowl use of the Bay. Species that were apparently unable to adapt to the loss of SAV have shown drastic declines in numbers (see table below) and several, including the Northern Pintail, Redhead, and American Wigeon have largely abandoned the Bay as a major wintering site (Haramis 1991b, Perry and Deller 1995).*

Global warming is likely to have a major impact on waterfowl populations in the coming decades, with changes projected to occur in both wintering and breeding habitats. Changes in MAR water temperature and quality resulting from climate change will likely affect waterfowl (and other birds) indirectly through changes in the distribution and abundance of food resources. Projections of warmer water temperatures, possible stream flow increases, and increasing human populations in the MAR suggest that water quality in the Bay and therefore SAV will continue to decline (Najjar et al. 2000), leading to further declines in SAV-dependent waterfowl. Warming water temperatures combined with continued heavy nutrient inputs are predicted to worsen benthic anoxia during the hot summer months, a recurring phenomenon of great concern in recent years. Prolonged lack of oxygen can trigger massive mortality and a decline in the diversity of other Bay benthic life (oysters, clams, mussels, crabs, and many invertebrates) that serve as important food sources for diving ducks and many other birds (Officer et al. 1984, Seliger et al. 1985). Sea level rise in the MAR may reduce the amount of suitable shallow water habitat available for wintering waterfowl. Finally, human population growth in the area will likely exacerbate various pressures already known to adversely affect waterfowl use of the Bay (e.g., hunting activity, recreational boating, habitat loss and degradation from construction of shoreline homes, increased pollutants, etc., Perry and Deller 1996). The additional stresses imposed by climate change on this already degraded ecosystem will make it increasingly difficult to restore and maintain quality waterfowl habitat in the Bay (e.g., U.S. EPA 1997) much less restore waterfowl populations to historic numbers.

Factors outside the MAR will also influence future waterfowl numbers in the Bay. The Prairie Pothole Region (PPR) of the north-central US and south-central Canada is known as the continent's "duck factory." Models that project warmer and drier conditions for this region imply fewer pothole wetlands and, in turn, fewer ducks breeding (and with less reproductive success) in the region (Sorenson et al. 1998, Sorenson et al. in prep.). Diminished breeding populations in the PPR could decrease waterfowl abundance in the Bay *because many of the ducks wintering in the Bay breed in the pothole region. These include the Mallard, Northern Pintail, American Wigeon, Canvasback, Redhead, Lesser Scaup, Common Goldeneye, Ruddy Duck, and Bufflehead. Breeding populations of these species fluctuate from year to year depending on wetland conditions on the breeding grounds. Historical fluctuations in numbers of birds using the Bay reflect, in part, these continental trends (Perry and Deller 1995).*

Virtually all of the Canvasbacks wintering in Chesapeake Bay are from the PPR and Chesapeake Bay is one of the major wintering areas for this species (Bellrose 1976). Band recovery data for this most famous Bay duck show that approximately 40% (346/875) of Canvasbacks breeding in the PPR winter in the Atlantic Flyway and 91% (316/346) of canvasback recoveries in the Atlantic Flyway are from MAR waters, 75% (236/316) of these on Chesapeake Bay. To estimate how prairie-breeding ducks like the Canvasback will be affected by climate change, we modeled future wetland conditions for this region using historical relationships between the Palmer Drought Severity Index (PDSI) and spring duck populations and wetland counts. We summarized projections of future climate conditions for this region from four different general circulation models (both sulfate and non-sulfate versions of Hadley and CCC models) in terms of the PDSI, allowing us to predict impacts of global warming on waterfowl and wetlands. Our analyses project declines in the number of ducks breeding in Prairie Canada ranging from 19% to 39% and 7% to 70% for the 2030s and 2090s, respectively (Sorenson et al., in prep.). Although many questions remain to be addressed, such as how alternate breeding grounds further north will be affected by climate change and how increasing climate variability will influence productivity, projections of declining breeding populations producing fewer young due to drier conditions on the prairies coupled with likely impacts of climate change on winter habitat quality bode poorly for future duck populations on MAR waters.

In summary, Chesapeake Bay supported far greater numbers of ducks historically than have been present in recent decades. Habitat loss and degradation, principally the Bay-wide reduction in SAV distribution and abundance is considered to be a primary cause of the decline of waterfowl populations that rely on this food. Although the influence of climate change on Bay water quality cannot be forecast precisely, our current knowledge of this region's sensitivity to climate suggests that warmer water temperatures, possible streamflow increases, and an increasing human population in coastal areas will negatively affect water quality in the Bay and therefore SAV and duck abundance. The potentially severe negative impacts of climate change on duck populations wintering in Chesapeake Bay should be viewed as an added impetus for expansion of current Bay restoration efforts.

Average wintering population sizes during the 1950s and 1985-1999 for 13 species of waterfowl wintering in Chesapeake Bay. Species are grouped according to major food items in the diet. Species marked with an asterisk formerly fed mainly on SAV, but switched to invertebrates (e.g., clams, molluscs, crustaceans) or field feeding (waste corn, winter cover crops) when SAV beds declined (Perry 1987). Species that were unable to adapt to the loss of SAV no longer winter in the Bay.

Species	*1950 – 1959 average (SE)*	*1985 – 1999 average (SE)*	*% Change*
SAV			
Redhead	*76,407 (9,586)*	*2,339 (396)*	*-97*
American Wigeon	*76,959 (14,177)*	*4,811 (730)*	*-94*
Northern Pintail	*40,422 (9,179)*	*2,643 (357)*	*-93*
Invertebrates			
Common Goldeneye	*22,076 (3,183)*	*5,676 (830)*	*-74*
*American Black Duck**	*143,043 (21,618)*	*44,803 (2,034)*	*-69*
*Canvasback**	*179,073 (35,498)*	*56,740 (2,277)*	*-68*
*Ruddy Duck**	*66,004 (12,510)*	*33,162 (6,925)*	*-50*
Scaup	*101,538 (37,937)*	*52,272 (7,055)*	*-49*
*Mallard**	*71,366 (17,820)*	*59,673 (2,579)*	*-16*
Bufflehead	*9,113 (2,068)*	*20,062 (1,828)*	*+55*
Agricultural Fields			
*Canada Goose**	*177,742 (26,532)*	*385,682 (27,512)*	*+54*
*Snow Goose**	*4,474 (1,783)*	*90,158 (9,821)*	*+95*
*Brant *^*	*12,852 (3,277)*	*21,664 (2,371)*	*+41*

^value for 1950-1959 is an average for 1955-59.

References

Aiken R. (1999) *1980-1995 Participation in Fishing, Hunting and Wildlife Watching, National and Regional demographic Trends*. Report 96-5, U.S. Fish and Wildlife Service, Washington, D.C.

Audubon JJ (1840). *The Birds of America*. New York: John James Audubon and J.B. Chevalier.

Bellrose F C: (1980) *Ducks, Geese, and Swans of North America*, Stackpole Books, Harrisburg, PA.

Funderbunk SL, Jordan SJ, Mihursky JA, and Riley D (eds). (1991) *Habitat Requirements for Chesapeake Bay Living Resources*, 2nd edition. Chesapeake Research Consortium, Inc., Solomons, Maryland.

Haramis GM (1991a) Canvasback. In S.L. Funderbunk, S.J. Jordan, J.A. Mihursky, and D. Riley (eds), *Habitat Requirements for Chesapeake Bay Living Resources*, 2nd edition. Chesapeake Research Consortium, Inc., Solomons, Maryland.

Haramis GM (1991b) Redhead. In S.L. Funderbunk, S.J. Jordan, J.A. Mihursky, and D. Riley (eds), *Habitat Requirements for Chesapeake Bay Living Resources*, 2nd edition. Chesapeake Research Consortium, Inc., Solomons, Maryland.

Haramis GM, Erwin RM, and Brinker DF (abstract only) (1999) Waterbirds in a changing environment: the Chesapeake Bay. Presentation at the 20th Annual Meeting of the Society of Wetland Scientists, Norfolk, Virginia 6-12 June, 1999.

Hurley LM (1991) Submerged Aquatic Vegetation. In S.L. Funderbunk, S.J. Jordan, J.A. Mihursky, and D. Riley (eds), *Habitat Requirements for Chesapeake Bay Living Resources*, 2nd edition. Chesapeake Research Consortium, Inc., Solomons, Maryland.

Munro RE (1980) Field feeding by Cygnus columbianus columbianus in Maryland. Pages 261-272 in G.V.T. Matthews and M. Smart, eds., Proc. Second Internat. Swan Symp., Internat. *Waterfowl Res. Bur*., Slimbridge, England. 396 pp.

Najjar RG, Walker H, Anderson P, Barron E, Bord R, Gibson J, Knight CG, Megonigal P, O'Connor R, Polsky C, Psuty N, Richards B, Sorenson L, Kennedy V, and Swanson R. 2000. The potential impacts of climate change on the Mid-Atlantic Coastal Region. *Climate Research* 14:219-233.

Officer CB, Biggs RB Taft JL, Cronin LE, Tyler MA, and Boynton WR (1984) Chesapeake Bay anoxia: Origin, development and significance. *Science* 223:22-27.

Perry MC (1987) Waterfowl of Chesapeake Bay. In S.K. Majumdar, L.W. Hall, and H.M. Austin (eds), *Contaminant Problems and Management of Living Chesapeake Bay Resources* The Pennsylvania Academy of Science.

Perry MC and Deller AS (1995) Waterfowl population trends in the Chesapeake Bay area. Pp. 490-500. In P. Hill and S. Nelson (eds.), *Toward a Sustainable Coastal Watershed: The*

Chesapeake Experiment. Proceedings of a Conference. Chesapeake Research Consortium Publication No. 149. Chesapeake Research Consortium, Inc. Edgewater, Maryland.

Perry MC and Deller AS (1996) Review of factors affecting the distribution and abundance of waterfowl in shallow-water habitats of Chesapeake Bay. *Estuaries* 19: 272-278.

Perry MC and Uhler FM (1988) Food habits and distribution of wintering canvasbacks, Aythya valisineria, on Chesapeake Bay. *Estuaries* 11: 57-67.

Seliger HH, Boggs JA, Biggley WH (1985) Catastrophic anoxia in the Chesapeake Bay in 1984. *Science* 228:70-73

Sorenson LG, Goldberg R, Root TL, and Anderson MG (1998) Potential effects of global warming on waterfowl populations breeding in the Northern Great Plains. *Climatic Change* 40: 343-369.

Sorenson LG, Goldberg R, Anderson MG, and Root TL In prep. Potential consequences of global warming for wetlands and ducks breeding in the Canadian Prairie Pothole Region.

U.S. Environmental Protection Agency. (1997) *Chesapeake Bay nutrient reduction progress and future directions*. EPA 903-R-97-030.

Wilkins KA and Cooch EG (1999) *Waterfowl Population Status, 1999*. U.S. Fish and Wildlife Service, Department of the Interior, Washington, D.C. 33 pp. + appendices.

Chapter 8. Ecosystems*

Introduction

Human activities alter the dynamics within ecosystems, which are 'interacting systems of biological communities and their non-living surroundings' (US Environmental Protection Agency [EPA] 1999), and result in changes of societal concern. This chapter focuses on ecosystems of the Mid-Atlantic Region (MAR), and addresses 4 questions that guide the National Assessment process: (1) What is the status of resources and what are the current stresses? (2) How might changes in climate and climate variability exacerbate or ameliorate current conditions? (3) What are the potential strategies for coping with risk and taking advantage of new opportunities? and (4) What are the policy-relevant research gaps? Other chapters in this report focus on forests, water, coastal systems, agriculture, and human health. Issues treated in these chapters are relevant, but to avoid redundancy are not treated in depth here. Cities and farms, important ecosystems in their own right, are discussed primarily in terms of how they affect other ecosystems, such as forests, wetlands, freshwaters, and coastal ecosystems.

Underlying our approach is the question: What aspects of ecosystems are important to people in the MAR? Unfortunately, our understanding of how people depend upon ecosystems and how people value different aspects of ecosystems is very incomplete. Based on currently available information, we emphasize aspects of ecosystems that we believe are important to residents of the MAR. Previous workshops (Climate Institute 1996a,b, Fisher et al. 1999, U.S. National Assessment 1997) provided useful guidance in identifying issues of concern. Assessment is an ongoing process. We expect to refine assumptions guiding the selection and treatment of specific assessment topics as our understanding improves about stakeholder values and the dependence of people on ecosystems.

Current Status and Stresses

The MAR (Figure 8.1), with its mountains, valleys and coastal plains, exhibits tremendous physical and ecological diversity (Jones et al. 1997). The lowlands of the Coastal Plain are characterized by estuaries, including the Chesapeake and Delaware Bays, and coastal wetlands. Rare terrestrial and inland communities arise in low-lying wetlands and in areas with sandy soils. Rising in elevation to the foothills of the Appalachians lies the Piedmont. Despite its dense

* This chapter is based on Rogers and McCarty, (2000) "Climate change and ecosystems of the Mid-Atlantic Region," *Climate Research*, 14:2. It appears with permission of Inter-Research.

population, the Piedmont still contains significant natural communities. The relatively rich soils and moderate climate of this region historically supported large expanses of deciduous forest but also made the land valuable for agriculture. To the west and north lie the Ridge and Valley System of the Appalachian Mountains and the Appalachian Plateau regions with their diverse forest communities and numerous, meandering streams and rivers. The ecological diversity of the MAR is in part a function of the large variations in topography, soils, and climate within the MAR.

Figure 8.1. Land use in the Mid-Atlantic Region.

(Source: US EPA MAIA program)

Prior to European settlement, forests covered about 95% of the MAR. Peak deforestation occurred in the mid-1800s, followed by substantial reforestation of agricultural lands in the last 100 years, and followed most recently by a slow loss of forests to urban development (Chapter 5). Forests currently cover 65% of the MAR; agriculture, wetlands and urban lands cover most of the rest, 25, 4, and 4%, respectively (Table 2.1). Agriculture is unevenly distributed: more than 70% of the Delmarva Peninsula is cleared, while parts of West Virginia and western Virginia remain more than 97% forested (Jones et al. 1997). Human population also is distributed evenly: the highest population densities occur along the urban corridor from Richmond VA, through Washington, DC, Baltimore MD, and Philadelphia PA, as well as in the Pittsburgh metropolitan area. During the past 30 years, human population in the region increased at approximately 0.7% per year, with higher rates in northern Virginia and the Delmarva Peninsula and low or negative growth rates in much of the western half of the MAR (Jones et al. 1997).

In addition to the urban and agricultural ecosystems that have substantial management, the MAR includes forested, wetland, freshwater and coastal ecosystems that are more natural. These ecosystems are described in the following subsections. Each discussion proceeds from value to status to stresses. Values determine the selection of attributes to describe status, and the selection and description of stresses emphasizes the key threats to valued attributes of ecosystems.

Forested Ecosystems

In addition to the direct economic value of forest products (Chapter 5 and Appendix F), forests also provide habitat for wildlife and play important roles in the cycling of water and nutrients in ecosystems (Daily et al. 1997). Public natural areas provide recreational opportunities and protect important communities and species. State and National Forests in Pennsylvania, West Virginia and Virginia provide some of the largest contiguous blocks of forest habitat in the region.

The forest ecosystems of the MAR include a diverse array of communities and species (Currie & Paquin 1987). The diversity of trees provides the basis for the wide range of forested community types found in the MAR (Barbour & Billings 1988). Forests of the MAR are dominated by oak-hickory communities, followed by maple-beech-birch communities; in localized regions, pine and mixed pine-hardwood forests are important forest types (Chapter 5). In addition, locally important terrestrial ecosystems include shrublands that provide crucial habitat for wildlife, and communities such as limestone and dolomite glades that are home to endangered plant species. On the coastal plain, extensive stands of northern pine-oak forest (also known as pine barrens) form unique habitats for rare plants and animals.

Forest ecosystems are stressed by fragmentation, which occurs as humans subdivide forest plots into ever smaller and more isolated sections. Fragmentation can result in reduced genetic diversity within populations, losses of species, and increases in undesirable non-native and weedy species (Noss & Csuti 1997). Large continuous forest patches exist in the region's southwestern area, but remaining forests in the region's urban corridor, Delmarva Peninsula, and the extreme eastern and western portions of Pennsylvania are heavily fragmented (Jones et al. 1997).

Ground level ozone and acid deposition (caused by NO_x and SO_x emissions from cars and power plants) stress forest trees (Likens et al. 1996), especially in Pennsylvania (Jones et al. 1997). Emissions have declined, and some areas are showing reduced levels of acid deposition (Schreiber 1995). Within the MAR, wet deposition of nitrates and sulfates is concentrated in Pennsylvania and declines to the south (Jones et al. 1997). Dry deposition of nutrients also contributes significantly to total inputs of nitrates and sulfates, but is more spatially variable, with dry deposition being concentrated closer to the source of pollutants than is wet deposition (Lovett 1994). Dry deposition can be responsible for over half the atmospheric inputs of nutrients.

Forests are also threatened by the invasion of non-native species. Non-native fungal diseases caused the effective extinction of two previously dominant trees, the American elm (*Ulmus americana*) and American chestnut (*Castanea dentata*), and threaten a third, the butternut hickory (*Juglans cinerea*) (Schlarbaum et al. 1999). Insect pests such as gypsy moths (*Lymantria dispar*) and balsam wooly adelgids (*Adelges piceae*) can severely stress forests (Office of Technology Assessment 1993).

Freshwater Wetland Ecosystems

Marshes and forested wetlands exist at the interface of terrestrial and aquatic ecosystems. Wetlands play a role in nutrient cycling, provide crucial fish and wildlife habitats, and remove pollutants from water (National Research Council 1995, Hammer 1997).

Several types of forested wetlands exist in the MAR. Northern swamp forests, dominated by red maple (*Acer rubrum*), are widespread. Red spruce-balsam fir and bald cypress-black gum wetland forests are found in some locations. Seasonally flooded forests along streams and rivers contain a mix of species. The MAR is home to one of the most critically endangered ecosystems in the United States: more than 98 percent of the original stands of the distinctive Atlantic white-cedar (*Chamaecyparis thyoides*) swamp forest of the Great Dismal Swamp of Virginia and northern North Carolina has been destroyed (Noss et al. 1995).

Non-forested wetlands or marshes in the region tend to be dominated by emergent plants such as cattails (*Typha*). These marshes often form the transition between uplands and freshwater ecosystems and include several species of sedges and rushes (National Research Council 1995). Losses of lowland evergreen shrub bogs (pocosins) and montane sphagnum bogs have exceeded 85% in some states in the region (Noss et al. 1995).

Drainage (for agricultural and urban purposes) is the major threat to freshwater wetlands. Total losses for all wetland types vary across the region. For Maryland, it is estimated that 73% of the original wetlands were drained between 1780 and 1980 (Noss et al. 1995). During the same period, approximately half of the wetlands in Pennsylvania and Virginia were destroyed, but losses were as low as 24% in West Virginia (Noss et al. 1995).

Additional threats to wetland ecosystems include pollution and non-native invasive species. High levels of chemical pollutants can accumulate in wetlands because pollutant-carrying sediments are trapped in wetland vegetation. Non-native invasive species, such as the European plant purple loosestrife (*Lythrum salicaria*), force out more beneficial native marsh plants.

Freshwater Ecosystems

The importance of freshwater ecosystems to residents of the MAR is difficult to put into words, in part because of the deep attachments that many people have to streams, rivers and reservoirs in their communities. Freshwater resources have multiple, sometimes conflicting, values. These include fishing, swimming, boating, water supply, beauty, flood control, navigation and transportation, and hydropower. Freshwater ecosystems support aquatic plants and animals, as well as organisms in wetland and terrestrial ecosystems that depend upon freshwater. Downstream estuaries, such as the Chesapeake Bay, also depend on freshwater inflows.

The diversity of freshwater mussels in the Southeast, which includes southern portions of the MAR, is unmatched by any other area in the world (Williams & Neves 1995). The number of mussel species historically known to occur ranges from 12 to 80 across the MAR's states, but the percentages at risk of extinction range from 46 to 71% (Williams & Neves 1995). The number of native freshwater fishes range from 70 to 201 across these states, and the percentages of these fish estimated to be imperiled range from 3 to 12% (Warren & Burr 1994).

Freshwater ecosystems, like terrestrial and wetland ecosystems, are stressed by habitat alteration, pollution and non-native invasive species. Stream habitat alterations include dams, road crossings, channelization, and loss of streambank vegetation. Dams are built to supply water for human uses, to control flooding, and to generate electricity. Dams also alter streamflow, sedimentation, temperature, and dissolved oxygen concentrations, impairing the ability of streams and rivers to support native fauna, especially freshwater fish and mussels. Dams occur in the highest densities in northeastern portions of the region and in southeastern Virginia; the largest electricity-producing structures are in mountainous areas (Jones et al. 1997).

Urban development diminishes the resilience of freshwater ecosystems to climate variability. Streamflows are moderated in vegetated watersheds because rain is absorbed into the ground and slowly released to streams. In contrast, in heavily paved urban areas, peak flows during storms are sharply increased, scouring stream banks, decreasing the reproductive success of aquatic insects and of fish that lay eggs near the edges of streams (Karr et al. 1986). Streamflows during dry periods are likewise diminished, significantly reducing available habitat for fish and aquatic insects.

The replacement of forests and wetlands by urban and agricultural ecosystems generally increases the input of sediments, nutrients and toxic chemicals into rivers, streams, lakes and estuaries. Sediments reduce water clarity, smother bottom organisms, and clog waterways; excessive inputs of nutrients cause eutrophication, and toxic chemicals affect plants and animals. Jones et al. (1997) describe the region's ecological status as resulted to its distribution of roads; agricultural, urban and forest land cover; land cover along stream banks; and areas with high potential for soil loss. Acid deposition and/or mine drainage are issues for about 1865 miles (3000 km) of trout streams in Pennsylvania (Carline et al. 1992), and 93% of 344 streams surveyed in western Virginia (Schreiber 1995).

Non-native invasive species, such as non-native fish and zebra mussels (*Dreissena polymorpha*), are other important stresses. Non-native fish prey upon native species and/or outcompete them for available food or habitat, posing serious threats in some areas (Frank McCormick, personal communication). Observations of zebra mussels in New York, Pennsylvania and West Virginia (U.S. Geological Survey: http://nas.er.usgs.gov/zebra.mussel) show that these mussels are invading the MAR. Although their effects in the MAR are currently minor, zebra mussels have had major impacts in areas near the MAR (e.g., in the Great Lakes region), suggesting the possibility of greater impacts in the future.

Coastal Ecosystems

The coastal zone of the MAR harbors a series of distinct ecosystems with enormous recreational, commercial and aesthetic value. The Chesapeake Bay is the largest and most productive estuary in the United States (U.S. EPA 1997). The Delaware Bay is an extremely important habitat for migratory shorebirds. Tidal salt marshes, occurring along the fringes of much of the coast, provide vital habitat for fish and wildlife and help to reduce the inputs of sediments, nutrients, and chemical pollutants from upland areas. Tidal marshes also help minimize damage from flooding, erosion, and storm surges.

The major threats to coastal ecosystems are habitat loss and pollution. Human development of coastal areas is associated with extensive loss of barrier island dunes, beaches and estuarine wetlands (Noss et al. 1995). Although 1.7 million acres (~0.69 million ha) of tidal and non-tidal wetlands still remain, over half of the original wetlands surrounding the Chesapeake Bay have been lost (Chesapeake Bay Program 1995a). Rising sea levels threaten many Chesapeake Bay communities. Historically, sea level has been increasing at a rate of about 1.6 inch per decade (3 to 4 mm per year) in the MAR (Titus & Narayanan 1995). Rising water levels threaten low-lying islands and change hydrologic and salinity characteristics of coastal wetlands. One-third of the Blackwater National Wildlife Refuge has been lost to sea-level rise in the last few decades (Climate Institute 1996a,b).

The greatest threat to the Chesapeake Bay (Chesapeake Bay Program 1995b) is eutrophication. Excessive nutrient inputs feed algae that block sunlight and reduce levels of dissolved oxygen in bottom waters when they die, sink and decompose. Submerged aquatic vegetation provides crucial habitat, but needs sunlight to grow. The combination of low oxygen conditions and reduced availability of submerged aquatic vegetation habitat seriously threatens fish, crabs and waterfowl. This problem is the motivation for a coordinated program to reduce nutrient inputs that has been in place since 1987 (U.S. EPA 1997).

Other threats to the Chesapeake and Delaware Bays include over-harvesting of commercially valuable species and loss of fish and shellfish to disease and toxic organisms. Oysters have not recovered from mass mortalities (losses >75%) in the 1980s caused by 2 parasites: *Perkinsus marinus* and *Haplosporidium nelsoni* (U.S. EPA 1998). These parasites, which cause oyster diseases known as Dermo and MSX, thrive in saline waters (15 to 30 ppt). Especially warm and dry years resulted in the intrusion of saline waters further up the estuaries than usual, resulting in the devastating incidence of oyster disease. *Pfiesteria*-caused fish kills have been centered in the southeast part of the region, especially the Pamlico Sound in North Carolina (Burkholder et al. 1995). *Pfiesteria* develop from cysts into toxin-producing/fish-killing cells when conditions are right (warm water, high nutrient loads, moderate salinity, poor flushing and large numbers of fish present; U.S. EPA 1998).

How Might Changes in Climate and Climate Variability Exacerbate or Ameliorate Current Conditions?

The following discussion of potential ecological responses to changes in climate and climate variability uses the Chapter 3 climate scenarios for the MAR, which are based on transient numerical models developed by the Hadley Centre for Climate Prediction and Research and the Canadian Climate Centre (CCC). These models project climate conditions for the next 100 years, accounting for sulfate aerosols and a 1% per year increase in carbon dioxide. Projections for sea-level rise are discussed in Chapter 7. Compared to 1990, sea level is projected to rise 4-12 inches (11 to 31 cm) by 2030 and 15-40 inches (39 to 102 cm) by 2095. Historical climatic conditions in the MAR provide context for these potential future changes. Over the last 100 years, average conditions have become warmer and wetter: average precipitation has gone up 10% (linearly) and average temperature has risen by 1°F. In the same period, the MAR region has seen a decrease in the number of very hot days (i.e. temperatures above 90°F [32°C]), yet an increase in the number of very cold days (i.e. below 0°F [-18°C]). This section's discussion of ecological impacts is rather general, due to uncertainties regarding the rate, magnitude, spatial distribution, and seasonality of temperature and precipitation changes.

Changes in long-term climate patterns and climatic variability would have significant effects on natural ecosystems, but will have different, and in many ways greater, impacts on the already-stressed ecosystems of the MAR. The preceding discussion of forested, wetland, freshwater and coastal ecosystems emphasized the combined impacts of habitat degradation/loss/fragmentation, pollution and non-native species. This section explains how changes in climate and climate variability might affect ecosystems already weakened by these other stresses (e.g., following discussion and Table 8.1).

When conditions change, some species benefit and some aspects of ecosystem functioning are potentially enhanced. Still, a discussion of the 'benefits' of climate change for ecosystems is problematic. The focus of conservation science is on minimizing or reversing changes in ecosystem structure and functioning, in part because of the value people place on local and familiar species and communities (Hunter & Hutchinson 1994). It is possible that timber productivity in the MAR could increase as a result of climatic changes, but it could take decades for the conditions underlying this projection to occur, and the new forests are likely to retain lower levels of native biodiversity due to the loss of some species that are unable to cope. Some species will become more abundant and widely distributed, as already seen in response to recent climate change (Alward et al. 1999, Parmesan et al. 1999, Thomas & Lennon 1999).

However, even some of these supposed benefits are likely to be reversed as expanding populations encounter new pathogens, parasites, competitors, and predators (Dukes & Mooney 1999, Harvell et al. 1999). In addition, increases in species may not be beneficial if those that respond favorably to climate change are invasive, exotic species already considered pests (Dukes & Mooney 1999).

It may be helpful to consider the ecological processes that determine how changes in climate and climate variability could affect ecosystem structure (e.g., which species are present, and in what abundances) and functioning. Environmental variables projected to change in the MAR include: carbon dioxide concentrations (increases are certain), temperature (increases are highly likely, but the distribution across space and time is uncertain), precipitation (projections are uncertain, increased frequency and intensity of severe storms and overall increases in precipitation are possible), sea level (already rising, highly likely to accelerate) and fires (predictions remain uncertain, Houghton et al.1996).

Table 8.1. The potential for adverse ecosystem impacts when changes in climate and climate variability interact with existing stresses.

Ecosystem	Existing stress	Interaction with climatic changes
Multiple ecosystems	Non-native invasive species	Climatic changes will probably tend to favor invasive species over rare and threatened species
	UV-B, air pollution	Adverse interactions with climatic changes (see text; Oppenheimer 1989)
Forests	Fragmentation	Fragmentation may hinder the migration of some species, and the loss of genetic diversity within fragments will reduce the potential for populations to respond to changing conditions through adaptive evolution (Peters & Darling 1985)
Freshwater wetlands	Habitat loss	Habitat loss reduces the resiliency of the MAR to the negative effects of storms because wetlands play a role in moderating destructively high stream-flows and pollution runoff
Freshwaters	Habitat degradation: stream channelization	Straightening stream channels reduces their resiliency to destructively high flows
	Altered streamflow in urban areas	Increases in the frequency or intensity of storms could exacerbate this existing problem
	Pollution: nutrients, sediments, toxics	Increased precipitation could increase pollution runoff
Coastal ecosystems	Habitat loss	Accelerated sea-level rise could accelerate the loss of coastal wetlands
	Pollution: nutrients, sediments, toxics	Increased precipitation could increase pollution runoff
	Disease and toxic organisms	Changes in temperature, precipitation and sea level may promote conditions favorable to Dermo, MSX and *Pfiesteria*

Species may respond to changes in environmental variables by adapting, shifting their range, changing their abundance, or by disappearing altogether. Rapid evolution might help species with short generation times, such as insects and annual plants, to adapt to environmental changes (Rodríguez-Trelles et al. 1998). Evolution may be slower in long-lived species, such as trees (Mátyás 1997). Optimal climates for the MAR's dominant tree species in maple-beech-birch and oak-hickory forest communities are predicted to shift to the north (Iverson & Prasad 1998), while conditions for southern species such as longleaf and loblolly pine will become more favorable in the MAR (Watson et al. 1996). Pest species may shift north or increase in abundance if temperatures increase. Shifts in fish species from cool and cold water species to warmer water species are likely (U.S. EPA 1995). Species (or whole coastal wetland ecosystems, in the case of sea-level rise) could fail to shift their range if they cannot disperse fast enough to keep pace with change, if landscape features (such as cities) block their movement, or if new suitable habitats are simply not available (Pitelka and the Plant Migration Workshop Group 1997). A species may fail to colonize a prospective habitat if it cannot adapt to that habitat's soils, to the level of human development, or if it cannot coexist with other species already in residence.

Invasive species share a set of traits that predispose them to invade pre-existing communities successfully (Dukes & Mooney 1999). These traits include a high rate of population growth, which contributes to rapid colonization; ability to move long distances, which contributes to colonizing distant habitats; tolerance of close association with humans; and tolerance of a broad range of physical conditions (Rejmánek & Richardson 1996). Since the traits of successful invaders tend to increase their resilience to a variety of disturbances, including climate and non-climate stresses, climate change could work in concert with other stresses to further reduce populations of rare and endemic species, while increasing populations of already abundant, widespread species (Dukes & Mooney 1999). MAR residents would be unlikely to welcome the northward spread of problem species such as kudzu and myriad non-native species currently damaging ecosystems in Florida, such as melaleuca, brazilian pepper, and a variety of non-native freshwater fishes.

In addition to potentially exacerbating problems with non-native invasive species, changes in climate and climate variability might interact adversely with other existing stresses (see Table 8.1). Oppenheimer (1989) proposed that the concentrations of hydrogen peroxide—an oxidant that is toxic to terrestrial vegetation and to many aquatic organisms—in fog, precipitation and surface waters may increase due to the combined effects of increased temperature, UV-B, NO_x and hydrocarbons. Increased levels of acidity and ground-level oxidants (including hydrogen peroxide) could degrade forests and watersheds and accelerate nutrient fluxes, leading to eutrophication of fresh- and coastal waters.

Stream channelization and wetland loss increase the MAR's vulnerability to precipitation changes. An increase in the frequency or intensity of storms could exacerbate existing problems. According to the Watson et al. (1998), increases in hydrological variability (larger floods and longer droughts) could result in increased sediment loading and erosion, degraded shorelines, reductions in water quality, and reduced stability of aquatic ecosystems, with the greatest impacts occurring in urban areas with a high percentage of impervious surface area. These changes may reduce productivity and biodiversity in streams and rivers. Increases in water temperature may lower dissolved oxygen concentrations, particularly in summer low-flow periods in mid-latitude areas. Altered precipitation and temperature patterns will affect the seasonal pattern and variability of water levels of wetlands, potentially affecting valued aspects of their functioning, such as flood protection, carbon storage, water cleansing, and waterfowl/wildlife habitat (Watson et al. 1998).

Watershed responses to climate change are complex. For example, the simulated impact of temperature and precipitation changes upon simulated fluxes of energy, water, carbon and nutrients is reduced by incorporating how the canopy physiology in forested watersheds adjusts to elevated concentrations of carbon dioxide (Band et al. 1996). Inputs of nutrients and other pollutants into aquatic habitats will vary with rainfall and other characteristics of the watershed (Meyer & Pulliam 1992). Farmers are likely to adapt to climate change (Chapter 4). Possible agricultural changes relevant to natural ecosystems include changes in the types of land cover and the use of toxic chemicals and fertilizers. Increases or decreases in agricultural pollution will thus depend upon both human responses to climate change and changes in runoff associated with altered precipitation patterns. Species will shift their geographic ranges at different rates, and some may be unsuccessful in reaching or colonizing new habitats. Because species will be affected differently by climatic changes, relationships among species will be altered. Ecosystem functions that depend upon interactions among species could be affected. The probability of ecosystem disruption and species extinction is positively related to the rate of climate change (Watson et al. 1998). Ecosystems are complex, and highly interconnected, making the effects of climate change extremely difficult to predict.

Losses of coastal wetlands are relatively easy to predict. Accelerated sea-level rise is likely and coastal wetlands are unlikely to be able to migrate inland quickly enough, particularly because the MAR's coast is heavily developed (Chapter 7). Changes in climate and climate variability would affect the Chesapeake and Delaware Bays via changes in temperature, sea level, precipitation, wind and water circulation patterns. Temperature is particularly important because it influences activity, feeding, growth, metabolism and reproduction. (See Chapter 7 for discussion of some of the consequences of climate change upon coastal ecosystems.) The incidence of two oyster diseases, Dermo and MSX, could increase if sea-level rise mimics saltwater intrusions caused in the mid-1980s by unusually warm and dry years that resulted in mass mortalities of oysters. If summer precipitation increased and resulted in increased streamflow, it could have an ameliorating effect by reducing salinities. Fish kills caused by Pfiesteria tend to occur in warm water with high nutrient loads, moderate salinity and poor flushing (U.S. EPA 1998). Harmful algal blooms caused by *Aureococcus anopahagefferens* are also sensitive to changing climate conditions and are favored by warm, saline, eutrophic waters (Beltrami 1989). Uncertainty in projections of climate and nutrient loading make it difficult to predict the future extent and magnitude of these problems.

What Are the Potential Strategies for Coping with Risk and Taking Advantage of New Opportunities?

Maintaining resilience in ecosystems is the primary objective of adaptation strategies to protect wildlife and habitats (Watson et al. 1996, Markham & Malcolm 1996). Compared to other sectors, adaptation options for ecosystems are limited, and their effectiveness is uncertain (Watson et al. 1998).

There is general agreement that humans already have overwhelming impacts on natural ecosystems (Vitousek et al. 1997) and that this interferes with the functioning of ecosystems in ways that are detrimental to our well being. A panel of 11 scientists (Daily et al. 1997, p.1) was "certain" that "ecosystem services are essential to civilization," that "human activities are already impairing the flow of ecosystem services on a large scale," and that "if current trends continue, humanity will dramatically alter virtually all of the earth's remaining natural ecosystems within a few decades." The primary threats are: land-use changes that cause loss of biodiversity; disruption of carbon, nitrogen and other biogeochemical cycles; human-caused nonnative species invasions; releases of toxic substances; possible rapid climate change; and depletion of stratospheric ozone. This panel was "confident that … the functioning of many ecosystems could be restored if appropriate actions were taken in time" (Daily et al. 1997, p.1).

Attempts to take timely action to minimize climate-related risks are hampered by: (1) the perception by some decision-makers that the impacts of climate change are distant and speculative and therefore do not warrant action, (2) the difficulty in making site-specific predictions of future climate at a scale relevant to ecological processes (Root & Schneider 1993), and (3) the global nature of climate change requiring large-scale efforts integrating local, regional, and national activities. It is increasingly unlikely that greenhouse gas emissions will be reduced quickly enough to fully prevent significant warming. Likewise, measures directed at specific effects of climate change are unlikely to be applied widely enough to protect the range of ecosystem services upon which society depends. Fortunately, reducing the impacts of nonclimate stresses on ecosystems would also buffer ecosystems from negative effects of climate change. The range of potential strategies (Table 8.2) is broad enough to involve every resident of the MAR. Activities that conserve biological diversity, reduce fragmentation and degradation of habitat, and increase functional connectivity among habitat fragments will increase the ability of ecosystems to resist anthropogenic environmental stresses, including climate change (Markham & Malcolm 1996; Watson et al. 1998, p. 279).

Several factors make it challenging to adopt effective strategies for addressing climate and non-climate related risks to ecosystems. Setting priorities among strategies is difficult, partly because so little is known about the effectiveness of alternative actions intended to reduce ecosystem vulnerability. Caution is needed in developing adaptive measures because lack of information and/or conflicting ecosystem goals can lead to maladaptation. For example, diverting hazardous pollutants from water to air or land may benefit aquatic ecosystems but cause problems in terrestrial ecosystems. Likewise, corridors connecting habitat fragments may help some species disperse but might also allow aggressive invasion species to enter fragile habitats (Simberloff et al. 1992).

Table 8.2. Strategies to increase resilience of ecosystems to climate change and other stressors.

Stressor	Strategy/human response	Examples
Physical habitat alteration	Conservation	Establish protected areas Protect natural features of managed landscapes Minimize water consumption (to protect aquatic habitats)
	Restoration	To date: Long-leaf pone ecosystems, Everglades hydrology Tall-grass prairie Manage species directly
Pollution (resulting in eutrophication, acid deposition, increased UV-B radiation, other problems)	Regulate emissions	Control SO_2, NO_x, and VOC [volatile organic compounds] emissions from power plants and motor vehicles Regulate emissions of CFCs (e.g., Montreal Protocol) Reduce point source water pollution
	Regulate land use and nonpoint sources	Protect riparian buffers Change urban and agricultural practices
Non-native invasive species	Prevent introduction and establishment	Monitor areas around ports of entry and eliminate new populations
	Manage established populations	Release biological controls Eradicate invasive species
Global climate change	Reduce greenhouse gas emissions	Reduce emissions from power plants and motor vehicles Conserve energy
	Reduce climate impacts via reduction of other stressors	Increase ecosystem resiliency to climate impacts by protecting habitat, reducing pollution, controlling invasive species
	Reduce climate change impact directly	Schedule dam releases to protect stream temperatures Transplant species Establish migration corridors

Research that can help to reduce uncertainties is discussed in the next section, but we are still left with societal issues that need to be addressed. There is an urgent need for expanded dialogue so that societal priorities for ecosystem protection can be articulated. Public education, supported by ongoing research, is essential to inform the dialogue. Decisions need to be made, with the understanding that the basis for decisions changes with increasing information.

What Are the Policy-Relevant Research Gaps?

The purpose of assessing the potential impacts of climate change upon ecosystems is to provide information to decision-makers and stakeholders about the consequences of possible actions. Research should be guided to meet these information needs. Crucial research gaps include:

- **Ecosystem valuation.**
  We need to improve our understanding of how society depends upon ecosystems and how people value different aspects of ecosystems. This information should be used in developing research priorities and in choosing among alternatives for increasing ecosystem resiliency.

- **Ecosystem functioning.**
  We still lack basic information about how ecosystems function, limiting our ability to predict and understand how changes in one part of an ecosystem affect other parts. Such changes include how current stresses, such as habitat loss and alteration, pollution, and non-native species are affecting ecosystems, and how these stresses could interact with climate change. The limits of our understanding are highlighted by the current difficulties in attempting to predict the ecological impacts of climate change.

- **Monitoring.**
  Indicators of the status of ecosystems, and the magnitude and distribution of stresses upon ecosystems, should be included in long-term ecological monitoring plans. Early warning signs of potential losses of valued ecosystem functions should be identified and included as indicators.

- **Management options.**
  Understanding the effectiveness of various management strategies is crucial to targeting limited resources for ecological protection.

An example drawn from experiences with the Chesapeake Bay illustrates the value of these areas of research. Concern about declines in fish, crabs and waterfowl stimulated research into ecosystem functioning and human impacts, revealing the links between land-use practices, nutrient runoff, overgrowth of algae, loss of submerged aquatic vegetation and depressed levels of dissolved oxygen in bottom waters, and the animal declines. Ecological monitoring was essential to the discovery of these relationships, and to measuring the effectiveness of ongoing efforts to control inputs of nutrients to the Bay. Such experience can serve as a model to design an integrated research strategy for the other major types of MAR ecosystems likely to be sensitive to climate change.

References

Alward RD, Detling JK, Michunas DG (1999) Grassland vegetation changes and nocturnal global warming. *Science* 283: 229–231.

Band LE, Mackay DS, Creed IF, Semkin R, Jeffries D (1996) Ecosystem processes at the watershed scale: sensitivity to potential climate change. *Limnol Oceanogr* 41(5): 928–938.

Barbour MG, Billings WD (eds) (1988) *North American terrestrial vegetation*. Cambridge University Press, New York.

Beltrami EJ (1989) Brown tide dynamics as a catastrophic model. In: Cosper EM et al. (eds) *Novel phytoplankton blooms*. Springer-Verlag, New York, p 307-315.

Burkholder JM, Glasgow HB Jr, Hobbs CW (1995) Fish kills linked to a toxic ambush-predator dinoflagellate: distribution and environmental conditions. *Mar Ecol Prog* Ser 124: 43–61.

Carline RF, Sharpe WE, Gagen CJ (1992) Changes in fish communities and trout management in response to acidification of streams in Pennsylvania. *Fisheries* 17: 33–38.

Chesapeake Bay Program (1995a) Chesapeake Bay: introduction to an ecosystem. Chesapeake Bay Program Headquarters, Annapolis, MD (accessed: August 1999); available at http://www.gmu.edu/bios/bay/cbpo/intro.htm

Chesapeake Bay Program (1995b) *The state of the Chesapeake Bay*. Chesapeake Bay Program Headquarters, US EPA, Annapolis, MD.

Climate Institute (1996a) Conference brings together broad local group to explore impact of sea level rise on Chesapeake. *Climate Alert* 9(6), Climate Institute, Washington, DC (accessed: August 1999); available at: http://www.climate.org/ Climate-Alert/articles/9.6/index.html

Climate Institute (1996b) Changing climate, rising sea level, and Chesapeake Bay: questions and answers. *Climate Alert*, Climate Institute, Washington, DC (accessed: August 1999); available at: http://www.climate.org/conferences/ChesapeakeConfStatement.html

Currie DJ, Paquin V (1987) Largescale biogeographical patterns of species richness of trees. *Nature* 329: 326–327.

Daily GC, Alexander S, Ehrlich PR, Goulder L, Lubchenco J, Matson PA, Mooney HA, Postel S, Schneider SH, Tilman D, Woodwell GM (1997) Ecosystem services: benefits supplied to human societies by natural ecosystems. *Issues in Ec*ology No. 2. Ecological Society of America, Washington, DC.

Dukes JS, Mooney HA (1999) Does global change increase the success of biological invaders? *Trends Ecol Evol* 14: 135–139.

Fisher A, Barron E, Yarnal B, Knight CG, Shortle J (1999) *Climate change impacts in the Mid-Atlantic Region—a workshop report*, September 9–11, 1997. The Pennsylvania State University, University Park.

Hammer DA (1997) *Creating freshwater wetlands*, 2nd edn. CRC Lewis Publishers, Boca Raton, FL.

Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes DJ, Hofmann EE, Lipp EK, Osterhaus ADME, Overstreet RM, Porter JW, Smith GW, Vasta GR 1999. Emerging marine diseases—climate links and anthropogenic factors. *Science* 285: 1505–1510.

Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds) (1996) *Climate Change 1995: the science of climate change*. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Hunter ML Jr, Hutchinson A (1994) The virtues and shortcomings of parochialism: conserving species that are locally rare, but globally common. *Conserv Biol* 8: 1163–1165.

Iverson LR, Prasad AM (1998) Predicting abundance of 80 tree species following climate change in the eastern United States. *Ecol Monog*r 68 :465–485.

Jones KB, Riitters KH, Wickham JD, Tankersley RD Jr, O'Neill RV, Chaloud DJ, Smith ER, Neale AC (1997) *An ecological assessment of the United States Mid-Atlantic region: a landscape atlas*. US Environmental Protection Agency, EPA/600/R097/130, Washington, DC.

Karr JR, Fausch KD, Angermier PL, Yant PR, Schlosser IJ (1986) Assessing biological integrity in running waters: a method and its rationale. *Ill Nat Hist Surv Spec* Publ 5.

Likens GE, Driscoll CT, Buso DC (1996) Long-term effects of acid rain: response and recovery of a forest ecosystem. *Science* 272: 244–246.

Lovett GM (1994) Atmospheric deposition of nutrients and pollutants in North America: An ecological perspective. *Ecological Applications* 4: 629-650.

Markham A, Malcolm J (1996) Biodiversity and wildlife: adaptation to climate change. In: Smith JB, Bhatti N, Menzhulin G, Benioff R, Budyko MI, Campos M, Jallow B, Rijsberman F (eds) *Adapting to climate change, assessments and issues*. Springer-Verlag, New York, p 384–398.

Mátyás C (1997) Genetics and adaptation to climate change: a case study of trees. In: Huntley B et al. (eds) NATO ASI Series, Vol 147, *Past and future rapid environmental changes: the spatial and evolutionary responses of terrestrial biota*. Springer-Verlag, Berlin, p n–n.

Meyer JL, Pulliam WM (1992) Modification of terrestrial-aquatic interactions by a changing climate. In: Firth P, Fisher SG (eds) *Global climate change and freshwater ecosystems*. Springer-Verlag, New York, p 177–191.

National Research Council (1995) *Wetlands: characteristics and boundaries*. National Academy Press, Washington, DC.

Noss RF, Csuti B (1997) Habitat fragmentation. In: Meffe GK, Carroll CR (eds) *Principles of conservation biology*, 2nd edn. Sinauer Associates, Inc, Sunderland, MA, p 269–304.

Noss RF, La Roe ET III, Scott JM (1995) *Endangered ecosystems of the United States: a preliminary assessment of loss and degradation*. Biological Report 28. US Department of the Interior, National Biological Service, Washington, DC.

Office of Technology Assessment (OTA) (1993) *Harmful non-indigenous species in the United States*, OTA-F-565. US Congress, US Government Printing Office, Washington, DC.

Oppenheimer M (1989) Climate change and environmental pollution: physical and biological interactions. *Clim Change* 15: 255–270.

Parmesan CN, Ryrholm C, Stefanescu JK, Jill CD, Thomas H, Descimon B, Huntley L, Kaila J, Kullberg T, Tammaru WJ, Tennet JA, Warren T, Warren M (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399: 579–583.

Peters RL, Darling JDS (1985) The greenhouse effect and nature reserves. *Bioscience* 35: 707–717.

Pitelka LF and the Plant Migration Workshop Group (1997) Plant migration and climate change. *Am Sci* 85: 464–473.

Rejmánek M, Richardson DM (1996) What attributes make some plant species more invasive? *Ecology* 77: 1655–1661.

Rodríguez-Trelles F, Rodríguez MA, Scheiner SM (1998) Tracking the genetic effects of global warming: Drosophila and other model systems. *Conserv Ecol* [online] 2(2):2, Ecological Society of America, Washington, DC (accessed: August 1999); available at http://www.consecol.org/vol2/iss2/art2.

Rogers CE, McCarty JP (2000) Climate change and ecosystems of the Mid-Atlantic Region *Climate Research*. Special 2000 14(2): 235-244.

Root TL, Schneider SH (1993) Can large-scale climatic models be linked with multiscale ecological studies? *Conserv Biol* 7: 256–270.

Schlarbaum SE, Hebard F, Spaine PC, Kamalay JC (1999) *Three American tragedies: chestnut blight, butternut canker, and Dutch elm disease*. USDA Forest Service, Southeastern Research Station, Asheville, NC.

Schreiber K (1995) Acidic deposition. In: La Roe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) *Our living resources: a report to the nation on the distribution, abundance, and health of US plants, animals, and ecosystems*. US Department of the Interior, National Biological Service, Washington, DC, p 418–420.

Simberloff DJ, Farr A, Cox J, Mehlman DW (1992) Movement corridors: conservation bargains or poor investments? *Conserv Biol* 6: 493–504.

Thomas CD, Lennon JJ (1999) Birds extend their ranges northwards. *Nature* 399: 213.

Titus JG, Narayanan VK (1995) *The probability of sea-level rise*. US Environmental Protection Agency, EPA 230R95008, Washington, DC.

US Environmental Protection Agency (1995) *Ecological impacts from climate change: an economic analysis of freshwater recreational fishing*. US EPA, EPA 230-R-96-004, Washington, DC.

US Environmental Protection Agency (1997) *Chesapeake Bay nutrient reduction progress and future directions*. US EPA, EPA903-R-97-030, Washington, DC.

US Environmental Protection Agency (1998) *Condition of the Mid-Atlantic estuaries*. Office of Research and Development, US EPA, EPA 600-R-98-147, Washington, DC.

US Environmental Protection Agency (1999) *Terms of environment*. US EPA, Washington, DC (accessed: February 1999); available at http://www.epa.gov/OCEPAterms/

US National Assessment (1997) *US Climate Forum: the consequences of global change for the nation*. US Department of Commerce, Washington, DC, November 12–13, 1997 (accessed: August 1999); available at http://www.nacc.usgcrp.gov/meetings/forum/

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of earth's ecosystems. *Science* 277: 494–499.

Warren ML, Burr BM (1994) Status of freshwater fishes of the United States: overview of an imperiled fauna. *Fisheries* 19(1): 6–18.

Watson RT, Zinyowera MC, Moss RH (eds) (1998) *The regional impacts of climate change: an assessment of vulnerability*. Cambridge University Press, New York.

Watson RT, Zinyowera MC, Moss RH, Dokken DJ (eds) (1996) *Climate change 1995: impacts, adaptations and mitigation of climate change: scientific-technical analyses*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Williams JD, Neves RJ (1995) Freshwater mussels: a neglected and declining aquatic resource. In: La Roe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) *Our living resources: a report to the nation on the distribution, abundance, and health of US plants, animals, and ecosystems*. US Department of the Interior, National Biological Service, Washington, DC, p 177–179.

Box 8.1 Climate Change and Bird Distributions in the Mid-Atlantic Region (Price)

There are both economic and ecological reasons to care about birds. Watching and feeding birds is big business, generating about $885 million annually in retail sales within the Mid-Atlantic region (MAR) (Bird Conservation 1997).

It is difficult to estimate how changes in bird distributions might affect the economics of watching and feeding birds. Spending would shift as some birdwatching sites become less favorable and others become more favorable. Although many bird watchers might adjust to diminished species richness, they will experience the loss of well-being that accompanies a reduction in their preferred activities.

Also of concern are potential indirect costs of changes in bird distributions and how these changes will affect ecosystems. Birds provide important ecological services including seed dispersal, plant pollination and pest control. For example:

- *Blue Jays are a major disperser of oak seeds.*
- *Birds eat up to 98% of the overwintering codling moth larvae in orchards.*
- *Wood warblers are largely responsible for holding down numbers of spruce budworm larvae, eating up to 98% of the non-outbreak larvae.*
- *While the white-footed deer mouse is a more important predator of gypsy moths, birds also hold down numbers of this pest.*

The table shows results from statistical models that associate bird distributions first with current climatic conditions (1985-1989) and then with temperatures increased by 1.8º F (1º C) from the CCC model (Price 2000; Price, in press; 1995). This temperature change is within the ranges suggested in Figure 3.5. The gross change represents the overall loss in the number of perching (passerine) species currently found in the area. The net change represents the loss of species currently found there, offset by species moving in from outside the area. Thus a 1.8º F increase in temperature could lead to a loss of 7% of the passerine species currently found in the MAR. These losses would be somewhat offset by birds colonizing from outside the region so the net change would be 3% fewer species than currently found there. This 3% translates into fewer than 5 perching species in the MAR.

The colorful wood warblers are a subset of the species from the table, are popular among bird watchers, and are important predators of insects. The same increase in temperature could lead to a gross loss of 14% of MAR warblers. This could be important because it is *unknown whether the species colonizing the region would perform the same ecological services of the species currently found there. Even if they did, the net change would still be an 8% reduction in the number of warbler species currently found in the MAR.*

How quickly these changes might occur is unknown. Across locations, the average latitude for warblers has shifted north by more than 43 miles over the last 20 years. This suggests such changes could occur relatively quickly.

In summary, climate change will affect bird distribution, perhaps quickly, and the magnitude of ecological and economic effects is unknown.

Changes in number of perching bird species

	With 1.8º temperature increase	
	Gross change (%)	**Net Change (%)**
Region	**-7**	**-3**
Delaware	-3	0
Maryland	-4	-1
New Jersey	-5	-1
New York	-10	-4
North Carolina	-5	-2
Pennsylvania	-9	-3
Virginia	-4	-1
West Virginia	-7	-3

References:

Price JT (1995) *Potential impacts of global climate on the summer distributions of some North American grassland birds*. Ph.D. dissertation, Wayne State University: Detroit, MI.

Bird Conservation (1997) "What's a bird worth? Bird Conservation Spring Migration 1997, *6-8.*

Price JT In press. *Potential impacts of climate change on the summer distribution of some North American grassland birds*. US Geological Survey, Northern Prairie Wildlife Research Center.

Price JT (2000) Modeling the Potential Impacts of climate Change on the Summer distribution of Michigan's Nongame Birds, *Michigan Birds and Natural History* 7(1): 3-13.

Chapter 9. Human Health*

Introduction & Overview

Reports by the Intergovernmental Panel on Climate Change (IPCC) (McMichael et al. 1996) and World Health Organization (WHO) (WHO 1990, 1996) discuss many ways that climate change could affect human health. Examples include changes in the frequency and intensity of extreme events such as heat waves, floods, and wind storms, changes in the geographic range and activity of disease vectors[1] such as mice and mosquitoes, changes in weather conditions affecting air and water quality, and changes in food supplies due to changes in growing conditions. For the global scale, the IPCC (McMichael et al. 1996) and WHO (1996) conclude that on balance, adverse health impacts of projected climate change will substantially outweigh the beneficial health impacts.

Because climatic and non-climatic factors affecting health vary across geographical areas and change over time, the relative importance of climate to human health varies from region to region and within regions over time (Patz et al. 1996; McMichael 1997). This chapter explores potential health impacts from climate change in the Mid-Atlantic Region (MAR). At the initial Workshop on Climate Change Impacts in the MAR, stakeholders expressed strong interest in the impacts of climate change on human health (Fisher et al. 1999). Their concerns included increased illness and mortality related to more frequent and/or severe extreme heat events, new or re-emergent diseases because of changes in the dynamics of transmission, distribution and resistance of disease agents, and increased contamination of public and private water supplies from increased flooding.

This chapter begins by discussing the relationships between climate and health. It next provides context in an overview of the region's current health status and stresses. We then examine selected climate-related health risks in the region.

* This chapter draws upon Benson et al. (2000) "Climate change and health in the Mid-Atlantic Region," *Climate Research*, 14:2. It appears with permission of Inter-Research. The chapter authors appreciate helpful comments from Ann Fisher, Janet Gamble, and members of the MARA Advisory Committee. We also appreciate the research assistance of Christine Jocoy, Cindy Wang, and Lubing Wang.

[1] A disease vector is an organism that acts as a host for and transmits a pathogen. Vector-borne diseases include Lyme disease and malaria, whose vectors are ticks and mosquitos, respectively.

Health Sensitivity and Vulnerability to Climate Change

General circulation model (GCM) results produced for the United States Global Climate Research Program (USGCRP) National Assessment predict future climate, focusing on the years 2030 and 2095. The climate projections are from the Hadley Centre for Climate Prediction and Research and the Canadian Centre for Climate Modeling and Analysis (CCC). As described in Chapter 3, they indicate a warmer, probably wetter and possibly stormier climate for the MAR. The MAR has one of the lowest levels of projected future warming among regions of the United States (US). The GCM results also indicate increases in precipitation and in its variance. The Hadley model projects the greatest increase in summer precipitation while the CCC model projects little summer increase but more increase in winter precipitation. Because of the uncertainty of these models, we examine the potential health effects of a somewhat warmer and possibly wetter MAR.

The effects of climate change on human health can be through direct or indirect pathways (McMichael et al. 1996; WHO 1996). Direct effects would occur predominantly through changes in the frequency and severity of weather events (e.g., temperature, wind, precipitation) that directly affect human physiology or psychology. Indirect effects of climate change on health would occur when climate change affects other biological or geophysical systems that influence human health. For example, climate change could influence the range and activity of disease vectors, the ecology of water-borne and food-borne infectious agents, the levels of air pollutants, and the productivity of food systems.

Compared with indirect effects of climate on human health, direct health effects are understood better and have received more attention in the literature (McMichael et al. 1996). The complex chain of causality from climate change through biophysical systems to human disease risks makes it more difficult to quantify indirect health effects (Haines and McMichael 1997). Yet, the emerging view of health impacts at the global level suggests that indirect impacts may be substantially more important than direct impacts (McMichael et al. 1996).

Human health sensitivity to climate does not necessarily imply significant risk or vulnerability to global climate change. Even if climate change increases some health risks, the region could adapt to reduce its vulnerability. Vulnerability is the extent to which health is susceptible to harm from climate change. It is a function of sensitivity of humans and their environment to climate and of how humans and the environment adapt. Factors affecting regional vulnerability to climate change include (1) the nature and extent of the change in regional climatic variables that directly or indirectly affect human health, (2) the degree to which humans are sensitive to these changes, (3) the ability of humans to adapt to new climates, (4) and the state of the current public health infrastructure and the degree to which it will be maintained and/or improved in the future. The incremental costs and secondary impacts of adaptation measures undertaken because of climate change must also be considered

Box 9.1 *Health Risk versus Vulnerability*

It is useful to distinguish between risk and vulnerability. For instance, research might show that as the region becomes warmer, urban areas are at higher risk for heat-related illnesses and death, particularly during heat waves. However, the region could adapt to reduce its vulnerability through measures such as increasing air conditioning usage or implementing hot weather warning systems. To be effective, adaptation must be technologically feasible, affordable, and acceptable. There often are trade-offs among these characteristics. For example, increased air conditioning is costly and uses more energy, which can further contribute to warming and pollution in urban areas. Or control measures might not be used by some vulnerable groups (such as susceptible elderly people who feel they cannot afford air conditioning or transportation to locations with air conditioning). Thus the availability of adaptation measures does not ensure their adoption, but successful adaptation to the (climate-induced) increase in risk means low vulnerability to that risk.

The impacts of weather and ecological change on human health in a region are moderated by several factors. In the short- to medium-term, these factors include the protections or risks associated with the region's existing natural and built environment, genetic endowment, socioeconomic conditions, population density, age, health, immune and nutritional status, access to health care, and public water and sanitation (Kalkstein et al. 1996). Presently,

- Most people in the MAR live and work in structures that protect them from the elements; many structures have sophisticated climate control systems. These structures are adaptations to the existing and changing climate.

- Most people in the MAR have access to water and sanitation systems that provide potable water and treat wastes. The region also has significant regulation to protect the safety of drinking water and foods. These systems reduce risks from water-borne and other diseases.

- Most people in the MAR have access to modern medical services that can provide vaccines and treatments against most communicable diseases that might migrate to the region.

- The region has modern food and energy distribution systems that reduce the importance of local production, and therefore local climate, for food and energy supplies.

In the medium- to long-term, climate change, and indeed, expectations of climate change, are likely to induce private and public responses to reduce vulnerability to health and other climate-related risks (Abler et al. 2000; Patz 1996). Human history has been shaped by adaptations to environments, ranging from the cold, barren Arctic tundra to the hot, arid deserts. For instance, in the US, the strength of the relationship between mortality and extreme temperatures has declined through the 20th century due to factors such as technological changes in housing construction and medical care (Larsen 1990a). Factors that influence adaptation include options that are (or will become) available and their effectiveness, costs and secondary impacts. Examples include control measures that are unaffordable for some vulnerable groups and concerns about unintended impacts on non-target species from pesticide use for mosquito control.

Nevertheless, the projected climate change could have personal health consequences as well as impacts on the costs of public health. We selected several broad areas of potential concern for our first assessment phase. These are the impacts of climate change on health effects associated with extreme events, heat- and cold-related mortality, vector-/water-/food-borne diseases, air quality, and mental health. The selection criteria for the impacts to study include the potential importance of the health impact, its sensitivity to climate variability and change, and the feasibility of performing a credible assessment given our time and resource constraints. Our choices also have been guided by the input of Mid-Atlantic Regional Assessment (MARA) stakeholder groups, the results of climate modeling indicating the projected climate change for the region, and the results of prior research. The methodology used includes a comparative risk assessment based on baseline data collection and analysis, literature reviews, guidance from MARA stakeholder groups, and selected specialized research (for heat- and cold- related mortality).

Current Population Health Status and Stresses

Health status is a measure of the physical and mental welfare of an individual or a population. It is a complex function of many factors including behavior, medical care, genetics, public health infrastructure, and environment (Banta and Jonas 1996). The relationship between health status and its determinants can be expressed using a health production function. This function highlights that health is an output (e.g., a final product) that is produced using many inputs such as medical care. Equation 1 illustrates a simple static version of a health production function.

$$(1) \quad Health = F(B, M, K, G, E)$$

B = Behavior
M = Medical Care

K = Capital
G = Genetic/Biological Endowment
E = Environment (Temperature, Storms, Disease Vectors, Environmental Quality (e.g., air pollution))

Behavior includes decisions people make such as living in a flood plain, driving in icy conditions, and lifestyle choices such as cigarette and alcohol consumption, diet, and fitness. Medical care includes the state of medical technology, and access issues such as availability, quality and price of care as well as health insurance status. Capital includes physical infrastructure such as water and sewage treatment as well as human capital such as education level. Genetic/biological endowment is the predisposition to certain diseases as well as other factors such as age and sex. Environment includes characteristics of the natural environment and of buildings in which people live and work. In this function, climate change acts on health directly through changes in temperature and storms or indirectly through changes in disease vectors or environmental quality such as air and water pollution. The importance of climate as an aggravating factor depends on the age, health status, and income of a population in a given region. For example, people who were at greatest risk of death during the Chicago 1995 heat wave had known medical problems and were without social contacts or access to air conditioning (Semenza et al. 1996).

Historically, the US population has been able to adapt and reduce vulnerability to health risks. The health systems of the United States and other developed nations have experienced an incredible evolution over the past 150 years, greatly improving the health status of their citizens and the capacity to manage public health risks (McKeown 1976). For example, the crude[2] mortality rate in 1900 was 1720 deaths per 100,000 people and the life expectancy was 47.3 years (Banta and Jonas 1996). By 1997, the crude mortality rate had dropped to 865 and life expectancy had increased to 77 years (WHO 1998; CDC 1999a). The MAR similarly enjoys high health standards (see discussion below). A century ago the predominant health problems were epidemics of acute infections. Today, the major health risks are chronic diseases such as heart disease and cancer, which are strongly related to lifestyle choices (CDC 1998a). The shift in the sources of health risks explains the changing emphasis in US health policy to issues such as access to health care (organizing the health care system to reach vulnerable populations) and promoting healthy behaviors (US DHHS 1991). With continued investment in public health infrastructure and systems and barring significant unforeseen developments, major U.S. health policy challenges in the coming decades will relate to cost, access, and disparity in care (Kajander 1996; Grayson 1998).

[2]The ratio of the number of deaths in a given population to the population, unadjusted for age composition of the population.

While the MAR enjoys good health by international standards, some segments of the MAR population are vulnerable to health threats primarily due to age, poverty, and lack of access to medical services. Examples for 1995 include: 15.7% of the Plateau region of the MAR was aged 65 and older (seniors) as compared to the national average of 12.8%; the average per capita income of the Ridge & Valley region of the MAR was $18,277 compared to the national average of $21,651; and 17.3% of the population in Washington, DC was uninsured compared to the national rate of 15.4% (NPA 1999; US Census Bureau 1997).

The current health status of the region's population reflects the combined effects of climatic and non-climatic factors, and provides a backdrop for evaluating the potential impacts of climate change in the region. Selected health assessment measures are presented below for the MAR, the US, and for four physiographic subregions of the MAR: Coastal, Piedmont, Ridge and Valley (R&V) and Plateau. County level data was collected and aggregated by physiographic region.

Mortality

Table 9.1 presents 1995 age-adjusted mortality rates (also called death rates) by physiographic region for the leading causes of death and weather-related causes of death. The year 1995 was the most recent year for which comprehensive mortality data were available at the time of data collection (CDC 1998b). The mortality rates shown are per 100,000 population. For example the number 880 means 880 deaths per 100,000 people.

Table 9.1 presents age-adjusted mortality rates, rather than crude mortality rates. A crude mortality rate is simply the ratio of the number of deaths in a given region to the population of the region. When comparing the mortality of different regions, crude mortality rates can be misleading because they do not show how much of the differences in mortality among the regions is due to the differing compositions of the regions' populations (e.g., age) as opposed to other factors. Age is a factor that is strongly associated with mortality, and age distribution varies among regions. Therefore, it is necessary to adjust the mortality rates for the age distribution of each region. Within the MAR for instance, more than 15% of the people in the Plateau and R&V regions are seniors, compared with 12.5% of the Coastal region and 12.8% of the Piedmont region and the nation (NPA 1999). Using the direct method of adjustment, age-specific rates from each region are applied to a standard population (we chose the 1995 US population) (Alderson 1988; Armitage and Colton, 1995). The resulting age-adjusted mortality rate shows what the rate for the population in the particular region would be if that population had the same age distribution as the US population in 1995.

Table 9.1. 1995 Age-Adjusted Mortality Rate per 100,000 Population by Physiographic Region for Selected Causes of Death.

Cause of Death	Coastal	Piedmont	Ridge and Valley	Plateau	MAR	US
All Causes	937.8	867.4	869.4	884.7	898.3	880.0
Top 12 Causes in the MAR (Rank in MAR):						
Heart Disease (1)	285.7	263.9	296.2	300.6	285.6	280.7
Cancer (2)	221.9	205.0	190.1	209.1	210.3	204.9
Stroke (3)	56.6	58.5	46.8	49.7	54.1	60.1
Lund Disease (4)	31.6	32.1	27.4	36.3	32.6	39.2
Pneumonia/Influenza (5)	27.6	27.5	23.5	27.0	27.0	31.6
Accidents (6)	29.1	23.4	13.9	18.2	23.0	35.5
Motor Accidents*	10.4	9.6	5.6	6.3	8.6	16.5
Diabetes (7)	22.9	20.1	15.3	16.4	19.5	22.6
HIV (8)	23.4	13.1	3.8	5.0	14.0	16.4
Kidney Disease (9)	10.4	8.4	5.1	7.4	8.4	9.0
Suicide (10)	8.4	8.6	4.9	6.1	7.5	11.9
Homicide (11)	11.8	6.0	1.8	2.2	6.8	8.7
Cirrhosis/Liver Disease (12)	8.2	6.2	3.3	4.7	6.2	9.0
Selected Other Causes:						
Cold Related	0.12	0.09	0.05	0.05	0.09	0.09
Heat Related	0.22	0.04	0.00	0.03	0.10	0.13
Storm/Floor/Lightning	0.01	0.02	0.03	0.00	0.01	0.06

Data source: CDC (1998b). Missing values have been converted to zeros.
*Motor accidents are a subset of all accidents and are included in the accident category.

The mortality rate from all causes in the MAR slightly exceeds the US national death rate. The four leading causes of death in the MAR, as in the US, are heart disease, cancer, stroke and lung disease. These are the reported causes for two-thirds of all deaths in the MAR (and in the US) in 1995. Genetic endowment and behavioral choices are major determinants of these causes of death (CDC 1998a). The MAR has somewhat higher mortality rates from heart disease and cancer than the US and somewhat lower stroke and lung disease mortality rates than the US. The remaining top twelve causes of death in the MAR (shown in Table 9.1) are responsible for 15% of all deaths in the MAR (17% in the US) in 1995. The MAR has lower mortality rates than the US for these eight causes of death.

Weather conditions, such as temperature extremes, have been associated with mortality due to heart disease, stroke, diabetes, kidney diseases, homicide, suicide and motor vehicle accidents (Kilbourne 1997; Loeb 1985; Zlatoper 1987; Marion et al. 1999; Salib 1997). Thus changes in climate could affect mortality from these causes. This is discussed in more detail in the Impacts of Climate Change section of this chapter.

Table 9.1 also shows age-adjusted death rates for causes of mortality that are directly related to weather. In 1995, the MAR had lower death rates than the nation for cold, heat and a combined storm, flood and lightning category, with 68 deaths attributed to these causes. Fifty percent of heat-related deaths and 57% of cold-related deaths occur in the MAR population aged 65 and older, similar to findings in the United States as a whole between 1979-1996 (Rackers and Donnell 1999). Even though figures in this category could be under-reported because of the categorization of some flood, storm and lightning deaths as accidental deaths, weather-related causes of death did not have a large impact on the region in 1995.

The 1995 weather-related deaths accounted for many fewer deaths than any of the leading causes of mortality. Because weather conditions vary from year to year, weather-related deaths should be considered over a longer period. Table 9.2 shows the annual weather-related mortality rates for the years 1990 through 1996. The MAR has lower weather-related death rates than the US in this period. Exceptions are higher MAR mortality rates for heat-related mortality in 1993 and storm-related deaths in 1996. Cold-related mortality rates increased during the 1990 to 1996 period. Rates also vary by physiographic region. The Coastal region had the highest heat-related mortality rates for all years, which may be due to its urban nature: in 1990, 80.6% of the Coastal population lived in urban areas (US DHHS 1997). Urban temperatures tend to be higher than nearby suburban or rural areas, posing a greater risk to human health (Kilbourne 1997).

Thus, very little mortality currently is directly (i.e., reported on death certificates) attributable to cold, heat, storms, flooding or lightning in the MAR. The average annual age-adjusted mortality rate in the MAR from 1990 to 1996 for a combined weather-related category (including deaths from heat, cold, storm, flood, and lightening) was only 0.13 deaths per 100,000 population. This is much lower than rates from the leading causes of death in the region as discussed above. However, the weather-related causes of death are not well documented and tend to be under-reported. For example, medical examiners attributed 118 deaths to the July 1993 Philadelphia heat wave (CDC 1994) while only 21 deaths had excessive heat as their cause on death certificate data during 1993 for Philadelphia County (CDC 1998b). Heat-related causes of death during heat waves have been underestimated by 22% to 100% (Kilbourne 1997).

Table 9.2. Age-Adjusted Death Rates per 100,000 Population by Physiographic Region for Climate-Related Causes of Death for Selected Years.

	Coastal	Piedmont	R & V	Plateau	MAR	US
1990						
Cold Related	0.10	0.02	0.03	0.03	0.05	0.12
Heat Related	0.05	0.02	0.03	0.00	0.03	0.05
Storm/Flood/Lightning	0.01	0.03	0.00	0.02	0.02	0.09
1991						
Cold Related	0.10	0.04	0.00	0.01	0.05	0.11
Heat Related	0.06	0.00	0.00	0.01	0.02	0.03
Storm/Flood/Lightning	0.01	0.04	0.02	0.00	0.02	0.06
1992						
Cold Related	0.06	0.02	0.10	0.06	0.05	0.10
Heat Related	0.02	0.00	0.00	0.01	0.01	0.02
Storm/Flood/Lightning	0.02	0.02	0.00	0.01	0.02	0.05
1993						
Cold Related	0.13	0.02	0.00	0.04	0.06	0.12
Heat Related	0.25	0.02	0.00	0.00	0.09	0.04
Storm/Flood/Lightning	0.02	0.02	0.00	0.02	0.02	0.06
1994						
Cold Related	0.11	0.07	0.05	0.04	0.07	0.13
Heat Related	0.02	0.01	0.00	0.00	0.01	0.03
Storm/Flood/Lightning	0.00	0.08	0.03	0.00	0.03	0.07
1995						
Cold Related	0.12	0.09	0.05	0.04	0.08	0.09
Heat Related	0.22	0.04	0.00	0.03	0.09	0.13
Storm/Flood/Lightning	0.01	0.02	0.03	0.00	0.01	0.06
1996						
Cold Related	0.16	0.09	0.13	0.02	0.10	0.13
Heat Related	0.01	0.01	0.00	0.01	0.01	0.04
Storm/Flood/Lightning	0.02	0.10	0.18	0.04	0.06	0.06
1990-1996 Average						
Cold Related	0.11	0.05	0.05	0.04	0.07	0.11
Heat Related	0.09	0.01	0.00	0.01	0.04	0.05
Storm/Flood/Lightning	0.01	0.04	0.04	0.01	0.02	0.06

Data source: CDC (1998b).

Demographic and Socioeconomic Factors relating to Health

Health varies by socioeconomic factors such as age, race, income, and education, which in fact may be correlated with each other (NCHS 1998). For example, people with higher levels of education may also earn higher incomes, and both education and income are positively associated with health outcomes (Grossman and Kaestner 1997; NCHS 1998). Higher income may allow more access to medical care, better nutrition and housing, and more opportunity to have a healthier lifestyle. Higher education may allow better understanding and access to more information on how to prevent illness, have a healthier lifestyle, and follow physicians' advice. Older populations tend to have lower health status in part due to the biological effects of aging. Race or ethnicity also have been associated with health outcomes; this may be due to differences in income and education levels as opposed to biological differences. For instance, black women are more likely to die from pregnancy-related complications than white women, and black and American Indian/Alaska Native infants have higher mortality rates than white infants (CDC 1999c).

Table 9.3 shows selected demographics for the MAR and the US. Note that the Ridge and Valley and Plateau subregions have higher proportions of the population that is aged 65 and

Table 9.3. Selected Demographics for the MAR by Physiographic Region.

	Coastal	**Piedmont**	**Ridge & Valley**	**Plateau**	**MAR**	**US**
Total Population [b,2] (in 000's)	12,665	10,093	3,478	8,934	35,170	262,760
% Population Aged 0-19 [b,2]	27.5	27.0	26.0	27.2	27.1	28.8
% Population Aged 20-64 [b,2]	60.0	60.2	58.6	57.1	59.2	58.5
% Population Aged 65 & Older [b,2]	12.5	12.8	15.4	15.7	13.7	12.8
Population Aged 65 & Older [b,2] (in 000's)	1,580	1,289	536	1,403	4,809	33,561
% Non-White [b,3]	30.3	17.7	5.4	5.8	18.0	17.0
% Black 95 [b,3]	26.8	14.9	4.4	4.7	15.6	12.6
% Urban Population [a,1]	80.6	67.7	41.0	53.5	66.0	75.2
% Population Aged 25+ with High School Education [a,1]	76.2	76.4	69.5	74.6	75.2	77.6
Per Capita Income (in 1992 US dollars) [b,2]	23,747	25,272	18,277	19,160	22,479	21,651

[a] 1990 data. [b] 1995 data..

[1] Data source is US DHHS (1997).

[2] Data source is NPA (1999).

[3] Data source is CDC (1998b).

older (seniors) than the MAR or the nation. Average per capita income in the MAR is similar to the nation's, but varies by subregion. While the MAR has a smaller proportion of urban population than the nation, the population of the Coastal subregion is predominantly urban. Overall, demographic characteristics for the MAR are similar to those for the nation.

Impacts of Climate Change

Several broad areas of potential concern were selected for initial assessment: impacts of climate change on health consequences of extreme events, heat- and cold-related mortality, vector-/water-/food-borne diseases (specifically, Lyme disease, malaria, cryptosporidiosis, and cholera), air quality, and mental health. Our choices have been guided by the input of MARA stakeholder groups (e.g., at the September 1997 initial scoping workshop, the June 1998 researchers' working meeting, the October 1998 and May 1999 advisory committee meetings), the results of climate modeling indicating the projected climate change for the region, and the results of prior research.

Extreme Events

This section describes the assessment how climate change might affect health consequences from extreme events in the MAR. Currently, extreme events do not have a large impact on health in the MAR. There is substantial uncertainty about how climate change will affect the frequency and intensity of extreme events, although more flooding could occur. This uncertainty makes it difficult to assess the impacts on health.

Extreme weather events can directly cause injuries and death and indirectly influence health by affecting public health infrastructure (e.g., overwhelming water treatment systems). Forecasts of storm tracks under climate change in the MAR are necessary in order to predict the resulting impacts on health status in the region. At this time, such forecasts are not available. While predictions about future impacts cannot be made, experience has shown that hurricanes can cause death and illness. For example, fifty-two deaths are attributed to Hurricane Floyd, which occurred in September 1999 (CDC 2000a). These include deaths by drowning (e.g., in a house, boat or motor vehicle), motor vehicle crashes, myocardial infarction (i.e., heart attack), fire, hypothermia and electrocution (CDC 2000a). Increases in morbidity also were observed immediately following the hurricane, as discussed in Box 9.2.

One of the anticipated effects of climate change is an increase in intensity and frequency of floods. Interestingly, while the MAR is currently a flood prone area, few deaths are directly attributed to flooding. The average annual crude mortality rate from 1990 to 1996 for a combined storm/flood/lightning category was only 2 deaths per 10 million population in the MAR, which is less than the corresponding US mortality rate of 6 deaths per 10 million population (see Table 9.3). The fact that mortality risks from extreme events are currently very small in the MAR suggests that modest changes in these risks would have little impact on the region's health status. This, however, excludes the impact of morbidity due to extreme events on health status.

Moreover, while the health consequences of hurricanes and floods are apparent, those of other types of weather are not. For example, fewer motor vehicle accident fatalities occur in snowy or rainy weather (Loeb 1985, Zlatoper 1987), perhaps because people drive less frequently and/or more carefully in such weather.

If weather events that pose threats to health become more frequent or severe, there are structural and nonstructural measures that can be undertaken to reduce vulnerability. These measures include building codes, land-use planning, and severe weather warning systems. Health surveillance during and after extreme events is important in order to choose the most appropriate responses and to evaluate the effectiveness of the responses.

Box 9.2. *Morbidity in North Carolina Following Hurricane Floyd*

After Hurricane Floyd struck North Carolina on September 15-16, 1999, North Carolina's Department of Health and Human Services (NC DHHS) monitored 18 hospital emergency rooms (ERs) in 16 affected counties (NC DHHS 1999). The NC DHHS compared visits made in the 2 weeks immediately following the hurricane with a control period in September 1998. Increases were observed in dermatologic and respiratory illnesses, hypothermia, and animal bites. Dermatologic illnesses increased by 65% the first week and 79% the second week following the hurricane. One potential cause was contact with flood water. There was a 15% increase in respiratory illness in the first week following the hurricane. This may have been caused by more people going to the Emergency Room rather than their usual source of care, or by the hurricane exacerbating illnesses such as asthma, for instance by mold growth. Following Hurricane Floyd, no increases in injuries (e.g., burns, trauma, electric shock) were observed for the 16 counties on average. However, some individual counties reported increases in injury rates. Fourteen cases of hypothermia were observed in the week following Floyd, while none were observed in the control period. This could be attributed to cold weather coupled with water exposure. Animal bites increased by 30% during the first week following Floyd. There were slight increases in insects and snake bites the first week following Floyd and large increases in dog bites were seen in both weeks following Floyd (by 246% the first week and 169% the second week). The increase in dog bites was attributed to frightened and displaced pets. While data is not available relating to mental* *health, stress-related services were expected to increase in the short- and long-term following Floyd (NC DHHS 1999). Data reported in this box is from NC DHHS, 1999.*

** Note: 7 of the 16 counties are located in the MAR. These are: Beaufort, Edgecombe, Nash, Pitt, Halifax, Hertford, and Wilson counties.*

Heat- and Cold-Related Mortality

This section describes the assessment of potential impacts of climate change on heat- and cold-related mortality in the MAR. Temperatures are projected to increase in the MAR. The assessment indicates with some certainty that heat-related mortality could increase, although still remain a relatively small factor in the region's health status. Cold-related mortality could decrease slightly, although this is not as certain because the temperature-mortality relationship for these types of deaths is not as strong for cold as for warm temperatures.

The intensity and frequency of thermal extremes may be altered by climate change. If climate change causes higher temperatures in the MAR, there may be reductions in cold-related mortality and morbidity and increases in heat-related mortality and morbidity. The Hadley Centre climate model predicts an increase in annual mean temperature in the MAR of 4.5°F for the period from 1990 to 2099 with minimum and maximum temperatures increasing 4°F and 5°F respectively. By 2030, minimum and maximum temperatures are expected to increase by 2°F with much of the change occurring in the summer. (The CCC model projects even more warming than the Hadley model.) Recognizing that a significant proportion of the MAR population lives in urban areas and that this population is more susceptible to warmer temperatures because urban areas act as heat traps (the urban heat island effect) (Kilbourne 1997), the predicted change in temperature is likely to increase heat-related mortality and morbidity in the MAR.

Higher mortality has been associated with very cold winters and very warm summers (Larsen 1990a). Increases in many causes of death, such as heart attacks and cerebrovascular events, have been observed during extremely hot weather in addition to hyperthermia (heat stroke) deaths (Kilbourne 1998). Heat waves have also been associated with increased mortality from causes (such as diabetes, kidney diseases, and homicide) without a clear medical relationship to heat (Kilbourne 1997). Because many causes of death have been associated with temperature extremes, studies sometimes relate weather to excess mortality. Excess deaths are the number of deaths (from all causes) during a particular type of weather that occur above the number typically expected in absence of the given weather condition. Excess deaths are useful because they give the researcher a larger number of observations to work with and can increase the statistical power of the weather-mortality relationship. However, excess deaths may overestimate the number of deaths by including causes without a plausible link to weather.

The elderly, the very young and those (indigent) without access to adequate heating and cooling are more vulnerable to extreme temperatures. In addition, heat stress can be harmful in high-risk pregnancies by decreasing uterine blood flow (Pirhonen et al. 1994). Semenza et al. (1996) determined that people at greatest risk of death during the Chicago 1995 heat wave were those who did not have social contacts or access to air conditioning and who had known medical problems. There is some evidence that heat waves may hasten the death of those with some pre-existing illness (Kilbourne 1997). Thus some may argue that those who die during heat waves would have died shortly anyway. However, many heat-related deaths are not such anticipated or displaced deaths (Kalkstein and Smoyer 1993). Kalkstein (1993) estimates that between 20% and 40% of heat-related deaths are displaced deaths.

Acclimatization is the physiological and behavioral adjustment or adaptation that people (or organisms) make in response to changes in climate and/or the environment. The degree of acclimatization will influence the impact of climate change on heat- and cold-related mortality. Different regions have different thresholds to weather/temperature, which can be attributed in part to acclimatization. Acclimatization is affected by the frequency and timing of extreme weather episodes. For instance, fluctuations in winter temperature have a larger effect on mortality in southern states where colder temperatures are experienced less frequently (Larsen 1990a, Larsen 1990b). Also, weather has a greater impact on health in areas with more variable weather conditions than in areas with little weather variation (Greene and Kalkstein, 1996; Kalkstein and Smoyer 1993). Even within a region, the timing of a hot spell is important. Early season heat waves generally have a larger impact on mortality than those later in the summer, indicating that some acclimatization to heat occurs over time (Kilbourne 1997; Kalkstein and Smoyer 1993). Heat waves in which nights are very warm and provide no relief from the heat are particularly lethal (Kilbourne 1997). Chestnut et al. (1998) find that hot weather-related mortality is strongly influenced by variability in minimum daily summer temperature. They show that acclimatization may be impeded in areas where minimum temperature variability is greatest. Thus, the impact of climate change on minimum temperature variability may be an important factor for determining the magnitude of heat-related mortality under climate change.

Several studies have examined the impact of temperature on mortality in MAR cities. Kalkstein and Smoyer (1993) examined weather-mortality relationships in fifteen US cities (as well as in Canada, China and Egypt). One MAR city, Philadelphia, is included in their analysis. Using historical data, they identified threshold temperatures and air masses (synoptic situations) associated with high mortality. Temperature thresholds are temperature levels above (or below) which mortality increases significantly. There is a stronger weather-mortality relationship in summer than in winter, and the strongest relationship between mortality and weather occurs in areas experiencing high temperatures in an irregular pattern. Thus, temperature had a smaller impact on mortality in southern areas with more constant temperatures and a larger impact in northern and Midwestern cities. Kalkstein and Smoyer (1993) applied historical weather-mortality relationships to a doubled CO_2 scenario developed by the NASA Goddard Institute for Space Studies. They estimate that warm weather-related mortality in the fifteen cities would increase by a factor of seven without acclimatization and by a factor of four including acclimatization. Under present conditions Kalkstein and Smoyer (1993) estimate that in Philadelphia 145 deaths per summer are attributed to weather. Under the doubled CO_2 scenario, this figure could increase by factors of 4.8 and 6.5 with and without acclimatization, respectively.

Kalkstein and Greene (1997) used a spatial synoptic classification (SSC) approach to examine the relationship between weather and mortality in 44 US cities under current and projected future climate change conditions. Five of these cities are located in the MAR: Baltimore, Greensboro[3], Philadelphia, Pittsburgh, Washington, DC. They identified air masses associated with high mortality during summer and winter months using data from 1964 to 1991. The SSC approach identifies air masses on a large scale, which allows comparison of similar air masses across regions. The air mass categorization allows Kalkstein and Greene (1997) to assess the impact on health of multiple weather variables (afternoon surface temperature, dew point, dew point depression, wind speed, wind direction, cloud cover, diurnal temperature range) acting together; other studies tend to rely on temperature alone. Kalkstein and Greene (1997) classify days by type of air mass for each city. Mean daily mortality was calculated for each synoptic category and categories associated with high mortality risk were identified for each city. Because of the high standard deviation in daily mortality, regression analysis was performed to develop estimates of excess mortality for each day in a given category (i.e., the number of deaths above typical levels due to each of the high risk air masses). Independent variables in the regression included meteorological variables as well as the day in the season (e.g., fifth day of summer or 20th day of winter) and day in sequence (e.g., whether it was the first or 4th consecutive day within a given air mass).

Kalkstein and Greene (1997) used three GCMs (from the Geophysical Fluid Dynamics Laboratory [GFDL], the United Kingdom Meteorological Office [UKMO], and the Max Planck Institute for Meteorology) to predict how the frequency of the high risk air masses might change in 2020 and 2050 with climate change. Their findings show increases in the frequency of summer high risk air masses and little change in frequency of winter high risk air masses under climate change. This research uses GCMs recommended by IPCC because it was done prior to the National Assessment Synthesis Team (NAST) recommendations. Nonetheless, these three GCMs provide a wide range of projections (GFDL low end, UKMO high end). Kalkstein and

[3] The Greensboro MSA includes Alamance, Forsyth, Guilford, and Stokes counties which are located in the MAR and Davidson, Davie, Randolph, and Yadkin counties which are not in the MAR.

Greene (1997) then applied the mortality regressions described above to the GCM climate projections to estimate future excess mortality due to the high risk air masses.

Kalkstein and Greene (1997) use an "analog city" approach to account for acclimatization. The mortality-climate relationships of analog cities (i.e., cities that currently have a climate similar to the climate projected for MAR cities) are used in conjunction with the projected climate scenarios of the MAR cities to estimate excess mortality under full acclimatization. This approach assumes that the analog cities are fully acclimatized to their current climate and that the original city and its analog have similar characteristics or differ in ways that do not influence the weather-mortality relationship. Kalkstein and Greene (1997) note that because full acclimatization is unlikely, these results provide lower-bound estimates of mortality.

The Kalkstein and Greene (1997) results are presented in Table 9.4, which shows net excess mortality, or the change in excess mortality between the current and future scenarios that is attributable to climate, by season (summer, winter, total) for each city. The results vary widely depending on the GCM used. Cities that currently do not have a significant relationship between climate and mortality have no projected excess mortality.

The Kalkstein and Greene (1997) estimates do not account for future demographic changes such as population growth and changes in the age distribution of the population. These changes will affect the magnitude of the estimates and are important for temperature-related mortality because older populations are more vulnerable. In an unpublished report for the US Environmental Protection Agency, Chestnut et al. (1995) adjusted the Kalkstein and Greene (1997) mortality estimates to incorporate population growth over time. They applied US population growth rates (historical and projected) between 1980 to 2050 by age (65 and older and under 65) to the Kalkstein and Greene mortality estimates. Note that they obtained mortality estimates for the 65 and older population directly from Kalkstein; these are not published in Kalkstein and Greene (1997), which includes mortality estimates for the total population only. Chestnut et al. assumed that the Kalkstein and Greene (1997) estimates of current mortality pertain to the 1980 population, so they inflated to the 1993 population. The US population-adjusted mortality figures of Chestnut et al. (1995) are larger in magnitude than the unadjusted figures, reflecting the projected population growth of the US and the increase in proportion of the population aged 65 and older.

Our assessment refines the work of Chestnut et al. (1995) to capture population changes in individual cities. Between 1980 and 2050, the total populations of Baltimore, Greensboro, and Philadelphia are projected to increase while the populations of Pittsburgh and Washington, DC are projected to decrease (NPA 1999). The population aged 65 and older increases for all five cities. The growth in the 65 and older population is a modest 15% for Washington, DC but is quite high for the other cities: 91% for Pittsburgh, 105% for Philadelphia, 198% for Baltimore,

Table 9.4. Heat- and Cold-Related Mortality for five MAR Cities

Below are estimates of current excess mortality (i.e., number of deaths attributable to climate and projections of changes in excess mortality) assuming full acclimatization, from Kalkstein and Greene (1997). Three general circulation models are used, from the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and the Max Planck Institute for Meteorology. This research uses GCMs recommended by IPCC because it was done prior to the NAST recommendations. Nonetheless, these three GCMs provide a wide range of projections (GFDL low end, UKMO high end) that most likely encompass the Hadley and CCC climate projections. Cities that currently do not have a significant relationship between climate and mortality have no projected excess mortality.

Excess Mortality		**Change in Excess Mortality (Net Excess Mortality)**					
		2020			**2050**		
	Present Climate	**GFDL**	**UKMO**	**Max Planck**	**GFDL**	**UKMO**	**Max Planck**
Summer							
Baltimore	84	-27	64	-21	40	80	47
Greensboro	22	6	21	5	15	23	7
Philadelphia	129	-30	233	62	117	348	194
Pittsburgh	39	-7	27	25	22	44	56
Washington, DC	0	0	0	0	0	0	0
Winter							
Baltimore	0	0	0	0	0	0	0
Greensboro	0	0	0	0	0	0	0
Philadelphia	85	-5	-71	-12	-49	-79	-3
Pittsburgh	19	1	10	2	5	12	2
Washington, DC	19	12	19	11	1	16	12
Total (Summer + Winter)							
Baltimore	84	-27	64	-21	40	80	47
Greensboro	22	6	21	5	15	23	7
Philadelphia	214	-35	162	50	68	272	191
Pittsburgh	58	-6	37	27	27	56	58
Washington, DC	19	12	19	11	1	16	12

and 312% for Greensboro. The population aged less than 65 is projected to decrease by about 19% in Pittsburgh and Washington, DC and increase modestly by 5% in Philadelphia and increase by 42% in Baltimore and 56% in Greensboro[4].

Following the methodology of Chestnut et al. (1995), city-specific population growth rates (NPA 1999) for two age categories (65 and older and under 65) are applied to the Kalkstein and Greene estimates. (Recall that the 65 and older mortality estimates are unpublished but can be found in Chestnut et al. 1995). As in Chestnut et al. (1995), we assume that the difference between mortality estimates for the total population and those for the 65 and older population yields estimates for the remaining population (aged 0-64). This assumption may be an oversimplification because Kalkstein and Greene (1997) estimate mortality for the 65 and older and total populations using separate regressions. Because the impact in the five MAR cities is primarily on the 65 and older population, using age-specific population growth rates may be more appropriate. For instance, only in summer in Baltimore, Greensboro, and Philadelphia do 65 and older and total mortality figures differ. Because of the high growth rates of the 65 and older population, using age-specific growth rates will yield higher estimates in most cases than using total population growth rates. The discussion in the remainder of this section pertains to estimates using age-specific growth rates. (For comparison, estimates using total population growth rates are presented in Appendix 9.A. As expected, the appendix estimates are smaller than those in Table 9.5 but larger than those in Table 9.4)

Table 9.5 shows current and net excess mortality (and net excess mortality rates) adjusted for city-specific population projections in 2020 and 2050 for the three GCMs. The impacts of climate change are projected to increase summer excess mortality in Philadelphia, Baltimore, Pittsburgh, and Greensboro. Infrequent but intense heat waves coupled with vulnerable elderly and poor populations make Philadelphia residents particularly susceptible to heat-related mortality. Winter mortality is not as strongly associated with air masses as summer mortality, and small changes in winter excess mortality are projected (with winter excess mortality projected to be lower in Philadelphia but higher in Pittsburgh and Washington, DC). In fact, decreases in winter mortality are not large enough to offset the increases in summer mortality. Combining the summer and winter projections reveals that annual excess deaths in 2050 could increase by 135-185% in Baltimore, 170-200% in Greensboro, 100 - 245% in Philadelphia, 125 - 210% in Pittsburgh, and 15 - 100% in Washington, DC.

---

[4] The above figures refer to NPA's baseline population projections. NPA also provides high- and low- end population projections. The low-end population growth rates between 1980 and 2050 are: 22% for Baltimore, 40% for Greensboro, -10% for Philadelphia, -26% for Pittsburgh, and -34% for DC. The high-end growth rates are: 97% for Baltimore, 128% for Greensboro, 46% for Philadelphia, 20% for Pittsburgh, and 7% for DC.

Table 9.5. Heat- and Cold-Related Mortality Adjusted for Projected Population Changes Using City- and Age-Specific (65 and older versus under 65) Population Growth Rates.

Net Excess Mortality (*Net Excess Mortality Rate per 100,000 Population)*

		2020			2050		
	Present Climate	**GFDL**	**UKMO**	**Max Planck**	**GFDL**	**UKMO**	**Max Planck**
Summer							
Baltimore	93	-8	106	-3	127	171	134
		(-0.28)	*(3.70)*	*(-0.12)*	*(3.65)*	*(4.91)*	*(3.85)*
Greensboro	29	28	38	28	55	59	49
		(2.01)	*(2.74)*	*(2.00)*	*(3.17)*	*(3.37)*	*(2.84)*
Philadelphia	146	-8	361	122	282	682	416
		(-0.15)	*(7.10)*	*(2.41)*	*(5.06)*	*(12.22)*	*(7.45)*
Pittsburgh	46	-1	47	44	66	107	129
		(-0.06)	*(1.99)*	*(1.87)*	*(2.68)*	*(4.33)*	*(5.22)*
Washington, DC	0	0	0	0	0	0	0
		(0.00)	*(0.00)*	*(0.00)*	*(0.00)*	*(0.00)*	*(0.00)*
Winter							
Baltimore	0	0	0	0	0	0	0
		(0.00)	*(0.00)*	*(0.00)*	*(0.00)*	*(0.00)*	*(0.00)*
Greensboro		0	0	0	0	0	0
		(0.00)	*(0.00)*	*(0.00)*	*(0.00)*	*(0.00)*	*(0.00)*
Philadelphia	100	24	-79	13	-29	-82	63
		(0.47)	*(-1.54)*	*(0.25)*	*(-0.51)*	*(-1.48)*	*(1.12)*
Pittsburgh	23	6	15	7	22	27	16
		(0.24)	*(0.65)*	*(0.30)*	*(0.88)*	*(1.11)*	*(0.65)*
Washington, DC	20	12	19	11	3	21	16
		(2.33)	*(3.74)*	*(2.13)*	*(0.62)*	*(3.79)*	*(2.95)*
Total (Summer + Winter)							
Baltimore	93	-8	106	-3	127	171	134
		(-0.28)	*(3.70)*	*(-0.12)*	*(3.65)*	*(4.91)*	*(3.85)*
Greensboro	29	28	38	28	55	59	49
		(2.01)	*(2.74)*	*(2.00)*	*(3.17)*	*(3.37)*	*(2.84)*
Philadelphia	246	16	283	135	254	600	478
		(0.31)	*(5.55)*	*(2.66)*	*(4.54)*	*(10.75)*	*(8.57)*
Pittsburgh	69	4	62	51	88	134	145
		(0.18)	*(2.65)*	*(2.17)*	*(3.56)*	*(5.43)*	*(5.88)*
Washington, DC	20	12	19	11	3	21	16
		(2.33)	*(3.74)*	*(2.13)*	*(0.62)*	*(3.79)*	*(2.95)*

Adapted from Kalkstein and Greene (1997). Full acclimatization is assumed. See Table 9.4 for more details.

The estimates in Table 9.5 are in general considerably higher than the Kalkstein and Greene (1997) original estimates. The combined summer and winter population adjusted net mortality figures of 2050 are 1.3 to 7.0 times larger in magnitude than the unadjusted figures, depending on the city and GCM, reflecting primarily the increase in the proportion of the population aged 65 and older. These estimates are lower than the estimates of Chestnut et al. (1995) for Philadelphia, Pittsburgh, and Washington, DC and in most cases higher for Baltimore and Greensboro. This reflects having a higher 65 and older population growth rate for Baltimore and Greensboro and a lower one for Philadelphia, Pittsburgh and Washington, DC, compared with the rate used by Chestnut et al. (1995).

Chestnut et al. (1998) and in their unpublished report Chestnut et al. (1995) convert the Kalkstein and Greene (1997) current weather-related mortality estimates to mortality rates. The rates associated with excess deaths from all causes are higher than the specifically weather-related causes discussed in the Mortality section above, but they still are very low. For instance, the summer mortality rates per 100,000 population for the five MAR cities are: Baltimore 3.86, Greensboro 2.64, Philadelphia 2.74, Pittsburgh 1.7, Washington, DC 0.0. The corresponding figures for winter mortality are: Baltimore 0.0, Greensboro 0.0, Philadelphia 1.80, Pittsburgh 0.84, Washington, DC 2.98 (Chestnut et al. 1995; Chestnut et al. 1998). These rates are considerably lower than the rates from the leading causes of death discussed above.

The population-adjusted net excess mortality predictions discussed above can be converted to mortality rates using the 2020 and 2050 city-specific population projections. Table 9.5 also presents net excess mortality rates. Converting the figures to mortality rates enables us to compare the magnitudes of climate-related mortality with the mortality rates of the leading causes of death discussed earlier. Of course, we do not know whether the mortality rates of the leading causes of death will change in the future, but this can provide a benchmark comparison. The total (summer plus winter) net excess mortality rates in 2050 are larger than the 2020 mortality rates and vary from 0.0 to 10.75 per 100,000 population depending on the GCM and the city. The mortality rates are less than 6 per 100,000 population except for Philadelphia estimates using the UKMO and MAX Planck GCMs. Currently in the MAR, the 12th leading cause of death is liver disease with a mortality rate of 6.2. So, in 2050, the net excess mortality attributable to climate is predicted to be lower than the current leading causes of death, except for Philadelphia.

Cities in the MAR could experience more increases in heat-related mortality under climate change than other US cities because of the infrequent but intense heat waves that the region experiences (Kalkstein 1998). Mortality variation among cities may be due to factors such as degree of acclimatization and demographics. Heat waves may affect cities to differing degrees because of varying building materials, architectural styles, and degrees of air conditioning usage

(Kilbourne 1997). Adaptation to reduce the urban heat island effect can be achieved by future urban planning. Because MAR cities already have widespread air conditioning usage, this factor cannot be expected to further reduce vulnerability to heat-related mortality (Kalkstein 1998). Hot weather/health watch warning systems may be an effective way to reduce vulnerability.

In sum, climate-related mortality is currently a minor problem in the mid-Atlantic region: current mortality rates attributed to climate are less than those of the twelve leading causes of death in the MAR. However, climate-related deaths are typically under-reported (Kilbourne 1997). Climate change may cause potentially large percentage increases in excess mortality, but mortality rates due to heat and cold extremes would remain low. However, this analysis may under-report the impact of climate change because it examines only mortality. Climate change will influence morbidity as well, although a lack of morbidity data makes this difficult to quantify at this time. Further studies are needed to examine the magnitude of the impact of climate change on temperature-related morbidity. Studies also are needed to estimate the costs of developing effective measures to protect against temperature-related mortality and morbidity.

Vector-, Water-, and Food-Borne Illnesses

This section describes the assessment of potential impacts of climate change in the MAR on risks from the following vector- and water-/food-borne diseases: Lyme disease, malaria, cryptosporidiosis and cholera. Currently, malaria and cholera are not health problems in the MAR while Lyme disease and cryptosporidiosis cases do occur. The assessment indicates that the impact of climate change on these diseases is highly uncertain and probably small, although change could make conditions more favorable for their transmission.

Climate change can affect health risks from vector-, water-, and food-borne diseases. These indirect health effects involve a complex chain of causality from climate change through biophysical systems to human disease risks, making them extremely difficult to quantify (Haines and McMichael 1997). Yet, the emerging view of health impacts at the global level suggests that indirect impacts may be substantially more important than direct impacts (McMichael et al. 1996).

Diseases that can be indirectly linked to climate include water/food-borne diseases such as cryptosporidiosis, giardiasis and cholera, and vector-borne diseases such as malaria, hantavirus, dengue fever and Lyme disease. Cholera, malaria, hantavirus and dengue fever are currently not health problems in the MAR: in 1995 there was one case of imported dengue fever, one case of imported cholera, 159 cases of malaria (all believed to be imported), and no cases of hantavirus (see Table 9.6).

Table 9.6. Selected Infectious Disease Rates per 100,000 Population by Physiographic Region for 1995.*

	Coastal	Piedmont	Ridge and Valley	Plateau	MAR	US
Giardiasis [a]	4.48	7.12	6.64	12.75	7.558	Unknown
Cryptosporidiosis [b]	0.03	0.009	0	0.73	0.205	Unknown
Lyme Disease	9.72	20.78	1.26	5.27	10.930	4.49
Malaria [c]	0.71	0.46	0.02	0.22	0.452	0.55

*In 1995, there was one case of imported dengue fever, one case of imported cholera, and no cases of hantavirus in the MAR.

Data sources are state health departments.
[a] Giardiasis cases are missing for North Carolina and Virginia in 1995, so the number of cases could be under-reported.
[b] Cryptosporidiosis was not a reportable disease in 1995 so could be under-reported.
[c] The malaria cases are believed to be imported (CDC 1999e).

Morbidity (illness) rates per 100,000 population for giardiasis, cryptosporidiosis, Lyme disease and malaria in 1995 are presented in Table 9.6. County level data was obtained from state health departments and aggregated to physiographic region. Giardiasis was the MAR's most prevalent water-borne disease and found throughout the MAR in 1995. Lyme disease was the most prevalent vector-borne disease in the MAR with 3,844 cases. It is also the most frequent vector-borne disease in the United States (Glass 1995; Barbour 1993). The MAR's Lyme disease morbidity rate was more than twice the nation's rate in 1995. Most cases are in the coastal region of the MAR. Nearly 60% of the Lyme disease cases were clustered in fifteen counties along or near the New Jersey-Pennsylvania border.

Much of the research to date focuses on the migration of tropical diseases to more temperate zones (Patz et al. 1996; Colwell et al. 1998). Few tropical diseases are common in the MAR. However, diseases could be imported into the region as has occurred with West Nile virus encephalitis in New York. Between the end of July to Mid-October, 1999, 7 people died and 49 became ill from this mosquito-borne virus, which was also responsible for bird deaths in New York, New Jersey and Connecticut (Fine et al. 1999). Vector-borne diseases already present in the MAR, such as Lyme disease could be influenced by climate change. The tick vector for Lyme disease also can carry an encephalitis-like virus (Telford et al. 1997). It feeds primarily on deer and deer-mice; the latter can carry hantaviruses.

Discussion of potential health impacts climate change on Lyme disease, malaria, cryptosporidiosis, and cholera is offered below. As stated above, our choice of diseases for examination in our initial assessment has been guided by the input of MARA stakeholder groups, the results of climate modeling indicating the projected climate change for the region, and the results of prior research.

Lyme Disease

Lyme disease is caused by *Borrelia burgdorferi,* a spirochete (corkscrew-shaped bacterium). Humans contract the disease from the bite of various tick species. In the eastern US, the carrier tick is usually *Ixodes scapularis* (CDC 1999b). Ticks pick up the spirochete by sucking the blood of infected deer or other animals. *I. Scapularis* feeds primarily on white-tailed deer and white-footed mice and is most active in summer

.

Ticks search for host animals from the tips of grasses and shrubs and transfer to animals or persons that brush against vegetation. Transmission of the bacteria is not instantaneous and usually requires the tick to remain on a person for over 24 hours (Barbour 1993). Lyme disease is usually transmitted to humans during the tick's nymph stage; nymphs are rarely noticed because of their small size (less than 2 mm). Adult ticks can transmit the disease; they are larger and more visible, thus more likely to be removed from a person's body before having sufficient time to transmit the infection (www.cdc.gov/ncidod/publications/brochures/lyme.htm).

Once a tick bites a person and the bacteria have been transmitted, it usually takes one week for the earliest signs to appear. The early stage of Lyme disease includes one or more of the following symptoms: fatigue, chills and fever, headache, muscle and joint pain, swollen lymph nodes, and a characteristic skin rash called erythema migrans.

Some symptoms of Lyme disease may not appear until weeks, months, or years after a tick bite, making accurate diagnosis more difficult. The potential for Lyme disease to become firmly established before diagnosis is one reason it can be very debilitating Symptoms of late stage Lyme disease include arthritis and nervous system disorders. Arthritis is most likely to appear as brief bouts of pain and swelling, usually in one or more large joints, especially the knees. Nervous system abnormalities can include numbness, pain, Bell's palsy (paralysis of the facial muscles, usually on one side), and meningitis (fever, stiff neck, and severe headache). Less frequently, heart rhythm irregularities occur. In some people, the rash never forms; in others, the first and only sign of Lyme disease is arthritis; and in still others, nervous system problems are the only evidence of Lyme disease.

Fortunately, Lyme disease is not considered fatal and can be treated easily with antibiotics. Early diagnosis is important and should take into account a history of possible exposure to ticks, especially in areas where Lyme disease is known to occur. Laboratory tests for Lyme disease are often inaccurate and have not yet been standardized nationally, but can be useful for diagnosis in later stages of illness. Patients treated in the early stages with antibiotics usually recover rapidly and completely. Most patients who are treated in later stages of the disease also respond well to antibiotics. In a few patients who are treated for Lyme disease, symptoms may persist or recur, making additional antibiotic treatment necessary. Varying degrees of permanent damage to joints or the nervous system can develop in patients with late chronic Lyme disease. Typically for these patients Lyme disease was not recognized in the early stages or initial treatment was unsuccessful (www.lymealliance.org/html/med3.html).

For Lyme disease to occur, three closely associated elements are required: the Lyme disease bacteria, ticks that can transmit them, and mammals (such as mice and deer and humans) to provide food for the ticks in their various life stages. The risk of contracting Lyme disease in a specific location is related to the tick population and the prevalence of the disease in the ticks (Varde et al. 1998).

One way Lyme disease is linked to the climate is by the range and activity of its host vector, the deer tick, which requires certain temperature and humidity conditions (Glass 1995). Ticks that transmit Lyme disease best flourish in temperate regions that may have periods of very low or high temperature and a constant high relative humidity at ground level (http://www.cdc.gov/ncidod/dvbid/Lymehistory.htm); the ticks prefer an environment that is moist and shaded (CDC 1999b). Links have also been made between acorn production, gypsy moth outbreaks, and Lyme disease risk (Jones et al. 1998). Climate change can cause forest species shifts and thus change patterns of acorn production and disease risk.

Several studies have examined Lyme disease risk in the MAR. For example, a study of rural Hunterdon County, New Jersey (which is in the MAR) found the bacteria that cause Lyme disease in at least one tick from 11 sampling sites and concluded that residents of this county were at risk for Lyme disease (Varde et al. 1998). Glass (1995) used geographic information systems to classify Lyme disease risk in Baltimore County, Maryland, with the risk being positively associated with forest edges, loamy soil (sandy soil suitable for conifers), and negatively related to highly developed areas. Schulze et al. (1991) developed an ecological index for risk assessment of Lyme disease in New Jersey. They found that *Ixodes scapularis* was abundant in forest edges characterized by a mixture of hardwood and conifer trees with layers of shrubby vegetation.

Amerasinghe et al. (1992) surveyed white-tailed deer in Maryland to discover tick density and rate of infection with the Lyme disease bacteria. They found that the Coastal region had the highest tick density as well as tick infection rates, followed by the Piedmont region, while the Ridge &Valley/Plateau regions had the lowest (the authors define the regions in a slightly different manner than we have for the MARA). In addition, Amerasinghe et al. (1992) also found a positive correlation between tick density and county level human disease rates.

The impact of climate change on Lyme disease risk is uncertain. Climate change could reduce Lyme disease risk in some parts of the MAR if the climate becomes less suitable for the tick vector. However, even if climate change increases the risk of Lyme disease in the MAR, adaptation measures can reduce vulnerability to the disease. Vector controls, prevention, vaccination and early detection are some examples. Methods of tick control include removing leaves and clearing brush and tall grass in close proximity to houses and the application of acaricides (chemicals toxic to ticks) to gardens, lawns, and the edge of woodlands. The latter has secondary impacts that should be considered. Reducing and managing deer populations in geographic areas where Lyme disease occurs may reduce tick abundance, although ticks still could feed on mice and other small mammals. Prevention by limiting exposure to ticks can be achieved through measures such as avoiding tick-infested areas and wearing light-colored clothing that leaves little skin exposed (long sleeved and long pants). In December of 1998, the FDA approved the use of LYMErix, a new vaccine against Lyme disease (CDC 1999d). Research suggests that at this time, it is cost effective to vaccinate only those individuals who spend a lot of time outdoors in areas of high Lyme disease risk rather than everyone (Meltzer et al. 1999, CDC 1999b). In addition, vaccinated people inadvertently may put themselves at higher risk, presuming the vaccine will be more effective than clinical trials have shown. Its cost (currently about $250) may leave lower income individuals at risk even if the region as a whole has low future vulnerability to Lyme disease. While some of these measures are being undertaken, they are not in widespread use nor are they fully effective. If risk is anticipated to increase, vulnerability will increase unless the scale of such measures is increased (e.g., through public education) or new measures are developed.

Malaria

Malaria is caused by infection with any of four species of *Plasmodium* (i.e., *P. falciparum, P. vivax, P. ovale, and P. malariae*) that can infect humans. The primary causative agent of human malaria is *Plasmodium falciparum.* The bite of an infected *Anopheles* mosquito transmits malaria from person to person. Malaria may also be passed congenitally (mother to child during pregnancy) or by blood transfusion, organ transplantation, and sharing of needles. In endemic areas of malaria, pregnant women and children are at the most risk (Marsh 1998). However, partial immunity develops after repeated infections. The signs and symptoms of malaria illness vary, but in most cases the pronounced symptom is a fever. Other common symptoms include headache, back pain, chills, increased sweating, myalgia, nausea, vomiting, diarrhea, and cough. Malaria can range from a mild to fatal disease.

Malaria was widespread in the US and Canada prior to the 20th century (Bruce-Chwatt 1988). The disease now is confined mainly to the poorer tropical areas of Africa, Asia and Latin

America. Inadequate health structures and poor socioeconomic conditions aggravate the problems of controlling malaria in these countries. During the late 1940s, a combination of improved socioeconomic conditions, water management, vector-control efforts, and case management successfully interrupted malaria transmission in the United States. Most of the malaria cases documented within the MAR are imported cases (contracted when traveling in a malaria endemic area).

There is a strong association between malaria outbreaks and climate (Powledge 1998). Climate change can lead to growth in malaria cases and malaria endemic areas (Powledge 1998; Martens et al. 1995; Martens et al. 1997). The life cycles of both the malaria parasite and the mosquito vector are closely linked to temperature (Martens et al. 1997; Pampana 1963; Zucker 1996; Horsfall 1972; Bates 1970), and increased temperatures in the MAR could increase the quantities of malaria-carrying mosquitoes. Martens et al. (1997) predict that the risk of malaria reintroduction to developed areas such as Australia, the United States and Europe is increasing because of climate change and the growing number of imported cases in those areas. Zucker (1996: 41) provides anecdotal evidence of this in a review of recent outbreaks of autochthonous cases (originating in the region) in the United States. A common feature of these recent outbreaks was that “the weather was hotter and more humid than usual.” This is consistent with the warmer, somewhat wetter scenario predicted for the MAR, although we do not have humidity predictions for the MAR.

Malaria is not common in the MAR. However, malaria can be sustained in any area where there are the four necessary ingredients for malaria transmission: 1) human carriers (visitors to malarious areas), 2) a non-immune human population (virtually everyone in the United States), 3) suitable *Anopheles* vectors (*An. quadrimaculatus*) and 4) temperatures above 60 degrees F (the summer season in the MAR) (Zucker 1996). Considering this, the MAR does have the potential for endemic malaria infection as was demonstrated by two cases that occurred in the New Jersey region of the MAR in 1991 (Crans 1992; Brook et al. 1994). There also have been recent locally acquired cases nearby the MAR: two in New York City in 1993 and two in Suffolk County, New York in 1999 (Layton et al. 1995; CDC 2000b).

A warmer and wetter MAR climate could make conditions favorable for the malarial parasite and mosquito vector potentiating an increased risk of malaria. Based on experiences in other developed countries (e.g., Australia), vulnerability to malaria can be reduced by vector controls, disease monitoring and medical treatment. Australia provides a useful analogue because it has had localized cases of malaria, and still has mosquitoes capable of transmitting malaria, yet has not been considered a malaria risk area since 1981. The success of Australia’s antimalarial program has been based to a large degree on the rapid diagnosis and treatment of humans with malaria. Similar public health measures could be implemented in the MAR. Key components to reducing vulnerability include educating physicians to recognize diseases not common to the region and improving surveillance of mosquitoes.

Cryptosporidiosis

Cryptosporidiosis is caused by ingesting the protozoan *Cryptosporidium parvum*. Healthy individuals infected by *Cryptosporidium* may experience watery diarrhea, headache, abdominal cramps, nausea, vomiting, and low-grade fever. The disease can be fatal for people with compromised immune systems because there is no medical cure (Juranek 1995, Guerrant 1997). There have been more than 20 documented water-related cryptosporidiosis outbreaks in the United States since 1983 (CDC 1995, Solo-Gabriele and Neumeister 1996; Smith and Rose 1998; Craun et al. 1996). Additionally, within the past five years, *Cryptosporidium* has been implicated in food-borne illnesses (CDC 1998c; CDC 1997a; CDC 1996).

Cryptosporidium is a serious public health threat (CDC 1995; Guerrant 1997; Juranek 1995) for several reasons. *Cryptosporidium* can infect a large number of people in a given location. This is illustrated by the most serious incident to date in the United States, when in 1993 more than 400,000 people became ill in Milwaukee from contaminated drinking water (Fox and Lytle 1996). The consequences of water contamination can be costly. The value to society of preventing drinking water contamination with *Cryptosporidium* has been estimated to be a minimum of $211 per statistical person or per average person exposed to a contamination event (Kocagil et al. 1998). Water-borne outbreaks have been confirmed in all regions of the United States from both ground and surface water sources (Solo-Gabrielle and Neumeister 1996; Craun et al. 1998). *Cryptosporidium* is difficult to detect and remove from water supplies. The small size of *Cryptosporidium* oocysts (4-6 Fm) renders most water filtration systems inadequate for effective removal of *Cryptosporidium* (Rose et al. 1997). In addition, *Cryptosporidium* is resistant to current chlorine-based disinfection techniques used to treat drinking water (Fayer 1997).

Cryptosporidium enters the environment when shed in the feces of infected people, livestock or wildlife. Although there are many possible sources of *Cryptosporidium*, an important one is cattle. Dairy and other livestock enterprises are important land uses in many MAR watersheds.

There have been three documented cryptosporidiosis outbreaks in the MAR. In 1991, contaminated well water in Berks County, Pennsylvania caused 551 suspected cases (Smith and Rose 1998). Contaminated lake water at a New Jersey state park caused 418 confirmed cases in the summer of 1994 (Kramer et al. 1996). This outbreak is associated with recreational swimming at a natural lake. The final outbreak occurred in Cortland County, New York in October 1996 with 20 confirmed cases and 11 suspected cases (CDC 1997b). This outbreak is unusual because the cause of the outbreak was contaminated apple cider. A ground water source for rinsing the apples before pressing is the suspected source of contamination. Investigation of the outbreak indicates, but does not confirm, ground water contamination from dairy farm run-off.

The difficulty and complexity associated with assessing indirect effects of climate change are illustrated by the case of cryptosporidiosis. Many factors influence the potential impact of climate change on cryptosporidiosis risk, including characteristics of watersheds and water supply systems, how they will change in the future, how climate affects the disease organism, *Cryptosporidium*, and its transport into waters used for drinking water or recreational uses. We have made considerable effort to assess the impact of climate change on cryptosporidiosis risk. But the lack of data and lack of knowledge about the linkages between climate, *Cryptosporidium* viability, transport and infectivity make it a difficult relationship to quantify.

When *Cryptosporidium* is present in a watershed, increased precipitation can cause greater surface water run-off and increase the transport of *Cryptosporidium* into water supplies. In addition, a severe influx of storm water could lead to a failure of water treatment plants. Increased concentrations of *Cryptosporidium* have been associated with rainfall in the Delaware River Basin (Atherholt et al. 1998). In addition, disease outbreaks have been observed during periods of heavy precipitation (Smith and Rose 1998; Atherholt et al. 1998). Thus a wetter climate in the MAR could lead to higher *Cryptosporidium* loads in water. But this assumes that there is a pool of *Cryptosporidium* in the area. Graczyk et al. (2000) found that 64% of livestock operations within the 100 year flood plain of one MARA county (Lancaster County, Pennsylvania) tested positive for *Cryptosporidium*. However, Abler and Shortle (2000) suggest management of agricultural wastes will improve in the future and perhaps reduce the risk of *Cryptosporidium* run-off. It is also possible that the amount of livestock in the region may decrease over time and that watershed protection will prevent what *Cryptosporidium* is present from entering water supplies. Unfortunately, we are unable to quantify whether risk will increase or decrease because of the uncertainty involved.

If there is an increased risk of cryptosporidiosis in the MAR with climate change, private (individual) and public responses can be taken to reduce vulnerability to the disease. For instance, households can boil water or use bottled water or specially designed home water filters (Juranek et al. 1995). Bacterial overgrowth on home filters may pose an additional health risk (Payment et al. 1991), and *Cryptosporidium* oocysts may concentrate on the outside of a filter cartridge increasing the risk of cross-contamination (Juranek 1995). Thus home filters must be properly designed, replaced and maintained for optimal performance. Surveillance for increased sales of antidiarrheal medications and diarrheal illness may alert public health officials to the presence of *Cryptosporidium* in water supplies so that boil water advisories could be issued to prevent further illness (Addis et al. 1995). Both public and private measures can be costly (Kocagil et al.1998). Table 9.7 presents a list of possible responses to reduce vulnerability to cryptosporidiosis.

Table 9.7 Responses to Reduce Vulnerability to Cryptosporidiosis

Type of Response	Notes about the response
Water Quality - Public	
Removal of cysts or oocysts in water treatment process	New approaches are needed to remove or kill infectious oocysts (e.g., reverse osmosis, membrane filtration or electronic or radiation methods) instead of ineffective chemical or difficult filtration techniques (Guerrant 1997). High-grade rapid sand filtration has been ineffective (Mackenzie et al. 1994); it is unlikely that lower-grade rapid sand filters would be effective (MacKenzie et al. 1995). UV light alone is not effective for disinfecting protozoa. Ozone may not be suitable for small systems because of the expense and technical expertise required. Even though ozone is more effective than chlorine against *Cryptosporidium* there may be a problem if no residual disinfectant is used (Moore et al. 1993).
Filtration	Eradication of the organism from drinking water supplies depends on adequate flocculation and filtration, rather than chlorination (Nieminski and Ongerth 1995; Guerrant 1997).
Boil Water Advisories	BWA's are not always complied with, limiting their effectiveness
Increased monitoring	Water supply organizations need to increase the frequency of oocyst monitoring during times of increased turbidity or decreased influent water quality (Hass et al. 1996; Atherholt et al. 1998).
Alternative water sources	Water that contains even one oocyst may be infectious to immunocompromised individuals (Juranek et al. 1995; Casemore et al. 1997). One solution is to use purified water sources certified for the removal of protozoa by the National Sanitation Foundation (Juranek et al. 1995).
Sewage management and control	Cryptosporidiosis outbreaks in England have been linked to public water supplies contaminated by human waste water. (Kindzierski and Gabos 1996). Increased monitoring, control and effective sanitization of waste water are necessary to prevent waterborne outbreaks.
Waste management from livestock sources	Three food-borne outbreaks of Cryptosporidiosis have been linked, but not confirmed, with contamination from livestock waste (CDC 1997b; CDC 1998c).

Water Quality - Private	
Alternative water sources	In an the event of oocyst detection in the public water supply, immunocompromised individuals should purchase and use certified bottled water (Juranek et al. 1995). Kocagil et al. (1998) estimate that the average daily cost per person is $0.38 for alternative water sources.
Boil drinking water	Kocagil et al. (1998) indicate that is costs $2.09 per person per day to boil water to prevent an illness outbreak.
Point-of-use filters	Certain types of individual or household filters are capable of removing *Cryptosporidium* oocysts from drinking water, but bacterial overgrowth on these filters may pose an additional health risk (Payment et al. 1991). *Cryptosporidium* oocysts also may concentrate on the outside of a filter cartridge that has been in use increasing the risk of cross-contamination (Juranek 1995). Thus home filters must be properly designed, replaced and maintained for optimal performance. Only filters that have an "absolute" 1 micron filter or meet NSF standard #53 for cyst removal are satisfactory for *Cryptosporidium* removal (Juranek 1995).
Public Health	
Health watches, alerts and warnings	Public health officials need to work in conjunction with water supply engineers and health care providers to notify the public if certain actions should be taken to prevent or limit and illness outbreak (Juranek 1995).
Increase monitoring of pharmacies and HMO's.	Public health officials need to monitor the sales of antidiarrheal medications and the logs of HMOs, providers and hospitals for complaints of diarrheal illness (Juranek et al. 1995). Increases in either of the above may indicate the presence of illness.
Health-Private (Personal Behavior)	
Hand washing	Since Cryptosporidium is transmitted via a fecal-oral route, effective hand washing is one of the best methods to prevent infection (Juranek et al. 1995). Several outbreaks in day care centers have been linked to improper handwashing (Guerrant 1997).

Public measures to reduce the risk of *Cryptosporidium* entering water supplies include use of groundwater, source water protection, and drinking water treatment practices, such as ozonation and specific types of filtration (Guerrant 1997). Groundwater systems, on average, have a lower risk from *Cryptosporidium* than surface water systems (Craun et al. 1996). However, groundwater systems have a 3-fold greater risk of a cryptosporidiosis outbreak if contamination occurs (Atherholt et al. 1998). Current and proposed EPA regulations will require surface water systems classified as large or very large (serving over 10,000 people) to have operational filtration systems that effectively remove *Cryptosporidium* from drinking water supplies (US EPA 1998a). However, the filtration systems must be properly installed, monitored, and maintained to effectively reduce vulnerability to cryptosporidiosis. In addition, costs associated with upgrading and operating these water systems may be high. Some insight about the vulnerability of the MAR population to cryptosporidiosis can be gained by examining public water systems. As part of the ongoing MAR assessment, we are studying public water systems in the region.

Cholera

Cholera is an acute diarrheal illness caused by ingesting the bacterium *Vibrio cholerae*. Common sources of cholera infection include contaminated drinking water, seafood, fruits, and vegetables and food contaminated during or after preparation (WHO 1993). Cholera affects the lining of the stomach. Although the infection is often mild or without symptoms, it can be severe. Approximately one in 20 infected persons develops a severe, life-threatening form of the disease, characterized by profuse watery diarrhea, vomiting, and leg cramps. In these persons, rapid loss of body fluids leads to dehydration and shock. Without treatment, death can occur within hours. With prompt fluid and salt replacement (orally or intravenously), recovery can be rapid, and the disease ordinarily runs its course in two to seven days.

Water-borne cholera is closely linked to the climate. *V. cholera*e has been found in different water sources, such as bays, streams, rivers, water tanks, ponds, lakes, canals, and ditches (Islam et al. 1996). Key factors for the bacteria's survival include appropriate temperature, pH, salt, bacterial and organic content (Collins 1996). Common physical characteristics of current cholera endemic areas are: location around rivers, bays or other bodies of water; areas of high population density; areas of low lying land; areas of high absolute humidity (CDC 1997c). Some epidemics have been related to surface water temperature and phytoplankton blooms (Kaysner and Hill 1994).

Cholera was prevalent in the US in the 1800s but has been virtually eliminated by modern sewage and water treatment systems. No major outbreaks have occurred in the US since 1911. The majority of US cholera cases between 1973 and 1996 are imported cases (contracted while traveling in a cholera endemic area). Sporadic cases have occurred in coastal areas suggesting the possible reintroduction of the organism into the US marine and estuarine environment. *V. cholera*e has been found in some US estuaries and coastal areas, although there have been no corresponding outbreaks of human cholera (Islam et al. 1996; Kaysner et al. 1987; Colwell et al.

1981).

Limiting exposure to the bacteria is an important way to reduce vulnerability to cholera.. The following four practices greatly reduce the risk of contracting cholera: 1) drink water from a safe source (properly treated water reduces the risk to near zero); 2) avoid uncooked food unless it can be peeled or shelled; 3) wash hands after contact with excreta; 4) safely dispose of human excreta (WHO 1993).

Vibrio Cholerae is present in the Chesapeake Bay (Colwell et al. 1981; Colwell and Huq 1994) although the disease is not currently a health problem in the MAR. Preliminary research indicates that climate change could facilitate the growth of *Vibrio cholerae* in the Chesapeake Bay (Gibson 1999). However, even though small pockets of cholera can develop, the probability of a region-wide epidemic is very small. This has been the case historically in the US. Areas where cholera is currently a major health problem are countries with less developed public health infrastructure than the US. Thus while the risk of cholera in the MAR could increase with climate change, proper food preparation and waste and water treatment can effectively reduce vulnerability to the disease.

Air Quality

This section describes the assessment of potential impacts of climate change on health consequences from air pollution, in particular ozone pollution. Higher temperatures in the MAR could increase levels of ozone pollution. However, this is dependent on future emissions of ozone precursors, which are highly uncertain, thus making it difficult to assess the impacts on health.

Air quality, air pollutants, and human respiratory ailments have gained the interest of climate change scientists. This is in part because of established linkages with temperature and ozone (WHO 1996; Lee 1993). The elderly and young are vulnerable to the effects of air pollution as are individuals with asthma (Neas et al. 1995; Neas et al 1996; Stebbings and Fogelman, 1979; Schwartz 1995; US EPA 1996). Diminished air quality can cause or exacerbate respiratory disorders and even lead to death. For example, six independent analyses of mortality in Philadelphia (1974-1988) showed a significant correlation between pollutant levels during the days just prior to death and on the actual day of death for total suspended particulates (small particles suspended in the air), sulfur dioxide (SO_2), and ozone (Kelsall et al. 1997). Temperature was a key factor: from 1974-1988, daily mortality from air pollution also was associated with hot days in summer and cold days in spring, fall and winter in Philadelphia. When specific pollutants were examined, SO_2 was associated with mortality in spring, fall, and winter, while ozone was associated with summer mortality (Moolgavkar et al. 1995).

Ground-level ozone can cause or exacerbate respiratory illness. In 1999, 186 US counties were in non-attainment areas, and over 17 million people lived in the 52 MAR counties that were in non-attainment (http://www.epa.gov/airprogm/airs/graphics/nonat.html). There is a non-linear relationship between ozone formation and temperature: below 70-80EF, temperature does not influence ozone concentration while above 90EF, ozone concentration is strongly dependent on temperature (NRC 1991: p50). Thus higher temperatures in the MAR could influence ozone formation if precursors are present. However, uncertainty about future emission levels of ozone precursors makes this difficult to assess. Ozone precursors include volatile organic compounds (VOC) and nitrogen oxides (NOx) (US EPA 1996). Anthropogenic sources of VOC include emissions related to transportation and industrial processes, and major sources of NOx include electric power generating plants and highway vehicles (US EPA 1996). The largest source of NOx is the Ohio River Valley while large urban areas, such as the Washington-New York corridor, are sources of both VOC and NOx (Guinnup and Collom 1997).

Wind speeds and patterns influence regional transport of ozone and its precursors in the MAR and northeastern US. Climate change may affect the process by which pollutants are transported and their range. For example, "extreme ozone events" are associated with slow-moving or stagnant high-pressure weather systems (NRC 1991). These conditions favor both ozone formation from heavily industrialized areas and transport further afield (Ryan et al. 1998). In summer, ozone levels in the Baltimore-Washington metropolitan area frequently exceed the National Ambient Air Quality Standards (NAAQS), and in July 1995 significant transportation of ozone and ozone precursors occurred in the region during an "extreme ozone event" (Ryan et al. 1998). Based on spatial patterns and transport considerations, general control measures should target urban non-attainment areas, which contribute significantly to their own ozone problems and affect down wind areas within 150-500 miles (OTAG 1997).

Without reductions in polluting emissions, heavily populated urban areas could experience more severe air quality problems as a result of climate change effects on the composition, concentration, and duration of chemical pollutants in the atmosphere (Slanina et al. 1999). A key issue for assessing air quality risks is future emissions. The US has made significant progress in reducing air pollution since the 1970s (US EPA 1998b). Future emissions of air pollutants that are harmful to human health will depend on a variety of factors (e.g., automobile use, technology, regulations) that are not easily forecasted (Davies and Mazurek 1998). Thus we are unable at this time to predict what impact climate change will have on air quality and respiratory health in the MAR. If efforts are undertaken to reduce greenhouse gas emissions, these would have the secondary benefits of reducing air pollutants harmful to human health.

Mental Health

This section describes the assessment of potential impacts of climate change on the mental health *of the MAR population. Extreme weather events such as hurricanes can cause post traumatic stress disorder. In addition, some weather conditions have been linked to suicide and seasonal affective disorder. However, the impact of climate change on extreme events and number of cloudy days is unknown. This uncertainty makes it difficult to assess the impacts on health.*

Climate change may affect mental health, an important component of human well-being. Depression and psychological changes can be related to persistent cloudy skies, precipitation, or thunderstorms (Collier and Hardaker 1995). Furthermore, experiencing extreme weather such as hurricanes or floods can inflict psychological stress and trauma, such as post traumatic stress disorder (PTSD). This was found to be the case in Pennsylvania from flooding after Hurricane Agnes (Logue et al. 1979). Similar findings were found following hurricanes in other regions. For example, PTSD, major depression, and other anxiety disorders were experienced by 51% of those sampled after Hurricane Andrew, with some people experiencing symptoms lasting over six months (David et al. 1996). Ironson et al. (1997) found that 33% of those sampled one to four months after Hurricane Andrew experienced high levels of post-traumatic stress. They also found that the stress was associated with two immune responses measured in blood tests (white blood cell counts and natural killer cell cytotoxicity). Children and adolescents are also vulnerable. For example, three months after Hurricane Hugo, more than 5% of school-aged children surveyed were classified as having PTSD with females and younger children more likely to exhibit PTSD (Shannon et al. 1994). Deviant behavior of minors was related to level of hurricane stress following Hurricane Andrew. (Khoury et al. 1997). La Greca et al. (1998) found that children with high anxiety levels prior to Hurricane Andrew were more likely to experience post-traumatic stress seven months after the hurricane. If climate change increases the number of extreme weather events, more people could suffer from PTSD.

Another possible mental disorder associated with weather is seasonal affective disorder (SAD), a type of depression with a seasonal pattern. The most common is winter SAD in which fall/winter depression is followed by summer remission (Partonen 1998). Its cause is uncertain. Decreased daylight or cooler temperatures are suggested weather-related causes, although other possible triggers include disorders relating to hormone (e.g., melatonin, serotonin) and temperature regulation (Partonen 1998). It has been suggested that 1.2% of the population is at risk for SAD (Partonen 1998). A study of children in Washington, DC suggests that 1.7% to 5.5% of people aged 9-19 may have SAD (Swedo 1995). Thus if climate change increases (decreases) the number of cloudy days, the amount of people suffering from SAD could increase (decrease). Fortunately, medical treatment such as light therapy and medication (antidepressants) have been useful in treating those afflicted with SAD (Schwartz 1996; Partonen 1998). Nevertheless, they are less effective than natural summer light (Postolache 1998) indicating that the adverse effects can not be fully addressed by medical treatment.

Weather may also influence the rate of suicide. Marion et al. (1999) found that deviations from the expected mean temperature were associated with higher elderly suicide rates in British Columbia. More specifically, warmer temperatures in the current month and colder temperatures in the previous three months were associated with higher suicide rates (Marion et al. 1999). Salib (1997) found a positive association between elderly suicide and hours of sunshine and lower relative humidity in England. Salib and Gray (1997) found similar results for deaths of all ages due to fatal self-harm (FSH), a category that includes self-inflicted deaths whether deliberate (suicide) or accidental. Thus contrary to SAD and PTSD studies, the Salib (1997) and Salib and Gray (1997) studies show that mental health is negatively related to fine, bright weather conditions and not to extreme weather conditions.

Experiencing an extreme weather event or living with persistent cloudy skies can inflict temporary or persistent psychological disorders. However, the impact of climate change on such disorders is highly uncertain. As mentioned above, without forecasts of storm tracks under climate change conditions, the intensity and frequency of extreme events such as hurricanes can not be predicted. Thus their impact on mental health (e.g., PTSD) can not be evaluated. Projections of the impact of climate change on the number of cloudy days in the region are necessary to assess the impact on SAD. However, such projections are not available. In addition, the medical linkage between climate and mental health is not always clear, as was shown with winter SAD whose cause is not certain, and with increased suicide in fine weather. Because psychological impacts are not fully understood in the current climate regime, it is very difficult to evaluate them under future climate change scenarios.

Conclusions

Understanding the impacts of climate change on human health is an exceptionally complex problem. Uncertainties about future climates are compounded by limited information about critical linkages between climate and health, the futures of other health drivers, and the highly time- and location-specific character of many weather-related health risks.

Mortality directly related to heat, cold, storms, flooding and lightning is likely to continue to be very small in the MAR. Climate change could aggravate or contribute to the region's leading causes of death (e.g., heart disease, strokes), but lifestyle choices (e.g., smoking, diet, fitness) and genetic endowment are likely to continue to dominate the health status of the region. Although much more speculative and highly uncertain, climate change could increase the region's risk from water-, food- and vector-borne diseases. In particular, this assessment examined four such diseases: cryplosporidiosis, cholera, malaria, and Lyme disease. Malaria and cholera are unlikely to become health risks in the MAR due to climate change, while climate change could increase the risk of cryptosporidiosis and Lyme disease. Uncertainty concerning several key components of air pollution and mental health makes it difficult to assess how climate change would affect morbidity and mortality related to air pollution or mental health.

The view emerging from our assessment is that the MAR's technological and medical infrastructure should be able to prevent significant regional health problems from climate change, although there may be subgroups with less access to public health measures. While health risks could increase, adaptive measures can be taken to reduce the region's vulnerability. There are costs associated with most measures to reduce vulnerability; although in some instances an action taken for other reasons will have the incidental benefit of reducing vulnerability to climate. When assessing the impacts of climate change, the incremental costs (i.e., costs incurred solely because of climate change) of adaptation measures must be considered. Accordingly, while health status may be little affected, the costs of public health could increase. In addition, some adaptation measures can have undesirable side effects (e.g., secondary impacts of pesticides used to control disease vectors). Moreover, if climate change does lead to fluctuations in the frequency of diseases, the incremental costs of illness (e.g., costs of medication, treatment, physician and hospital services, and time lost from work and leisure activities) as well as the loss of well-being experienced by disease sufferers should be included when measuring the impact of climate change.

Research Needs

It is evident that further research is needed, particularly to increase our understanding of the indirect effects of climate change on health. Integrated modeling efforts are needed to quantify the complex biophysical and behavioral linkages connecting climate to health. Of equal importance is research on the costs, effectiveness and acceptability of adaptation options. Additional major research gaps are how climate change affects heat-related morbidity, air pollution, and motor vehicle accidents. Currently, motor vehicle fatalities are an important cause of death in the MAR, and thus the health consequences of climate change from such fatalities may be larger than other weather-related causes of death. Finally, research on the variation of health risks within the region by location and population characteristics is needed to address the distribution of climate-induced health impacts, especially because different segments of the population (e.g., elderly, poor, less educated) currently tend to face greater health risks in general.

References

Abler D, Shortle J (2000) Climate Change and Agriculture in the Mid-Atlantic Region. *Climate Research*. 14(3):185-194.

Abler D, Shortle J, Rose A, Oladosu G (2000) Characterizing Regional Economic Impacts and Responses to Climate Change. *Global and Planetary Change*, in press.

Addiss DG, Arrowood MJ, Bartlett ME, Colley DG, Juranek DD, et al. (1995) *Assessing the Public Health Threat Associated with Waterborne Cryptosporidiosis: Report of a Workshop*. MMWR 44(RR6):1-20.

Alderson M (1988) *Mortality, Morbidity and Health Statistics*. Stockton Press, New York. p 70-74.

Amerasinghe FP, Breisch NL, Azad AF, Gimpel WF, Greco M, Neidhardt K, Pagac B, Piedsman J, Sandt J, Scott TW, Sweeney K (1992) Distribution, Density, and Lyme Disease Spirochete Infection in Ixodes dammini (Acari: Ixodidae) on White-Tailed Deer in Maryland. *Journal of Medical Entomology*. 29(1):54-61.

Anderson RN, Kochanek KD, Murphy SL (1997) Report of Final Mortality Statistics, 1995. *Monthly Vital Statistics Report*. 45(11):Supplement 2.

Armitage P, Colton T, editors-in-chief (1998) *Encyclopedia of Biostatistics*. Volume 6, Spi-Z, Index. John Wiley and Sons, New York. p 4237-4241.

Atherholt TB, LeChevallier MW, Norton WD, Rosen J (1998) Effect of Rainfall on Giardia and Crypto. *Journal of The American Water Works Association* 90(9). 66-80.

Banta HD, Jonas S (1996) Health and Health Care. Chapter 2 in: Kovner AR (ed) *Jonas's Health Care Delivery in the United States*, Fifth Edition. Springer Publishing Company, New York: NY. p 11-33.

Barbour AG (1993) The biological and social phenomenon of Lyme disease. *Science*. 260(5114): 1610-1616.

Bates M (1970) *The Natural History of Mosquitoes*. Peter Smith, Gloucester, MA. 378 pp.

Benson K, Kocagil P, Shortle J. (2000) Climate change and health in the Mid-Atlantic Region. *Climate Research* 14(3):245-253.

Brook JH, Genese CA, Bloland PB, Zucker JR, Spitalny KC (1994) Brief Report: Malaria Probably Locally Acquired in New Jersey. *New England Journal of Medicine*. 331(1):22-23.

Bruce-Chwatt LJ (1998) History of Malaria from Prehistory to Eradication. Chapter 1 in Wernsdorfer WH, McGregor I (eds) *Malaria: Principles and practice of Malariology.* Churchill Livingstone, Edinborough, New York.

Casemore DP, Wright SE, Coop RL (1997) Cryptosporidiosis - Human and Animal Epidemiology. Chapter 4 in: Fayer, R (ed) *Cryptosporidium and Cryptosporidiosis* CRC Press, Boca Raton, Florida.

CDC (Centers for Disease Control and Prevention) (1994) Heat-Related Deaths- Philadelphia and the United States, 1993-1994. *Mortality and Morbidity Weekly Report (MMWR).* 43(25):453-455.

CDC (1995) Assessing the Public Health Threat Associated with Waterborne Cryptosporidiosis: Report of a Workshop. *Mortality and Morbidity Weekly Report (MMWR)* Recommendations and Reports. 44(RR-6).

CDC (1996) Foodborne Outbreak of Diarrheal Illness Associated with Cryptosporidium parvum - Minnesota, 1995. *MMWR*. 45(36):783-784.

CDC (1997a) *Cryptosporidium and Water: A Public Health Handbook 1997*. Atlanta, GA: Working Group on Waterborne Cryptosporidiosis.

CDC (1997b) Outbreaks of Escherichia coli O157:H7 Infection and Cryptosporidiosis Associated with Drinking Unpasteurized Apple Cider-Connecticut and New York, October 1996. *MMWR*. 46(1):4-8.

CDC (1997c). Technical Guidelines on Detection and Control of Epidemic Cholera. *Data for Decision Making (DDM)/CDC*.

CDC (1998a) *Chronic Diseases and Their Risk Factors: The Nation's Leading Causes of Death*. Atlanta, GA.

CDC (1998b) *Compressed Mortality File*. Data collected July 1998 from wonder.cdc.gov. Office of Analysis and Epidemiology, National Center for Health Statistics, Centers for Disease Control and Prevention, Atlanta, GA.

CDC (1998c) Foodborne Outbreak of Cryptosporidiosis - Spokane, Washington, 1997. *MMWR*. 47(27) 565-567.

CDC (1999a) Mortality Patterns - United States, 1997. *MMWR*. 48(30):664-668.

CDC (1999b) Recommendations for the use of Lyme disease vaccine. *MMWR*. 48(RR-7): 1-26.

CDC (1999c) Achievements in Public Health, 1900-1999: Healthier Mothers and Babies. *MMWR*. 48(38):849-858.

CDC (1999d) Availability of Lyme Disease Vaccine. *MMWR*. 48(2) 35-36.

CDC (1999e) Malaria Surveillance - United States, 1995. *MMWR Surveillance Summaries*. 48(SS-1).

CDC (2000a) Morbidity and Mortality Associated With Hurricane Floyd ---North Carolina, September--October 1999. *MMWR*. 49(17):369-372.

CDC (2000b) Probable Locally Acquired Mosquito-Transmitted Plasmodium vivax Infection–Suffolk County, New York, 1999. *MMWR*. 49(22):495-8.

Chestnut LG, Breffle W, Smith J, Kalkstein L (1995) *Estimates of Willingness to Pay for Potential Changes in Risks of Mortality Due to Climate Change*. Final Report funded under US EPA Cooperative Agreement No. CR-817693, Feb. 24.

Chestnut LG, Breffle WS, Smith JB, Kalkstein LS (1998) Analysis of Differences in Hot-Weather-Related Mortality Across 44 U.S. Metropolitan Areas. *Environmental Sciences Policy*. 1:59-70.

Collier CG, Hardaker PJ (1995) Weather, Air Quality and Health. *Meteorological Applications*. 2:313-322.

Collins, AE (1996) The Geography of Cholera. Chapter 8 in *Cholera and the Ecology of Vibrio cholerae*. Edited by B.S. Drasar and B.D. Forrest. Chapman & Hall, London. New York.

Colwell R, Epstein P, Gubler D, Hall M, Reiter P, Shukla J, Sprigg W, Takafuji E, Trtanj J (1998) Global Climate Change and Infectious Diseases. *Emerging Infectious Diseases*. 4(3) 451-452.

Colwell RR, Huq A (1994) Vibrios in the Environment: Viable but Nonculturable Vibrio cholerae. Chapter 9 in Wachsmuth IK, Blake PA, Olsvik O (eds) *Vibrio cholerae and Cholera: Molecular to Global Perspectives*. American Society for Microbiology Press, Washington, DC.

Colwell RR, Seidler RJ, Kaper J, Joseph SW, Garges S, Lockman H, Maneval D, Bradford H, Roberts N, Remmers E, Huq I, Huq A (1981) Occurrence of Vibrio cholerae Serotype O1 in Maryland and Louisiana Estuaries. *Applied Environmental Microbiology*. 41(2):555-558.

Crans WJ (1992) *A History of Malaria in New Jersey*. Proceedings of the Seventy-Ninth Annual Meeting of the New Jersey Mosquito Control Association, Inc., 1992 pp 115-122.

Craun GF, Calderon RL, Frost FJ (1996) An Introduction to Epidemiology. *Journal of the American Water Works Association*. 88(9). 54-55.

David D, Mellman TA, Mendoza LM, Kulick-Bell R, Ironson G, Schneiderman N (1996) Psychiatric morbidity following Hurricane Andrew. *J Trauma Stress*. 9(3):607-612.

Davies JD, Mazurek J (1998) *Pollution Control in the United States: Evaluating the System*. Resources for the Future, Washington, DC, 319 pp.

Fayer R (1997) *Cryptosporidium and Cryptosporidiosis*. CRC Press, New York, p337.

Fine A, Layton M, Miller J, Cimini D, et al. (1999) Update: West Nile Virus Encephalitis – New York, (1999) *MMWR*. 48(41):944-946,955.

Fisher A, Barron E, Yarnal B, Shortle J (1999) *Climate Change Impacts in the Mid-Atlantic - A Workshop Report*. Report to the U.S. Environmental Protection Agency Office of Research and Development, Global Climate Change Research Program (Coop. Agreement No. CR 826554-01) and Office of Policy (Coop. Agreement No. CR 824369-01).

Fox KR, Lytle DA (1996) Milwaukee's Crypto Outbreak: Investigation and Recommendations. *Journal of the American Water Works Association*. 88(9):87-94.

Gibson J (1999) *Modeling Chesapeake Bay Salinity and Phytoplankton Dynamics in Response to Varying Climate*. Master's Thesis. The Pennsylvania State University.

Glass GE (1995) Environmental Risk Factors for Lyme Disease Identified with Geographic Information Systems. *American Journal of Public Health*. 85(7):944-948.

Graczyk, TK, Evans BM, Shiff CJ, Karreman HJ, Patz JA (2000) Environmental and geographical factors contributing to watershed contamination with Cryptosporidium parvum oocysts. *Environmental Research*. 82(3): 263-271.

Grayson M (1998) Report Offers a Glimpse into the Future of Health Care. *Spectrum: The Journal of State Government*. 71(2) 1-3.

Greene JS, Kalkstein LS (1996) Quantitative Analysis of Summer Air Masses in the Eastern United States and an Application to Human Mortality. *Climate Research*. 7:43-53.

Grossman M, Kaestner R (1997) Effects of Education on Health. Chapter 4 in Behrman JR, Stacey N (eds) *The Social Benefits of Education*. University of Michigan Press, Ann Arbor

Guerrant RL (1997) Cryptosporidiosis: An Emerging, Highly Infectious Threat. *Emerging Infectious Disease*. 3(1): 51-57.

Guinnup D, Collom B (1997) *Final Report, Vol. I: Executive Summary OTAG Air Quality Analysis Workgroup*.
http://capita.wustl.edu/otag/reports/aqafinvol_I/animations/v1_exsumanimb.html

Haas CN, Crockett CS, Rose JB, Gerba CP, Fazil AM (1996) Assessing the Risk Posed by Oocysts in Drinking Water. *Journal of the American Water Works Association*. 88(9):131-136.

Haines A, McMichael AJ (1997) Climate Change and Health: Implications for Research, Monitoring and Policy. *British Medical Journal*. 315(7112) 870-874.

Horsfall WR (1972) *Mosquitoes: their bionomics and relation to disease*. Hafner Pub. Co., New York, NY. 723 pp.

Ironson G, Wynings C, Schneiderman N, Baum A, Rodriguez M, Greenwood D, Benight C, Antoni M, LaPerriere A, Huang HS, Klimas N, Fletcher MA (1997) Posttraumatic stress symptoms, intrusive thoughts, loss, and immune function after Hurricane Andrew. *Psychosom Med*. 59(2):128-41.

Islam MS, Drasar BS, Sack RB (1996) Ecology of Vibrio cholerae: Role of Aquatic Flora and Fauna. Chapter 6 in Drasar BS, Forrest BD (eds) *Cholera and the Ecology of Vibrio cholerae*. Chapman & Hall, London, New York.

Jones CG, Ostfeld RS, Richard MP, Schauber EM, Wolff JO (1998) Chain Reactions Linking Acorns to Gypsy Moth Outbreaks and Lyme Disease Risk. *Science*. 279(5353):1023-1026.

Juranek DD (1995) Cryptosporidiosis: Sources of Infection and Guidelines for Prevention. *Clinical Infectious Diseases*. 21:S57-61

Juranek DD, Addiss DG, Bartlett ME, Arrowood MJ, Colley DG, Kaplan JE, Perciasepe R, Elder JR, Regli SE, Berger PS (1995) Cryptosporidiosis and Public Health: Workshop Report. *Journal of the American Water Works Association*. 87(9):69-80.

Kajander J (1996) Future Trends in the Health Care Economy. *Journal of Health Care Finance*.

23(1) 17-22.

Kalkstein LS (1993) Direct Impacts in Cities. *Lancet*. 342(8884):1397-1399.

Kalkstein LS (1998) Associate Director, Center for Climatic Research, University of Delaware. Personal communication, November 1998

Kalkstein LS, Greene JS (1997) An Evaluation of Climate/Mortality Relationships in Large U.S. Cities and the Possible Impacts of Climate Change. *Environmental Health Perspectives*. 105(1):84-93.

Kalkstein LS, Maunder WJ, Jendritzky G (1996) *Climate and Human Health*. 2nd ed. Geneva, Switzerland, World Meteorological Organization.

Kalkstein LS, Smoyer KE (1993) The impact of climate change on human health: some international implications. *Experientia*. 59, 969-979.

Kaysner CA, Hill WE (1994) Toxigenic Vibrio cholerae 01 in Food and Water. Chapter 2 in Wachsmuth IK, Blake PA, Olsvik O (eds) *Vibrio cholerae and Cholera: Molecular to Global Perspectives*. American Society for Microbiology Press, Washington, DC.

Kaysner CA, Abeyta C Jr, Wekell MM, DePaola A Jr, Stott RF, Leitch JM (1987) Incidence of Vibrio cholerae from Estuaries of the United States West Coast. *Applied Environmental Microbiolog*y. 53(6):1344-1348.

Kelsall JE, et al. (1997) Air pollution and mortality in Philadelphia, 1974-1988. *Am J Epidemiol. 146(9): 750-62.*

Khoury EL, Warheit GJ, Hargrove MC, Zimmerman RS, Vega WA, Gil AG (1997) The Impact of Hurricane Andrew on deviant behavior among a multi-racial/ethnic sample of adolescents in Dade County, Florida: a longitudinal analysis. *J Trauma Stress*. 10(1):71-91.

Kilbourne EM (1997) Heat Waves and Hot Environments. Chapter 12 in Noji EK (ed) The *Public Health Consequences of Disasters*. Oxford University Press, New York, p 245-269.

Kilbourne EM (1998) Illness Due to Thermal Extremes. Chapter 27 in Wallace RB (ed) *Maxcy-Rosenau-Last public health & preventive medicine*, 14th ed. Appleton & Lange, Stamford, Conn.

Kindzierski WB, Gabos S (1996) Health Effects Associated with Wastewater Treatment, Disposal and Reuse. *Water Environment Research*. 68(4):819-826.

Kocagil P, Demarteau N, Fisher A, Shortle JS (1998) The Value of Preventing Cryptosporidium Contamination. *Risk: Health, Safety and Environment*. 9:175-196.

Kramer MH, Herwaldt BL, Craun GF, Calderon RL, Juraneck.DD (1996) Surveillance for Waterborne Disease Outbreaks - United States, 1993-1994. *MMWR Surveillance Summaries*. 45(SS-1):1-33.

La Greca AM, Silverman WK, Wasserstein SB (1998) Children's predisaster functioning as a predictor of posttraumatic stress following Hurricane Andrew. *J Consult Clin Psychol*. 66(6):883-892.

Larsen U (1990a) The Effects of Monthly Temperature Fluctuations on Mortality in the United States from 1921 to 1985. *International Journal of Biometeorology*. 34:136-145.

Larsen U (1990b) Short-term Fluctuations in Death by Cause, Temperature, and Income in the United States, 1930-1985. *Social Biology*. 37(3-4):172-187.

Layton M, Parise ME, Campbell CC, Advani R, Sexton JD, Bosler EM, Zucker JR (1995) Mosquito-transmitted Malaria in New York City, (1993) *Lance*t. 346:729-731.

Lee D (1993) Climate change and air quality in London. *Geography*. v78 (Pt. 1). 77-79.

Loeb PD (1985) The Efficacy and Cost Effectiveness of Motor Vehicle Inspection Using Cross-Sectional Data. *Southern Economic Journal*. 52(2):500-509.

Logue JN, Hansen H, Struening E (1979). Emotional and Physical Distress Following Hurricane Agnes in Wyoming Valley of Pennsylvania. *Public Health Reports*. 94: 495-502.

MacKenzie WR, Hoxie NJ, Proctor ME (1994) A Massive Outbreak in Milwaukee of *Cryptosporidium* Infection Transmitted Through the Public Water Supply. *New England Journal of Medicine* 331(3):161-167.

MacKenzie WR, Kazmierczak JJ, Davis JP (1995) An Outbreak of Cryptosporidiosis Associated with a Resort Swimming Pool. *Epidemiology and Infection*. 115:545-553.

Marion SA, Agbayewa MO, Wiggins S (1999) The Effect of Season and Weather on Suicide Rates in the Elderly in British Columbia. *Canadian Journal of Public Health*. 90(6): 418-422.

Marsh K (1998) What is Malaria? *World Health*. 51(3):6-7.

Martens WJM, Jetten TH, Focks DA (1997) Sensitivity of Malaria, Schistosomiasis and Dengue to Global Warming. *Climatic Change*. 35(2):145-156.

Martens WFM, Niessen LW, Rotmans J, Jetten TH, McMichael AJ (1995) Potential Impacts of Global Climate Change on Malaria Risk. *Environmental Health Perspectives*. 103(5):458-464.

McKeown T (1976) *The Modern Rise of Population*. Academic Press, New York.

McMichael AJ (1997) Global climate change: The potential effects on health. *British Medical Journa*l. 315(7111). 805-809.

McMichael AJ (1999) Globalization and the sustainability of human health. *Bioscience*. 49(3) 205-209.

McMichael AJ, Ando M, Carcavallo R, Epstein P, Haines A, Jendritzky G, Kalkstein L, Odongo R, Patz J, Piver W, et al. (1996) Human Population Health. Chapter 18 in Watson RT, Zinyowera MC, Moss RH (eds) *Climate change, 1995: impacts, adaptations and mitigation of climate change: scientific-technical analyses : contribution of Working Group II to the second assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York.

Meltzer MI, Dennis DT, Orloski KA (1999) The Cost Effectiveness of Vaccinating against Lyme Disease. *Emerging Infectious Diseases*. 5(3): 321-328.

Moolgavkar SH, et al. (1995) Air pollution and daily mortality in Philadelphia. *Epidemiology*. 6(5): 476-84.

Moore AC, Herwaldt BL, Craun GF, Calderon RL, Highsmith AK, Juranek DD (1993) Surveillance for Waterborne Disease Outbreaks - United States, 1991-1992. *MMWR*. 42(22-5):1-22.

NC DHHS (North Carolina Department of Health and Human Services) (1999) *Hurricane Floyd: Hospital Emergency Room Surveillance*, Eastern, North Carolina. http://www.schs.state.nc.us/epi/hurricane/summary.html, http://www.schs.state.nc.us/epi/hurricane/surv1020.html, http://www.dhhs.state.nc.us/docs/floydmentalhealth.htm.

NCHS (National Center for Health Statistics) (1998) *Health, United States, 1998 With Socioeconomic Status and Health Chartbook*. Hyattsville, Maryland.

NRC (National Research Council) (1991) *Rethinking the Ozone Problem in Urban and Regional Air Pollution*. National Academy Press. Washington, DC.

Neas LM, et al. (1995) The association of ambient air pollution with twice daily peak expiratory flow rate measurements in children. *Am J Epidemiol*. 141(2): 111-22.

Neas LM, et al. (1996) Fungus spores, air pollutants, and other determinants of peak expiratory flow rate in children. *Am J Epidemiol*. 143(8): 797-807.

Nieminski EC, Ongerth JE (1995) Removing Giardia and Cryptosporidium by Conventional Treatment and Direct Filtration. *Journal of the American Water Works Association*. 87(9):96-106.

NPA Data Service, Inc (1999) Regional Economic Projections Series. Demographic Database, May (1999) *Economic Database*, April (1999)

OTAG (1997) *Telling the OTAG Ozone Story with Data: The Ozone Transport Assessment Group (OTAG) Report*. Guinnup D, Collom, B (co-chairs).
http://www.epa.gov/ttn/rto/otag/finalrpt/

Pampana E (1963) *A textbook of malaria eradication*. London: Oxford University Press.

Partonen T (1998) Seasonal Affective Disorder. *Lancet*. 352(9137):1369-1374.

Patz JA (1996) Health Adaptations to Climate Change: Need for Farsighted Integrated Approaches. In: Smith JB et al (eds) *Adapting to Climate Change*. Springer, New York

Patz JA, Epstein PR, Burke TA, Balbus JM (1996) Global Climate Change and Emerging Infectious Diseases *JAMA* 275(3) 217-223.

Payment P, Franco E, Richardson L, Siemiatycki J (1991) Gastrointestinal health effects associated with the consumption of drinking water produced by point-of-use domestic reverse-osmosis filtration units. *Applied Environmental Microbiology*. 57(4):945-857.

Pirhonen JP, Vaha-Eskeli KK, Seppanen A, Vuorinen J, Erkkola RU (1994) Does thermal stress decrease uterine blood flow in hypertensive pregnancies? *American Journal of Perinatology*. 11(5):313-316.

Postolache TT (1998) Greater Improvement in Summer than with Light Treatment in Winter in

Patients with Seasonal Affective Disorder. *American Journal of Psychiatry*. 155(11):1614-1616.

Powledge F (1998) Mosquitoes, Malaria, and Controversy. *Bioscience*. 48(6):439.

Rackers DC, Donnell H (1999) Heat-Related Illnesses and Deaths – Missouri, 1998 , and United State, 1979-1996. *MMWR*. 48(22):469-472.

Rose JB, Lisle JT, LeChevallier M (1997) Waterborne Cryptosporidiosis: Incidence, Outbreaks and Treatment Strategies. Chapter 4 in Fayer R (ed) *Cryptosporidium and Cryptosporidiosis*. CRC Press: Boca Raton.

Ryan WF, et al. (1998) Pollutant transport during a regional O3-episode in the mid-Atlantic states. *J Air Waste Manag Assoc*. 48(9):786-97.

Salib E (1997) Elderly suicide and weather conditions: is there a link? *International Journal of Geriatric Psychiatry*. 12(9):937-941.

Salib E, Gray N (1997) Weather conditions and fatal self-harm in North Cheshire 1989-1993. *Br J Psychiatry*. 170: 473-477. 12(9):937-941.

Schulze TL, Lakat MF, Bowen GS, Parkin WE, Shisler JK (1984) Ixodes dammini (Acari: Ixodidae) and associated ixodid ticks collected from white-tailed deer in New Jersey, USA: geographical distribution and relation to selected environmental and physical parameters. *Journal of Medical Entomology*. 21:741-749.

Schulze TL, Taylor RC, Taylor GC, Bosler EM (1991) Lyme Disease: A proposed ecological index to assess areas of risk in the northeastern United States *American Journal of Public Health*. 81(4) 714-718.

Schwartz J (1995) Short term fluctuations in air pollution and hospital admissions of the elderly for respiratory disease. *Thorax*. 50(5):531-8.

Schwarz PJ (1996) Winter seasonal affective disorder: a follow-up study of the first 59 patients of the National Institute of Mental Health seasonal studies program. *American Journal of Psychiatry*. 153(8):1028-1036.

Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, Wilhelm JL (1996) Heat-Related Deaths During the July 1995 Heat Wave in Chicago. *NEJM*. 335(2):84-90.

Shannon MP, Lonigan CJ, Finch AJ Jr, Taylor CM (1994) Children exposed to disaster: I. Epidemiology of post-traumatic symptoms and symptom profiles. *J Am Acad Child Adolesc Psychiatry*. 33(1): 80-93.

Slanina J, ten Brink HM, Khlystov A (1999) Fate of products of degradation processes: consequences for climatic change. *Chemosphere* 38(6):1429-44.

Smith HV, Rose JB (1998) Waterborne Cryptosporidiosis: Current Status. *Parasitology Today* 14(1) 14-22.

Solo-Gabriele H, Neumeister S (1996) US Outbreaks of Cryptosporidiosis. *Journal of the American Water Works Association*. 88(9):76-86.

Stebbings JH Jr, Fogleman DG (1979) Identifying a susceptible subgroup: effects of the Pittsburgh air pollution episode upon schoolchildren. *Am J Epidemiol*. 110(1): 27-40.

Swedo SE (1995) Rates of seasonal affective disorder in children and adolescents. *American Journal of Psychiatry*. 152(7):1016-1019.

Telford SR III, Armstrong PM, Katavolos P, Foppa I, Olmeda Garcia AS, Wilson ML, Spielman A (1997) A New Tick-borne Encephalitis-like Virus Infecting New England Deer Ticks, Ixodes dammini. *Emerging Infectious Diseases*. 3(2):165-170.

US Census Bureau (1997) *Statistical Abstract of the United States: 1997*. Washington, DC, p 120

US DHHS (Deptartment of Health and Human Services), Public Health Service. (1991) *Healthy People 2000: National Health Promotion and Disease Prevention Objectives*. Washington, DC.

US DHHS, Health Resources and Services Administration, Bureau of Health Professions. (1997) Bureau of Health Professions Area Resource File, 1940-1995: United States [Computer file]. Rockville, MD: U.S. Dept. of Health and Human Services, Office of Data Analysis and Management [producer], (1996) Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor].

US EPA (1996) *Air Quality Criteria and Related Photochemical Oxidants* Volume I.

US EPA (1998a) National Primary Drinking Water Regulations: Interim Enhanced Surface Water Treatment; Final Rule. *Federal Register*. 63(241).

US EPA (1998b) *National Air Quality and Emissions Trends Report, 1997*. EPA Document Number 454/R-98-016.

Varde S, Beckley J, Schwartz I (1998) Prevalance of tick-borne pathogens in Ixodes scarpularis in a rural New jersey county. *Emerging Infectious Diseases* 5(1) 34-38.

WHO (World Health Organization) (1990) *Potential Health Effects of Climatic Change*. Geneva, Switzerland, World Health Organization.

WHO (1993) *A Global Strategy for Malaria Control*. Geneva, Switzerland, World Health Organization.

WHO (1996) *Climate Change and Human Health*. Edited by A.J. McMichael, A. Haines, R. Slooff and S. Kovats. Geneva, Switzerland, World Health Organization.

WHO (1998) *The World Health Report 1998 - Life in the 21st Century: A Vision for All*. Geneva, Switzerland, World Health Organization.

Zlatoper TJ (1987) Testing for Functional Form and Autocorrelation in the Analysis of Motor Vehicle Deaths. *Quarterly Review of Economics and Finance*. 27(4):6-17.

Zucker JR (1996) Changing Patterns of Autochthonous Malaria Transmission in the United States: A Review of Recent Outbreaks. *Emerging Infectious Diseases*. 2(1):37-43.

Appendix 9.A. Heat-and Cold-Related Mortality Adjusted for Projected Population Changes using Total (All ages) Population Growth Rates.

As mentioned in the Heat- and Cold-Related Mortality section above, the Kalkstein and Greene (1997) estimates of mortality can be corrected for population growth using two methodologies: age-specific population growth rates or total population growth rates. This Appendix presents results using total population growth rates while the chapter itself presents results using age-specific growth rates. Table 9.A1 shows net excess mortality adjusted for city-specific population projections in 2020 and 2050 for the three GCMs as well as the associated net excess mortality rates.

The estimates in Tables 9.A1 are in general less than their corresponding estimates in Table 9.5. The larger estimates resulting from using age-specific growth rates reflect primarily the high growth rates in the population aged 65 and older. The estimates presented here are higher than the Kalkstein and Greene (1997) original estimates for Baltimore, Greensboro and Philadelphia and reflect the expected population growth of these cities; the estimates are in general lower for Pittsburgh and Washington, DC, reflecting their expected decline in population. Table 9.A1 shows that combined summer and winter annual excess deaths in 2050 could increase over the current level by 110 - 180% in Baltimore, 110 - 225% in Greensboro, 50 - 155% in Philadelphia, 50 - 105% in Pittsburgh, and 0 - 75% in Washington, DC.

The total (summer plus winter) net excess mortality rates in 2050 are larger than the 2020 mortality rates and vary from 0.0 to 6.2 per 100,000 population depending on the GCM and the city. Currently in the MAR, the 12th leading cause of death is liver disease with a mortality rate of 6.2. So, in 2050, the net excess mortality attributable to climate is predicted to be lower than the current leading causes of death.

Table 9.A1. Heat- and Cold-Related Mortality Adjusted for Projected Population Changes Using City-Specific and Total (all ages) Population Growth Rates; % changes in parentheses.

	Excess Mortality	Net Excess Mortality (Net Excess Mortality Rate per 100,000 Population)					
		2020			2050		
	Present Climate	GFDL	UKMO	Max Planck	GFDL	UKMO	Max Planck
Summer							
Baltimore	92	-18 (-0.64)	99 (3.45)	-11 (-0.37)	102 (2.92)	164 (4.72)	113 (3.24)
Greensboro	25	16 (1.11)	37 (2.66)	14 (1.01)	42 (2.39)	56 (3.22)	27 (1.57)
Philadelphia	133	-28 (-0.55)	251 (4.94)	70 (1.37)	153 (2.75)	423 (7.57)	243 (4.36)
Pittsburgh	36	-7 (-0.32)	23 (1.00)	22 (0.92)	22 (0.89)	43 (1.74)	54 (2.21)
Washington, DC	0	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Winter							
Baltimore	0	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Greensboro	0	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Philadelphia	88	-3 (-0.05)	-73 (-1.43)	-10 (-0.20)	-46 (-0.82)	-77 (-1.38)	8 (0.14)
Pittsburgh	18	0 (0.02)	9 (0.37)	1 (0.06)	5 (0.21)	12 (0.48)	2 (0.10)
Washington, DC	17	7 (1.43)	13 (2.51)	6 (1.27)	0 (-0.01)	13 (2.31)	9 (1.69)
Total (Summer + Winter)							
Baltimore	92	-18 (-0.64)	99 (3.45)	-11 (-0.37)	102 (2.92)	164 (4.72)	113 (3.24)
Greensboro	25	16 (1.11)	37 (2.66)	14 (1.01)	42 (2.39)	56 (3.22)	27 (1.57)
Philadelphia	221	-31 (-0.60)	179 (3.51)	60 (1.17)	108 (1.93)	345 (6.19)	251 (4.50)
Pittsburgh	54	-7 (-0.30)	32 (1.37)	23 (0.98)	27 (1.10)	55 (2.23)	57 (2.30)
Washington, DC	17	7 (1.43)	13 (2.51)	6 (1.27)	0 (-0.01)	13 (2.31)	9 (1.69)

Adapted from Kalkstein and Greene (1997). Full acclimatization is assumed. See Table 9.4 for more details.

*Planning for the 21st Century**

Summary of Key Findings

Earlier chapters demonstrate many uncertainties in projecting a) how the population, economy and environment of the MAR will evolve, b) how the region's climate will change, and c) how changes in the region's climate will affect its population, economy and environment. The assessment is based on the convergence of climate model projections of a somewhat warmer and somewhat wetter MAR, with the potential for greater variability in the region's climate in the coming decades. These projections implicitly assume that the causes of global climate change will not abate. The models' uncertainties are compounded by the fact that different people, communities, species and ecosystems have differing capabilities for adapting to climate change. Though these preliminary assessment results include uncertainties, the region's citizens and decision makers can use them to inform decisions that affect the future of the region.

Impacts/consequences from changes in climate and climate variability

The Mid-Atlantic Region's economy is robust because it is diversified, technologically advanced, and highly integrated with the rest of the United States and the world. The region's economy has relatively little dependence on climate-sensitive economic sectors. For example, agricultural production and forestry each account for only about one percent of the region's gross output. In addition, impacts are moderated over time because buyers and sellers within the MAR are able to adapt to changes in the availability of products from climate-sensitive sectors. These features make the MAR economy resilient to current climate variability. The region's economic resilience, along with anticipated technological, institutional, and behavioral adaptations suggest that the MAR **economy** will be reasonably able to adapt to projected climate change.[1]

On the other hand, the MARA suggests that climate change poses diverse and potentially large risks to the region's **ecosystems**, which already show signs of stress for diverse reasons. Lingering effects from earlier degradation are compounded by continuing pressures on many of

---

* This section is based on Fisher A, (2000) "Preliminary Findings from the Mid-Atlantic Regional Assessment," *Climate Research*, 14:2. It appears with permission of Inter-Research.

[1] This presumes no major surprises (i.e., rapid, large non-linear responses) that would cause negative ecosystem impacts to dominate humans' overall well-being.

the region's ecological resources. Increased recognition of these pressures has come at a time of growing societal interest in ecological resource protection, both for its own sake and for recreational uses. These broad themes -- economic resilience combined with ecological vulnerability -- are reinforced by the summary of results in the following subsections, and illustrated in Figure P.1.

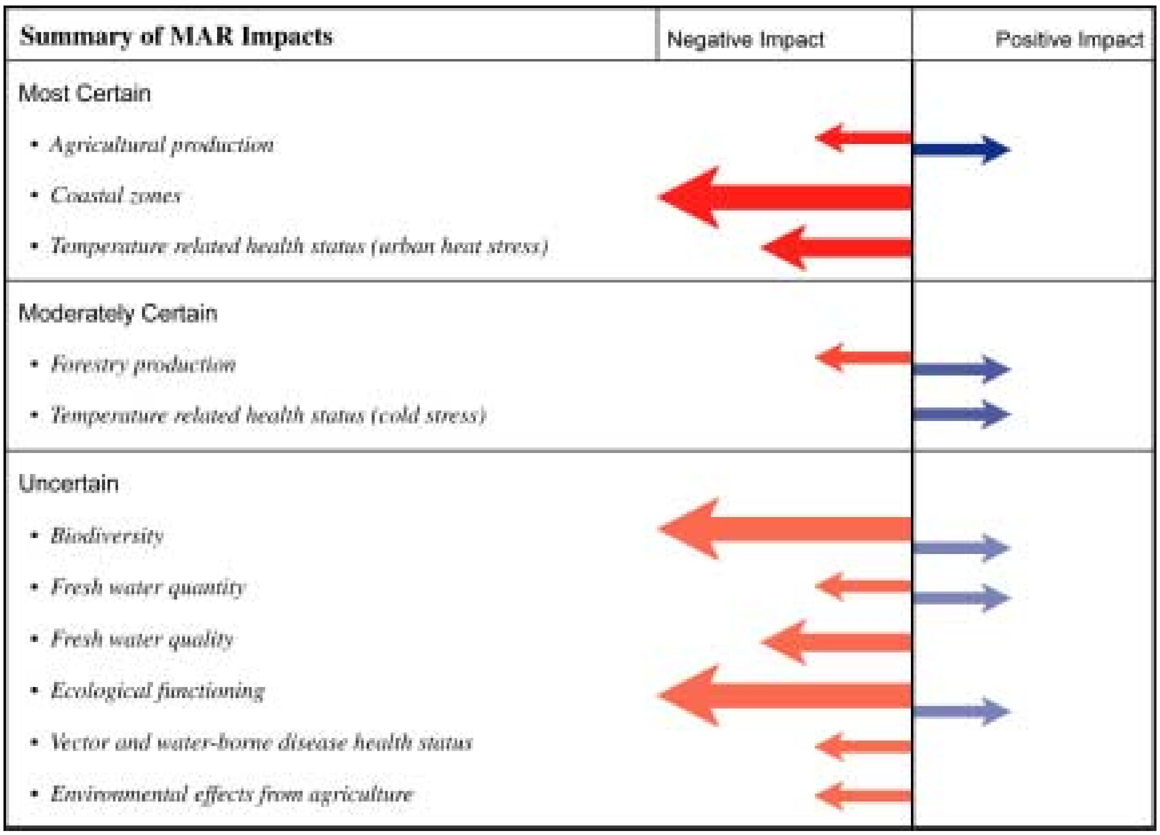


Figure P.1. Summary of impacts. The size and direction of the arrow illustrate the size and direction of the anticipated impact of climate change in the MAR.

Agriculture

Reflecting national trends, agriculture within the MAR has declined in importance while simultaneously adapting rapidly to changes in production and processing technology and to changing demands for different agricultural products. Chapter 4 assessed potential impacts by 2030 for two scenarios, one based on the status quo for the agricultural sector and a second based on "more environmentally friendly and smaller" (EFS) agriculture. The EFS scenario is more likely, given the expected increases in regulation and the relatively higher values of land in other uses. Climate change is unlikely to have major effects on the region's agricultural production, because of farmers' ability to adapt, the fertilization and reduced transpiration effects of CO_2, and the projected changes in regional temperature and precipitation. Despite uncertainties about how climate change will affect weeds as well as crop and livestock pests and diseases, there might be modest increases in the production of soybeans, and perhaps of corn and tree fruits. Climate change could have modest negative impacts on tobacco production, primarily from the indirect effects of increased competition from outside the MAR. These effects are shown in the top part of Figure P.1. The region's other two major agricultural categories, dairy and poultry production, are not expected to be affected by climate change. Higher summer temperatures projected for the MAR are unlikely to be a major detriment to livestock production, and an increasing share of livestock production occurs under controlled (indoor) climate conditions.

The main environmental effects from the region's agricultural production are erosion and runoff from nutrients and pesticides. If livestock production continues to be as important in the MAR as it is now (i.e., the status quo scenario), nutrient leaching and runoff could increase – particularly if there is a substantial increase in extreme weather events. The resulting water quality impacts could raise the risks of waterborne diseases and of ecological damages to fresh water and estuarine resources from eutrophication. Because of greater uncertainties about potential climate-induced environmental impacts from agricultural production, the corresponding arrow is in the bottom portion of Figure P.1.

Forests

Whether forests are managed for watershed protection, harvesting of saw timber, or maintenance of forest aesthetics, their managers report increased operating costs when extreme weather occurs. These costs would be higher if extreme weather becomes more frequent or intense. Although projections of future patterns of extreme events are uncertain, there is more certainty that higher temperatures and changes in precipitation will affect tree growth and survival. Increased atmospheric concentrations of CO_2 may fertilize trees and allow them to use water more efficiently. Using a statistical procedure developed by Iverson and Prasad (1998), chapter 5 shows that climate change is likely to reduce the dominance of maple-beech-birch forests in the MAR, while increasing oak-hickory forests, and, to a lesser extent, southern pine and mixed oak-pine forests. Overall primary forest productivity might increase, but shifts in forest types and their locations could diminish the competitiveness of the many small hardwood processors (e.g., for furniture and cabinetry). Arrows in the middle portion of Figure P.1 reflect these potential impacts. Similar to the findings for agricultural production, forest changes are expected to be modest in size, but are somewhat more uncertain.

The relatively rapid shift in dominant forest types might foster invasive species and decrease biodiversity (and possibly ecosystem functioning) in the region’s forests. Rapid shifts in forest types also might affect hydrology so that forests provide less filtering and moderation of stream flow. Relatively little is known about how the changes in forest types might affect recreation opportunities in forests. Along with conclusions from other chapters, these findings contribute to the arrows for biodiversity, water quality, and ecological functioning in Figure P.1.

Fresh water quantity and quality

Rapid development in parts of the MAR that rely on ground water wells, especially for residential use, has created stresses because of surface water infiltration, or salt water intrusion in the coastal zone. Water systems also are sensitive to weather extremes. At least 25 percent of surveyed water system managers reported difficulties at least once a year with each of the following: drought, floods, high and low air temperatures, electrical storms, snows, and wind. Projections of stream flow (Najjar 1999) show a 24 percent increase by 2095 using the Hadley model, but a 4 percent decrease for the Canadian Climate Centre model. Despite these uncertainties, the potential for a wetter regional climate, punctuated by droughts, suggests higher water supply management costs to protect the quality of both surface and ground water sources and to provide more storage capacity. Increased storage capacity has the potential to buffer the region against additional flooding, if the extra precipitation tends to arrive in intense storms. However, as is true in many other regions, environmental concerns have made it increasingly difficult to build many types of water storage facilities in the MAR. Smaller water systems and individual well owners have the disadvantage of not being able to spread storage or quality protection costs over large numbers of users. Fortunately, improved use of water markets could increase the efficiency of water use for both large and small systems. Uncertainties about future precipitation and stream flow lead to small water quantity arrows going in both directions in the bottom part of Figure P.1.

The effects of changed climate on the MAR hydrology are likely to stress ecosystems. Biological oxygen demand will be higher because the region’s water bodies will be warmed somewhat by the higher average air temperatures. Runoff from thunderstorms and rapid snow melt will carry more contaminants and sediment to streams. Changes in the amount, timing, and quality of water might affect ecosystems from the headwaters throughout the drainage basins until they reach the region’s estuaries and bays. In turn, this will affect recreation opportunities as well as the general quality of life. For example, habitat for warm water fisheries will increase, while less habitat will be available for cold water fisheries. Because land use decisions will have long-lasting effects on the quantity and quality of runoff, future water resource vulnerabilities will be influenced by the interaction between land use decisions and climate change impacts.

Although some of these impacts could be substantial, uncertainties place them in the bottom part of Figure P.1.

Coastal zones

The dense population of the MAR coastal zone (38 percent of the region's population in 15 percent of its area) puts people in harm's way from storm surges. Thus the benefit of longer coastal recreation seasons could be more than offset by storms. Storminess could increase in the MAR, but there is substantial uncertainty about its extent. Storm surges will be exacerbated by the effects of sea-level rise from climate change and from combined ongoing effects such as tectonics, post-glacial rebound, subsidence and subsurface compaction. Sea level is projected to rise by 2 feet by 2095, a level that would flood 22,000 acres in Delaware. Although this is only 1.6 percent of the state's land area, it amounts to 21 percent of its marsh land. Clearly, the diverse and productive ecosystems in salt marshes are vulnerable to sea-level rise, because sediments and organic matter are not deposited fast enough to allow them to keep up with sea-level rise or to traverse barriers to inland migration. The costs of protecting valued infrastructure or natural areas could be quite high, and policies for strategic retreat from coastal areas are controversial.

Projecting impacts of climate change on MAR estuaries is complicated by uncertainties about future stream flows, which will affect both the quality and quantity of water reaching the estuaries. For instance, increased storminess could flush more nutrients, sediment and contaminants into the estuaries. There is more certainty that warmer temperatures will exacerbate already low summer oxygen levels in MAR estuaries because of increased oxygen demand and decreased oxygen solubility. Even by itself, warming will shift northward the location of some estuarine species. Although warmer winters might enhance habitat for the blue crab, which is commercially important in the Chesapeake and Delaware estuaries, warmer waters also sustain diseases that affect another commercially important species: oysters.

Coastal zones are both sensitive and vulnerable. Although a few potential positive impacts can be identified, the overall range of impacts in coastal zones contributes to the large negative arrow in the top part of Figure P.1, and to the large negative (but less certain) arrows for biodiversity and ecological functioning.

Ecosystems

Many ecosystem components are quite resilient, while others are very fragile. Changes in CO_2 concentration, temperature, precipitation, and sea level in the MAR will affect individual species differently, partly because ecosystems already are stressed in many MAR locations (e.g., forest fragmentation or cities and sea walls could hinder the migration of some species) and partly because of indirect effects (e.g., that favor pathogens, parasites, predators, and competitors). Development and wetland losses leave the MAR's rivers, streams, and near-shore areas vulnerable to damage from storms, and increased input of sediments, nutrients and toxic substances, especially if precipitation increases. Aquatic and terrestrial populations of rare native species could decline because of climate-induced changes in habitat (such as a mismatch between when birds migrate and when food sources are available for them). Species that benefit (such as Kudzu and gypsy moths) could crowd out others not directly affected by changes in climate variables, as well as those that suffer direct impacts from climate change.

Although some desired species might become more abundant (e.g., because of increased warm water fisheries habitat), the overall result is likely to be a reduction in biodiversity. Reduced biodiversity has uncertain implications for ecosystem functioning that is crucial for evolution of the ecosystem, as well as for functions that people value, such as crop pollination, moderation and purification of water flows, and diverse wildlife. This chapter reinforces findings in other chapters that ecological impacts from changes in climate and climate variability could be quite large, but are uncertain. Most of these impacts are judged to be undesirable. The lower portion of Figure P.1 (reflecting substantial uncertainty) shows large negative impact arrows for biodiversity and ecological functioning.

Human health

Mortality directly related to heat, cold, storms, flooding, and lightning currently accounts for 0.13 deaths per 100,000 population in the MAR. The warmer, wetter, possibly stormier projections indicate that there could be increased morbidity and mortality from extreme events. The assessment suggests substantial percentage increases in heat-related mortality, but more uncertain, smaller decreases in cold-related mortality, as shown by the arrows in the upper two parts of Figure P.1. While of concern, these increases still will account for a very small mortality rate. Even if climate change causes a large percentage increase in excess mortality (i.e., mortality above expected levels) from the weather-related causes listed above, mortality rates associated with these causes would remain low.

Indirect impacts from climate change could be important. For instance, climate change could increase the region's risk from water borne (e.g., Cryptosporidiosis) and vector borne (e.g., Lyme disease) diseases. The region's current and future health infrastructure are expected to be able to cope with these risks, albeit at increased costs from measures to protect the safety of food and water, control disease vectors, and provide health services. The elderly and those with limited access to health care could be disproportionately affected, particularly because of subregions with higher than average shares of the elderly and of those without health insurance.

Thus a small negative arrow appears in the lower part of Figure P.1 for these health impacts.

Final Thoughts

Recall that Figure P.1 shows that the MAR can expect both positive and negative impacts from climate change. Despite efforts to identify as many positive impacts as possible, results show that benefits tend to be fewer and smaller than damages. Underestimating potential damages would be more worrisome than underestimating potential benefits. For benefits that are traded in markets, people and organizations will more-or-less automatically take advantage of opportunities created by climate change, and thus experience the consequent improvement in well-being. Assessment that identifies potential market benefits can spur the market to work more quickly. By identifying potential nonmarket benefits, assessment can provide information for pro-active decisions that enable society to reap those benefits. Even more important, assessment can identify potential damages over which individuals have little control, or that might be managed more effectively at a community or regional level than by individual citizens or firms. Identifying such risks can be a first step in evaluating options for reducing or adapting to them.

The impacts we have summarized will make some of the region's citizens and organizations better off while making others worse off. This unevenness in who reaps the benefits or bears the costs is referred to as *distributional impacts*. Distributional impacts merit special attention because small average effects can mask impacts that are substantial for vulnerable individuals, groups, communities, industries, or places.

Figure P.1 also depicts differing levels of certainty associated with potential impacts. The more we know about a particular change in climate and its impacts, and the more such impacts are managed through existing institutions, the more confident we can be that effective adaptation strategies can be implemented readily (Downing 1999). As uncertainty increases, it becomes more difficult to determine whether specific adaptive actions will work or be warranted. Fortunately, however, the MAR can reduce much of its vulnerability to climate change by taking actions already justified for other reasons.

Chapter 10 summarizes the most important actions for the relatively near term to take advantage of opportunities and enhance the region's resiliency to climate variability and change. Chapter 11 takes a longer view, setting priorities for filling gaps in information and understanding needed to improve the region's future decisions related to climate variability and change.

Box P.1. Climate Change and Mid-Atlantic Cities (Knight and Pike)

The Mid-Atlantic Region's six largest metropolitan areas (Baltimore, Norfolk, Philadelphia, Pittsburgh, Richmond and Washington) account for more than half of the region's population. Expected growth makes urban areas among special places where impacts of climate change warrant particular attention. For the U.S. National Assessment, the Metro East Coast assessment examines how climate change might affect the New York City area (http://metroeast_climate.ciesin.columbia.edu). Rather than summarizing the details from that research group's workshop, we draw attention to several issues impinging on urban areas: urban climate, the urban forest, air quality, and flood risk. Climate change impacts affecting water supplies, water quality, agriculture, ecology, and human health also will have manifestations in urban areas. Although urban areas were not a major emphasis in the MARA's first phase, this box on cities is included here to reflect the cumulative urban impacts suggested in other chapters and the need for additional research on these impacts.

Urban Climate

The climate of cities differs from the climate of the surrounding countryside (Oke 1987). There are distinct differences between urban and less built-up areas in terms of air quality, temperature, visibility, humidity, wind, and precipitation. These differences are mainly the result of human activities that produce and use energy and that change the land cover.

The air over cities tends to have higher concentrations of pollutants, including both gases and particulates. These chemicals and particles are injected into the atmosphere by industrial processes, fuel combustion, and solid waste burning. The concentration of urban air pollutants depends on the size and intensity of local emissions sources and on the prevailing weather conditions. Air pollution affects the temperature, visibility, and precipitation in and around cities.

City centers are warmer than outlying areas. Urban daily minimum temperatures can be as much as 10 °F warmer than corresponding rural sites (Oke 1987). Four processes work to form the urban "heat island." First, building materials tend to store and reradiate solar energy more readily than vegetation and soil. The reflection of radiation due to street canyon geometry couples with radiation losses from urban buildings and streets to keep the city air warmer than in surrounding rural areas, especially at night and in winter. Second, because the urban landscape tends to flush water faster than the rural landscape, less solar energy is used for evaporative cooling in urban areas. In rural areas, much more energy goes into evaporation than into heating the air. Third, the urban atmosphere is warmed by heat given *off by home heating, power generation, industry, and transportation. Finally, the blanket of pollutants over the city absorbs some of the radiation emitted by the urban surface, further warming the surrounding air (Camilloni and Barros 1997).*

Despite their higher temperatures, cities receive less sunlight than rural areas because of the heavy concentration of particulates over the city. Particulates reduce visibility by scattering and absorbing sunlight. In addition, some particles form the nucleus of airborne water droplets, further obscuring light. The combination of reduced light and increased particles and water droplets reduces visibility in urban areas. (Malm 1992)

Cities are usually less humid than the surrounding countryside during the day, but may be more humid at night. The two main reasons for this difference are the increased runoff of precipitation and the decreased evapotranspiration from vegetation. The urban heat island can create a pressure gradient that causes moist rural air to flow toward the city at night (Holmer and Eliasson 1999).

Urban areas also alter wind speed and direction. Wind speeds in cities are 20 to 30 percent lower than winds in adjacent rural areas (Landsberg 1981). Simply, urban terrain is much rougher than rural terrain, resulting in increased friction over cities (Ca et al. 1999). Still, wind is often funneled into urban canyons and around buildings, so despite overall decreased wind speeds, low-level winds can be gusty in some areas (Aynsley 1989). Because cities are warmer than the surrounding countryside, winds flow into cities from all directions.

Cities change local precipitation patterns. The urban heat island produces updrafts that allow for sustained precipitation; the friction of the city surface slows air movement causing existing precipitation systems to hang over the city (Lowry 1998). Pollution aerosols also may enhance urban precipitation by increasing the number of condensation nuclei that form water drops (Changnon 1992). However, recent research suggests that pollution from urban and industrial sources actually can suppress precipitation by reducing the size of cloud particles. By increasing the number of condensation nuclei in the atmosphere, pollutants cause each droplet to contain less water, creating more evaporation and making precipitation less likely (Rosenfeld 2000). Plumes of condensation nuclei will develop over areas downwind of cities, as well, causing urban pollutant sources to have an impact well beyond their immediate environs.

Although scientists understand why cities have different climates than surrounding countrysides, it is not clear how climate change will affect urban climates and these urban-rural differences. One reason is that each city is unique, so it is hard to develop generalizations without extensive research on the impacts of climate change on many cities. Perhaps more important, climate models and even climate downscaling techniques do not yet *have sufficiently detailed spatial resolution to incorporate urban areas. An important aim of future research will be to increase this resolution or to develop techniques to work around this problem.*

If the present differences between urban and rural areas continue under climate change, the following impacts might occur: more health impacts from heat waves (Chapter 9); a greater summer heat island effect when air conditioning is increased to modify interior climates; the potential for more precipitation in and downwind of cities (or amelioration of regionally drier conditions during drought episodes); and lower costs for snow removal with warmer winters. Conversely, there could be increased water demand in warmer summers for evaporative cooling and recreational use.

The Urban Forest

Traditionally, urbanization has meant major impacts on forests and agricultural lands. Conversion of existing forested land to urban/suburban uses can involve direct loss of trees and related forest benefits, especially microclimatic and hydrologic functions. Trees in urban areas increase human comfort levels and reduce heating and cooling needs by modifying microclimate through providing shade, reducing air temperature and reducing wind speed at ground level (Grey 1996). Trees and associated vegetation also help maintain high infiltration rates in soils and help prevent rapid runoff of water from urban areas. In addition to outright removal to make way for development, trees in urban areas often are exposed to stresses such as: damage to boles, roots and branches during construction; increased levels of air pollution; higher urban air temperatures; and road salt in runoff water. Only the latter of these would be improved by warmer conditions. Programs for preserving existing forest vegetation during development and for planting trees to provide shade, windbreaks, habitat for urban wildlife, visual screening of undesirable views and green space to infiltrate runoff water and enhance the overall aesthetic appeal of urbanizing areas. All would help moderate urban impacts from climate change. At the same time, specific action to mitigate increasing stress on urban forests may be needed.

Air Quality

There are important links among cities, air quality, and climate in the Mid-Atlantic Region (McCormick 1991; Yarnal 1991). Two major air quality concerns are smog and acid rain. The main pollutant in urban smog is ozone, which results from the interaction of high temperatures, sunlight, and a suite of chemical precursors (most important of which are oxides of nitrogen—NO_x). Many energy-consuming and energy-producing processes emit NO_x, but the largest source is automobiles. Thus, smog production is greatest on hot, sunny summer days where automobiles concentrate; that is, in cities (Sydow et al. 1997). Not only is *smog build-up greater over cities, ozone levels also often exceed EPA air quality standards in remote rural areas of the Mid-Atlantic Region during the summer growing season (Comrie 1994). Ozone damages commercially important forest and crop species. Note that although urban ozone comes mostly from the city itself, most rural ozone comes from upwind cities. Thus the Mid-Atlantic Region's rural ozone comes primarily from the Ohio River valley (Lynch et al. 2000; Malm 1992).*

Similar to ozone, acid rain results from the complex interaction between the atmospheric environment and chemicals emitted by industry. The series of changes that take place in a typical migrating weather system enable the chemical precursors to evolve into acids, which fall in precipitation as the systems pass over the region. The main culprit is the sulfates that are released by the combustion of high-sulfur coal in the urban Ohio River valley; these develop into acids in transit and fall over the Mid-Atlantic Region (Malm 1992). Although the Clean Air Act of 1990 has resulted in notable decreases in acid rain, areas of the Mid-Atlantic Region still receive the most acidic precipitation in the nation (Lynch et al. 2000). Sulfate levels in the region, however, are more related to meteorology and upwind sources than local sources. In fact, pollution over cities may make urban precipitation less acidic than that in rural areas, because ambient ammonia given off by urban emissions neutralizes some of the acids (McCurdy et al. 1999). The region's carbonate geology buffers some of the damage, but acid rain still damages many ecosystems, structures, and machines in urban and rural settings (DeWalle et al. 1987).

Because air quality depends on both human activities and climate, both must be studied to understand the future trajectories of ozone and acid rain. One set of unknowns is future legislation and urban development, which will affect the emissions of the precursors of ozone and acid rain. The other set of unknowns is the extent to which future weather systems will be conducive to developing and delivering ozone and acid rain to the Mid-Atlantic Region. Although interannual variation is normal, the present climate favors these systems. Will future climatic conditions increase or decrease the number of these systems or affect their nature, thus influencing regional ozone and acid rain problems? This research is yet to be done.

Flood Risk

Many urban areas have a lot of development adjacent to rivers or coasts. Climate changes that influence the frequency and magnitude of riverine or coastal floods may create substantial threats to these portions of urban areas. The Federal Emergency Management Agency has encouraged a change in society's response to flood risk. The old approach was largely structural: storing flood water in dams or preventing it from entering threatened areas (using dikes, levees, or sea walls). The new approach recognizes the importance of *limiting development in flood-prone areas through zoning regulations and building codes (Kundzewicz and Kaczmarek 2000). However, application of these regulations is largely based on the spatial extent of floods of a defined historical frequency, such as a 100-year flood. Changing hydrological conditions upstream in a river basin (such as cutting forests, channelizing streams, filling flood plains, and increasing impervious surfaces) can increase flood frequency and extent downstream (Dunne and Leopold 1978; Changnon and Demissie 1996). Changing climatic conditions can have a similar effect, perhaps compounded by up-stream hydrological changes. Small increases in storm intensity can drastically reduce the recurrence interval for severe floods. Flood plain definitions that guide land use management for flood hazard mitigation today are likely to be inadequate in the future (Smith 1993). A similar issue will affect coastal cities, where flood risk mapping is based on today's sea-level.*

References

Aynsley RM (1989) Politics of pedestrian level urban wind control. *Building and Environment* 24: 291-295.

Ca VT, Asaeda T, Ashie Y (1999) Development of a numerical model for the evaluation of the urban thermal environment. *Journal of Wind Engineering and Industrial Aerodynamics* 81: 181-196.

Camilloni I, Barros V (1997) On the urban heat island effect dependence on temperature trends. *Climatic Change* 37: 665-681.

Changnon SA (1992) Inadvertent weather modifications in urban areas: Lessons for global climate change. *Bulletin of the American Meteorological Society* 73: 619-627.

Changnon SA, Demissie M (1996) Detection of changes in streamflow and floods resulting from climate fluctuations and land use-drainage changes. *Climatic Change* 32: 411-421.

Comrie AC (1990) The climatology of surface ozone in rural areas: A conceptual model. *Progress in Physical Geography* 14: 295-316.

Comrie AC (1993) A synoptic climatology of rural ozone pollution at three forest sites in Pennsylvania. *Atmospheric Environment* 28A: 1601-1614.

Comrie AC (1994) Tracking ozone: Air-mass trajectories and pollutant source regions influencing ozone in Pennsylvania forests. *Annals of the Association of American Geographers* 84: 635-651.

Comrie AC, Yarnal B (1992) Relationships between synoptic-scale atmospheric circulation and surface ozone concentrations in metropolitan Pittsburgh, Pennsylvania. *Atmospheric Environment* 26B: 301-312.

DeWalle DR, Dinicola RS, Sharpe WE (1987) Predicting baseflow alkalinity as an index to episodic stream acidfication and fish presence. *Water Resources Bulletin* 23: 29-35.

Dunne T, Leopold LB (1978) *Water in Environmental Planning*. WH Freeman, San Francisco.

Grey GW (1996) *The Urban Forest: Comprehensive Management*. John Wiley & Sons, New York.

Holmer B, Eliasson I (1999) Urban-rural vapour pressure differences and their role in the development of urban heat islands. *International Journal of Climatology* 19: 989-1009.

Kundzewicz ZW, Kaczmarek Z (2000) Coping with hydrological extremes. *Water International* 25: 66-75.

Landsberg HE (1981) *The Urban Climate. International Geophysics Series 28*, Academic Press, New York.

Lowry WP (1998) Urban effects on precipitation amount. *Progress in Physical Geography* 22: 477-520.

Lynch JA, Bowersox VC, Grimm JW (2000) Acid rain reduced in Eastern United States. *Environmental Science and Technology* 34: 940-949.

Malm WC (1992) Haze in the continental United States. *Earth Science Reviews* 33: 1-36.

McCormick J (1991) Urban Air Pollution. United Nations Environment Programme, Nairobi.

McCurdy T, Zelenka MP, Lawrence PM, Houston RM, Burton R (1999) Acid aerosols in the Pittsburgh metropolitan area, *Atmospheric Environment* 33: 5133-5145.

Oke TR (1987) *Boundary Layer Climates*, Second edition. Methuen, New York.

Rosenfeld D (2000) Suppression of rain and snow by urban and industrial air pollution. *Science* 287: 1793-1796.

Simini M, Skelly JM, Davis DD, Savage JE, Comrie AC (1992) Sensitivity of four hardwood species to ambient ozone in northcentral Pennsylvania. *Canadian Journal of Forest Research* 22: 1789-1799.

Smith DI (1993) Greenhouse climatic change and flood damages, the implications. *Climatic Change* 25: 319-333.

Sydow A, Lux T, Mieth P, Schafer R (1997) Simulation of traffic-induced air pollution for mesoscale applications. *Mathematics and Computers in Simulation* 43: 285-290.

Yarnal B (1991) The climatology of acid rain. In: *Air Pollution: Environmental Issues and Health Effects*, Majumdar SK, Miller EW and Cahir J (eds), Pennsylvania Academy of Science, Harrisburg, PA, p.155-169.

Chapter 10. What can we do now?*

MARA findings suggest win-win actions that have substantial benefits even if climate stays the same, plus a bonus of making the region more resilient to climate change. Many of these win-win strategies will be cost-effective even in the absence of climate change but have not been high on society's agenda. It is desirable to consider such actions sooner rather than later because they make sense even in the face of substantial uncertainties in projecting global climate change and its impacts on the MAR:

- Improve watershed management to reduce flood and drought damages and protect water quality (in streams and rivers, lakes and reservoirs, and ground water). For example, many communities do not have a watershed management plan even when the state requires one; implementation of existing plans tends to be uneven, too.

- Remove incentives for practices (e.g., that promote building or subsidize agriculture in areas vulnerable to erosion and flooding) that place people, investments, and (especially coastal) ecosystems at greater risk to climate variability.

- Establish communication and learning tools and programs that help the region's people identify how they can capitalize on benefits and reduce damages from climate change.

The first two strategies would reduce risks from several causes–including climate change. They imply actions (such as preserving forests and wetlands, minimizing urban and agricultural runoff, protecting stream habitat and reducing the release of toxic chemicals) that also reduce ecosystem stresses; although less certain than the large threats to the coastal zone, Table 4 indicates that threats to ecosystems could be quite large.

We already know about actions that can implement many of these strategies. One example is the weather warning system which has been effective for reducing heat stress in Philadelphia. Such demonstrations of effectiveness can be implemented elsewhere in the MAR.

More specific recommendations are to:

- Identify where coastal protection options such as beach nourishment, dikes or seawalls are cost-effective and where allowing coastal retreat is more cost-effective; prepare strategies for preventing or dealing with losses (in wetlands, infrastructure) from sea-level rise.

* This chapter is based on Fisher, (2000) "Preliminary Findings from the Mid-Atlantic Regional Assessment," *Climate Research*, 14:2. It appears with permission of Inter-Research.

- Improve water pricing to increase the efficiency of water use.

- Give higher priority to implementing government programs that indirectly reduce vulnerability to climate variability and change. Examples include the Safe Drinking Water Act (SDWA) regulations, coastal zone management plans, building codes, and land use planning.

- Foster forestry practices to encourage pine and oak-hickory forests, including cutting to minimize wind and ice damage, and monitoring for potential increases in fire, insect pests and diseases that might be more prevalent under climate change conditions.

- Foster continued adaptation in agriculture, especially for precision agriculture and biotechnology (if concerns about unintended effects of biotechnology can be addressed).

- Monitor for the higher-risk climate-related disease vectors identified in the MAR.

The MARA team judges the first three of these specific recommendations to be particularly important.

Chapter 11. What do we still need to know?*

People in the MAR can make better decisions related to climate change if they know more about potential impacts from climate variability and change and the effectiveness of alternative actions. People tend to think of climate change as happening slowly. Of particular concern, however, is the possibility that there could be major surprises because of the many uncertainties about how the region's climate will change and how these changes will affect the region's citizens and ecosystems. Surprises can be defined as rapid, non-linear responses (Watson et al. 1996). For example, a surprise might be several extreme weather events in a short time span, strong enough to reverse the direction of anticipated effects. Efforts to reduce vulnerability are important when such surprises could create serious damages. Downing (1999) reinforces the need to monitor impacts so that people will know when they need to accelerate adaptation. Uncertainties about trends, variability, and surprises suggest that the most important information and research needs are to:

- Improve projections for frequency, timing, and intensity of average and extreme weather (especially precipitation), at a regional level.

- Improve understanding of how both average and extreme weather affect agriculture, forests, fresh water quantity and quality, coastal zones, ecosystems, and human health, including assessing differences in the sensitivities and vulnerabilities of these systems, determining whether they have climate-sensitive thresholds, and considering how adaptation would moderate negative impacts and enhance positive impacts.

- Improve models to evaluate the benefits and costs of alternative adaptation options, so that economic efficiency can be considered in management and policy decisions. Options to be evaluated range from insurance coverage to structural "hardening" against extreme events to land use restrictions to subsidized changes in land use.

- Improve methods for evaluating how proposed shifts in policy (e.g., health policy, land use policy, agricultural policy) might affect vulnerability to climate variability and change.

More specific information needs include understanding:

* This chapter is based on Fisher, (2000) "Preliminary Findings from the Mid-Atlantic Regional Assessment," *Climate Research*, 14:2. It appears with permission of Inter-Research.

- How changes in climate variables affect different ecosystems (with respect to how they function; what fragile components might be affected by invasive species or by changes in nutrient runoff; and how ecosystem changes affect disease vectors).

- How to assign values to climate-related changes in ecosystem components and processes.

- How biophysical impacts from climate change, especially related to ecosystem processes, affect people in different locations (e.g., rural versus urban, coastal versus inland) and with different characteristics (e.g., age, income, education) through impacts on their health, institutions, and other determinants of the quality of life.

- How best to provide information about climate variability and change (i.e., what types of information, what communication modes, what types of interaction strategies) so that diverse stakeholders can make more informed choices about actions that affect future opportunities and vulnerabilities.

- How temperature and precipitation interact, and implications for evapotranspiration, as well as direct CO_2 impacts on evapotranspiration.

- How climate change would affect **environmental impacts** from development patterns, agriculture and silviculture, including water quality, landscape amenities, and carbon sequestration.

- How temperature and humidity affect the human immune system; how they interact with air pollution to affect conditions such as asthma.

- How climate change might affect weeds, insects, and diseases in crops, livestock, and forests, and how increases in such adverse impacts might be controlled.

- How a warmer, wetter climate will affect the amount, timing, and quality of water available for human and ecosystem use.

- How adaptations in turn will feed back into the production of greenhouse gases.

A fundamental lesson from the MARA is that nonmarket goods deserve particular attention in assessing impacts from climate change. People having property rights in market goods stand to reap the rewards or suffer the consequences of direct and indirect effects of climate change on the value of their assets. This automatically gives them incentives to anticipate climate change and respond to its impacts. In contrast, while nonmarket goods (such as environmental quality) are essential to human welfare and of great importance, the absence of markets for these goods means there is no automatic provision of incentives or mechanisms to reduce risks or exploit opportunities. Thus nonmarket goods tend to be neglected, relative to market goods. Moreover, many nonmarket goods are ecosystem services that are sensitive to the climate, but limited in their capacity to adapt to climate changes. The combination of missing markets and biophysical constraints on adaptation make ecosystems particularly vulnerable to climate change.

An additional lesson for the choice of assessment topics is the implications of economic, demographic and ecological connections to other regions. For example, trade with other regions in forest and agricultural products can reduce the vulnerability of the region's consumers to climate-induced changes in the production of these commodities within their region. Conversely, both beneficial and adverse impacts of climate change in other regions can be transmitted through markets, human migration, and migration of wildlife and disease-carrying insects. Identifying such linkages can help set priorities for research.

Although listed in order of the MARA team's "first cut" at priorities, refining priorities among the information and research needs can be facilitated by assessing public understanding of, and potential reactions to, climate change and its multiple subtle yet significant impacts. Working with stakeholders can clarify misunderstandings about climate change and their priorities for research on potential impacts from climate change. For example, the MARA shows that ecosystems are especially vulnerable to climate variability and change. The MARA researchers and stakeholders are developing a process for setting priorities for additional ecological assessment.

Our experience shows that stakeholders can be an important contributing resource in the assessment process because of their knowledge of local conditions and their access to valuable information otherwise not available. As research and assessment results become available, continuing stakeholder collaboration is crucial for designing and implementing effective strategies to disseminate the findings for citizens' use.

Appendices

Appendix A. Partners and Participants

An interdisciplinary Pennsylvania State University (Penn State) team is leading the first Mid-Atlantic Regional Assessment (MARA) of Climate Change Impacts. The core team has included 13 faculty members, 6 post-doctoral or associate researchers, 33 graduate assistants, and 11 undergraduates or interns. The core team's expertise has been expanded by substantive collaboration with another 14 researchers at Penn State and other universities plus 3 at private organizations and 5 in government. This entire group has interacted frequently with the Advisory Committee, which provides input about what questions are most important to a broad range of stakeholders in the region. The Advisory Committee also provides feedback on draft assessment plans, approaches, and results. Interested stakeholders who cannot participate as fully are Corresponding Advisors. Each of these groups is listed below. Interactions are described in Appendix C.

In addition, sections at the end of this appendix list MARA sponsors as well as primary authors for report chapters.

Core Penn State Faculty

Ann Fisher
David Abler
Eric Barron
Richard Bord
Robert Crane
David De Walle
C. Gregory Knight
Ray Najjar
Egide Nizeyimana**
Robert O'Connor
Adam Rose
James Shortle
Brent Yarnal

** indicates finished working on MARA prior to July 2000

Post-doctoral Scholars and Research Staff

Patti Anderson**
Keith Benson**
Jeff Carmichael**
Mary Easterling
Pat Kocagil
Shuang-Ye Wu

Graduate Research Assistants

Jason Allard**
Tatania Borisova
Tony Buda
Yiqing Cao**
Richard Caplan**
Bahar Celikkol**
Heejun Chang

Onelack Choi
Ken Corradini
Nate Currit
Kerri Dane**
Jan Dutton
Marta Galopin**
Alexandra Garcia
Jody Gibson**
Gauri Guha
Matt Heberling
Maria Inclan**
Hyun Jin**
Christy Jocoy**
Shu-Yi Liao
Julio Molineros
Rob Neff**
Steve Norman**
Debo Oladosu**
Adetokunbo Oluwole**
William Pike
Colin Polsky**
Byeong-ok Song**
Bob Swanson**
Robin (Lubing) Wang
Grant (Gwo Liang) Yang**
Tao Zhu**

Undergraduates/Interns

Matt Balazik
Brette Bornstein**
Andrea Denny**
Katie Filbert**
Eric Houston**
Loan Le**
Brian Schorr**
Andrea Soltysik**
Eric Steele**
Melanie Swartz**
Marisa Trenkle**

Collaborators

Dennis Calvin
Entomology Department
Penn State University

William Easterling
Earth Systems Science Center
Penn State University

Donald Epp
Dept. of Ag Econ. & Rural Sociology
Penn State University

Paola Ferreri
School of Forest Resources
Penn State University

Louis Iverson
Forest Service

Hoyt Johnson
Prescott College

Laurence Kalkstein
University of Delaware

Victor Kennedy
Horn Point Lab
University of Maryland

Dan Knievel
Agronomy Department
Penn State University

John McCarty
AAAS Fellow,
Environmental Protection Agency

J. Patrick Megonigal
George Mason University

Wilson Orr
Prescott College

Jonathan Patz
Johns Hopkins University School of Public Health

Roger Pielke, Jr.
National Center for Atmospheric Research

Jeff Price
American Bird Conservancy

Norbert Psuty
Department of Marine and Coastal Sciences
Rutgers University

Bruce Richards
Center for Inland Bays

Catriona Rogers
Office of Research and Development
Environmental Protection Agency

Lisa Sorenson
Boston University

Kent Thornton
FTN Associates

Henry Walker
Office of Research and Development
Environmental Protection Agency

Bud Ward
Environmental Health Center
National Safety Council

MARA Advisory Committee Members

William Adams
PA Farm Bureau

John Balbus
Department of Environmental & Occupational Health
George Washington University

Christopher Ball
Ozone Action

Timothy Banfield
Allegheny Power

Maria Bechis
Sierra Club

Richard Birdsey
USDA Forest Service

Perry Bissell
Consul, Inc.

Janine Bloomfield
Environmental Defense Fund

Barbara Blonder
NC Division of Coastal Management

Irene Brooks
Office for River Basin Cooperation
PA Department of Environmental Protection

Donald Brown
Senior Counsel for Sustainable Development
PA Department of Environmental Protection

Claire Buchanan
Interstate Commision on the Potomac River Basin

Arthur Butt
VA Department of Environmental Quality

Michael Calaban
NY Department of Environmental Control
Charles Carson
U.S. Steel

Lynne Carter
National Assessment Coordination Office

Peter Colket
American Reinsurance Co.

Betty Connor
PA League of Women Voters

Thomas Cronin
U.S. Geological Survey

Thomas DeMoss
EPA Mid-Atlantic Integrated Assessment Team

Guy Donaldson
PA Farm Bureau

Gerald Esposito
Tidewater Utilities

Barry Evans
Environmental Resources Research Institute
Penn State University

John Falconer
American Forests (through 4/99)

Jeffrey Featherstone
Delaware River Basin Commission

Agnes Flemming
Norfolk Department of Public Health

Stuart Freudberg
Washington Area Council of Governments

Richard Fromuth
Delaware River Basin Commission
Hector Galbraith
Stratus Consulting

Donald Garvin
Trout Unlimited

Phyllis Gilbert
Sierra Club

Caren Glotfelty
ClearWater Conservancy

Mark Handcock
Department of Statistics
Penn State University

Gil Hirschel
Susquehanna River Basin Commission

Joseph Hoffman
Interstate Commission on the Potomac River Basin

Richard Janoso
PP&L

Jan Jarrett
PA Campaign for Clean Affordable Energy

Zoe Johnson
Coastal Zone Management Division
MD Department of Natural Resources

Marshall Kaiser
Safe Harbor Water Power Corp.
Alliance for the Chesapeake Bay

John Kauffman
Alliance for the Chesapeake Bay

Howard Kunreuther
University of Pennsylvania (through 2/99)

Jon Kusler
Association of State Wetland Managers

Ray Lassiter
National Environmental Research Lab
Environmental Protection Agency

Daniel Leathers
DE Climatologist

Robert Leipold
American Forests

Ed Linky
Region 2
Environmental Protection Agency

James Lynch
School of Forest Resources
Penn State University

John MacSparran
Susquehanna River Basin Commission

Adam Markham
World Wildlife Fund

Stephen Matthews
Population Research Institute
Penn State University

Linda Mortsch
Environment Canada

Stuart Nagourney
NJ Department of Environmental Protection

George Nichols
Washington Area Council of Governments

Albert Nunez
ICLEI

Sam Pearsall
The Nature Conservancy (through 4/99)

Michele Pena
Climate Institute

Robert Penn
Vanguard Management Group

Gary Petersen
Penn State University

Lou Pitelka
Center for Environmental Science
University of Maryland

Jon Plaut
NAFTA Environmental Commission

Sethu Raman
NC Climatologist

Lynn Ratzell
PP&L Environmental Manager

Sharon Ross
Allegheny Power

Joel Rotz
PA Farm Bureau

Ralph Rudd
ClearWater Conservancy

Joel Scheraga
Environmental Protection Agency

Michael Schmidt
CIGNA

Gwynne Schultz
Coastal Zone Management Division
MD Department of Natural Resources

David Schwarzwaelder
Columbia Gas

Dick Shafer
College of Health & Human Development
Penn State University

David Small
DE Dept. of Natural Resources and Environmental Control

Betsy Smith
National Environmental Research Lab
Environmental Protection Agency

Jack Stevens
Professor of Management,
Penn State University

Ann Swanson
Chesapeake Bay Commission (MD)

Eric Walbeck
EPA Mid-Atlantic Integrated Assessment Team

Brooks Way
Way Fruit Farm

Fred Wertz
PA Department of Agriculture

Thomas Wilbanks
Oak Ridge National Lab/NCEDR

Corresponding Advisors

Chris Bernabo
RAND Corporation

Karl Blankenship
Bay Journal
Doug Burns
U.S. Geological Survey

Joanne Denworth
10,000 Friends of PA

Tom Falke
Coal industry representative

David Friedman
American Forest and Paper Association

Annette Goldberg
PA Economy League (through 2/99)

Vivien Gornitz
NASA Goddard Institute for Space Studies
Columbia University

Diane Herkness
CIGNA

Scott Hunter
Philadelphia Energy Coordinating Agency

Arch McDonnell
Environmental Resources Research Institute
Penn State University

Hugh McKinnon
National Risk Management Research Lab
Environmental Protection Agency

Edward Mongan
DuPont

Nancy Parks
Sierra Club

Joshua Reichert
Pew Charitable Trusts

Robert Shinn
NJ Department of Environmental Protection

Larry Simns
MD Watermen's Association

Michael Slimak
Office of Research and Development
Environmental Protection Agency

Joel Smith
Stratus Consulting

Lawrence Tropea
AMP Corporation

Christophe Tulou
DE Dept. of Natural Resources and Environmental Control

Melanie Wertz
The Chesapeake Bay Foundation

James Winebrake
James Madison University

Sponsors and Institutional Support

MARA has received financial support from the U.S. Environmental Protection Agency. Institutional support is being provided by the following Penn State units: Earth System Science Center and Center for Integrated Regional Assessment within the College of Earth and Mineral Sciences, Department of Agricultural Economics & Rural Sociology and the College of Agricultural Sciences, Environmental Resources Research Institute, and Office of Research. Institutional support also is being provided by the home organizations of our collaborators, especially U.S. EPA and U.S. Forest Service. Additional institutional support comes from National Center for Atmospheric Research, University of Delaware, University of Maryland, Rutgers University, Johns Hopkins University, Boston University, George Mason University, Prescott College, National Safety Council, Oak Ridge National Laboratory, FTN Associates, Stratus Consulting, and American Bird Conservancy.

As part of the national assessment process, the regional and sectoral teams also receive diverse types of information, data, input and feedback from the National Assessment Synthesis Team (NAST), the National Assessment Coordinating Office (NACO) and the National Assessment Working Group (NAWG).

Primary Authors

Preparing this report truly has been a team effort. Nevertheless, the enormity of the assessment task dictated that we share writing responsibilities on the basis of expertise. Thus primary authors are indicated below, by report section.

Chapter 1:	Fisher, Shortle, Knight
Chapter 2:	Polsky, Rose, Yarnal
Box 2.1:	Fisher
Box 2.2:	Yarnal
Chapter 3:	Polsky, Crane, Allard, Abler, Fisher, Shortle, Najjar
Box 3.1:	Barron
Chapter 4:	Abler, Shortle
Chapter 5:	DeWalle, Easterling, Rose, Buda, Iverson, Prasad
Chapter 6:	Yarnal, Neff, Chang, Pike
Box 6.1:	Thornton, Heberling
Chapter 7:	Najjar, Anderson, Knight, Walker, Megonigal, Psuty, Kennedy, Swanson, Gibson, Steele
Box 7.1:	Sorenson
Chapter 8:	Rogers, McCarty
Box 8.1:	Price
Chapter 9:	Benson, Kocagil, Shortle
Box 9.1:	Fisher, Shortle, Kocagil
Box 9.2:	Kocagil
Box P.1:	Knight, Pike
Chapter 10:	Entire MARA Team
Chapter 11:	Entire MARA Team
Appendix A:	Fisher
Appendix B:	MacCracken
Appendix C:	O'Connor
Appendix D:	MARA Team
Appendix E:	MARA Team
Appendix F:	Rose, Liao, Guha

Appendix B. National Assessment of the Consequences of Climate Variability and Change for the United States

Prepared by Michael MacCracken, National Assessment Coordination Office

The influence of climate permeates life and lifestyles in the US. Year-to-year variations are reflected in such things as the number and intensity of storms, the amount of water flowing in our rivers, the extent and duration of snow cover, and the intensity of waves that strike our coastal regions. Science now suggests that human activities are causing the climate to change. Although the details are still hazy about how much the changes will be in each region of the country, changes are starting to become evident. Temperatures have increased in many areas, snow cover is not lasting as long in the spring, and total precipitation is increasing with more rainfall occurring in intense downpours. These changes appear to be affecting plants and wildlife. There is evidence of a longer growing season in northern areas and changing ranges for butterflies and other species. The international assessments of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch) project that these changes will become even more evident over the next 100 years.

The Global Change Research Act of 1990 [Public Law 101-606] gave voice to early scientific findings that human activities were starting to change the global climate: "(1) Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few generations; (2) Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being."

To address these issues, Congress established the U.S. Global Change Research Program (USGCRP) and instructed the Federal research agencies to cooperate in developing and coordinating a "comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural process of global change." Further, the Congress mandated that the USGCRP

"*shall prepare and submit to the President and the Congress an assessment which*

1) integrates, evaluates, and interprets the findings of the Program and *discusses the scientific uncertainties associated with such findings;*

2) *analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and*

3) *analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."*

The USGCRP's National Assessment of the Potential Consequences of Climate Variability and Change, which is focused on answering the question about why we should care about and how we might effectively prepare for climate variability and change, is being conducted under the provisions of this Act.

The overall goal of the National Assessment is to analyze and evaluate what is known about the potential consequences of climate variability and change for the Nation in the context of other pressures on the public, the environment, and the Nation's resources. The National Assessment process has been broadly inclusive, drawing on inputs from academia, government, the public and private sectors, and interested citizens. Starting with public concerns about the environment, the Assessment is exploring the degree to which existing and future variations and changes in climate might affect issues that people care about. A short list of questions has guided the process as the Assessment has focused closely on regional concerns around the US and national concerns for particular sectors:

- What are the current environmental stresses and issues that form the backdrop for potential additional impacts of climate change?

- How might climate variability and change exacerbate or ameliorate existing problems? What new problems and issues might arise?

- What are the priority research and information needs that can better prepare the public and policy makers for reaching informed decisions related to climate variability and change? What research is most important to complete over the short term? Over the long term?

- What coping options exist that can build resilience to current environmental stresses, and also possibly lessen the impacts of climate change?

The National Assessment has three major components:

1. Regional analyses: Regional workshops and assessments are characterizing the potential consequences of climate variability and change in regions spanning the US. A total of 20 workshops were held around the country, with the Native Peoples/Native Homelands workshop being national in scope rather than regional; based on the issues identified, 16 of these groups have been supported to prepare assessment reports. The reports from these activities address the issues of most interest to those in the particular regions by focusing on the regional patterns and texture of changes where people live. Most workshop reports are already available (see http://www.nacc.usgcrp.gov) and, as of July 2000, three of the summaries of the assessment reports have been completed.

2. Sectoral analyses: Workshops and assessments are also being carried out to characterize the potential consequences of climate variability and change for major sectors that cut across environmental, economic and societal interests. The sectoral studies analyze how the consequences in each region affect the Nation, making these reports national in scope and of interest to everyone. The sectors being focused on in this first phase of the ongoing National Assessment include Agriculture, Forests, Human Health, Water, and Coastal Areas and Marine Resources. The sector assessment reports started to become available in early 2000.

3. National overview: The National Assessment Synthesis Team has responsibility for providing a national perspective that summarizes and integrates the findings emerging from the regional and sectoral studies and that then draws conclusions about the importance of the consequences of climate change and variability for the United States. Their draft report was released for public comment in June 2000 and will be published in the Fall 2000.

Each of the regional, sectoral, and synthesis activities is being led by a team comprised of experts from both the public and private sectors, from universities and government, and from the spectrum of stakeholder communities. All of the reports are going through an extensive review process involving experts and other interested stakeholders. The assessment process is supported in a shared manner by the set of USGCRP agencies, including the departments of Agriculture, Commerce (National Oceanic and Atmospheric Administration), Energy, Health and Human Services, and Interior plus the Environmental Protection Agency, National Aeronautics and Space Administration, and the National Science Foundation. Through this involvement, the USGCRP is hopeful that broad understanding of the issue and its importance for the Nation will be gained and that the full range of perspectives about how best to respond will be aired.

Extensive information about the assessment, participants on the various assessment teams and groups, and links to the activities of the various regions and sectors are available over the Web at http://www.nacc.usgcrp.gov or by inquiry to the Global Change Research Information Office, PO Box 1000, 61 Route 9W, Palisades, New York 10964.

Appendix C. Stakeholder Involvement*

Introduction

Consistent with recommendations by the National Research Council (1996), stakeholder participation has been a crucial component of the Mid-Atlantic Regional Assessment (MARA) of Possible Consequences of Climate Variability and Change. Note that a second phase of the MARA was initiated in mid-2000, continuing seamlessly as an extension of the first phase. The information here pertains to stakeholder participation during the first phase. This appendix discusses the reasons for involving stakeholders, MARA's experience, and lessons for future work. In one sense, everyone in the region was a stakeholder in the MARA project because all of the region's citizens could be affected by climate change. In identifying stakeholders to participate in the assessment process, the MARA research team paid special attention to groups likely to be particularly affected by climate change (e.g., communities vulnerable to sea level rise), researchers whose work is relevant to climate change, and to groups that have expressed an interest in the issue.

There is an extensive scholarly literature, perhaps starting with Aristotle, on public participation in the formation and implementation of environmental policies. This participation has taken many forms including lawsuits, protest marches, campaign contributions, petition drives, expert testimony, advisory committees, negotiated rulemakings, dispute mediation, and referenda voting. One subset of this literature comprises government programs that invite stakeholders to participate in the policy process. The literature contains few models that would explain why one approach might be more effective than another (O'Connor and Bord 1994; Chess and Hance 1994; Fisher et al. 1995; Renn 1999). Instead, most of the literature fits into two categories. One category contains descriptions and occasional evaluations of stakeholder participation in assessment; most of these are related to solving current local problems that are highly salient to citizens. Examples include where to locate a waste facility or highway, minimizing water quality and odor impacts from concentrated animal feeding operations, determining the extent of the cleanup or remediation from contamination, or determining whether an apparent cancer cluster is real (e.g., US EPA 1990; Gregory 2000). The second category consists of "guidelines" based on what has seemed effective but without much conceptual basis to explain why (e.g., Lundgren 1994, US EPA 1997; Chess and Purcell 1999). A recent and thorough review of the literature on formal stakeholder processes in environmental policy concludes that they work best when designed to accomplish specific goals tied to specific contexts, e.g., deciding among remediation options at a Superfund site (Yosie and Herbst, 1998, p. 15).

---

*This appendix is based on O'Connor et al. (2000) "Stakeholder Involvement in Climate Assessment: Bridging the Gap between Scientific Research and the Public," *Climate Research*, 14:2. It appears with permission of Inter-Research. Additional information was presented in Fisher et al. 2000.

In contrast, stakeholder engagement in the US National Assessment requires attention to a complex issue with many uncertainties and with impacts that might not be evident for 30-100 years—long beyond the planning horizon of most individuals, businesses, and organizations. The literature has little to offer, either conceptually or descriptively, about stakeholder participation in such assessments. Exceptions include recent work by the European Urban Lifestyles, Sustainability, and Integrated Environmental Assessment (ULYSSES) and Climate, Energy, and Alpine Regions (CLEAR) projects, using structured focus groups to explore the issues of climate change and energy use (Kasemir et al. 2000). Another exception is in-progress activities by components of the US National Assessment; the one for the MARA is described in this appendix. Because the assessment process still is underway, this appendix provides insights about stakeholder participation in the MARA; a formal evaluation of its effectiveness would be premature.

Three elements of the assessment's context are important for understanding the reasons for involving stakeholders:

First, the primary goal of the assessment's first phase was to produce a scientific document that reports the potential consequences of climate variability and change in the Mid-Atlantic region. The need to produce a document and the short time available to do the work focused stakeholder involvement on the process for producing a report and thus bounded the opportunities for their participation. In order to reconcile the desire for significant stakeholder involvement with the requirements of the assessment timetable, the MARA research team's approach was to organize an Advisory Committee that would maintain ongoing communications through e-mail, facsimile, and telephone as well as meet twice with the MARA research team.

Second, at least in 1997, public opinion about climate change in the region was dominated by ambivalence and uncertainty.[1] Although public opinion was decidedly mixed, more people were concerned than unconcerned about risks to society from climate change. When asked about the likelihood of potential changes, Table C.1 shows that many people were in the middle category, which usually indicates ambivalence and uncertainty. The modal category is that middle category for questions about whether people think there will be global warming and whether they will experience serious threats to their own health or overall well-being from global warming. Even though there is evidence that the debate over the Kyoto accords has had a somewhat polarizing impact on public opinion (Krosnick, Visser, and Holbrook, 1998), it is likely that public opinion in 2000 is still divided

[1] The data here are responses from a national survey, but restricted to residents of Mid-Atlantic states. Geographic clustering methods were not used for sample selection in the national study. Therefore, the results for the Mid-Atlantic sample may be viewed as derived from a random sample. See Bord, Fisher, and O'Connor (1998, p. 76) for details on the survey and evidence that these findings tend to be similar across locations and time periods.

among a minority certain that the threat is real, an even smaller minority certain that the threat is bogus, and the largest group of skeptics looking for more certainty. Regarding whether society will suffer extremely harmful, long-term impacts from global warming, half the Mid-Atlantic respondents are on the "likely" side in Table C.1. Yet, only 9 percent of those sampled consider themselves well informed about climate change and misinformation is widespread (O'Connor, Bord, and Fisher, 1998). Uncertainty combines with perceptions of large risks to suggest that the public is likely to be receptive to climate change information, especially when that information is about possible impacts close to home.

Table C.1. Risk Estimates of Mid-Atlantic Region Residents

	Not very likely 1 (%)	**2 (%)**	**3 (%)**	**4 (%)**	**Very likely 5 (%)**
How likely do you think it is that average annual temperatures will increase by 3 degrees Fahrenheit within the next 50 years?	15	12	32	17	25
In your judgment, how likely are you, sometime during your life, to experience serious threats to your health or overall well-being from each of the following: (global warming)?	21	26	29	17	8
In your judgment, how likely is it that each of the following (global warming) will have extremely harmful long-term impacts on our society?	10	16	25	25	25

N's vary from 276 to 284 with missing data. Row totals do not sum to 100% because of rounding.

Third, environmental interest groups argue that the evidence for climate change is so convincing that government should move ahead immediately with strong policies to reduce greenhouse gas emissions. Other interest groups, representing the coal and oil industries, large utilities, farmers, and manufacturers, argue that more research is needed before action should be considered. Although the purpose of the MARA project is neither to endorse nor to reject specific government policies, stakeholder involvement inevitably will be influenced by the contentious nature of "climate change" as symbol as well as scientific phenomenon.

Why involve stakeholders? The goals of stakeholder involvement

We started with the expectation that our core research team and stakeholders have differing strengths, and that sharing information through two-way communication would contribute to a better assessment that would be more useful to a wide range of stakeholders. At the outset, we identified six reasons for involving stakeholders in the regional assessment:

- **To ensure that the assessment addresses stakeholder concerns.**
  It is impossible to assess every possible regional impact of global change. Thus priorities must be set regarding which impacts will be assessed and which impacts will receive more in-depth assessment. One measure of an assessment's quality is whether it includes potential impacts of particular concern to stakeholders. The only way to identify those concerns is to communicate with stakeholders.

- **To enhance the technical quality of the assessment.**
  The team needs to identify any gaps or biases in the methods or data sets used in the assessment to allow for re-analysis. Stakeholders include scientists as well as citizens untrained in technical disciplines. In addition, stakeholders sometimes know about or have access to data otherwise not available to the assessment team.

- **To provide a forum for sharing ideas among stakeholders with diverse constituencies.**
  Advisory Committee meetings provide a non-adversarial setting to share ideas among members from a variety of affiliations and backgrounds. By focusing on the science and the process of the assessment, stakeholders may discover unexpected areas of common interest.

- **To facilitate dissemination of assessment findings**.
  Stakeholders can help with dissemination both by informing their own constituencies and by advising MARA regarding dissemination strategies and identifying specific opportunities.

- **To improve stakeholder awareness of possible impacts as well as adaptation strategies.**
  Participation in the MARA process should sensitize stakeholders to potential impacts of climate change in the Mid-Atlantic region and to options for adaptation that will exploit opportunities while effectively coping with risks.

- **To legitimize the process to third parties.**
  Broad stakeholder involvement enhances the credibility of the assessment process and its findings. Engaging a broad group of stakeholders makes it more difficult for critics to assert that the results would have been different if others had been included in the process.

Stakeholder involvement in the MARA

A broad definition of stakeholders includes everyone who might be affected by changes in climate and its variability. For a regional assessment, those most likely to be affected are the people who live in the region. Other stakeholders include people who do not live in the region but who own at-risk property or visit there, or have values for its special places even though they might not intend to visit them. For the MARA, stakeholders are defined as those who might be affected by climate change in the MAR or who might make decisions based on output from the assessment.

The MARA team involved stakeholders even before beginning the assessment work in 1998. An initial step was to set up a 17-member Steering Committee that helped in planning the September 9-11, 1997 workshop. Steering Committee members represented public interest groups, industry, state and federal government agencies, river basin commissions, and other universities. Workshop goals were to summarize scientific agreements as well as uncertainties and the role of the news media in communicating about climate change. Even more important, the workshop elicited stakeholder input about what types of potential impacts they could envision or were of concern, focusing on the watersheds for the Chesapeake Bay and Delaware River Basin. Participants provided input through a questionnaire mailed before the workshop. They received background papers that summarized the available literature on what the impacts might be for the MAR. This information was reinforced by plenary sessions. During working group and summary sessions, more than 90 participants identified issues that would deserve special attention in an assessment of potential regional impacts from climate change. They provided additional feedback in a follow-up questionnaire mailed after the workshop.

While awaiting authorization to conduct an assessment, the MARA team kept in touch with the September 1997 workshop participants and others who had expressed interest. Upon receiving the go-ahead, we established a stakeholder Advisory Council to ensure interactive communication would be a routine part of the MARA. The intent was to form an Advisory Committee small enough to focus constructively on a set of important issues yet large enough to represent the group likely to experience substantial impacts in the region. Attention focused on enlisting representation from two groups: 1) those most likely affected and 2) those expressing particular interest in the process. The MARA Advisory Committee represents myriad experiences and perspectives, including members from industry, non-governmental organizations, and government as well as researchers. Citizen groups include civic and environmental organizations. Businesses and industries include chemical companies, coal companies, electric utilities, steel manufacturers, and insurance. The state and local governments include municipal health departments, councils of government, river commissions, and state departments of agriculture and of conservation. Table C.2 summarizes the distribution of Advisory Committee by affiliation.

Table C.2. Advisory Committee Members

Citizen Groups	25
Business and Industry	19
State and Local Governments and Commissions	22
Federal Government Researchers	13
Academic Researchers	13
Total	*92*

The selection process was informal and broad. We identified individuals and groups that had expressed skepticism about global warming as well as those supporting actions to reduce greenhouse gas emissions. Substantial effort went into recruiting representatives from business and industry to ensure that those sectors were represented. Every individual who sought to participate was welcomed.

For reasons of size and manageability, we did not recruit elected officials. Climate change is a contentious and sometimes partisan political issue. Extending an invitation to participate to one state legislator, one county commissioner, or one member of Congress would have obliged us to invite all elected officials. While most would have declined, a substantial number might have become involved. Thus to maintain workable numbers and ensure balanced membership, we did not invite elected officials to be members of the Advisory Committee.[2]

One group of stakeholders is the community of climate change researchers. Nearly 40 researchers, including both natural scientists and scholars who study human dimensions, met at Penn State in June

[2] In retrospect, we understand that inviting state, regional, or national associations of elected officials (e.g., The Pennsylvania Association of County Commissioners) to participate might have provided representation without unduly increasing the size of the Advisory Committee.

1998. Researchers from universities and government agencies provided an accounting of the resources (e.g., data sets, studies, expertise) available for an integrated assessment of potential impacts from climate change in the MAR. This meeting also included formal and informal discussions regarding the structure and process of the assessment.

The Advisory Committee met at Penn State October 19-20, 1998, and May 2-3, 1999. The members helped refine research questions at the October meeting. For example, participants expressed concerns about the implications of climate change for insurance coverage and the insurance industry. They also reinforced concerns about a broad range of potential coastal impacts, which had generated a lot of discussion at the scoping workshop in September 1997. A general recommendation from the Advisory Committee encouraged the team to address issues of uncertainty as clearly and comprehensively as possible.

Approximately bimonthly, the Advisory Committee members received (via e-mail, fax, or regular mail) updates on the MARA team's progress, with a request for feedback on items such as work plans for specific topics (e.g., forestry, coastal zones), outlines of working group reports, draft scenarios that would serve as the basis for assessing impacts, or early materials for the draft preliminary report. Input also was solicited from them to identify priorities among agenda items for Advisory Committee meetings.

At the May 1999 meeting stakeholders provided feedback on the draft preliminary assessment and offered advice about displaying findings, developing materials, and disseminating the assessment results to a wide audience. Their suggestions also were used to hone plans for the second year's assessment activities.

A number of individuals wanted to provide input but were unable to participate fully. As corresponding members of the Advisory Committee, these individuals provided somewhat less extensive feedback on assessment plans and reports by e-mail, phone, and mail.

Table C.2 summarizes how often and why Advisory Committee members were contacted in writing between the formal start of the MARA on May 15, 1998 and May 30, 2000. The table omits telephone calls and contacts about meeting logistics. Many of the contacts have included stakeholders beyond the formal Advisory Committee; Table C.3 summarizes their responsiveness.

In addition to coming together for working meetings and reviewing draft documents, many Advisory Committee members maintained informal communications with specific team members. This two-way communication enhanced the quality of the assessment report.

TABLE C.2. Outreach to Advisory Committee

Purpose/Time Period	Number
Through October 19-20, 1998 workshop	8
On scenarios, vignettes, outlines, draft chapters, agenda and through May 1999 workshops	15
On April 1999 draft preliminary report	6
On September 1999 *Overview* draft	6
On March 200 *Overview*	4
On April 2000 *Foundations* draft	2

TABLE C.3. Stakeholder's provision of substantive input/feedback

Purpose/Time Period	Number
On scenarios, vignettes, outlines, draft chapters, agenda and through May 1999 workshops	31
On April 1999 draft preliminary report	16
On September 1999 *Overview* draft	49
Volunteered feedback on final *Overview*	21
On April 2000 *Foundations* draft	22
Miscellaneous exchanges	93

In addition to its regular contact with the Advisory Committee, the MARA team has used multiple communication methods to reach diverse audiences. These methods included a site on the World Wide Web (http://www.essc.psu.edu/mara/). Presentations at scholarly conferences and articles in journals also publicized the work in the researcher community.

An informal evaluation

At this stage of the Mid-Atlantic Assessment we are able to comment on the first three goals for stakeholder involvement — address concerns, enhance technical quality, provide a forum. The remaining goals — disseminate results, sensitize stakeholders, and legitimize the process — await evaluation in future assessment work.

To ensure that the assessment addresses stakeholder concerns. We are confident that the assessment *Overview* report addresses stakeholder concerns for two reasons: 1) stakeholders told us that the analysis plan and the draft document reflected their concerns, and 2) we focused the assessment to respond to their recommendations.

At the October 1998 meeting stakeholders reviewed the preliminary analysis plan and suggested additional emphases. At the May 1999 meeting they reviewed the draft document. Between those meetings we used e-mail, facsimile, and phone communications to ask stakeholders if the work was addressing their concerns. They told us that we were on track.

At different stages, the assessment was revised as stakeholders told us we needed to attend more to certain topics. The assessment plans reflected those concerns and, as a result, stakeholder involvement changed the substantive content of the assessment. At the September 1997 workshop we learned that stakeholders were concerned about potential health impacts. Much less attention would have been given to health effects had those concerns not been expressed. At the October 1998 meeting we learned that stakeholders were interested in potential impacts on insurance and the insurance industry. In response, we modified research plans for three sections of the assessment. At the May 1999 meeting, stakeholders identified the recreation and tourism industry for study. In response, we prepared a recreational baseline and continued research on these topics. Most importantly, we have heard throughout the process that the research team needed to address the issue of uncertainty in the projections used in the assessment. This concern has been central to the conception and writing of this (and our other) assessment report(s). For examples, this led to expressing judgments about confidence in projections (Table 3, p. 14 in the *Overview* report) and to segmenting the summary figure (Table 4, p. 17 in the *Overview* report) so that it shows three categories of expected likelihood.

To enhance the technical quality of the assessment. Advisory Committee members alerted us to sources of data, both archives and people, as well as to individuals who were able to participate in the writing of the report. Experts identified at the June 1998 meeting have played a pivotal role in the development of the assessment. Some of them served as formal collaborator, and others served as active members of the Advisory Committee. Numerous parts of the analysis would have been done differently (and not as well) without the input of the researcher contingent of the Advisory Committee. Whether in their role as researchers or as representatives of interested or potentially affected groups, stakeholders frequently have been invited to provide feedback on draft materials. The nearly 50 sets of comments stakeholders provided for the *Overview* draft suggests that they recognize how important the MARA team considers their input to be. Responses to each comment received on that draft are documented in the section of the web site that has the final *Overview* (http://www.essc.psu.edu/mara/results/overview_report/index.html). Thus in several ways, stakeholder involvement has modified the MARA coverage of important topics and improved the technical analysis of potential impacts.

To provide a forum for stakeholders with diverse constituencies to share ideas. Post-meeting surveys find that Advisory Committee members learned from assessment documents and the MARA researchers as well as from each other. They found meetings to be productive—designed to improve reports and to shape thinking.

Lessons learned

Engaging stakeholders has been an integral part of The First National Assessment of climate change impacts and an explicit goal of the MARA. We found that stakeholders could bring surprising perspectives and highlight special concerns. For instance, we found substantive interest among stakeholders for topics, such as human health, that had been a low priority for researchers. Responding to stakeholder input ensured that the assessment provided information in a useful form and that the interests of people within the region were addressed.

References

Bord R J, Fisher A, O'Connor, RE (1998) Public perceptions of global warming: United States and international perspectives. *Clim Res* 11: 75-84.

Chess C, Hance BJ (1994) *Communicating with the Public: Ten Questions Environmental Managers Should Ask*, Center for Environmental Communication, State University of New Jersey-Rutgers, New Brunswick, NJ.

Chess C, Purcell K (1999) Public Participation and the Environment: Do We Know What Works? *Environmental Science and Technology*, 33(16): 2685-2692.

Fisher A, Shortle J, O'Connor R, and Ward B (2000) "Engaging Stakeholder Participation in Assessing Regional Impacts from Climate Change," in *Climate Change Communication: Proceedings of an International Conference*, ed. by D. Scott, B. Jones, J. Audrey, R. Gibson, P. Kay, L. Mortsch, and K. Warriner. University of Waterloo and Environment Canada (www1.tor.ec.gc.ca/airg): A4-1 – A4-9.

Fisher A, Emani S, Zint M (1995) *Risk Communication for Industry Practitioners: An Annotated Bibliography*, plus Appendix. Society of Risk Analysis, McLean, VA.

Gregory R (2000) "Using Stakeholder Values to Make Smarter Environmental Decisions." *Environment* 42(5), June: 34-44.

Kasemir B, Schibli D, Stoll S, Jaeger CC (2000) Involving the Public in Climate and Energy Decisions, *Environment*, 42(3): 32-42.

Krosnick JA, Visser PS, Holbrook AL (1998) American opinion on global warming: the impact of the fall 1997 debate. *Resources*, 133: 5-9.

Lundgren R (1994) *Risk Communication: A Handbook for Communicating Environmental, Safety, and Health Risks*. Columbus, OH: Battelle Press.

National Research Council, 1996. *Understanding Risk: Informing Decision in a Democratic Society*. Washington, DC: National Academy Press.

O'Connor RE, Anderson PJ, Fisher A, Bord RJ (2000) Stakeholder involvement in climate assessment: bridging the gap between scientific research and the public. *Climate Research*. Special 2000, 14(2): 255-260.

O'Connor RE, Bord RJ, Fisher A (1998) The curious impact of knowledge about climate change on risk perceptions and willingness to sacrifice. *Risk Decision and Policy*, 3: 145-55.

O'Connor RE, Bord RJ (1994) The Two Faces of Environmentalism: Environmental Protection and Development on Cape May, *Coastal Management*. 22(2): 183-194.

Renn O (1999) "A Model for Analytic-Deliberate Process in Risk Management," *Environmental Science and Technology*. 33(18): 3049-3055.

US Environmental Protection Agency (1990) *Sites for Our Solid Waste: A Guidebook for Effective Public Involvement*. Washington, DC: EPA/530-SW-90-019.

US Environmental Protection Agency (1997) *Community-Based Environmental Protection: A Resource Book for Protecting Ecosystems and Communities*. Washington, DC: EPA 230-B-96-003.

Yosie TF, Herbst, TD (1998) *Using stakeholder processes in environmental decisionmaking: An evaluation of lessons learned, key issues, and future challenges*. WWW.riskworld.com/nreports/1998/STAKEHOLD/HTML/.

Appendix D. Glossary

accretion: An increase in land area because of sediments deposited by flowing water, especially along shores. If accretion keeps pace with sea level, then relative sea level rise has little impact on coastal wetlands. If sea level rises faster than organic matter and mineral deposits can accumulate (or if sediments are trapped behind dams) coastal land can be inundated, especially during spring tides when tides are highest, for example at full moon.

algal blooms: A population explosion of aquatic plants, often as the result of nutrient-rich runoff.

algae: Plants having no true root, stem or leaf, including seaweeds and pond scum.

anoxia: Without oxygen.

aquatic: Living or growing in fresh water (in contrast with marine organisms found in salt water).

atmospheric: In the air surrounding the Earth.

benthic: Bottom dwelling aquatic or marine organisms.

biodiversity: The range of organisms present in an ecosystem. Biodiversity can be measured by the numbers and types of different species, or the genetic variations within and between species.

biomass: The mass of living matter in an area (for example, grams of leaves and stems per cubic meter)

CCC model: Canadian Climate Centre global climate model.

Cryptosporidiosis: Illness with diarrhea as the main symptom, caused by tiny cysts transmitted from animal or human feces through contaminated water.

dinoflagellate: A group of marine protozoans (single-celled organisms) with two flagella (whip-like filaments used for propulsion).

downscaling: Reducing the scale of the model from global to regional level.

ecosystem: A unit of ecological analysis in which the physical and biological entities are considered in relation to each other, including energy flows and chemical feedbacks within a defined geographical area.

estuary: An estuary is in essence an interface: it is an area where a river meets the sea, where aquatic and marine life meet terrestrial life in marshes and wetlands, and where fresh water can still be influenced by tides. Estuaries can be defined by a salinity gradient that ranges from ocean salinity of 35.0 ppt (parts per thousand) to fresh water with salinity of less than 0.5 ppt.

eutrophication: An oversupply of the essential elements necessary for growth of tiny (microscopic) floating organisms, causing them to grow very quickly. This can block sunlight from larger plants growing underwater and deplete dissolved oxygen.

evapotranspiration: Loss of water from the soil both by evaporation and by transpiration from trees and other plants.

fauna: Animal life, especially the animals found in a particular region.

flora: Plant life or vegetation of a region.

fragmentation: Occurs when habitat is split by changing land use, leaving isolated pockets of the original habitat.

GENESIS model: Global climate model.

geomorphology: The study of land configuration and evolution, primarily by geologists.

greenhouse gases: Several gases that allow the earth's atmosphere to trap solar radiation by absorbing heat radiated back from the surface of the earth. These gases include carbon dioxide, methane, water vapor, and nitrous oxide.

Hadley model: Global climate model developed by Hadley Centre for Climate Prediction and Research in Great Britain.

human capital: Refers to the knowledge, information, skills and abilities possessed by people.

hydrology: Properties, distribution and circulation of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere.

hypoxia: A condition of having low levels of oxygen, often too low to support animal life.

invasive species: Species that grow aggressively in an area and stifle pre-existing species.

invertebrate: An animal without a backbone
mesoscale models: Models that focus on a regional, rather than a global or local, level.

natural capital: Encompasses all renewable and nonrenewable natural resources, and all marker and nonmarket natural resources. It includes not only conventional commodity resources, such as fossil fuels, metal, fisheries, and forests, but other elements of nature that directly or indirectly affect human welfare (e.g. genetic material, the ozone layer, and hydrologic and carbon cycles).

non-point source: Dispersed emitters of pollutants (such as farms, automobiles, or city streets).

non-target species: Species not intended for particular treatment (e.g., by pesticides aimed at other species) that could be affected by the treatment.

nutrient: An element that is necessary for growth and replacement of tissues, such as nitrogen, phosphorus, and potassium.

nutrient loading: The amount of nutrients in a water body.

oocyst: Tiny hard-shelled organism.

passerine: Birds of the order Passeriformes, including perching birds and warblers such as sparrows, finches, and jays.

pathogen: Any microorganism or virus that can cause disease.

physical capital: Refers to machines, transportation and communications infrastructure, water resource management structures, buildings, and other tangible goods. Physical capital is usually just known as “capital,” but referring to it as physical capital helps distinguish it from other forms of capital.

physiographic region: Area with similar land form.

phytoplankton: Microscopic plants that float in aquatic or marine environments (fresh or salty water).

point source: A specific location (such as an effluent pipe or a smokestack) that discharges pollutants into the environment.

precision agriculture: Incorporates advanced remote sensing, computer, and information technologies in order to achieve very precise control over agricultural input applications (chemicals, fertilizers, seeds, etc.) so that farmers can compensate for small-scale variations within a farm field in soil nutrients and crop pests.

primary productivity: The products of photosynthesis, the primary conversion of the sun's energy into chemical energy that can be stored as sugars or starches in plants. Net primary productivity is the amount of energy available after the plant has met its own energy needs.

riparian: Along the bank of a river or stream, or sometimes of a lake or a tidewater.

rolling easement: The right of access to waterfront, which "rolls" back as the beach is flooded or eroded so as to maintain the same access distance from the water.

sediment: Fine grains of solid material suspended in water or settled out of water to be deposited on land.

SIC level: Standard Industrial Classification of economic activities. A one-digit SIC is the most aggregated; very detailed information is available at the disaggregated 4-digit SIC level.

silviculture, silvicultural: Development and care of forests.

sphagnum bog: Wet, acid area where mosses grow; their remains become compacted with other plant debris and eventually form peat.

stakeholder: Potentially affected or interested person.

subsidence: Lowering of land elevation. Such sinking can be caused by groundwater withdrawals or by long-term settling of the Earth's crust.

sulfate aerosols: A suspension of fine particles in the air, containing sulfates. These suspensions act like clouds, making the Earth's surface cooler.

surficial: Taking place on or relating to the surface of the earth.

taxa: categories of plants and animals.

topography: The physical features, such as elevation, of an area or the representation of its features on a map.

transpiration: Evaporation from plant foliage.

trophic level: Trophic levels refer to particular positions in a food web. Eutrophic means well nourished (or over fed); oligotrophic means underfed or with low nutrient levels.

turbidity: In water bodies, the condition of having suspended particles that reduce the ability of light to penetrate beneath the surface. Some rivers and streams are naturally more turbid than others; soil erosion and runoff into streams can increase turbidity.

vector: An organism such as a mosquito or tick that transmits disease from infected individuals or animals to humans.

watershed: The drainage basin for a particular watercourse or body of water. Watershed scales range from that for a small pond to much larger regions such as the Chesapeake Bay drainage basin.

Appendix E. Acronyms and Abbreviations

AgSci: College of Agricultural Sciences (PSU)

CBP: Chesapeake Bay Program (EPA)

CCC: Canadian Climate Center (global climate model)

CDIAC: Carbon Dioxide Information Analysis Center

CENR: Committee on Environmental and Natural Resources (NSTC)

CGE: Computable General Equilibrium model

CIESIN: Consortium for International Earth Science Information Network

CIRA: Center for Integrated Regional Assessment (PSU)

CO_2: carbon dioxide (a greenhouse gas)

CWC: Cooperative Wetlands Center (PSU)

CZMA: Coastal Zone Management Act

DHHS: Department of Health and Human Services

DOD: Department of Defense

DOE: Department of Energy

DOI: Department of Interior

EFS: Environmentally Friendly and Smaller

EHC: Environmental Health Center (National Safety Council)

EMS: College of Earth and Mineral Sciences (PSU)

EPA: U.S. Environmental Protection Agency

EPIC: Environmental Planning Information Center

ERRI: Environmental Resources Research Institute (PSU)

ESSC: Earth Systems Science Center (PSU)

FEMA: Federal Emergency Management Agency

FIA: Forest Inventory and Analysis (by U.S. Forest Service)

FIPS: Federal Information Processing System (a code that identifies counties)

FS: Forest Service (USDA)

GCLP: Global Change/Local Places

GCM: General Circulation Model

GCOS: Global Climate Observing System

GEIA: Global Emissions Inventory Activity

GENESIS: a global climate model

GFDL: Geophysical Fluid Dynamics Laboratory (NOAA, Princeton)

GHCN: Global Historical Climatology Network (at CDIAC)

GHG: Greenhouse Gas(es)

GIS: Geographic Information System

GISS: Goddard Institute for Space Studies (NASA)

HAD: Hadley Centre global climate model

HDGC: Human Dimensions of Global Change

IMPLAN: Impact Analysis for PLANning System (regional modeling package)

I-O: Input-output model

IPM: integrated pest management

IPCC: Intergovernmental Panel on Climate Change

JSTC: Joint Scientific and Technical Committee (of GCOS)

m: meter (39.37 inches)

MACZ: Mid-Atlantic coastal zone

MAHA: Mid-Atlantic (Mid-Appalachians) Highlands Assessment

MAIA: Mid-Atlantic Integrated Assessment (EPA/ORD)

MAR: Mid-Atlantic region

MARA: Mid-Atlantic Regional Assessment

MLRA: Major Land Resource Area (with uniform soil, climate, water resources and land use)

MPE: Mission to Planet Earth (NASA)

MSA: Metropolitan Statistical Area

NACO: National Assessment Coordination Office

NAS: National Academy of Sciences

NAST: National Assessment Synthesis Team

NASA: National Aeronautics and Space Administration

NAWG: National Assessment Working Group

NCAR: National Center for Atmospheric Research

NCDC: National Climatic Data Center

NCEDR: The National Center for Environmental Decision-Making Research

NFIP: National Flood Insurance Program

NGVD: National Geodetic Vertical Datum

NIEHS: National Institute for Environmental Health Services (DHHS)

NIGEC: National Institute for Global Environmental Change

NOAA: National Oceanic and Atmospheric Administration

NO_x: oxides of nitrogen

NPA: NPA Data Services, Inc.

NSF: National Science Foundation

NSTC: National Science and Technology Council

OMB: Office of Management and Budget

OPPE: Office of Policy, Planning and Evaluation (EPA)

ORD: Office of Research and Development (EPA)

ORNL: Oak Ridge National Laboratory (TN)

OSTP: Office of Science and Technology Policy

Penn State (PSU): Pennsylvania State University

PET: potential evapotranspiration

PPR: Prairie Pothole Region

ppt: parts per thousand

RTA: Regression Tree Analysis

RTP: Research Triangle Park, NC

SAM: social accounting matrix

SAV: submerged aquatic vegetation

SEF: smaller environmentally friendly

SGCR: Subcommittee on Global Change Research (in NSTC's CENR)

SIC: Standard Industrial Classification

SLR: sea-level rise

SO_x: oxides of sulfur

SQ: status quo

SRB: Susquehanna River Basin

SDWA: Safe Drinking Water Act

UCAR: University Corporation for Atmospheric Research

UKMO: United Kingdom Meteorological Office (global climate model)

UNEP: United Nations Environmental Program

USDA: U.S. Department of Agriculture

USGCRP: U.S. Global Change Research Program

USFS: U.S. Forest Service (USDA)

USGS: U.S. Geological Survey

USDA: U.S. Department of Agriculture

VEMAP: Vegetation/Ecosystem Modeling and Analysis Project

WMO: World Meteorological Organization

Appendix F. A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS OF FOREST SECTOR DAMAGE FROM CLIMATE VARIABILITY (Rose, Liao and Guha) *

Introduction

Most studies of the potential economic losses to the United States from Climate Change are based on a projected doubling of CO_2 and focused on directly affected receptors such as agriculture, coastal areas, forests, health, and amenities. Early estimates of these direct losses were between \$50 and \$67 billion annually (see Cline 1992; Nordhaus 1994; and Fankhauser, 1994), and more recent estimates have ranged significantly higher (see IPCC 2000). However, indirect losses typically have not been included in previous studies. It is likely that indirect effects will spread throughout the entire economy, reflecting price changes and factor and product market linkages within a country or region and changes in competitiveness between it and its trading partners. A priori, it is not known whether these general equilibrium effects will largely offset or reinforce each other. Thus, indirect damages may be less than the direct damages or may be several times as great.

This Appendix demonstrates the potential of a methodology for estimating indirect impacts. Specifically, it analyses the impact on the Mid-Atlantic Region (MAR) economy of climate variability damage to its forests. We utilize a computable general equilibrium (CGE) model for the MAR that is designed to focus on climate-sensitive sectors, their vulnerabilities, and their linkages to the rest of the economy. We compare the results with those of an analogous study performed using an input-output model, which we refer to as the MARIO study (Rose et al., 2000). The analysis clearly indicates the advantage of the CGE approach, though it also uncovers some limitations of the current version of our model. It also indicates the need for scenario and sensitivity analyses at this stage of our knowledge of climate impacts and how they might affect economic growth (see, e.g., Abler et al. 2000).

* The authors are grateful to Rajnish Kamat and Gbadebo Oladosu for providing data and suggestions for constructing the MAR CGE Model, and to Ann Fisher, James Shortle, and David Abler for helpful comments.

MAR Forests: Profile and Issues

Forests, managed mostly by non-industrial private landowners, dominate the MAR landscape, with a diversity ranging from coastal wetland species in the south to hardwoods in the north. The stock of wood, mostly in the 10 to 12 inch diameter class, has been fairly stable, with a recent decadal decline of only about 1% in area. The major forest-types of the region, in terms of area coverage are oak-hickory, maple-beech-birch and pine-hardwood, with commercially dominant species being (Fisher et al. 2000):

softwood: hemlock, loblolly, short leaf, and white pine
hardwood: red/white oak, red/sugar maple, beech, cherry, sweet gum, and yellow poplar

The gross value of output from the nine Forest-Related sectors of the MAR in 1995 was $41.8 billion, which is about 2.5% of the total output of the Region.[1] These figures should be viewed with some caution, because they reflect only the direct, measured value of timber products. Forests also yield a large variety of other goods and services, whose value, although subject to conjecture, is by no means trivial. Such goods, previously known as *minor forest produce,* and now formally classified by the Food and Agriculture Organization of the United Nations (FAO) as *Non-Timber Forest Produce* (NTFP), include medicinal and aromatic plants, fuel wood, barks, roots, mushrooms, honey, sap, etc. Services provided by forests include soil and moisture conservation, carbon sequestration, stabilization of the microclimate, recreation, and wildlife habitat. Moreover, economic *multiplier,* or *ripple,* effects, transmitted through interindustry, interinstitutional, and interregional linkages, indirectly amplify the value of direct forest output or redistribute any changes in it.

Chapter 5 points out that current stresses on MAR forests include increased atmospheric deposition of acidic ions that lead to loss of essential soil cations, insects, and competing landuse demands due to urbanization. Climate change may bring about new stresses and exacerbate existing ones. It also may yield beneficial impacts for some species.

Model Specification

Computable general equilibrium (CGE) models are multi-market simulation models based on the

[1] Forest-related sectors include not only primary forest growing and harvesting activities but also downstream processing, nine 4-digit SIC sectors in all (see Table F.2). The three primary forest sectors (Forest Products, Forestry Products, and Forestry Services) had a total gross output in 1995 of only about $4.7 billion, or less than 1% of the MAR Economy.

simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints (Shoven and Whalley 1992). With only a few exceptions (see, e.g., Scheraga et al. 1993, who examined the general equilibrium impacts of climate-induced increases in agricultural production costs, electricity rates, and coastal protection measures), most of the climate-related applications of CGE models have been to mitigation policy (see, e.g., Jorgensen and Wilcoxen 1993; Kamat et al. 1999), but recent applications have included impacts of short-term climate variability in the form of riverine flooding (Rose et al. 1999) and longer-term climate change primarily affecting agriculture and health (Abler et al. 2000). Moreover, advances are being undertaken to incorporate non-market inputs and environmental amenities (see, e.g., Smith and Espinosa 1996; Oladosu 2000).

For this study, we designed and implemented a new model to fit the context of climate impact analysis in the MAR. Considerations regarding production technology, consumer behavior, interregional competitiveness, and factor market flexibility were chosen accordingly. A sectoring scheme was chosen that allowed for a fine delineation of climate sensitive sectors. Additional refinements of the model are underway following the advances developed by Oladosu (2000). These include enhanced ability to capture non-market effects, such as amenity values, and a finer delineation of socioeconomic effects, such as income distribution.

Supply Side

a. Production technology is specified as a four-level nested constant elasticity of substitution (CES) production function. At the first level of decision-making, producers choose the mix of fuels of the Energy (E) aggregate according to a CES function. Components of the material (M) aggregate are modeled in fixed proportions, however (a standard assumption in CGE models). On the second level, capital and energy "combine" (substitute for one another according to a CES function) to form a KE aggregate. On the third level, the KE aggregate is combined with labor. On the fourth level, the KLEM aggregate is formed by combining a capital, energy, and labor aggregate with materials.

b. The demand for domestic and competitive imported producer inputs and consumer goods, including imports from the rest of the U.S. and imports from the rest of the world, is specified as an Armington CES function, i.e., imports are imperfect substitutes for domestically produced goods.

c. The profit-maximizing behavior of regional industry production is specified as a constant elasticity of transformation (CET) function that describes the choice between domestic supply and exports.

d. The Mid-Atlantic economy is considered to be a "small open-economy," i.e., all the import and export prices are fixed.

Demand Side

a. Households are classified into three income types: low, medium, and high. The income of each household consists of shares in factor payments and transfers from other institutions. Demand for goods and services by each household is specified in terms of a Cobb-Douglas utility function (elasticities of substitution between consumption categories equal to unity). Saving of each household is specified as a fixed portion of disposable income calculated from the base year data.

b. Governments, separated into federal and state/local (combined), obtain revenues from taxes, tariffs, and transfers from other institutions. The taxes specified in the model include indirect business taxes, social security taxes, corporate profit taxes, and household income taxes. All tax rates and tariff rates are fixed and calculated from the base year data. Demand for goods and services for each government is in fixed proportions of base year levels.

c. Investment supply for each sector is calculated from the base year proportions. Investment demand is calculated as a fixed proportion of capital stock by each sector. Inventory change is calculated as a fixed proportion of commodity supply.

Market Clearing and Closure Rules

a. Demand and supply are equated in all goods markets, including domestically produced goods, export, and import markets.

b. Capital stock of each sector is fixed in the short run. In the medium run, total capital stock for the economy as a whole is fixed to the base year levels.

c. Both the Neoclassical (full employment) closure rule and the Keynesian (unemployment equilibrium) closure rule are applied in the model. For the Keynesian closure rule used in this appendix, the wage rate is fixed and labor supply adjusts (labor is mobile across sectors and across regions).

Data and Model Construction

The Mid-Atlantic Region covers 358 counties in Delaware, Maryland, North Carolina, New Jersey, New York, Pennsylvania, Virginia, West Virginia and Washington, DC (see Fisher et al. 2000). The main source of data used in constructing the Social Accounting Matrix (SAM) and Input-Output Table comes from the IMPLAN database for the Mid-Atlantic region (Minnesota IMPLAN Group 1998). Other data includes various elasticities for the region (see Oladosu 2000).

SAM and Input-Output Table

The 1995 SAM of Mid-Atlantic Region is presented in Table F.1. Several accounts are included in the SAM to decompose the regional economy, including industry, commodity, factor income, household, government, capital, and trade accounts. Each entry of the table represents the sum total of transactions in 1995 between the sector labeled on the left and the sector labeled (by number only because of space constraints) at the top. For example, the first row indicates that MAR sold $1,153 billion of goods and services to intermediate producers and consumers in the MAR Region, exported $81 billion overseas, and exported $438 billion to other regions within the United States.

a. The industry account contains 51 sectors, with relatively finer delineations for climate-sensitive sectors (primarily agriculture and forestry). Therefore, the Mid-Atlantic CGE model can be used to evaluate the regional non-market impacts of global warming in the future. The total gross output of the Mid-Atlantic Region in 1995 is $1,671 billion including interindustry transactions ($682 billion) and total value-added ($989 billion). The total domestic commodity supply and total (foreign plus domestic) exports of the MAR in 1995 was $1,153 billion and $518 billion, respectively. According to the original 1995 Input-Output Table, each industry produced both primary products and several byproducts.[2]

[2] In the model, the production technology is simplified by using a share parameter for each sector to translate the original non-diagonal “make matrix” of joint products into a diagonal make matrix so that each industry produces only one commodity. This is standard practice in CGE modeling. Because there is minimal joint-product production for the generally aggregated categories of the MAR CGE model, this simplification is unlikely to have any serious effect on the results.

Table F-1. Social Accounting Matrix of Mid-Atlantic Economy (millions of 1995 dollars)

		1001	2001	5001	6001	8001	10001	10002	10003
1001	Industry Total	0	1152866	0	0	0	0	0	0
2001	Commodity Total	373578	0	0	0	0	65973	178455	230735
5001	Employee Compensation	581254	0	0	0	0	0	0	0
6001	Capital Income	333954	0	0	0	0	0	0	0
8001	Indirect Business Taxes	74377	0	0	0	0	0	0	0
10001	Households-Low Income	0	0	19308	7523	0	99	436	823
10002	Households-Medium Income	0	0	182168	40311	0	307	1348	2545
10003	Households-High Income	0	0	294406	92320	0	918	4025	7603
11001	Federal Government	0	163	75952	-2276	12010	4528	26892	53733
12001	State/Local Govt	0	13991	9421	1350	62367	7788	11257	19306
13001	Enterprises (Corporations)	0	0	0	89336	0	0	0	0
14001	Capital	0	0	0	81809	0	0	13353	64378
14002	Inventory Additions/Deletions	0	0	0	0	0	0	0	0
25001	Foreign Trade	45572	0	0	985	0	6030	18362	25992
28001	Domestic Trade	262402	0	0	22596	0	22244	60989	80285
Total		*1671138*	*1167021*	*581254*	*333954*	*74377*	*107889*	*315116*	*485400*

		11001	12001	13001	14001	14002	25001	28001	Total
1001	Industry Total	0	0	0	0	0	80764	437508	*1671138*
2001	Commodity Total	113791	119009	0	79918	5562	0	0	*1167021*
5001	Employee Compensation	0	0	0	0	0	0	0	*581254*
6001	Capital Income	0	0	0	0	0	0	0	*333954*
8001	Indirect Business Taxes	0	0	0	0	0	0	0	*74377*
10001	Households-Low Income	52586	8641	1455	14181	0	2497	341	*107889*
10002	Households-Medium Income	47165	25469	8457	0	0	4187	3158	*315116*
10003	Households-High Income	36143	15716	25578	0	0	3612	5079	*485400*
11001	Federal Government	85484	0	25028	107150	0	251	303	*389219*
12001	State/Local Govt	25783	55849	5748	22156	0	29	4746	*239790*
13001	Enterprises (Corporations)	0	0	0	0	0	0	0	*89336*
14001	Capital	0	0	23070	0	0	22370	54548	
14002	Inventory Additions/Deletions	0	0	0	4781	0	241	5074	*10097*
25001	Foreign Trade	4853	2113	0	8272	1771	661	0	*114612*
28001	Domestic Trade	23414	12994	0	23070	2764	0	0	*510758*
Total		*389219*	*239790*	*89336*	*259527*	*10097*	*114612*	*510758*	*6349488*

a. Factor income accounts describe the allocations of value-added to various institutions, including households and governments. Employee compensation is the major source of income within the Region, accounting for 59% of the total valued-added. The other major source of income is property income, accounting for 28% of total valued-added. Most of these two major income sources are allocated to three different household categories and only about 15% of these incomes are distributed to government taxes and capital investment. Indirect business taxes are $74 billion, and State & Local government receives almost 85% of them.

b. Total household income is about $908 billion (see the sum for 10001, 10002, and 10003 in the italicized "Total" column). The Medium- and High-Income households receive 35% and 53% of the total household income, respectively (see the row entries for households). Expenditures of household income include payments to goods consumption, taxes to governments, savings, and various transfers.

c. Total Federal and State/Local government income is about $389 billion and $240 billion, respectively. The expenditures of these government entities, including transfers to households are presented in the government-related rows.

d. The major sources of savings are from industries (mainly in the form of Capital Consumption Allowance and Inventory Additions/Deletions), Medium-income, and High-Income households. The majority of total savings are allocated to capital formation purchases and borrowing by Federal and State/Local governments.

e. The trade accounts are separated into Foreign and Domestic Trade. The net domestic trading surplus is about $31 billion and the net foreign trading surplus is about $21 billion (see export and import differentials in Table F.1).

Other Data

In addition to the SAM and Input-Output Table, other data including sectoral employment, sectoral capital stock, capital composition matrix, and various elasticities are required to complete the model specification. Sectoral employment data are obtained directly from IMPLAN database. Sectoral capital stock data are calculated as a fixed multiple of the base year operating profits. Capital composition for each sector is assumed to be the same as the composition of aggregate investment demands in the base year. In this Appendix, most of the elasticity parameters required for calibrating the model are assumed to be the same as those in the Susquehanna River Basin CGE Model (Oladosu 2000; Kamat et al. 1999).

Model Calibration and Benchmark Equilibrium

The parameters of the model equations are calculated using the base year variable values. Calibrated parameters include various coefficients, weights of the standardized price index, share and shift parameters, and exponents of CES and CET functions, etc. Under the assumption that the economy is in equilibrium in the base year, the CGE model was solved for the benchmark equilibrium by using the summation of household bracket utility functions of each household as the objective function. A comparison of the generated SAM and the actual base year SAM indicates that the percentage differences between the figures are all below 0.1%. Therefore, the model replicates the base year equilibrium very accurately.

Analysis of Regional Impacts Forest Sector Damage

Direct Damage Estimates

The direct damage data for this study are based on a survey of 300 landuse managers, concerning cost impacts of extreme weather such as wind, rain, and snow (see Dewalle and Buda 1999, and Chapter 5). According to the survey, only the Forest Products, Forestry Products, and Logging & Contractors sectors directly suffer increased production costs due to extreme weather events. Forest managers' experience over the last decade indicates an average cost increase of 5.2% in the most severely impacted year.[3] A previous I-O study (Rose et al. 1999), as well as the CGE simulations below, are based on a projection that extreme weather events could potentially become commonplace, i.e., the high damage estimates (corresponding to the most severely impacted year) could take place on an annual basis in the future, admittedly an upper-bound estimate. This 5.2% translates into a productivity, or output loss of approximately $63 million (in 1995 U.S. dollars).

The MARIO study (Rose et al. 2000) simulated upstream output (demand-linkage), downstream output (supply-linkage), and price (cost-push) inflation effects on the MAR economy. Based on the work of Haynes et al. (1995) for another region, it "rounded" estimates for supply and demand elasticities to +1 and -1, respectively. For lack of data, it assumed that 50% of the cost increases in the primary forest sectors were passed on to their customers. No import or export substitution was allowed due to standard restrictions of the input-output model.

[3] These impacts were not "normally" distributed, and, their application is to an uncertain future. This consideration and others noted below dictate that caution should be applied in interpreting our results as other than "ball park" estimates.

Below we use the MAR CGE model to simulate the effect of a production cost increase and compare the results with the MARIO study. Specifically, we simulate the effect of the 5.2% increase in production costs in terms of productivity decreases in a Hicks-neutral manner, which means that all factor inputs are affected in an equal proportional manner. Implicitly the invocation of this assumption and related ones below eliminate the possibility of adaptation to climate change, thereby causing our simulations to yield "upper-bound" estimates in this report. Given the fact that the MAR is a relatively open region (i.e., highly dependent on imports and exports), we also take special steps to analyze the effects of changes in trade competitiveness. Our supply and demand elasticities are noted in Table F.2, as is the cost pass-through percentage. These parameters[4] are based on an extensive survey of the literature and adaptation of elasticities, many of which emanate from econometric estimation (as opposed to the rough assumptions of the I-O study).[5] Fixed proportion input requirements are assumed for the material (intermediate goods, including forest-related) aggregate, but substitution (in response to price changes) is allowed across aggregate input categories. The elasticities presented in this column of Table F.2 are for the substitution between materials (M) and all other input categories (K, L, E) combined.[6]

Ironically, the supply elasticity for each of the three primary forest sectors affected by climate variability is reasonably approximated by 1.0 (equivalent to our I-O modeling assumption), because the output price changes of these three sectors have no effect on the wage rate and the capital rate of return (these variables are not a function of the output price of these three sectors alone because they are such a small part of the regional economy). Also, the fixed-proportion assumption pertaining to material inputs in the model translates into a vertical demand function and hence the complete pass-through of climate variability damage costs for this input category alone. The fact that there is some substitution between materials as a whole and other inputs reduces the pass-through somewhat.[7] Also presented in Table F.2 are import and export elasticities. The first number for each sector represents the elasticity of substitution between the regional commodity and its counterpart from the rest of the world (ROW), while the numbers in

---

[4] Note that the pass-through percentage is not itself a parameter but is based on supply and demand elasticities for several sectors.

[5] The I-O simulation parameters were based on a loose interpretation of Haynes et al. (1995).

[6] Note that demand elasticities for each commodity in Cobb-Douglas utility function are computed as unity minus expenditures on all other goods. Consumers purchase only very small quantities of Forest and Forestry Products directly and no Logging Services.

[7] This should be less than 10%, and we are working on ways to compute it exactly.

parentheses represent the elasticity between MAR and the rest of the U.S. (RUS). Note that in the I-O analysis the import and export elasticities are implicitly zero.

Table F.2. Parameters for MAR CGE Model.

Sector	Production Demand Elasticity	Household Demand Elasticity	Supply Elasticity	Cost Pass-Through (%)	Import Elasticity	Export Elasticity
Forest Products	0.054	0.998	1.0	90+	2.0 (4.0)	0.9 (1.5)
Forestry Products	0.054	0.998	1.0	90+	2.0 (4.0)	0.9 (1.5)
Logging	0.304	n.a	1.0	90+	0.8 (0.8)	0.9 (0.9)

Discussion of Basic Results

Given any sustained exogenous stimulus that alters the relative price structure of inputs or productive processes, the economy adapts to rough changes in the level or mix of inputs or processes. The impact is measurable by the changes in the equilibrated output. The trade-driven effect can rival the input substitution effect in regional economies and that the strength of the former is inversely proportional to the size of the region. Results from economic models that do not explicitly account for trade adjustments tend to exaggerate domestic input substitution and neglect the crucial role of imports (see Stevens et al. 1983). However, CGE models are capable of accounting for both trade-driven and input substitutions, and this forms the basis for considering two distinct scenarios in our model.

The first is the *localized* impact scenario, where the changes in average production costs are assumed to be contained solely within the region. Based on this assumption, we assume that average production costs of the primary stages of the forest production chain (Forest Products, Forestry Products, and Logging & Contractors) within the MAR is increased by 5.2% due to extreme weather events. However, prices in the rest of the United States are unaffected.

The second scenario, and the more likely one, portrays *nationwide* climatic impacts in the three primary forestry sectors. In this case, we assume that price increases in primary forest products in the rest of the United States are the same as in the MAR, but that the import and export prices for all other sectors remain at their initial levels. Based on this assumption, it is expected that trade-driven substitution effects in the MAR will be relatively lower in the three primary sectors. However, trade-driven impacts on forest-related downstream processing sectors would be greater because of costlier imported inputs in the MAR.[8] Since the MAR is a relatively small region, the scenarios provide a mechanism to assess the trade-driven adjustments. As may be expected the impacts on the primary stages of the forest production chain under the first scenario is the bigger of the two, since relative border-prices become higher than their pre-existing levels, leading to greater trade-driven substitution effects.

Columns 1 and 2 of Table F.3 show the simulation results of the *localized* impact scenario. The total impacts are a $1,120 million decrease in total gross output for the MAR, or 0.07% of the economy as a whole. Most of the impacts are contained within the grouping of the forest-related sectors themselves, accounting for 72% of the total impacts. Among forest-related sectors, Forest Products, Forestry Products, and Logging & Contractors are the most affected sectors. The equilibrium output prices of these 3 sectors increase by 5.8%, 5.8%, and 7.9%, respectively (not shown). These price increases result in significant import substitutions and reductions in exports, and their gross output decreases by 8.7%, 8.7%, and 4.7%, respectively. The most affected forest-related downstream processing sector is Paper & Paper Products, whose gross output decreases by 2.4% due to the reduction in foreign and regional exports. With respect to other sectors, the Manufacturing (excluding forest-related products) sector suffers the majority of the impacts (in absolute terms) due to the reduction in exports and the increase in import substitutions.

Columns 3 and 4 of Table F.3 show the simulation results of the *nationwide* impacts scenario. This results in higher composite (domestic + import) prices of forest-related products compared to the prices in the first scenario. With higher prices of forest-related products, the overall consumer price index (not shown) in this case increases by 0.031%, which is almost double that of the first scenario (0.016%). This leads to greater reduction in overall exports of the MAR. Therefore, the total negative impacts ($1,216 million) on the MAR are higher than that in the first scenario ($1,120 million). This represents a gross output reduction for the MAR of 0.073%. In this scenario, most forest-related sectors, except Sawmills, Other Wood Products, and Paper & Paper Products, have smaller output decreases because the trade-driven substitution effect is not as strong. The output reduction of Paper & Paper Products is about $893 million, accounting for 79% of total forest-related impacts. Therefore, the total output reduction of forest-related sectors is about $1,060 million, which is significantly larger than that in Scenario 1 ($801 million), mainly because Paper & Paper Products suffers greater negative trade-driven substitution effects. Once again, among other sectors, Manufacturing suffers the majority of the impacts due to the reduction in exports and the increase in import substitution.

[8] The majority of MAR downstream forest-related sectors imported at least 50% of their forest-related inputs.

Table F-3. MAR economy-wide impacts of direct climate variability damage to forest-related sectors.

Sector	CGE Simulation				Input-Output Simulation			
	Total Impacts (Local)		Total Impacts (Nationwide)		Demand-Driven Impacts		Total Impacts[1]	
	(10^3 $1995)	(% change)	(10^3 $1995)	(% change)	(10^3 $1995)	(% change)	(10^3 $1995)	(% change)
Forest-Related Sectors								
Forest Products	-25,446	-8.68	-7,801	-2.66	-10,002	-3.41	-10,005	-3.42
Forestry Products	-78,684	-8.68	-24,123	-2.66	-31,495	-3.48	-32,913	-3.63
Ag, Forestry, Fishing Services	-11,629	-0.32	9,042	0.25	-3,765	-0.10	-3,795	-0.10
Logging Camps & Contractors	-57,753	-4.74	-43,898	-3.60	-33,529	-2.75	-43,705	-3.58
Sawmills	-53,252	-1.43	-75,470	-2.03	-156	-0.00	-26,922	-0.72
Millwork & Plywood	-4,782	-0.15	813	0.02	-48	-0.00	-6,876	-0.21
Other Woodproducts	-50,635	-1.32	-72,327	-1.88	-40	-0.00	-4,823	-0.12
Wood Furniture & Fixtures	-7,854	-0.19	-7,222	-0.17	-36	-0.00	-1,192	-0.03
Paper & Paper Products	-510,520	-2.43	-839,060	-4.00	-12	0.00	-12,823	-0.06
Subtotal	-800,555	-1.91	-1,060,045	-2.52	-79,083	-0.19	-143,054	-0.34
Other Sectors								
Agriculture	16,004	0.12	7,004	0.05	-403	-0.00	-528	-0.00
Mining	-16,996	-0.12	-44,996	-0.32	-38	0.00	-203	-0.00
Construction	186,032	0.18	515,032	0.49	-1,304	-0.00	-13,606	-0.01
Manufacturing (except F-R)	-301,875	-0.07	-446,875	-0.11	-3,092	-0.00	-9,497	-0.00
Transport & Communication	-56,974	-0.07	-75,974	-0.09	-1,424	-0.00	-1,721	-0.00
Utilities	-34,986	-0.09	-53,986	-0.12	-468	-0.00	-756	-0.00
Wholesale & Retail Trade	-47,938	-0.02	11,062	0.01	-2,749	-0.00	-3,398	-0.00
Finance & Services	-57,822	-0.01	-61,822	-0.01	-8,375	-0.00	-10,411	-0.00
Government	-4,946	-0.00	-5,946	-0.00	-1,449	-0.00	-2,456	-0.00
Subtotal	-319,500	-0.02	-156,500	-0.01	-19,302	-0.00	-42,576	-0.00
MAR-Total	-1,120,055	-0.07	-1,216-545	-0.07	-98,385	-0.01	-185,630	-0.01

[1]Total Impacts are the sum of total Demand-Driven Impacts and total Supply-Driven Impacts but include only one set of direct impacts (to avoid double-counting).

Note also that some sectors gain as a result of forest sector impacts. For example, forest products are not a significant input into agriculture and hence ag prices are likely to be unaffected, thus making ag products relatively more attractive than other products. The increase in Construction sector output, however, is counter-intuitive, since lumber is a major input. We are subjecting this result to further analysis.

A sensitivity analysis was performed to determine how the results might change if we altered our assumptions about import elasticities. We ran two alternative simulations: a) 50% reduction in import elasticities and b) a 100% increase in elasticities for both rest of U.S. and rest of world imports, in the localized impact scenario. The simulations (not shown) indicate that the results presented in Table F.3 are not very sensitive to this important parameter. Gross regional output decreases by 0.067% in the original case, by 0.074% in the case import elasticities are reduced and by 0.063% in the case where they are increased. There is no perceptible change in the overall price index at the three decimal place level. The parameter changes do, however, have a significant effect on overall imports. The RUS imports in the Base Case decline by 0.03% and by 0.04% when import elasticities were reduced; however, RUS imports increased by 0.01% when import elasticities were increased by 100%. Qualitatively similar results apply to ROW imports, though on an accentuated basis.

The above results may appear counter-intuitive at first, as one might conclude that the MAR's competitive advantage would be decreased in the localized scenario more than in the nationwide scenario. However, the MAR is modeled as a "small open-economy" in both scenarios (an assumption analogous to that of the perfectly competitive firm), meaning that it can sell (export) as much as it desires at prevailing prices (even if they are increased by climate change).[9] On the other hand, for the nationwide scenario, the prices of imports increase and affect the MAR's production costs directly and indirectly, thereby reducing regional purchasing power and hence output. Overall, the import effect of climate damage is significantly negative, while the export effect is neutral. The reasonableness of this result rests on the "small, open-economy" assumption. The MAR is a significant player in forest-related products and it is possible that its actions could affect national and international prices. On the other hand, this effect is likely to be significant only if output and price changes are significant. It is not clear whether output increases of less than 10% and price increases of even less pass this significance threshold.

[9] Note that the CET export elasticities are not infinite. The values represent the division of production in each sector between goods produced for the regional market and for export. This does not violate the "small open-economy" assumption, but simply indicates that no region is inclined to shift all of its production to export even if it can sell larger quantities at the going price.

Further examination is underway

Comparison with I-O Model Results

Columns 5-8 of Table F.3 show the results of demand-driven impacts and total impacts of climate change on the MAR economy using I-O analysis by Rose et al. (2000). In general, the output impacts appear significant in absolute terms, but they represent a gross output reduction for the MAR of only 0.006% and 0.011% for the demand-driven impact and total impact analyses, respectively. (This does not show in Table F.3 because the estimates were rounded for easier reading.) A comparison of the results of the CGE and I-O analyses indicates that the latter tends to produce lower estimates of the negative impacts of climate change on the MAR economy, despite the fact that I-O impact components are typically uni-directional (i.e., there were no offsetting effects modeled, in contrast to CGE analysis, where price or unemployment effects often offset output effects). The major reason is that I-O analysis fails to take into account the negative impacts of input and trade-driven substitution effects. These are especially pronounced in Paper & Paper Products and in Manufacturing as a whole.

Ironically, it appears that the I-O analysis is superior to the CGE analysis in one way. Recall that the I-O simulations assumed only part of the forest-related cost increases were passed through to their customers (usually, I-O analysis does not explicitly allow for substitution, but we developed a methodology to incorporate at least this substitution possibility into the analysis). Basically, this is appropriate for a longer term analysis where consumers of forest products can substitute other items. On the other hand, although the CGE model is intended for longer-run analysis, our assumption that components of the material aggregate are used in fixed proportions is more consistent with the shorter-run analysis. We are in the process of improving our model to eliminate this problem by converting Leontief production functions within the M aggregate to a CES function, as in the rest of the model. This modification will decrease the negative impacts of climate variability in our CGE analyses. Again, however we would surprised if they decreased by more than 10-20%, given the fact that substitution possibilities, even within the CES function, are somewhat limited for forest products. Thus, the 50% pass-through of the I-O model, although imparting much needed flexibility into the model, is probably overly optimistic in this regard and in terms of the impact results.

Conclusion and Extensions

The analysis above indicates that short-run impacts of increased climate variability damage to forests in the MAR will have a very small impact on the regional economy. Of course, this conclusion should be tempered because we have omitted several considerations, although several of them are likely to offset or neutralize one other. First, we included only a limited set of potential forest sector damages, e.g., we omitted non-market damages to wildlife habitat. Also, the impacts are likely to be a much higher proportion of total economic activity in sub-regions of the MAR that are highly dependent on forest-related sectors. On the other hand, we used an “upper-bound” interpretation of the DeWalle-Buda questionnaire results with respect to future direct climate variability damage. We also omitted consideration of the longer-run adaptation to damages in both the forest sector and with respect to customers of forest products.

Still, the results provide a great deal of insight about potential climate change impacts. First, our CGE analysis indicates that total impacts on the economy might be nearly twenty times the size of direct forest sector damage (compare the total impact of $1.2 billion with the direct loss estimate of $63 million). This does not represent an inflated multiplier process, but instead reflects interactions between the MAR region and other regions through forest product markets. The much larger impacts of our CGE analysis, as compared to the previous I-O study, are due to the additional considerations pertaining to regional competitiveness and the relative openness of the MAR economy to imports and exports. Not only does forest sector damage cause MAR exports to be less competitive, but damage to forests elsewhere, ironically, have a significantly negative impact on the MAR economy because various downstream processing sectors (primarily pulp and paper manufacturing) are so dependent on imports.

Most of the previous analyses of forest sector impacts in the literature are restricted either in geographical coverage, use of climatic variables and ecological models, aggregation of impacts, or use of exogenous economic variables. Some of these limitations are, of course, a result of deliberate omissions due to project desiderata and do not appear as crucial restrictions for economic modeling of the effects of ecological changes (for example, the economic modeler may dismiss the extra effort required to obtain 1% more resolution in vegetative mapping in favor of say 10% more exactness in the determination of economic parameters). Hence, an improvement would be to use more accurate (region-specific) substitution elasticities and an endogenous determination of economic growth (rather than a statistical extrapolation).

Besides a broad translation of ecological changes into economic impacts, a realistic *regional* economic model should attempt to capture some of the important local specificities. For example, suppose a broad analysis of changes in MAR forests shows that the on-ground harvestable stocks increase by 10% after 50 years. Does this signify a net economic gain? The answer requires looking at the changes in species composition vis-à-vis the type of indigenous furniture industry. At this time, the furniture industry in Pennsylvania is dominated by the use of red oak and black cherry. If these species decline and are replaced with alternate higher productivity vegetation, it would still imply a high replacement cost. A counter-balancing effect, however, could be the higher carbon sequestration due to higher leafiness of the new vegetation.

In some other forest economic analyses, it was felt that due consideration was not given to the distributional impacts of changes in forest cover and type. Most studies tend to treat the human activity related to forests as homogenous. The distributional effect may be captured by more carefully identifying and delineating uses of forests and forest-products.

Forests were used to demonstrate the relative merits of the computable general equilibrium methodology for analyzing impacts of climate change. Although the impacts obtained for this sector are small, they could be larger if we incorporated a broader set of direct forest damages and included non-market considerations, as well as an assessment of forest damages in other regions. At first pass, we might surmise that total economic impacts on the MAR economy from climate damage to other primary sectors would be small, because these sectors are such a small part of the Region's economy. Here again, it is important to consider not just primary sectors alone but also much larger downstream processing (e.g., agricultural production leading to food processing). However, until we establish these linkages for other sectors, as we did for forest-related sectors, and until we are confident that we have encompassed the broad range of direct impacts on them, application of our CGE model would be premature. Even then, scenario modeling, incorporating a range of assumptions about the future of the MAR economy and key parameters, should be undertaken. We reiterate that the numbers presented in this study are intended to illustrate the advantages of the methodology and identify its shortcomings rather than to pin-point actual damage estimates.

References

Abler D, Shortle J, Rose A, Oladosu G (2000) Characterizing regional economic impacts and responses to climate change. *Global Planetary Change* (in press).

Adams D, Haynes R (1996) *The 1993 timber assessment market model (TAMM): structure, projections and policy simulations* (General Technical Report PMW-GTR 368). Pacific Northwest Research Station, USDA - Forest Service, Corvalis, OR.

Binkley C (1988) A case study of the effects of CO_2 -induced climatic warming on forest growth and the forest sector: economic impacts on the world's forest sector. In Parry M, Carter T, Konjin N (eds.), *The impact of climate variability on agriculture*. Kluwer, Dordrecht.

Bolon N, Hansen-Murray C, Haynes R (1995) *Estimated economic impacts on the timber, range and recreation programs on NFS and BLM public lands from adopting the proposed interim pacfish strateg*y (General Technical Report PNW-GTR 344). Pacific Northwest Research Station, USDA - Forest Service, Corvalis, OR.

Bowes M, Sedjo R (1993) *Toward an integrated impact assessment of climate change*. Kluwer, Boston, MA.

Callaway M, Smith J, Keefe S (1994) *The economic effects of climate change for U.S. forests.* USEPA, Washington, DC.

Cline W (1992) *The economics of global warming.* Institute for International Economics, Washington, DC.

DeWalle D, Buda A (1999) *Effects of extreme weather on forest land management within the Mid-Atlantic region*. Environmental Resources Research Institute, The Pennsylvania State University, University Park, PA.

Fankhauser S (1994) The social costs of greenhouse gas emissions: an expected value approach. *Energy* J 15: 155-184.

Fisher A et al. (2000) *Preparing for a changing climate: the potential consequences of climate variability and change—Mid-Atlantic Overview*. The Pennsylvania State University, University Park, PA.

Hanley N, Shogren J, White B (1997) *Environmental economics in theory and practice*. Oxford University Press, New York.

Hansen A, Garman S, Weigand J, Urban D, McComb W, Raphael M (1995) Alternate silvicultural regimes in the pacific northwest: simulations of ecological and economic effects. *Eco App* 5(3): 535-554.

Haynes R, Adams D, Mills J (1995) *The 1993 RPA timber assessment update* (General Technical Report RM-GTR 259). USDA - Forest Service, Fort Collins, CO.

IMPLAN (Minnesota IMPLAN Group) (1999) *Impact analysis for planning (IMPLAN) system*, Stillwater, MN.

Intergovernmental Panel on Climate Change (2000) *Climate change 2000, working group* (draft report).

Jorgensen D, Wilcoxen P (1993) Reducing U.S. carbon dioxide emissions: an econometric general equilibrium assessment. *Resour Energy Econ* 15: 7-25.

Joyce L (1995) *Productivity of America's forests and climate c*hange (General Technical Report RM-GTR 271). USDA - Forest Service, Fort Collins, CO.

Kamat R, Rose A, Abler D (1999) The impact of a carbon tax on the Susquehanna river basin economy. *Energy Econ* 21: 363-384.

Nordhaus W (1994) *Managing the global commons: the economics of climate change.* MIT Press Cambridge, MA.

Oladosu G (2000) *A non-market computable general equilibrium model for evaluating the economic impacts of climate change in the Susquehanna river basin*. PhD thesis, The Pennsylvania State University, University Park, PA.

Perez-Garcia J, Joyce L, McGuire A, and Binkley C (1997) Economic impact of climate change on global forests: an integrated ecological/economic assessment. In *Critical reviews in environmental science and technology*.

Rose A, Cao Y, and Oladosu G (2000) Simulating the regional economic impacts of climate change in the mid-Atlantic region. *Clim Res* 14(3): 175–183.

Rose A, Carmichael J, Oladosu G, and Abler D. (1999) Modeling for Economic and Natural Hazard Impacts and Policy Responses Using Computable General Equilibrium Analysis. Department of Energy, Environmental & Mineral Economics, The Pennsylvania State University, University Park, PA.

Rose A, Miernyk W (1989) Input-output analysis: the first fifty years. *Econ Syst Res* 1: 229-271.

Scheraga J, Leary N, Goettle R, Jorgensen D, and Wilcoxen P (1993) *Macroeconomic modeling in the assessment of climate change impacts*, IIASA Collaborative Paper Series, CP-93-2, Laxenburg, Austria.

Shoven J, Whalley J (1992) *Applying general equilibrium*. Cambridge University Press, NY.

Smith VK, Espinosa JA (1996) Environmental and trade policies: some methodological lessons. *Environ Dev Econ* 19: 19-40.

Sohngen B, Mendelsohn R (1999) Impact of climate change on the US timber market. In Mendelsohn R, Neumann J (eds.), *The impact of climate change on the United States economy*. Cambridge University Press, Cambridge.

Solomon A (1986) Transient response of forests to CO_2-induced climate change: simulation modeling experiments in eastern North America. *Oecologia* 68: 567-579.

Stevens BH, Treyz G, Ehrlich S, Bower J (1983) A new technique for the construction of non-survey regional input-output models and comparisons with two survey-based models, *Internat'l Reg Sci Rev* 8: 271-286.