Pennsylvania Climate Impacts Assessment Update

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Pennsylvania Climate Impacts Assessment Update[1]

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1.0 Executive Summary

The Pennsylvania Climate Change Act, Act 70 of 2008, directed Pennsylvania's Department of Environmental Protection (DEP) to initiate a study of the potential impacts of global climate change on Pennsylvania over the next century. This study was conducted for the DEP by a team of scientists at The Pennsylvania State University and presented to the department in the 2009 reports: ***Pennsylvania Climate Impacts Assessment*** and ***Economic Impacts of Projected Climate Change in Pennsylvania*.** This report presents an update on those findings that were also mandated by the Pennsylvania Climate Change Act, Act 70 of 2008.

The 2009 ***Pennsylvania Climate Impacts Assessment*** (2009 PCIA) contained an assessment of the impacts of global climate change on Pennsylvania's climate in the 21st Century. It presented assessments of the impacts of climate change in Pennsylvania on climate sensitive sectors (agriculture, ecosystems and fisheries, forests, energy, outdoor recreation and tourism, human health, water and insurance) and the general economy. The 2012 update is based on a review and evaluation of pertinent scientific literature and data analyses conducted by The Pennsylvania State University team since the conclusion of the last report. The update includes new simulations conducted using results from the North American Regional Climate Change Assessment Program (NARCCAP). It includes updates for all the sectors considered in the previous report except insurance and the general economy. The 2009 PCIA concludes that Pennsylvania's insurance sector is well-managed and not highly vulnerable to climate change. There was no new information indicating a need to revisit this conclusion. The ***Economic Impacts of Projected Climate Change in Pennsylvania*** indicates that while significant economic impacts could occur within certain climate sensitive sectors, Pennsylvania's overall economy would be little affected by projected climate change. There was no new information suggesting a need to revisit this conclusion.

Pennsylvania's Climate Futures

The update on Pennsylvania's climate futures includes new simulations that were conducted using results from the North American Regional Climate Change Assessment Program (NARCCAP). The 2009 PCIA was based on Global Climate Models (GCMs) that had a very coarse horizontal resolution (several hundred km). The NARCCAP results use higher resolution (50 km) Regional Climate Models for North America that are nested inside of GCMs. At 50 km resolution, Pennsylvania can be broken down into nearly 40 grid boxes, effectively providing results approaching the scale of an individual county. Greater spatial resolution and potentially greater GCM based certainty allow for more accurate investigation of the impacts of climate change. Simulations with the higher resolution models were conducted for the recent past (1971-2000) and one future period (2041-2070) for the A2 emissions scenario (a medium-high scenario) designed by the Intergovernmental Panel on Climate Change.

In addition to repeating and extending the analysis of the Pennsylvania-wide averages of temperature and precipitation from the 2009 PCIA, this update takes advantage of the improved resolution of the NARCCAP models to evaluate their ability to simulate spatial variations in Pennsylvania's climate. Furthermore, we present future projections of temperature, precipitation and soil moisture change at 50 km resolution. The update also presents a brief analysis of temperature change over Pennsylvania since 1900.

The use of higher resolution models does not change the overall picture of simulated climate as presented in the 2009 PCIA. The regional climate models do not seem to reproduce the spatially averaged climate over Pennsylvania any better than the global climate models. The regional climate models do, however, capture the broad spatial distribution of temperature across Pennsylvania, though this is not the case for precipitation. The projections of future climate are not substantially different from the previous report (at least for the time period and scenario for which we could compare the GCMs and RCMs).

Our analysis of temperature change over the commonwealth during the past 110 years shows long-term warming with a brief (but dramatic) mid-20th century cooling. Global climate model simulations (with and without anthropogenic forcing) suggest that greenhouse gases are the main cause of the long-term warming.

The 2009 PCIA used the IPCC A2 and B1 emissions scenarios. The medium-high A2 scenario assumes high population growth, slow economic growth and locally based environmental policies with little global cooperation. The B1 scenario assumes a mid-century population growth which later declines, lower economic efficiency (but higher than the A2 scenario) due to environmental and social concerns, and global integration leading to more environmental-based development. Figure 1.1 includes a summary of all four scenarios. An in-depth look of all 4 storylines can be found in Appendix 11.2.

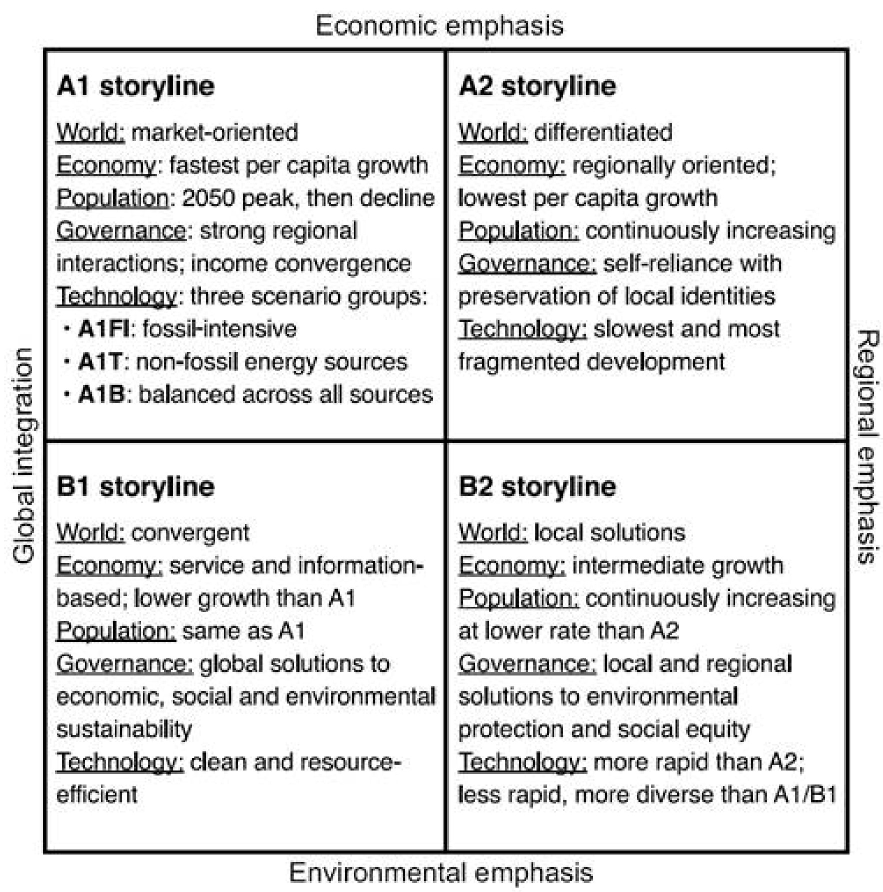

Figure 1.1. Source: Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

The sectoral assessments in this update also refer to these scenarios. The Climate Futures updates focus on the value added of the additional spatial resolution provided by RCMs and utilizes the A2 scenario. The findings of the analysis confirm the findings of the 2009 PCIA for the A2 scenario. We would expect the same to be true for the B1 scenario. Figure 1.2 includes annual CO_2 projections for different emission scenarios (including A2 and B1 which were used in the 2009 PCIA).

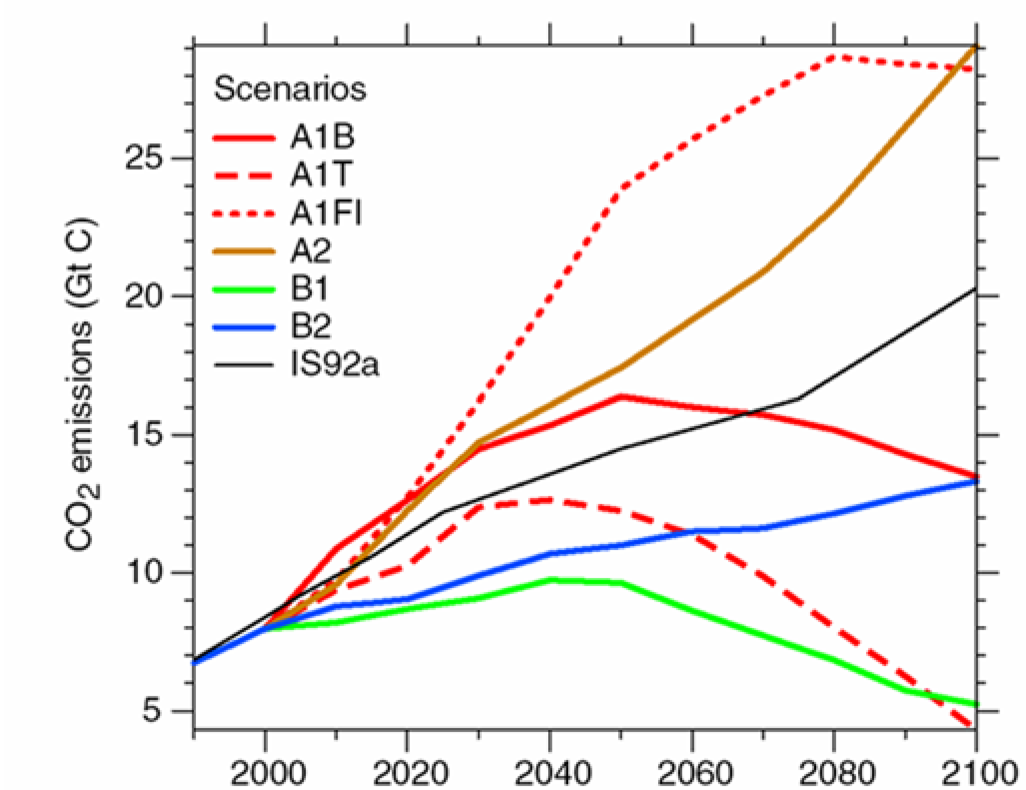

Figure 1.2. Annual CO2 emissions for the 21st century in gigatons of carbon (Gt C) for a range of possible world development path ways. Source: IPCC 2007a3.

Agriculture

Analogous to our findings for Pennsylvania's climate futures, our findings for climate sensitive sectors are largely consistent with the findings of the 2009 ***Pennsylvania Climate Impacts Assessment***. Principal differences found in the agricultural sectors concern the near-term economic environment between now and 2020 in which changes in climate will occur. We find that there is likely to be tight market situations for most agricultural products during the current decade in which extreme weather events are likely to lead to greater swings in global agricultural prices than would have been the case 10 or 20 years ago. We also find that conversion of agricultural land to housing and other urban uses in southeastern Pennsylvania [where much of agriculture in the state is concentrated] will be lower between now and 2020 than we anticipated in the 2009 PCIA. In addition, the difficult federal fiscal situation may restrict funding for crop insurance and agricultural research. Should this occur, the private sector will need to commit to a greater role in insuring against weather risks, and in developing new crop varieties and livestock breeds suited to a changed climate.

Water Resources and Aquatic Ecosystems

This update confirms the 2009 PCIA that risks related to hydrologic systems and aquatic ecosystems are significant and will pose challenges for water resource and ecosystem mangers. The update contains new information on vulnerabilities in these sectors in Pennsylvania based on recent case studies. Adaptation strategies for water management under potential climate change have to be developed while considering scenarios for future regional population and economic development. Population growth, urbanization and other land cover change, and pollution of water bodies could be equal or even more important stressors than climate change - at least in the near future. A holistic approach to developing adaptation strategies will be required, while the existing uncertainty in current projections of climate change impacts suggests that “no regret” strategies might be the best option for now. Strategies are classified as “no regret” if they lead to societal benefits regardless of the degree of climate change. Examples of such strategies include water conservation and better monitoring of hydrological and other environmental variables. Strategies to limit harm emphasize maintaining and improving the resiliency of aquatic systems through minimization of increased stream temperature, nutrient enrichment, hydrologic modification, habitat fragmentation and degradation, and species loss. Such actions would include:

- *Protection of existing stream and wetland habitat, especially intact habitat for identified species of interest, such as eastern brook trout;*
- *Maintaining riparian forests for moderation of stream temperature and treatment of runoff from adjoining lands;*
- *Implementation of Best Management Practices to reduce nutrient loading;*
- *Restoration of aquatic ecosystems such as streams and wetlands wherever possible; and*
- *Minimizing groundwater pumping (for irrigation, human consumption, etc.) that removes water from aquatic and wetland ecosystems.*

Energy

The likely impacts of climate change on energy production and utilization in Pennsylvania have not changed significantly from the 2009 PCIA. Warming in Pennsylvania is likely to increase the demand for electricity for cooling in the summertime, and can be expected to decrease demand for heating fuels (in Pennsylvania, the primary fuels used for heating are natural gas, fuel oil and electricity). The increase in cooling demand is likely to outweigh the decline in heating demand, implying that electricity consumption is likely to increase as a result of climate change. Perhaps more notably, peak-time electricity demand is likely to increase. Meeting peak-time electricity demand without sacrificing reliability is challenging and costly, although recent policy initiatives to increase demand-side participation in regional electricity markets may help to reduce costs and impacts on electric reliability.

Forests

Climate impacts on Pennsylvania’s forest are likely to include species composition shifts, shifts in tree regeneration rates, greater tree stress, changes in the phenology of forest ecosystem species, changes in tree chemistry and growth rates, greater insect, disease and invasive species activity, and shifts in faunal populations. Many of these shifts have already begun to occur, and while many may be expected to lead to greater tree mortality, at least for the present, increases in mortality that can be attributed to climate change have been minor. The effects of longer growing seasons and the CO_2 fertilization on tree growth rates has not yet been observed in Pennsylvania's forests, and may be offset by the negative effects of pollutants such as ozone and sulfate deposition. These effects will interact in very complex ways, making highly specific projections of future forest conditions difficult.

As a significant reservoir of carbon, Pennsylvania's forests can contribute to mitigating future climate change, but these effects are not likely to be large, as the growth rate of Pennsylvania's forests is relatively slow and difficult to accelerate. The most promising forest management strategies for mitigating climate change in Pennsylvania are to reduce rates of conversion of forestland to non-forest uses and to plant trees in areas where they are not currently found (e.g., abandoned strip mines and some urban areas).

A challenge for Pennsylvania's forest managers will be to actively adapt forests to climate change. A key adaptation strategy will be to maintain or increase forest connectivity. This may be a significant challenge in areas where road and pipeline networks are being built and expanded to develop natural gas from the Marcellus Shale and other promising geological strata. For some key species that are particularly vulnerable to climate change, assisted migration may be an option, but accomplishing this in practice for very many species will be difficult.

Human Health

Understanding of human health impacts of climate change has advanced from 2009 report research. A consistent finding is that the impact of climate change on human health is uncertain, but likely to be small. Research has consistently shown that warming temperatures would result in increased heat-related deaths and decreased cold-related deaths. The net effect is uncertain, though recent research suggests that the increase in heat-related deaths will be larger than the decrease in cold-related deaths, so that total temperature-related deaths will increase. Adaptation strategies to reduce heat-related deaths include warning systems, provision of emergency shelters during heat waves and cold snaps, assistance to low income households to assure adequate heating and cooling in the home, and changes to building codes to reduce urban heat island effects. Research on the impact of climate change on ozone and particulate concentrations in relation to significant air pollution related health risks is ambiguous. Warmer summer temperatures favor ozone and particulate creation. However, pollution concentrations depend on other factors as well, such as: cloud cover, precipitation, and air mixing. All of these are potentially affected by climate change. Regardless of whether climate change will increase or decrease pollution concentrations, other factors will have a larger effect on local air quality. Primary among these other factors is policies to reduce emissions of two volatile organic compounds: SO_2 and NO_2.

Research on extreme weather events is not sufficient to project whether Pennsylvania will be subject to less or more severe storms or flooding. Pennsylvania is likely to experience fewer snowstorms and fewer freezing rain events. However, as pointed out in the 2009 PCIA, traffic fatalities are not necessarily higher when roads are slippery. There is some evidence that Pennsylvania will experience a fewer quantity of rain events, but more intense rain events. Consequently, flood risk may increase. River monitoring is critical for effective warning and emergency response. Careful hydrologic and land use planning can reduce flood risk and reduce the number of buildings at risk of flooding.

As more research is conducted on the potential impacts of climate change on infectious disease, two things have become increasingly clear. First, our understanding of the biology and ecology of infectious disease is insufficient to project with confidence what impact climate change might have on its distribution or prevalence. Second, factors other than climate change, such as habitat disturbance, human behavior, and health care access, will have a larger impact on disease incidence and outcomes than will climate change.

The health impacts of climate change will fall disproportionately on vulnerable subpopulations. These include the very young, the elderly, those with low socio-economic status, those with chronic medical conditions, and those without access to health care. Cost-effective adaptation strategies should be targeted to those at-risk groups.

A consistent finding highlighted by several recent studies on the impacts of climate change on human health is that health impacts will vary within the population, with some identifiable groups more vulnerable to health impacts from climate change than others. For each climate change health impact discussed, this chapter will summarize: what is known about which subpopulations are more vulnerable and discuss how those vulnerabilities could be reduced.

Outdoor Recreation and Tourism

The main conclusions for outdoor recreation mirror those in the 2009 PCIA. The outdoor recreation activity that will be most affected by climate change is winter recreation. Snowfall is expected to decline and winter temperatures are expected to rise. Both trends work against snow depth, which is the critical factor for snow-based recreation. There are few opportunities for adaptation for dispersed winter recreation such as cross-country skiing and snowmobiling. Downhill skiing can adapt for a limited time through increased and improved snowmaking. Moreover, ski resorts that depend upon summer revenue sources can remain financially viable for an extended period of time. As temperatures continue to rise through the latter half of the century, the only available adaptation approach for downhill skiers will be to travel to other regions located farther north or at higher elevations.

2.0 Introduction

The Pennsylvania Climate Change Act, Act 70 of 2008, directed Pennsylvania's Department of Environmental Protection (DEP) to initiate a study of the potential impacts of global climate change on Pennsylvania over the next century. This study was conducted for DEP by a team of scientists at The Pennsylvania State University and presented to the department of in the 2009 reports ***Pennsylvania Climate Impacts Assessment***, and ***Economic Impacts of Projected Climate Change in Pennsylvania*.** This report presents an update of on those findings, also mandated by the Pennsylvania Climate Change Act, Act 70 of 2008.

The 2009 PCIA contained an assessment of the impacts of global climate change on Pennsylvania's climate in the 21st Century. It presented assessments of the impacts of climate change in Pennsylvania on climate sensitive sectors (agriculture, ecosystems and fisheries, forests, energy, outdoor recreation and tourism, human health, water, insurance) and the general economy. This update is based on a review and evaluation of pertinent scientific literature and data analyses conducted by The Pennsylvania State University team since the conclusion of the last report. The update includes new simulations were conducted using results from the North American Regional Climate Change Assessment Program (NARCCAP). It includes updates for all the sectors considered in the previous report except insurance, and the general economy. The 2009 PCIA concludes that the Pennsylvania's insurance sector is well-managed and not highly vulnerable to climate change. New information indicating a need to revisit this conclusion was not found. Our assessment of the impacts of climate change on Pennsylvania's overall economy presented in the ***Economic Impacts of Projected Climate Change in Pennsylvania*** indicated that while significant economic impacts could occur within certain climate sensitive sectors, Pennsylvania's overall economy would be little affected by projected climate change. New information suggesting a need to revisit this conclusion was not found.

The report begins with Pennsylvania's climate futures, which is foundational information for the entire report. It then presents the individual sector assessments.

3.0 Pennsylvania Climate Futures

This update presents new simulations of Pennsylvania's future climate using results from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2009). Further details of the NARCCAP can be found on the NARCCAP web site (http://www.narccap.ucar.edu/about/index.html). Results for Pennsylvania's climate futures, presented in the 2009 ***Pennsylvania Climate Impacts Assessment,*** (2009 PCIA) were based on Global Climate Models (GCMs), which have very coarse horizontal resolution (several hundred km). In the NARCCAP, Regional Climate Models (RCMs) of higher resolution (50 km; 31 miles) for North America are nested inside of GCMs. At this resolution, Pennsylvania can be broken down into nearly 40 grid boxes, effectively providing results approaching the scale of individual counties. Figure 3.1 shows the domain of the NARCCAP models and the topography at a resolution of 50 km (31 miles). Coastlines and mountain ranges are resolved much better with RCM resolution than with GCM resolution. For example, the Appalachian Mountains are barely noticeable in GCM topography (not shown) whereas they show up quite clearly at 50 km (31 miles) resolution. This improved resolution, though still not ideal, affords the possibility of investigating the impacts of climate change with greater spatial resolution and potentially greater certainty.

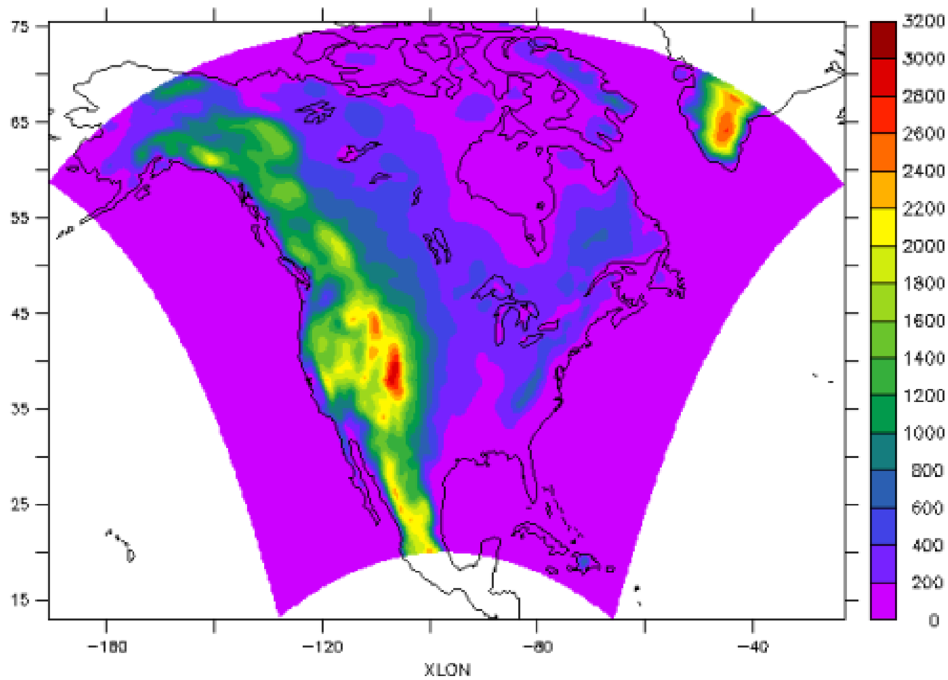

Figure 3.1. The NARCCAP domain illustrated by the topography (m) at a horizontal resolution of 50 km. Source: NARCCAP, www.narccap.ucar.edu.

To illustrate the difference between a climate projection by a GCM alone and one by an RCM nested inside a GCM, see Figure 3.2, which shows the projected change in precipitation during the winter by mid-century under the A2 emissions scenario. While the broad patterns are similar in the two projections, there are substantial regional differences and there is clearly more detail in the RCM output. For example, in Pennsylvania the projected change simulated by the GCM is uniform across the commonwealth while the RCM projects a somewhat smaller change that increases from the southeast to the northwest.

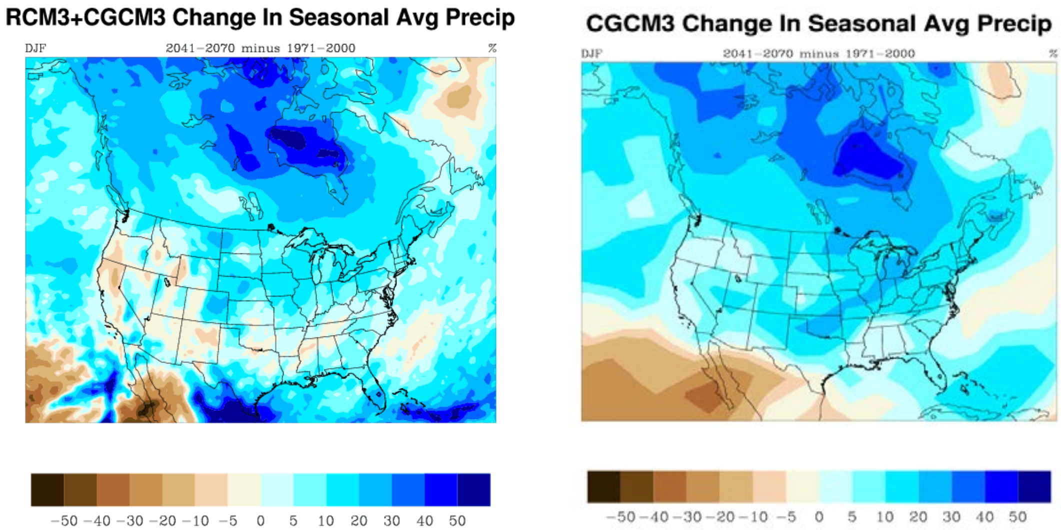

Figure 3.2. An example illustrating the difference between output from a global, coarse resolution climate model (left) and a high-resolution regional climate model nested in a global climate model (right). Shown here is the projected winter precipitation change (percent) under the A2 emissions scenario by the middle of the 21st century simulated by the Coupled Global Climate Model Version 3 (CGCM3, left) and the Regional Climate Model Version 3 (RCM3, right) nested in CGCM3. Source: NARCCAP, www.narccap.ucar.edu.

The main questions we seek to answer with the higher resolutions models are [1] do high-resolution regional models perform better than coarse-resolution global models at simulating the Pennsylvania-average climate; and [2] is model consensus in future climate projections improved by using regional climate models?

In addition to repeating and extending our analysis of the Pennsylvania-wide averages of temperature and precipitation from the 2009 PCIA, we take advantage of the improved resolution of the NARCCAP models to evaluate their ability to simulate spatial variations in Pennsylvania's climate. Furthermore, we present future projections of temperature, precipitation, and soil moisture change at a resolution of approximately 50 km (31 miles).

Finally, building on related ongoing research at The Pennsylvania State University concerning climate trends within the Delaware River Watershed, we present a brief analysis of temperature and precipitation change over Pennsylvania since the beginning of the 20th century.

3.1 Differences in GCM analysis between this update and the 2009 PCIA

We found ways to improve our analysis of GCM output since the 2009 PCIA, and so to understand why some of the GCM results shown here are slightly different, we clarify the three main changes that we made in the analysis.

The first difference is in the total number of GCMs used, which are now 12 compared to the original 14. Two of the models (CCSM3 and PCM) have been dropped because they do not have complete daily precipitation files for future climate scenarios, which are needed for calculation of the extreme precipitation metrics. Note that these two models *were* used in the 2009 PCIA for the analysis of other metrics, including those based on daily temperature (e.g., frost days).

The second difference is in the treatment of realizations. A realization is an individual simulation by a GCM with a specified forcing (e.g., greenhouse gas scenario) and a specified initial state at the beginning of the simulations. The initial state includes, for example, the three-dimensional distribution of temperature in the ocean. Due to observational error, many different initial states are possible, and thus to capture the impact of different initial states on the simulated climate, many different simulations are run with slightly different initial conditions. In the 2009 PCIA, multiple realizations were used for the 20th century (see Table 3.1) and one realization was used (due to availability) for the 21st century scenarios. In the 2009 PCIA, metrics from the multiple realizations for the 20th century were averaged. Differences between the 21st and 20th century were computed by comparing the 21st century metric to the average of the 20th century metrics. This creates some inconsistency because some of the difference computed in this way reflects a change in the initial state of the 21st century simulation as opposed to the change in the greenhouse gas forcing, which the difference was intended to reflect. To address this inconsistency in this update, we only use one 20th century realization for each GCM, which corresponds to the single realization used for the 21st century.

The third difference is that we now use a common period for model evaluation, 1979-1998. In the 2009 PCIA, we had used 1901-1997 for metrics based on monthly averages of temperature and precipitation and 1979-1997 for metrics based on daily averages of temperature and precipitation.

3.2 Regional climate models, data sets, and analysis

NARCCAP includes a wide range of possible GCM-RCM combinations so as to provide a measure of uncertainty in climate projections that is due to the climate models themselves. In total, there are four GCMs and six RCMs participating in NARCCAP, though only 12 of the possible 24 combinations are used due to computational resource limitations. When our analysis began in the fall of 2011, there were nine combinations available to U.S., which are listed in Table 3.2. Simulations with these models were conducted for the recent past (1971-2000) and one future period (2041-2070). These were conducted for the A2 emissions scenario, designed by the Intergovernmental Panel on Climate Change (IPCC) and utilized in the 2009 PCIA (Nakićenović & Swart, 2000). The A2 scenario, which can be described as a medium-high scenario, assumes continued growth in global emissions of greenhouse gases throughout the 21st Century.

Originating Group(s)	**Country**	**CMIP3 I.D.**	**Realizations**
Bjerknes Centre for Climate Research	Norway	BCCR-BCM2.0	1
National Center for Atmospheric Research	USA	CCSM3*	9
Canadian Centre for Climate Modeling & Analysis	Canada	CGCM3.1(T47)	5
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3	1
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0	3
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.5	3
Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM	4

Originating Group(s)	Country	CMIP3 I.D.	Realizations
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	Germany / Korea	ECHO-G	3
U.S. Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0	3
U.S. Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1	3
Institute for Numerical Mathematics	Russia	INM-CM3.0	1
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(medres)	3
Meteorological Research Institute	Japan	MRI-CGCM2.3.2	5
National Center for Atmospheric Research	USA	PCM*	4

Table 3.1. Global climate models used in the 2009 PCIA. This is similar to Table 5.1 in the 2009 PCIA except that it also shows the number of 20th-century realizations used in the 2009 PCIA. Only one realization is used in the current report. An asterisk indicates a model not used in Section 3.3 of the current report.

Model ID	Modeling Group
CRCM_ccsm	OURANOS / UQAM
CRCM_cgcm3	OURANOS / UQAM
ECP2_gfdl	UC San Diego / Scripps
HRM3_hadcm3	Hadley Center
MM5I_ccsm	Iowa State University
RCM3_cgcm3	UC Santa Cruz
RCM3_gfdl	UC Santa Cruz
WRFG_ccsm	Pacific Northwest National Lab
WRFG_cgcm3	Pacific Northwest National Lab

Table 3.2. List of regional climate models used in this update.

Our analysis of the NARCCAP simulations follows the same approach used for the GCM analysis in the 2009 PCIA. In short, we evaluated each model based on its ability to simulate mean annual cycles of Pennsylvania-wide averages of surface temperature and precipitation (mean, interannual variation, and intramonthly variation), and an overall ranking for each model was computed. The time periods for analysis are 1979-1998 for the baseline and 2046-2065 for the future time period.

The two data sets for model evaluation of these six metrics are the same as those used in the 2009 PCIA. The data set used for characterizing long-term statistics in monthly means is from the University of Delaware (Matsuura & Willmot et al., 2007a,b). The version we are using here is an update of the version used in the 2009 PCIA. Here we are using Version 2.01 (released on June 22, 2009), whereas the 2009 PCIA used a version downloaded from the University of Delaware website in May 2008 (it is unclear what version this was). The data set for computing metrics based on daily temperature and precipitation is from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006).

In our examination of the spatial patterns of temperature, precipitation, and soil moisture, we use a horizontal grid spacing of 0.59° longitude and 0.575° latitude, chosen to create a 4 × 10 grid that is aligned with Pennsylvania's southern, western and northern borders. The monthly observational data from the University of Delaware (0.5° resolution) were linearly interpolated to this grid. The RCMs, at 50 km resolution, were up-scaled to this grid by simply averaging any model grid points within each grid box.

3.3 Results

3.3.1 Model evaluation

Figures 3.3, 3.4 and 3.5 show an evaluation of the NARCCAP models and the GCMs used in the 2009 PCIA. Each figure shows 95 percent confidence intervals (calculated using bootstrapping) of multi-model ensemble averages of the RCMs and GCMs; the observations are shown as well. These figures show that there are some differences between the GCMs and RCMs in their simulation of the climate averaged across the commonwealth. We demonstrated in the 2009 PCIA that the GCMs have a slight cold and wet bias and here we see that this bias is slightly worse for the RCMs (Figure 3.3). Whereas the GCMs had mainly a winter cold bias, the RCM bias is more constant throughout the year, which means that the amplitude of the annual temperature cycle (summer minus winter) is actually improved for the RCMs. Except for the fall, the GCMs showed a wet bias and this is amplified for the RCMs, which show a wet bias in all months except September. Interannual and intramonthly variability in temperature is similar in the RCMs and GCMs, with modest biases that vary with season (Figures 3.4 and 3.5). Interannual and intramonthly variability in precipitation, however, is clearly worse for the RCMs as it is too high compared to observations (Figures 3.4 and 3.5). Despite the differences and slight degradation in skill of the RCMs, the simulations on the whole capture many features of Pennsylvania-averaged climate, such as the clear annual cycles in temperature-based metrics.

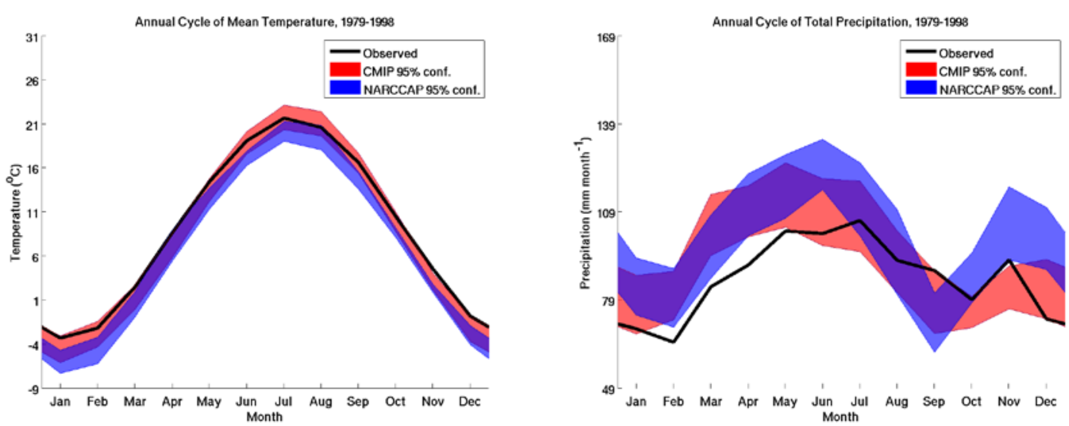

Figure 3.3. Mean annual cycles of observed and simulated Pennsylvania-mean temperature (left) and precipitation (right) for the period 1979-1998. Blue shading is the 95 percent confidence interval of the average of all of the NARCCAP models (the nine RCMs) and red shading is the 95 percent confidence interval of the average of the CMIP3 models (the 12 GCMs), and the black line is the observations.

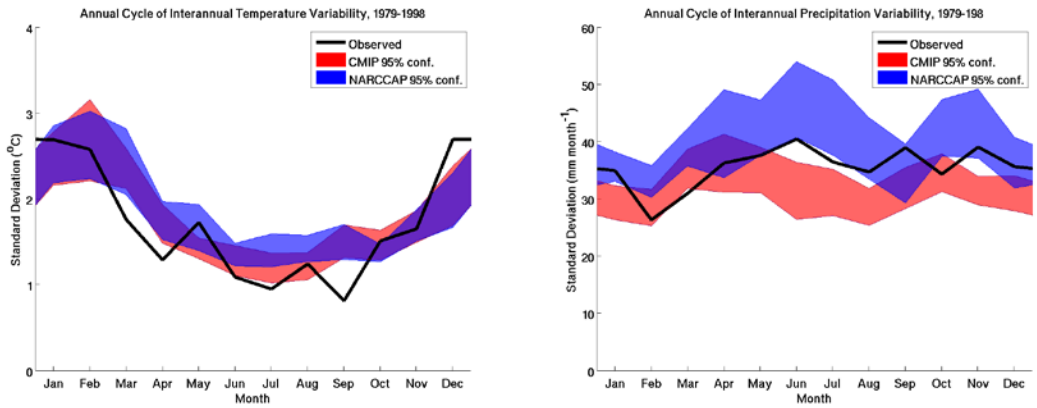

Figure 3.4. Annual cycles of observed and simulated Pennsylvania-mean interannual variability in temperature (left) and precipitation (right) for the period 1979-1998. Blue shading is the 95 percent confidence interval of the average of all of the NARCCAP models (the nine RCMs) and red shading is the 95 percent confidence interval of the average of the CMIP3 models (the 12 GCMs), and the black line is the observations.

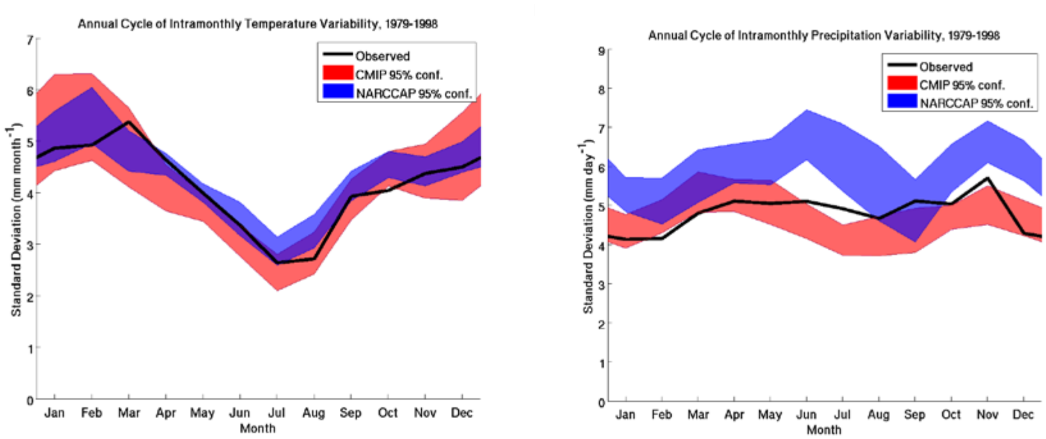

Figure 3.5. Annual cycles of observed and simulated Pennsylvania-mean intramonthly variability in temperature (left) and precipitation (right) for the period 1979-1998. Blue shading is the 95 percent confidence interval of the average of all of the NARCCAP models (the nine RCMs) and red shading is the 95 percent confidence interval of the average of the CMIP3 models (the 12 GCMs), and the black line is the observations.

The superiority of the GCM simulations can be seen in the error index computed using the mean annual cycles of the mean, interannual variability, and intramonthly variability of temperature and precipitation, following the exact same protocol we used in the 2009 PCIA (Figure 3.6). The error index (I^2) for an average model is equal to one and for a perfect model is equal to zero. The multi-model ensemble average for the GCMs is the best model representation of the commonwealth's climate, with an error index of 0.29, and the RCM average is the second best, with an error index of 0.56.

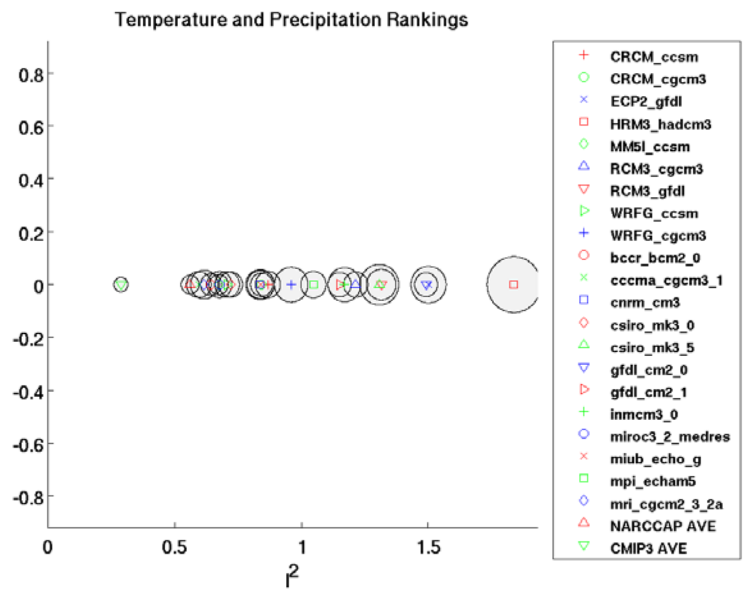

Figure 3.6. Error index for each model and the multi-model ensemble averages for the regional and global models.

We also compared the RCMs and GCMs in their ability to simulate hydrological extremes (metrics that are described in detail in the 2009 PCIA). Results are shown in Figure 3.7. We see that both sets of models do reasonably well; but, again, the GCMs tend to perform slightly better, with the RCMs slightly on the extreme side.

Figure 3.8 shows the spatial distribution of annual-mean temperature and precipitation for the multi-model RCM ensemble average and the observations, as well as the average model bias. The models, in spite of their cold and wet biases, are able to capture some aspects of the spatial patterns of temperature and precipitation patterns across Pennsylvania. Surface air is relatively cool along the central portion of the northern border and relatively warm in the southeast. The temperature difference between these two regions is about 4°C and is reproduced reasonably well by the RCM ensemble average. The distribution of annual-mean precipitation across Pennsylvania indicates relatively wet regions along the northern and southern borders in the western portion of the state and in much of the east, with dry regions in the center and along the central portion of the western border. The model ensemble average picks up these features, with the exception of the latter.

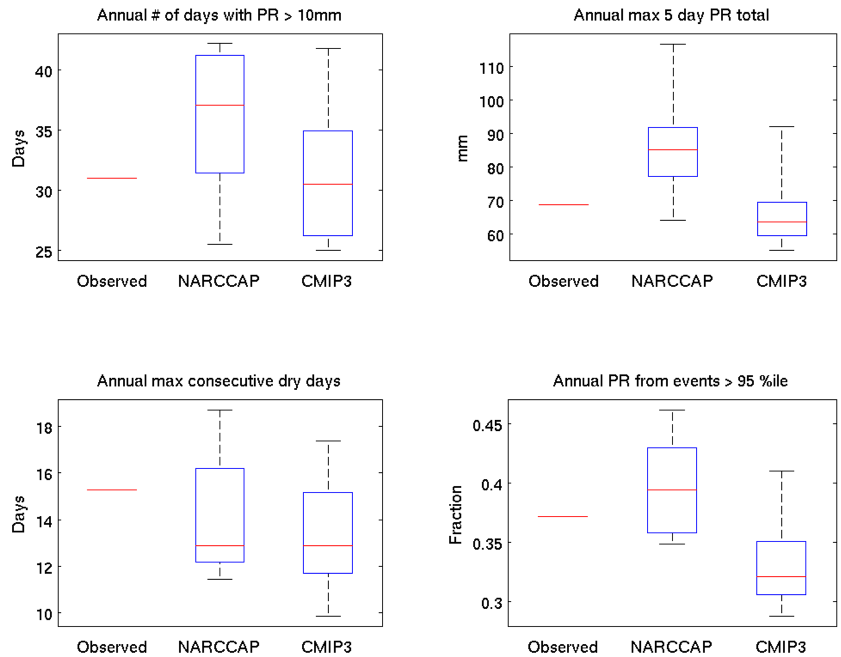

Fig. 3.7. Evaluation of the RCM (NARRCAP) and GCM (CMIP3) simulation of hydrological extremes: the annual number of days with precipitation > 10 mm (upper left), the annual maximum 5-day precipitation total (upper right), the annual maximum number of consecutive dry days (lower left), and the fraction of the annual precipitation that comes from the top 5 percent of daily precipitation events (lower right).

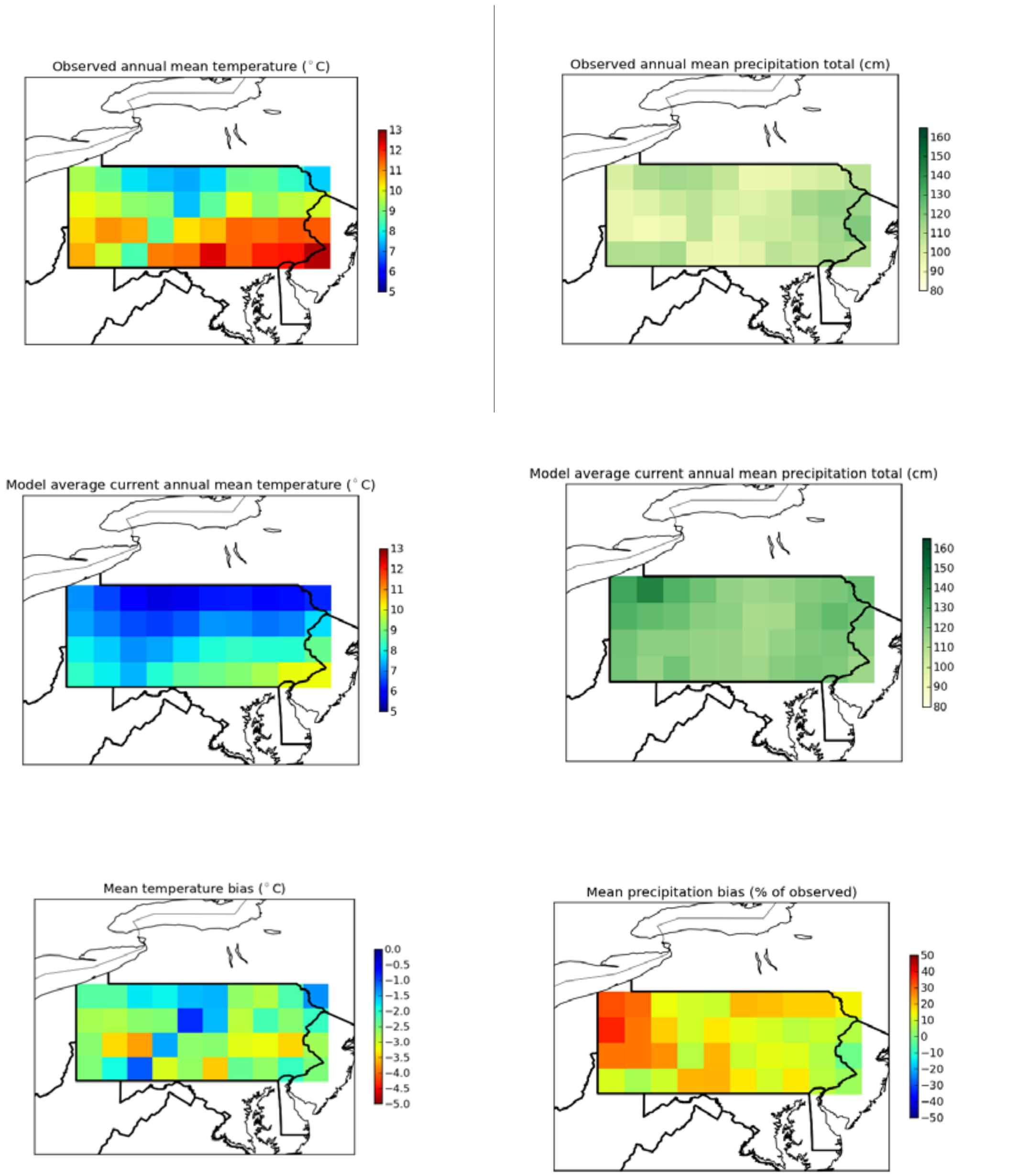

Figure 3.8. Observed (top panels) and ensemble-averaged RCM (middle panels) annual-mean temperature (left panels) and precipitation (right panels) for the 1979-1998 time periods. The bottom panels show the bias for temperature (simulated minus observed, left) and precipitation (simulated minus observed, expressed as a percent of the observed, right).

3.3.2 Model projections

Figures 3.9 and 3.10 show the seasonal-mean temperature and precipitation changes by mid-century under the A2 scenario. The RCM results are consistent with many of our findings with the GCMs, as described in the 2009 PCIA. Specifically, we see that [1] all models warm, [2] there is slightly greater median warming in summer than in winter, and [3] more than ¾ of the models get wetter in winter. One difference we find is that more than ¾ of the RCMs get drier in summer, whereas the GCMs are nearly evenly split during this season between getting wetter and drier.

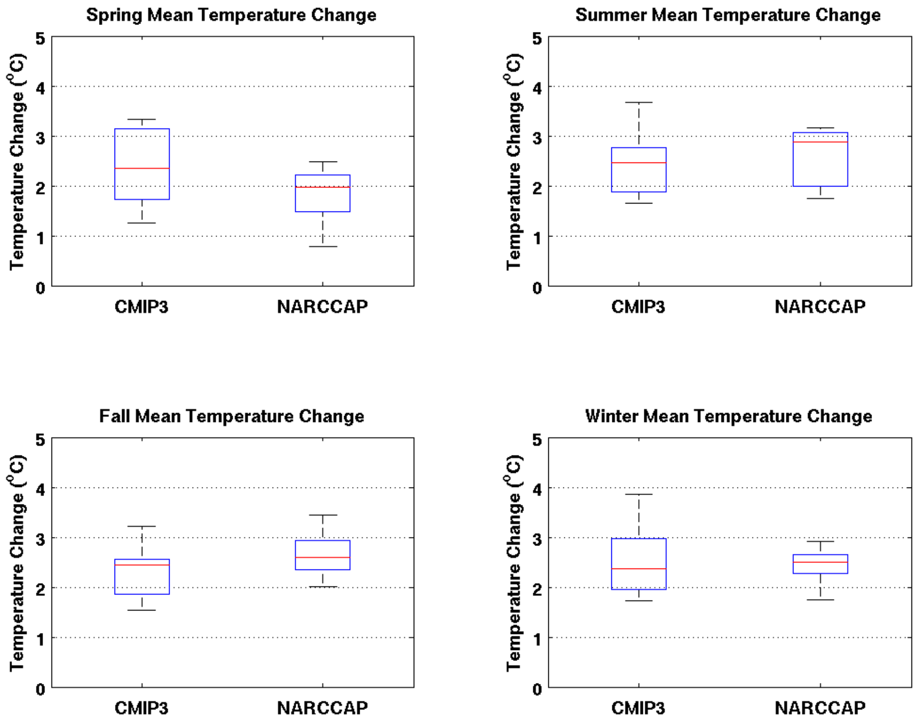

Figure 3.9. Box-whisker plots of simulated seasonal-mean temperature change across Pennsylvania by the 12 GCMs (CMIP3) and the nine RCMs (NARCCAP) by mid-century under the A2 emissions scenario. The red line is the median change, the blue horizontal lines represent the 25th and 75th percentile changes, and the black lines the extreme.

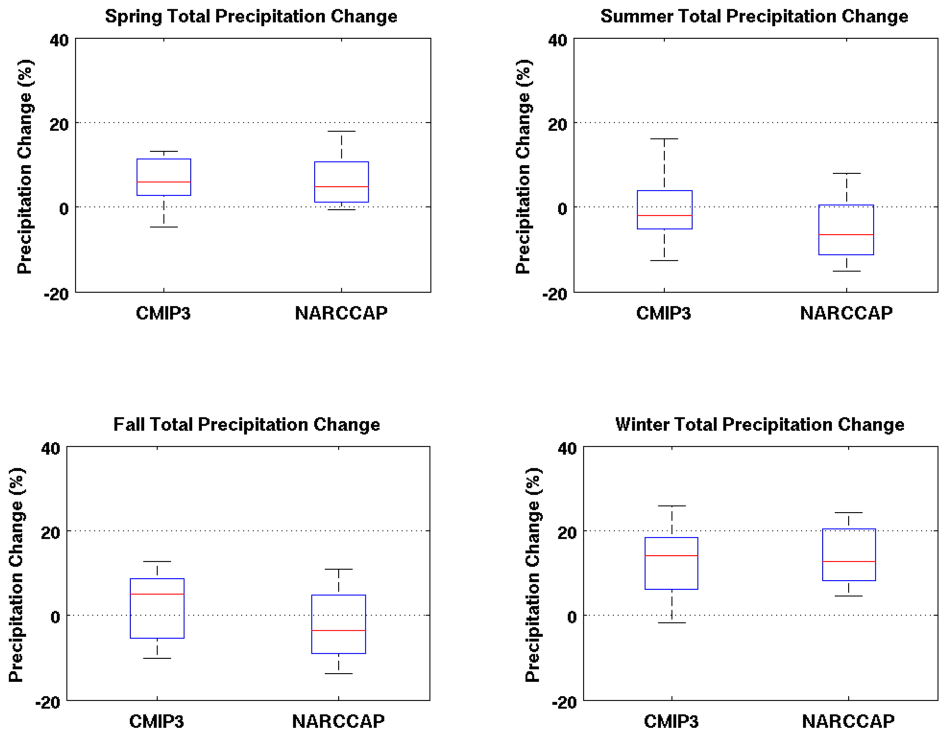

Figure 3.10. Box-whisker plots of simulated seasonal-mean precipitation change across Pennsylvania by the 12 GCMs (CMIP3) and the nine RCMs (NARCCAP) by mid-century under the A2 emissions scenario.

Changes in hydrological extremes predicted by the RCMs tend to be similar to those predicted by the GCMs, as shown in Figure 3.11. There is a slight tendency, however, for the RCMs to predict smaller changes.

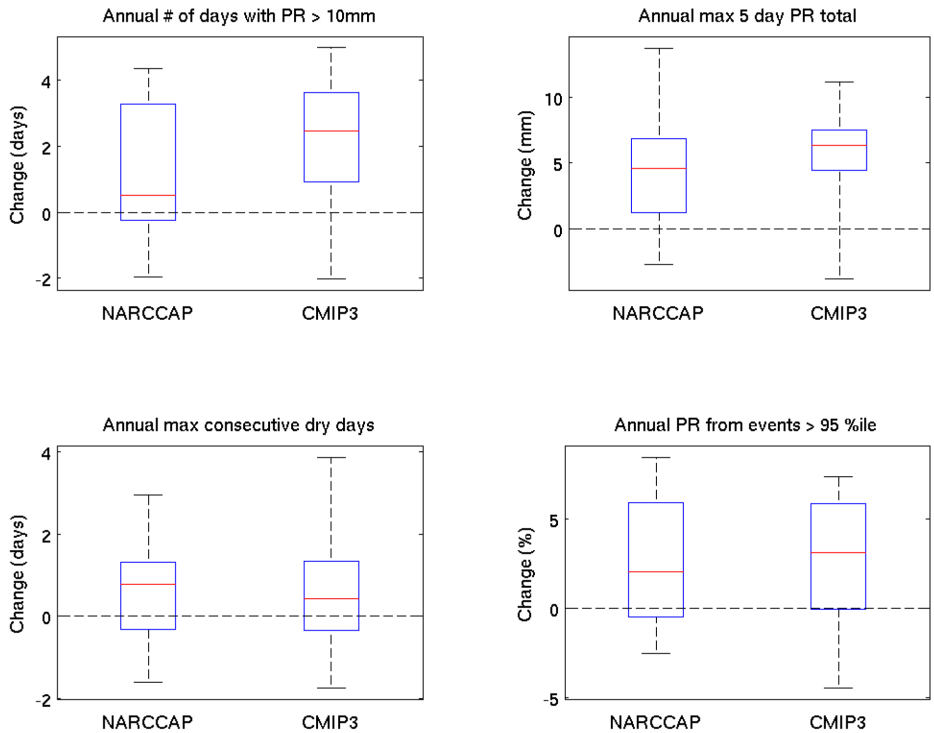

Fig. 3.11. Box whisker plots of simulated changes of hydrological extremes averaged across Pennsylvania by the 12 GCMs (CMIP3) and the nine RCMs (NARCCAP) by mid-century under the A2 emissions scenario: the annual number of days with precipitation > 10 mm (upper left), the annual maximum 5-day precipitation total (upper right), the annual maximum number of consecutive dry days (lower left), and the fraction of the annual precipitation that comes from the top 5 percent of daily precipitation events (lower right).

The spatial variability of projected change as well as the degree of consensus among models is very different for temperature and precipitation (Figure 3.12). Temperature change is quite uniform, varying by no more than 10 percent for the multi-model ensemble average of the RCMs. There is also a strong consensus among models for warming throughout the commonwealth. Precipitation, on the other hand, has projected multi-model mean increases throughout the state but with substantial consensus (at least eight of the nine models agreeing on the sign of the change) in only about half the commonwealth.

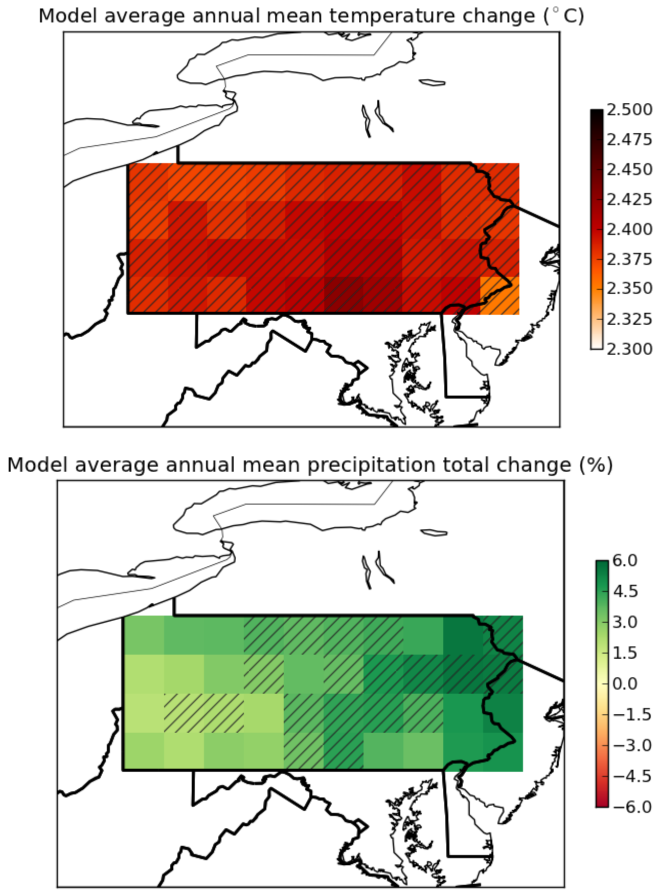

Figure 3.12. Spatial distribution of temperature (top) and precipitation (bottom) change across Pennsylvania by mid-century under the A2 emissions scenario (multi-RCM average). Shading indicates where at least eight of the nine models agree on the sign of the change.

Projected soil moisture change is shown in Figure 3.13 for the summer. The multi-model mean for the RCMs shows a decline ranging from 0 to 6 percent throughout the commonwealth, and there is considerable consensus of drying among the models. The soil moisture declines presumably occur as a result of warming (which will increase potential evapotranspiration) and precipitation declines during the summer (Figures 3.9 and 3.10).

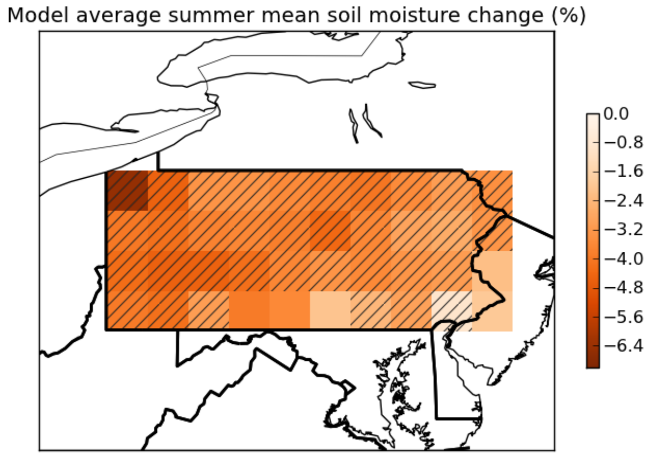

Figure 3.13. Multi-model ensemble averages in the changes in summer average soil moisture from the regional climate models. Shading indicates where at least eight of the nine models agree on the sign of the change.

3.4 Historical temperature and precipitation change across Pennsylvania

We analyzed changes in temperature and precipitation since 1901 across Pennsylvania using data from 24 stations that are part of the United States Historical Climate Network, Version 2 (Menne et al., 2009; Menne et al., 2010). These data are similar to those that underlie the University of Delaware gridded atlas (Matsuura & Willmot, 2007a,b), which was used earlier (e.g., in Figures 3.3. and 3.4). The usHCN, however, is a high-quality data set specifically designed for long-term trend analysis, and has undergone extensive quality control and adjustments to account for spurious trends due to, for example, changes in station location and the time at which daily observations were made. These adjustments can be considerable, as shown below.

During the past 30 years, station trends vary between 0.1 to 0.5 °C (0.2 to 0.9 °F) per decade with an average of 0.3 °C (0.6 °F) per decade (Figure 3.14). The temporal pattern of change is very similar across the state, as shown in the decadal-averaged temperature anomalies (Figure 3.15, left panel). Temperature increased by about 0.7 °C (1.3 °F) from the beginning of the 1900s to the 1950s. It then dropped rapidly by about 0.5 °C (0.9 °F) over the next decade or so. Since the 1960s, there has been a steady increase of about 1 °C (1.8 °F). The temporal pattern of change in Pennsylvania is broadly similar to the global average temperature change (Trenberth et al., 2007). Overall, the temperature increase in Pennsylvania from the first decade of the 20th century to the first decade of the 21st century is about 1.3 °C (2.4 °F).

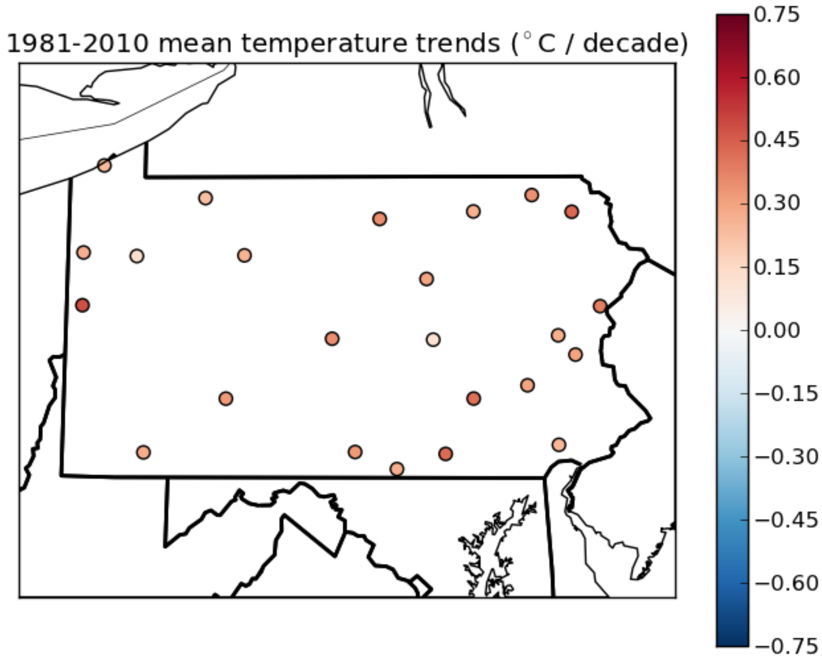

Figure 3.14. Mean temperature trends at the USHCN stations in Pennsylvania between 1981 and 2010.

What caused the long-term warming in Pennsylvania? We can use the GCMs to help U.S. answer this question. The left panel in Figure 3.16 shows the observed and simulated temperature change from the average over the 1900-1919 period to the average over the 1979-1998 period. The bar on the left is the average temperature change simulated by the 12 GCMs used in this study (0.7 °C, 1.3 °F) and agrees well with the mean of the USHCN stations over Pennsylvania (0.6 °C, 1 °F). These models include the observed 20th century increases in greenhouse gases as well as natural forcings, such as changes in solar output and volcanic aerosols. We searched for the output of GCM simulations that contained only the natural forcings in order to determine their impact. We found two such GCMs (CCSM3 and PCM), which, coincidentally, are the same GCMs that were dropped from the analysis in Section 3.3 due to a lack of daily output for future scenarios. Output was acquired from the Earth System Grid gateway at the National Center for Atmospheric Research (www.earthsystemgrid.org). As Figure 3.16 shows, these two models simulate warming over the 20th century when all forcings are included (though less warming than the average of the 12 models) and less warming or cooling when only natural forcings are included. This result suggests that a substantial portion of the observed warming in Pennsylvania is a result of anthropogenic climate forcing (i.e., greenhouse gases).

However, as indicated by the last set of bars in Figure 3.16, the actual amount of warming in Pennsylvania over the 20th century is subject to substantial uncertainty resulting from adjustments made to the USHCN data. Without the adjustments, very little increase in temperature is seen. This is consistent with the change estimated from the University of Delaware data, which also shows much less warming than the adjusted USHCN data. These adjustments are important and necessary for making our best estimate of temperature change over the commonwealth, but the uncertainty introduced by them is not well constrained and deserves further study. Note that the adjustments are very minor over the past several decades (not shown), which means there is little uncertainty in the trends over this time period.

We conducted a similar analysis for precipitation change over Pennsylvania. Figure 3.15 (right panel) shows that Pennsylvania has become increasingly wetter, with substantial changes from one decade to the next. The 1960s were remarkably dry, with annual precipitation 10 cm (about 10 percent) less than normal, whereas the most recent decade was about 10 percent wetter than normal. Seager et al. (2012) suggested that these anomalies were not a result of greenhouse gas increases nor were they driven by changes in surface ocean temperature. Our analysis is consistent with that. The right panel in Figure 3.16 shows large variations among model-predicted precipitation change over the 20th century. Furthermore, including anthropogenic greenhouse gases can either result in a precipitation increase (PCM) or decrease (CCSM3).

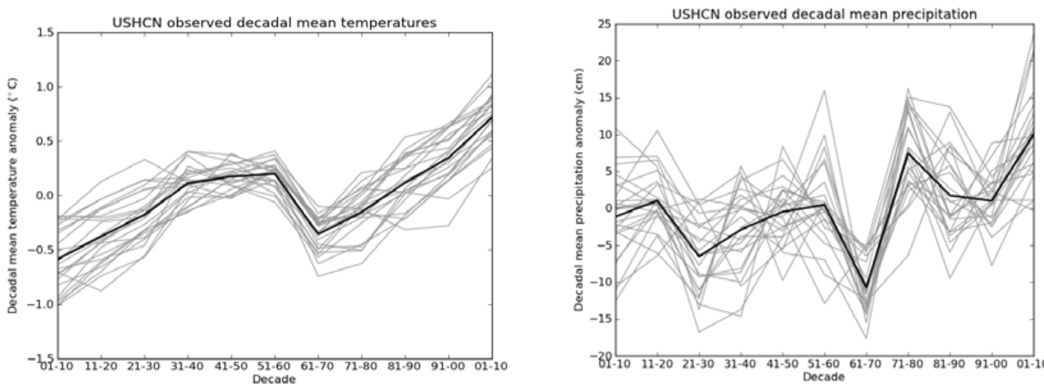

Figure 3.15. Decadal averages of temperature (left) and annual precipitation (right) anomalies at each of the 24 USHCN stations in Pennsylvania (gray lines) from 1901 to 2010. The anomaly for each station was computed with respect to the 1895-2010 mean. The black line is the average of all of the stations.

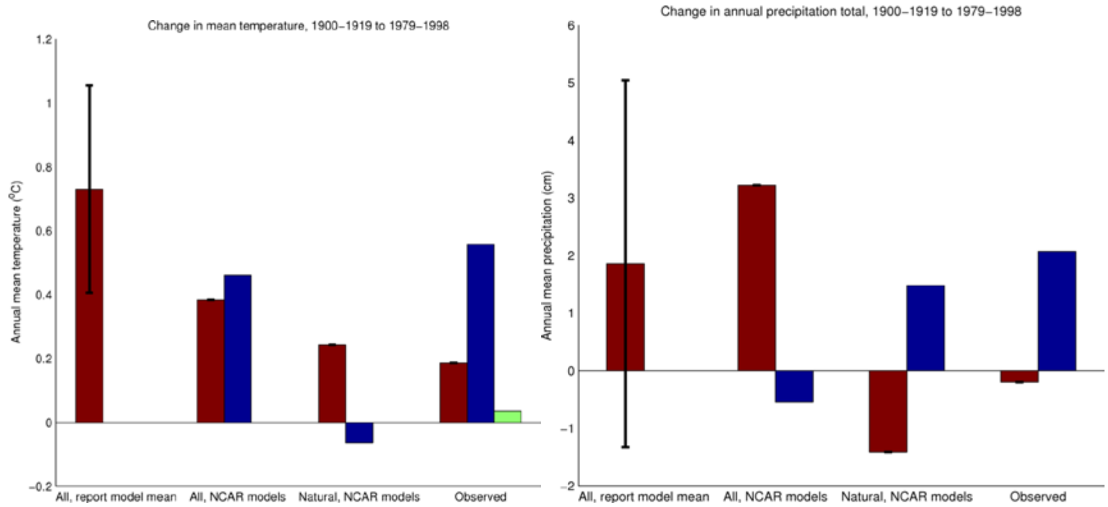

Figure 3.16. A comparison of simulated and observed temperature (left) and annual precipitation (right) change in Pennsylvania from the early 20th century (1900-1919) to the late 20th century (1979-1998). The left bar in each panel represents the mean ± 1 standard deviation of the 12 GCMs used in most of this report, which include all forcings (anthropogenic and natural). The next two sets of bars represent the GCMs CCSM3 (red) and PCM (blue) under all forcings (second set) and natural forcings only (third set). The last set of bars represents the observations: University of Delaware (red), USHCN (blue), and usHCN unadjusted (green, temperature only).

3.5 Conclusions

The use of higher resolution models does not change the overall picture of simulated climate as presented in the 2009 PCIA. The regional climate models do not seem to reproduce the spatially averaged climate over Pennsylvania any better than the global climate models. The regional climate models do, however, capture the broad spatial distribution of temperature and precipitation across Pennsylvania. The projections of future climate are not substantially different from our previous report (at least for the time period and scenario for which we could compare the GCMs and RCMs). Finally, our analysis of temperature change over the commonwealth over the past 110 years shows long-term warming despite a brief (but dramatic) mid-20th century cooling. Though the temperature data have been corrected for changes in station location and other factors, the uncertainty introduced by these changes is not well constrained. Nevertheless, global climate models simulate the observed temperature change and indicate that much of it is due to anthropogenic greenhouse gases. Precipitation has increased as well, but this appears to be a result of natural climate variability.

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4.0 Agriculture

Chapter 9 of the 2009 ***Pennsylvania Climate Impacts Assessment*** report reached the following conclusions about the impacts of climate change on Pennsylvania agriculture:

1. Moderate climate change may raise Pennsylvania yields of hay, corn, and soybeans, but it may also raise yields elsewhere in the U.S. and around the world – increasing global production and pushing down prices received by Pennsylvania farmers.
2. Yields of cool-temperature adapted fruits and vegetables such as potatoes and apples are likely to decline as a result of climate change, while yields of fruits and vegetables better suited to a warmer climate such as sweet corn are likely to rise.
3. In the dairy industry, heat stress and a decline in feed quality are likely to drive milk yields downward and increase production costs. For operations that rely on grazing and on-farm production such as dairy and beef herds, changes in pasture yields and feed quality will impact production costs.
4. For the state's hog and poultry producers, while climate control costs are likely to increase with warmer summer months, this same effect in southern states may make Pennsylvania more attractive to these industries and could induce a northward shift in production operations.

This chapter summarizes new knowledge of about these impacts that has been developed since the 2009 PCIA.

4.1 The Near- and Long-Term Future for Pennsylvania Agriculture

Agriculture in Pennsylvania has changed dramatically since 1900 and will likely continue to change in profound ways between now and 2100, regardless of whether climate change is large or small. This section discusses some of the major forces in addition to climate changes that are likely to impact Pennsylvania's agricultural sector in coming years and decades. This section also covers how our understanding of those forces has changed since 2009, and the implications of these forces for potential impacts of climate change on Pennsylvanian agriculture.

4.1.1 National and Global Agricultural Markets

Pennsylvania is part of local, regional, national and global markets for food and agricultural products. In some cases, such as hay, certain seasonal fruits and vegetables, prices are determined by local and regional markets. Changes in demand or supply within Pennsylvania will affect prices for farmers, consumers and others in the supply chain. In other cases, such as dairy products and mushrooms, prices are determined by national and global markets. However, Pennsylvania is a large enough producer of these products that changes in supply within the state will have a noticeable impact on markets. By contrast, in cases such as corn and soybeans, Pennsylvania has such as small share of the global market that what happens within the state has no significant impact on market prices.

Prices on national and global agricultural markets have been quite volatile during the past five years, with prices in 2011 significantly above long-term averages. Figure 4.1 illustrates monthly trends from January 1990 to October 2011 in the Food and Agriculture Organization (FAO) food price index.[2] The

[2] The USDA, World Bank, and International Monetary Fund (IMF) also publish monthly food price indices, and their indices exhibit similar trends to the FAO index (Trostle et al., 2011).

index is inflation-adjusted and scaled so that the 2002-2004 average is 100. The index measures international prices of a basket of food commodities. Figure 4.2 illustrates monthly trends for three of the commodity groups in that basket that are particularly important to Pennsylvania: meat, dairy, and grains.

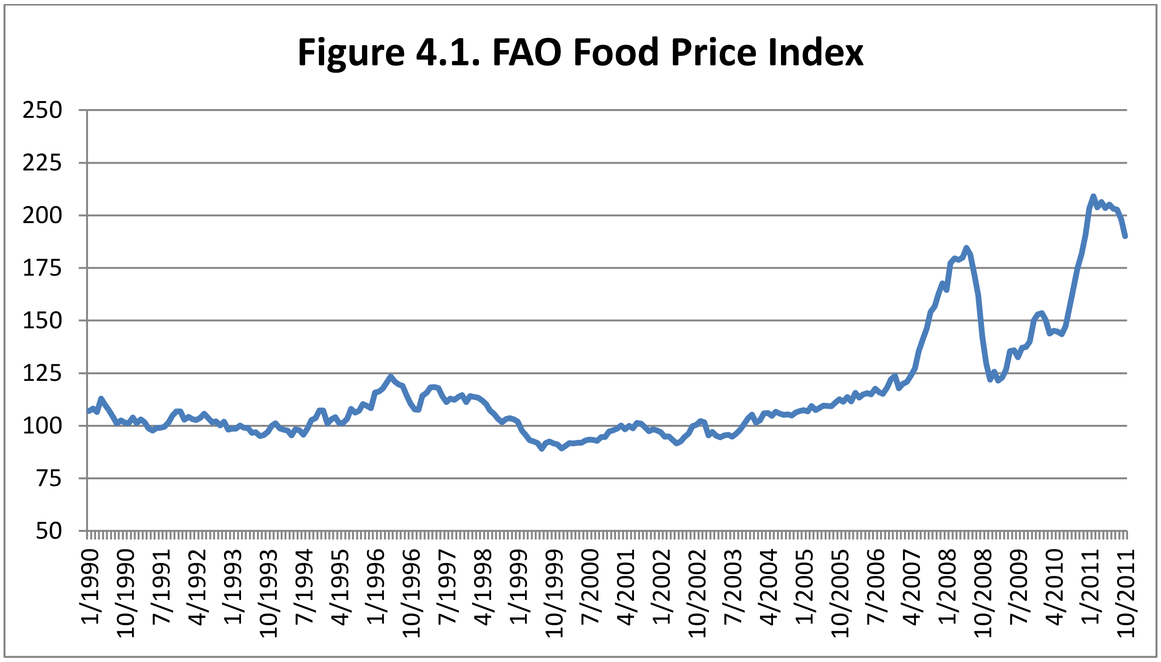

Figure 4.1. FAO Food Price Index. Price indices are inflation adjusted and scaled so that 2002-2004 = 100. Food and Agriculture Organization (2011)

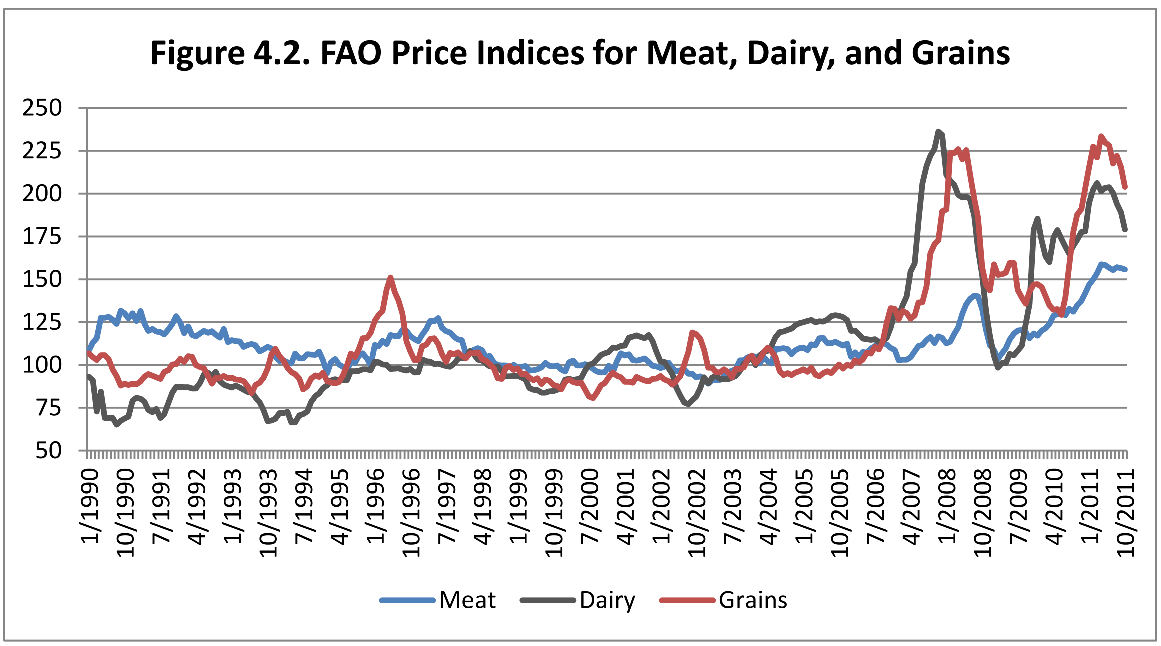

Figure 4.2. FAO Price Indices for Meat, Dairy, and Grains. Price indices are inflation adjusted and scaled so that 2002-2004 = 100. Food and Agriculture Organization (2011)

Agricultural commodity markets have a long history of booms and busts. Many Pennsylvania farmers in business today were also in business, or beginning their careers, in the mid-1970s. The agricultural commodity boom of that era was followed by a major bust in the 1980s. In 2009 the boom of 2007-2008 had just ended, prices of agricultural commodities were declining, and it was difficult to project where prices would head next. Since then prices have risen again and the FAO's food price index hit all-time highs in 2011. Contributing factors to recent high prices include (Trostle et al., 2011):

- *Macroeconomic factors:* the global economic recovery since 2009 and the declining value of the U.S. dollar;
- *Supply shocks:* a series of adverse weather events around the world during 2010-2011;
- *Consumer demand growth:* growing demand for meat and dairy products in emerging market countries such as China and India;
- *Biofuels:* growing use of corn, sugarcane, and other crops in the global production of biofuels; and
- *Agricultural export restrictions:* taxes, quotas, and bans on exports of key commodities enacted by Argentina, Russia, Ukraine and several other agricultural exporting countries (some policies since removed).

Based on past experience, markets will adjust and prices are likely to decline from their 2011 highs; however that could take several years. USDA agricultural baseline projections to 2020 show prices for grains, oilseeds, fruits and vegetables gradually declining during this decade before leveling off at prices significantly greater than average prices during the 1990-2005 period (USDA, Economic Research Service, 2011). Among livestock products, poultry and egg prices are projected to remain significantly above 1990-2005 averages while dairy and meat product prices are projected to decline close to their historical averages by 2020 (USDA, Economic Research Service, 2011). If dairy and meat prices decline while grain and oilseed prices remain high, this would lead to cost-price pressure on Pennsylvania meat and dairy producers and could lead to an increase in the number of farms exiting these two industries.

Overall, USDA projections suggest a tight market situation for most agricultural products during this decade. During this period, extreme weather events are likely to lead to greater swings in global agricultural prices than would have been the case 10 or 20 years ago.[3] Compounding the effects of weather are policy responses to adverse weather events observed in several emerging market countries since 2008. These policies attempted to hold down domestic food prices in those countries but at the cost of restricting supplies to world markets and pushing up world prices. For example, Russia's ban on wheat exports during 2010-2011 in response to a severe drought in that country was one important factor behind the run-up in global wheat prices during that time.

With the partial exception of dairy products, where U.S. prices are somewhat insulated from world prices by U.S. import tariffs and tariff-rate quotas (TRQs), Pennsylvania producers of internationally traded commodities are exposed to developments in world markets. If climate variability continues to increase this decade, Pennsylvania farmers are likely to face more price volatility than in the past (at least through 2020) due to weather shocks in various regions of the world.

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[3] The USDA projections are based on the assumption of normal weather worldwide during the projection period (2011-2020), a standard assumption in projections of this type. Of course, the weather in any given year is never completely normal, and extreme weather events may cause agricultural prices to deviate from the values projected by USDA.

Beyond 2020, the uncertainties involved in agricultural market projections—including uncertainties about population growth, income growth, technological change, land and water availability, energy markets and biofuels, and agricultural policies—become far greater. FAO published projections in 2006 for global agricultural markets to 2050. These projections indicate that global agricultural supplies will keep pace with growing demands and that average food consumption per person will increase significantly between now and 2050 in emerging market countries – especially consumption of meat and dairy products. In developed countries such as the U.S., where per capita food consumption levels are already high, increases in consumption between now and 2050 are projected to be modest. In a recent review of these projections in light of developments since 2006, Alexandratos (2011) concluded that they are still broadly valid for 2050.

Beyond 2050, the uncertainties rise by another order of magnitude because of the possibility of technological changes that lead to a dramatic transformation of the agricultural sector. During the 20th century, tractors and other farm machinery virtually eliminated the use of draft animals and made it possible for a single farmer to cultivate tracts of land orders of magnitude larger than a century ago.

Listed below are more changes that have occurred since the beginning of the 20th century.

- *Synthetic organic pesticides revolutionized the control of weeds and insects.*
- *Tremendous growth occurred in the use of manufactured fertilizers; hybrid seeds and more recently, genetically modified (GM) seeds were developed and widely adopted.*
- *Livestock production was transformed from a small-scale basis to, in many cases, a very large-scale basis with productivity levels far higher than a century ago; farmers became highly specialized in the livestock products and crops they produce.*
- *Crops that were virtually unheard of 100 years ago, such as soybeans, grew to major importance today.*

It is likely that Pennsylvania agriculture in 2100 will bear only a faint resemblance to today, but we cannot say with any confidence what it might look like.

4.1.2 Agricultural Land Conversion

One issue identified in the 2009 PCIA was future trends in farmland availability in light of agricultural land conversion to urban uses such as housing, retail, and office space. This speaks to the question of where agriculture will be located within Pennsylvania in the future—climate change can only impact agricultural production if agriculture continues to exist. Agricultural land conversion is being driven in large part by growth in the number of suburban households. using 2000 Census data, the U.S. Census Bureau (2005) projected that Pennsylvania's total population would increase only about 4 percent between 2000 and 2030, compared to about 29 percent for the U.S. as a whole. Projections by the Pennsylvania State Data Center (2008) using 2000 Census data suggest a somewhat higher population growth of about 7 percent for the state between 2000 and 2030.

At the county level, Pennsylvania State Data Center (2008) projections indicate continued strong population growth in the southeastern Pennsylvania and population losses in most of western and northern Pennsylvania. Agriculture in Pennsylvania is currently concentrated in the southeast part of the state. Lancaster County, which accounted for nearly one-fifth (18 percent) of total agricultural product sales in Pennsylvania in 2007,[4] is projected to see its population increase by about 18 percent between 2000 and 2030. The population of neighboring Chester County, which accounted for 10 percent of Pennsylvania's agricultural product sales in 2007, is projected to rise by almost 60 percent. Other southeastern counties with high projected rates of population growth during 2000-2030 include Adams (26 percent), Berks (32 percent), Cumberland (32 percent), and York (27 percent).

The Chesapeake Bay Program has a land use change model that has been used to project farmland loss within the Chesapeake Bay region over the period of 2006-2025 (Irani, 2011). The principal driver of farmland loss in the model is projected county-level population growth. The farmland loss projections are shown in Figure 4.3. The largest losses in farmland acreage in the Pennsylvania portion of the Chesapeake Bay region are projected to occur in Adams, Cumberland, Franklin, Lancaster, and York counties.

County-level population projections have not yet been updated to reflect the 2010 Census figures or economic developments during the past few years. With the economic recovery from the 2007-2009 recessions occurring more slowly than many anticipated two years ago, suburban population and household growth may be dampened. For example, the growth projected by Masnick et al. (2010) in the number of households nationally between 2010 and 2020 is about 6-to-7 percent lower than the projections they made in 2009. In some parts of the U.S. where there have been steep declines in residential land values and increases in farmland values, agricultural land that had been sold to developers but was never developed is being repurchased by farmers and put back into agriculture (Whelan, 2011). What these national trends will mean for new housing starts in Pennsylvania is not entirely clear, considering that the excess supply of housing is greater in many other states than in Pennsylvania.

It seems likely that conversion of agricultural land to housing and other urban uses in southeastern Pennsylvania between now and 2020 will be lower than what we anticipated in our 2009 PCIA. Beyond 2020, it is much harder to say as it depends on future population growth, economic growth, and the housing market.

4.1.3 Pennsylvania Food Demand

Two trends identified in the 2009 PCIA were growing demand for organic food products and growing demand for local foods. We indicated that the result of the trend toward organic food combined with technological change through biotechnology could be a split in Pennsylvania agriculture into two production systems: one heavily invested in biotechnology, and one organic. The trend toward local food implies greater demand over time by Pennsylvania consumers for Pennsylvania food and agricultural products, particularly fresh fruits and vegetables.

[4] From the *2007 Census of Agriculture* (USDA, National Agricultural Statistics Service, 2009).

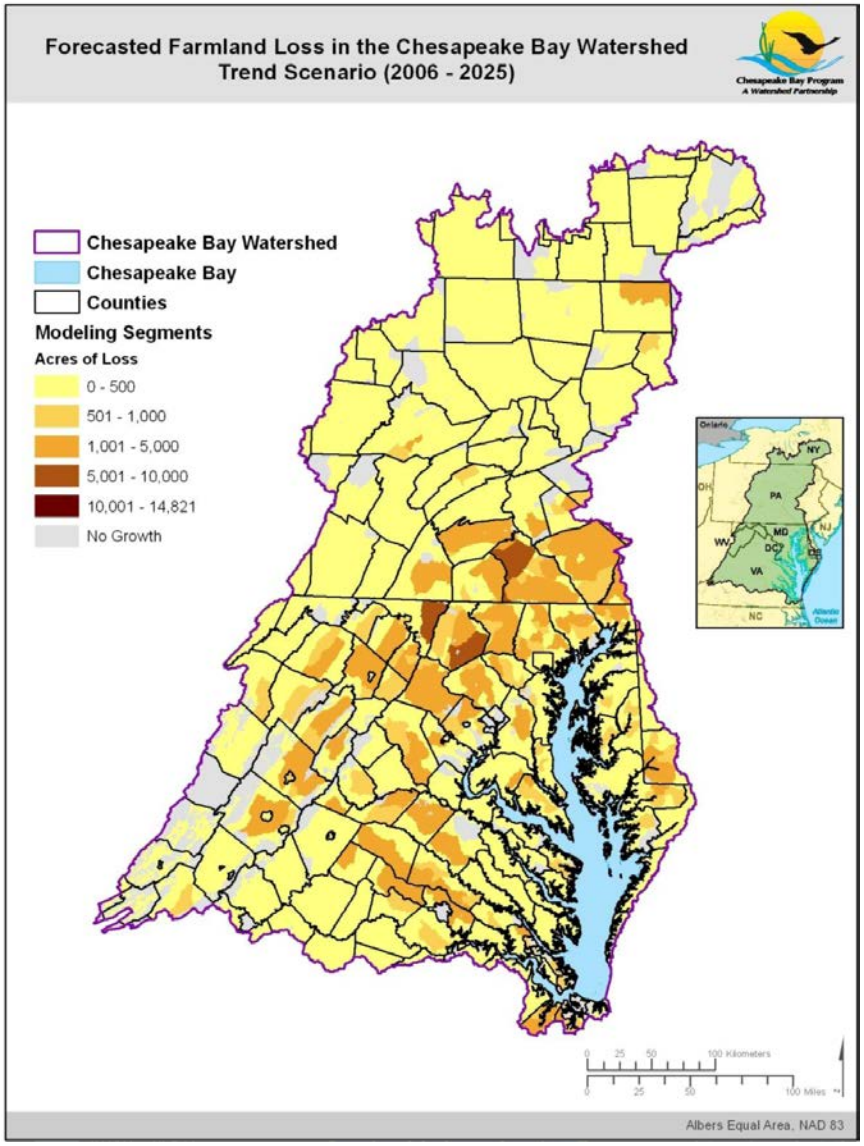

Figure 4.3. Projected Farmland Loss in the Chesapeake Bay Watershed, 2002-2030. Source: Chesapeake Bay Land Change Model.

The slow recovery from the 2007-2009 recession led to slower growth in demand for organic products in 2010 than the double-digit growth rates of previous years, but total U.S. organic product sales still grew by about 8 percent from 2009 to 2010 (Organic Trade Association, 2011). Statistics on growth in demand for local foods are scarcer and less reliable (Martinez et al., 2010). The conclusion is that the growth in demand for organic food products will continue in the near term, even if the economy remains weak, and will accelerate once the economy recovers.

Over the longer term, the typical assumption in economic projections is that the economy moves towards its long-run rate of growth, so that periods of below-average growth or negative growth (recessions) are followed by periods of above-average growth. For example, the usDA's agricultural baseline projections to 2020 assume that inflation-adjusted growth in gross domestic product (GDP) will rise from -2.6 percent in 2009 to 2.8 percent in 2012 and then level off at 2.6 percent growth per year during 2013-2020 (usDA, Economic Research Service, 2011).

4.1.4 Federal Agricultural Budgets

The federal government is under considerable fiscal pressure at the present time due to high budget deficits and debt. The long-term fiscal outlook for federal entitlement programs, which account for the majority of federal spending, is poor. This fiscal situation could result in an extended period of restricted federal funding for agricultural programs, including agricultural research, conservation programs, and crop insurance.

As discussed in the 2009 PCIA, any future increase in the variability of temperature and precipitation in Pennsylvania is likely to increase the demand by farmers for risk management products, including insurance against losses due to drought, flooding, hail, wind, frost, insects, and disease. We also noted that the ability of Pennsylvania agriculture to adapt to climate change hinges in part on the development and adoption of new crop varieties and livestock breeds suited to a warmer and more variable climate.

With an extended period of restricted federal agricultural funding likely, this means that the private sector and/or the state government will need to play a greater role in helping Pennsylvania farmers adapt to climate change. The market for private (not federally subsidized) crop insurance is currently negligible, but that market might grow if federal crop insurance subsidies were reduced. As Goodwin (2001) indicates, the question is whether government-subsidized crop insurance exists because private insurance markets have failed or whether the lack of private insurance is due to direct expenditure offsets by government involvement. One common argument for why private crop insurance markets may fail is systemic risk for example, a major crop failure due to drought that exposes insurers to large losses that overwhelm their reserves. There is debate over whether the reinsurance industry would be willing to cover these systemic risks. Systemic risk also figures prominently in insurance against other extreme weather events such as hurricanes and floods (Hecht, 2008).

Alternatively, the federal government could continue to play an active role in crop insurance but cut expenditures by trimming premium subsidies received by agricultural producers and/or reducing subsidies to private insurance companies that deliver federal crop insurance. Subsidies to private insurance companies consist of administrative and operating (A&O) subsidies and net underwriting gains (the portion of gains kept by insurance companies in years when premiums exceed claims). Figures in Babcock (2010) indicate that premium subsidies on federal crop insurance averaged nearly 60 percent of total premiums during 2005-2009, and that subsidies to private insurance companies (A&O subsidies plus net underwriting gains) averaged more than 40 percent of total premiums during 2005-2009.

With respect to agricultural research, Huffman and Evenson (2006) estimate that the private sector accounted for approximately 70 percent of total (public plus private) U.S. agricultural research expenditures in 2000. They also estimate that inflation-adjusted agricultural research expenditures during the 1980s and 1990s grew more rapidly in the private sector (2.5 percent per year) than in the public sector (0.9 percent per year). As such, the private sector has considerable scope for engaging in R&D to assist agricultural producers in adapting to climate change. At the same time, it should be recognized that the public and private sectors have different focal areas in agricultural research. The private sector is focused on the development of commercially successful products and services, whereas the public sector is focused more on basic research and issues such as natural resources and the environment where there may be no commercial payoff (Schimmelpfennig & Heisey, 2009). In addition, an increase in research resources devoted to climate change adaptation might come partly at the expense of resources devoted to advancing agricultural technology in other ways.

4.2 Recent Research on Climate Change and Agriculture

This section recapitulates some key points from the 2009 PCIA and discusses recent scholarly research on climate change and agriculture relevant to Pennsylvania. No recent research focuses specifically on Pennsylvania. As a result, other regions of the U.S. with a similar climate and agriculture to Pennsylvania were used to draw conclusions.

4.2.1 Climate Change and Crop Production

Statistics from the *2007 Census of Agriculture* indicate that the three most important feed crops in terms of acreage in Pennsylvania are hay, corn (for grain and for silage), and soybeans, and the most important in terms of sales are corn and soybeans. Statistics from the *2007 Census of Agriculture* also indicate that the largest food crop in terms of sales in Pennsylvania is mushrooms; the two other food crops on the top-ten list in terms of sales are fruits and vegetables.[5]

One issue identified in the 2009 PCIA is that elevated levels of CO_2 may lead to an increase in photosynthesis and thus increased yields of these three crops, a phenomenon often called the CO_2 fertilization or enrichment effect. Carbon dioxide is an indispensable component in the process of photosynthesis. This effect is commonly expected to be stronger for C_3 crops than for C_4 crops.[6] Most crops grown in Pennsylvania and worldwide are C_3 crops. C_3 feed crops include soybeans and different types of hay, among them alfalfa, timothy, tall fescue, orchardgrass, and perennial ryegrass. C_3 food crops include wheat, barley, fruits, vegetables, and potatoes. C_4 crops include corn and sorghum.

In a recent review of the literature on experimental approaches to investigating crop responses to elevated CO_2, Ainsworth and McGrath (2010) find that major C_3 grain crops show an increase in seed yield of approximately 13 percent at 550 ppm atmospheric CO_2, while C_4 crops do not show a significant yield increase at elevated CO_2 levels. They also found that additional crop growth comes at the expense of grain quality: crop growth at elevated CO_2 reduces the protein content of non-leguminous grain crops by 10 to 14 percent and reduces the content of minerals such as iron and zinc by 15 to 30 percent. These represent the effects of elevated atmospheric CO_2 specifically and not the effects of changes in climate in response to elevated CO_2.

There have been a number of studies in recent years that have examined the response of feed crop yields to changes in temperature and precipitation, and our 2009 PCIA discussed some of that literature relevant to Pennsylvania. One study published since our earlier report was completed is Schlenker and Roberts (2009). Their study found that corn yields increase slightly with average temperature during the growing season up to an average of about 29°C (84°F), beyond which yields decline significantly. They found a similar pattern for soybeans, with a threshold of about 30°C (86°F) beyond which yields decline

[5] The top-ten list in order of sales is: 1. Dairy; 2. Poultry and eggs; 3. Cattle and calves; 4. Mushrooms; 5. Other nursery and greenhouse products (aside from mushrooms); 6. Hogs and pigs; 7. Corn; 8. Fruits, tree nuts and berries; 9. Vegetables, melons, potatoes and sweet potatoes; and 10. Soybeans. These ten product categories account for 93 percent of total agricultural product sales in Pennsylvania.

[6] In the first step of photosynthesis, C_3 plants convert the carbon from carbon dioxide into a three-carbon molecule, while C_4 plants convert it into a four-carbon molecule.

with higher temperatures. Average growing season temperatures for corn and soybeans in Pennsylvania are on the order of 20°C (68°F), depending on location, which is well below the thresholds identified by Schlenker and Roberts (2009). The implications of this study are similar to the conclusions reached in the 2009 PCIA: moderate climate change on the order of 1-3°C (1.8-5.4°F) should increase Pennsylvania corn and soybean yields. Greater climate change (5-6°C; 9-11°F) could harm yields in Pennsylvania insofar as it leads to a greater frequency of years in which average growing season temperatures exceed 29-30°C (84-86°F). The projections in Chapter 3 indicate warming of about 2.1-2.6°C (3.8-4.7°F) by middle of the 21st century.

With respect to mushrooms, our 2009 PCIA concluded that the effects of climate change are ambiguous. Mushrooms in Pennsylvania are almost entirely cultivated inside of specialized growing houses under carefully controlled temperature and humidity. As such, the effects of climate change on mushroom production will primarily be manifested in changes in heating and cooling requirements for growing houses. With warmer outside temperatures, there will on average be less heating required during the winter months but additional cooling during the summer months. The net effects on annual energy use and annual production costs are unclear, and we cannot say with any confidence whether they will increase or decrease.

Regarding fruits and vegetables, our 2009 PCIA concluded that yields of cool-temperature adapted crops such as potatoes and apples are likely to decline as a result of climate change, while yields of fruits and vegetables better suited to a warmer climate, such as sweet corn, are likely to rise. Pennsylvania farmers are likely to adapt to climate change by changing the types and varieties of fruits and vegetables grown. Warmer temperatures will permit some of Pennsylvania's food crop producers to grow a wider variety of crops by day length, particularly sweet corn. This will allow sweet corn producers to deliver their product to market earlier in the year, increasing their competitiveness with corn grown in southern states that have traditionally dominated the early summer market for sweet corn.

One area of significant uncertainty discussed in our 2009 PCIA was the effects of higher atmospheric CO_2 concentrations and climate change on plant pests and pathogens, and effects on natural enemies of crop pests such as birds and beneficial insects. It does not appear that research published during the past two years has moved the science very far in the direction of resolving this uncertainty. A review of the literature on crop diseases and climate change by Newton et al. (2011) concluded that complex biological interactions among pests, pathogens, mutualists, and parasites can lead to outcomes that differ from those predicted from the responses of each individual organism to temperature, precipitation, or atmospheric CO_2. A review of the literature on climate change and invasive species (pathogens, insects and weeds) by Ziska et al. (2011) identified a number of research gaps and concluded that the research to date is inadequate to characterize the impacts of climate change on invasive species beyond the micro scale (e.g. beyond the scale of a leaf).

What the recent research on climate change and crop production does not answer is the question of how crop producers in Pennsylvania will fare relative to producers in other states and countries. Moderate climate change on the order of 1-3°C (1.8-5.4°F) may raise Pennsylvania feed crop yields, but it may also raise yields elsewhere in the U.S. and around the world, increasing global production and pushing down prices received by Pennsylvania farmers. Greater climate change could lower Pennsylvania yields of these crops, but it could also lower yields elsewhere, reducing global production and raising prices received by Pennsylvania farmers. In either case, the net effect on Pennsylvania farm revenues for these crops is likely to be ambiguous. Our 2009 economic analysis of climate change impacts in Pennsylvania found that these changes in prices and yields essentially offset each other, with the result that there is very little change in revenues for Pennsylvania grain and oilseed producers.

4.2.2 Climate Change and Livestock Production

Statistics from the *2007 Census of Agriculture* indicate that four livestock products are among the top 10 agricultural product categories in Pennsylvania in terms of sales: dairy, poultry and eggs, cattle and calves, and hogs and pigs. The 2009 PCIA focused on three potential impacts of climate change on Pennsylvania livestock production: [1] heat stress among livestock kept outdoors during much of the year; [2] parasites, pathogens, and disease vectors; and [3] nutritional stress due to changes in forage quality.

Like all warm-blooded animals, livestock require ambient temperatures that allow them to maintain a relatively constant body temperature (Boesch, 2008). If their body temperature moves outside of their normal range, the livestock must expend excess energy to conserve or eliminate heat. This reduces energy that can be devoted to production of products such as milk, bodily growth and reproduction. Heat stress can lead to reduced physical activity, reduced eating or grazing, higher mortality and lower fertility (Nardone et al., 2010). Temperature thresholds vary according to the species and breed of livestock, as well as each individual animal's genetics and health.

In Pennsylvania dairy and cattle production, livestock are often outdoors much of the time. Poultry and eggs in Pennsylvania are mostly produced in large-scale indoor facilities where the birds are kept in close quarters. Housing large numbers of birds with a high metabolism in these conditions makes them vulnerable to heat stress during the summer (Boesch, 2008). Birds can be at least partially protected against heat stress through investments in insulation, ventilation, fans and air conditioning in growing facilities. The existence of large-scale poultry production in southern states such as Alabama, Arkansas, Georgia and Mississippi suggests that these investments can be made at an acceptable cost (i.e., at least with current energy prices). Higher energy prices might alter that calculation. Hogs and pigs in Pennsylvania are typically housed inside of growing facilities, with ventilation and fans used to keep them cool during the summer. The existence of large-scale hog production in southern states such as North Carolina and Oklahoma suggests that Pennsylvania hog production is likely to continue being economically viable in a warmer climate.

Climate change is also likely to impact livestock production through parasites, pathogens and disease vectors (Boesch, 2008). There is likely to be northward migration of livestock pests currently found in southern states and greater overwintering of pests already present in Pennsylvania. High temperatures and moisture can also encourage the growth of mycotoxin-producing fungi, which can cause acute disease episodes among livestock if consumed in sufficient quantities (Nardone et al., 2010). The conclusion is that Pennsylvania livestock producers will face a different set of pest and disease management challenges than they face today.

Research on the effects of changes in temperature and precipitation on forage quality has yielded conflicting results (Craine et al., 2010). Craine et al. (2010) used a long-term, national database of cattle fecal chemical composition to analyze the impacts of temperature and precipitation on crude protein (CP) and digestible organic matter (DOM) in forage crops. For forested regions with a climate similar to Pennsylvania, they find that higher annual temperatures are associated with lower levels of CP and DOM. They do not report impacts of changes in precipitation for these regions.

The 2009 PCIA noted that a wetter climate may lead to higher levels of non-detergent fiber in alfalfa that could reduce the ability of dairy cows to convert feed into milk. On the other hand, longer growing seasons created by warmer temperatures would allow dairy and cattle producers to graze their livestock for more of the year, reducing expenses on purchased feed and the amount of feed crops that need to be grown on the farm.

Like crop production, the recent research on climate change and livestock production does not answer the question of how Pennsylvania livestock producers will fare relative to producers in other states and countries. For products with national and global markets, such as meat and dairy products, changes in production elsewhere will impact prices facing Pennsylvania farmers. If declines in supply from other states and countries cause prices to rise by a sufficiently large amount, Pennsylvania farmers could find it profitable to increase herd sizes and produce more meat and dairy products in spite of declines in livestock productivity. Our 2009 economic analysis of climate change impacts in Pennsylvania found this to be the case for all the livestock products considered in that analysis—beef, dairy, poultry and eggs, and hogs and pigs.

4.3 Adaptation Strategies

As stated in the 2009 PCIA, the existence of a productive and dynamic agriculture in states to the south of Pennsylvania demonstrates that Pennsylvania agriculture can continue to prosper in a warmer climate, but changes will be required. Any producers who fail to adjust to climate change are likely to see their yields and profitability decline.

Alfalfa may decline in importance; if so, farmers will plant other types of hay better suited to a warmer climate. Farmers in South Carolina and Georgia grow various types of hay, such as orchardgrass, bermudagrass and tall fescue. Farmers will need to plant corn and soybean varieties suitable to a warmer environment and better able to withstand a likely increase in the variability of temperature and precipitation. Acreage devoted to cool-temperature fruits and vegetables such as potatoes and apples is likely to decline, while acreage devoted to crops better suited to a warmer climate such as sweet corn is likely to rise. One factor that could limit the decline in acreage devoted to cool-temperature fruits and vegetables is a demand for locally grown foods, if that demand increases significantly in coming decades. For bedding/garden plants and nursery stock, climate change is likely to necessitate changes in the types of species that are grown and sold to consumers. For grapes, Pennsylvania wineries may choose to replace some of their Native American grape varieties with European varieties that do better in a warmer climate.

Producers of dairy products, cattle and calves, and hogs and pigs can adapt to climate change by selecting breeds that are genetically adapted to a warmer climate. However, breeds that are more heat tolerant tend to be less productive (Boesch, 2008). Warming may lead producers who currently keep their livestock outdoors much of the time to move them indoors into climate-controlled facilities, which would increase energy use and costs of production relative to present-day production systems (Boesch, 2008). On the other hand, dairy and beef producers may benefit from a longer grazing season.

An increase in the variability of temperature and precipitation is likely to increase the demand by farmers for risk management products. To the extent that federal funding for crop insurance is restricted due to the federal fiscal situation, Pennsylvania farmers may need to increasingly turn to private crop insurance rather than government insurance programs; or to federal insurance at higher rates than at present if the federal government decides to reduce crop insurance subsidies.

The ability of Pennsylvania agriculture to adapt to climate change hinges in part on the development and adoption of new crop varieties and livestock breeds suited to a warmer and more variable climate. Genetic diversity for response to temperature and water stress has already been identified in the primary gene pools of most major crop species, but there are significant challenges in introducing these genes into the crops grown by farmers (Trethowan et al., 2010). With public funding for agricultural research likely to be constrained in the coming years, the task of developing new varieties and breeds will fall mainly to the private sector. Land grant universities will need to play a major role in graduating scientists who can successfully carry out this research.

4.4 Conclusions

This update is largely consistent with the 2009 PCIA in regards to climate change and Pennsylvania agriculture. The principal differences concern the near-term economic environment between now and 2020 in which changes in climate will occur. We find that there is likely to be a tight market situation for most agricultural products during the current decade in which extreme weather events are likely to lead to greater swings in global agricultural prices than would have been the case 10 or 20 years ago. We also find that conversion of agricultural land to housing and other urban uses in southeastern Pennsylvania (where much of agriculture in the state is concentrated) will be lower between now and 2020 than we anticipated in our 2009 PCIA. In addition, the difficult federal fiscal situation may restrict funding for crop insurance and agricultural research. Should this occur, the private sector will need to play a greater role in insuring against weather risks, and in developing new crop varieties and livestock breeds suited to a changed climate.

The existence of a productive and dynamic agriculture in states to the south of Pennsylvania demonstrates that Pennsylvania agriculture can continue to prosper in a warmer climate, but changes will be required in order to attain productivity in a climate that is new to Pennsylvania. By identifying the key areas that need attention and taking steps today to overcome these obstacles, we can ensure that Pennsylvania agriculture remains vibrant for decades to come.

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5.0 Pennsylvania Climate Change and Water Resources

This section is an update on Chapter 6 of the 2009 ***Pennsylvania Climate Impacts Assessment*** which came to the following conclusions.

1. There is an expected increase of precipitation to fall in liquid rather than snow form. Increased evapotranspiration has been observed and is expected to continue. This has led to a lengthening of the growing season. Studies confirm a slight increase in streamflow and, therefore, runoff. An increase in spring soil moisture is predicted; however, an overall trend towards decreased soil moisture has been observed. On the other hand, groundwater is expected to increase, but not at a rate that will compensate the withdrawal rate. Lastly, stream temperature is projected to increase, which will likely negatively impact aquatic ecosystems.
2. Floods are difficult to predict under climate change scenarios; however, higher snow melt will likely increase winter and spring flooding. Also, Pennsylvania is likely to suffer short-term summer droughts. Decreased streamflow and an increase in stream temperature could lead to a decrease in water quality. Lastly, the Delaware Estuary can expect to face higher salinity due to increasing sea-levels and streamflow changes.

This update on the impacts of climate change on water resources integrates the results of recent studies, and includes some new and improved graphics. A notable integration is of the recent research that has evolved in the area of stream temperature in Pennsylvania. This subsequent literature confirms and builds upon conclusions drawn in the 2009 PCIA.

5.1 Historical Climate and Hydrology of Pennsylvania

Pennsylvania is a temperate region with a river drainage network that is defined by a large number of small perennial streams (Sankarasubramanian & Vogel, 2003; Freeman et al., 2007). Precipitation is distributed relatively uniformly throughout the year with little differences between monthly average amounts. The distribution of temperature, on the other hand, shows a strong seasonal trend with a summer peak. Potential evapotranspiration follows the same distribution. Streamflow distribution throughout the year is related to evapotranspiration amounts and the relative occurrence of precipitation as rain or snow. Spring snowmelt events, in particular rain on snow events, will generally produce the largest streamflow. Precipitation in Pennsylvania predominantly falls as rainfall with snow only accounting for 10 to 25 percent (depending on where in PA) of the total annual precipitation on average. Precipitation itself is also quite variable across the state, but averages slightly over 102 cm (40 in) per year. The part of the precipitation that falls during the growing season is returned almost completely to the atmosphere as evapotranspiration – about 53 cm (21 in) on average. Of the remaining precipitation, about 18 cm (7 in) produce runoff relatively quickly while the rest (33 cm; 13 in) recharges the groundwater. Most of this recharge occurs from rain and melting snow during early spring and late fall when the soil is not frozen and plants are not actively growing (Swistock, 2007). Pennsylvania mainly has perennial streams, which typically receive ⅔ of their flow from groundwater. Groundwater aquifers in Pennsylvania can sometimes be found only a few feet below the surface, but most often are at depths greater than 30 m (100 feet). These aquifers provide a great freshwater resource though the use of this resource (mainly for water supply) has remained relatively constant over the last few decades (Swistock, 2007).

Pennsylvania's climate, and therefore its hydrology, has already seen significant changes over the last century. These changes provide an indication of potential future changes (Table 5.1). The last 100 years have seen an increase in annual temperatures (by over .28 C; 0.5˚ F) and in annual precipitation in most of the state (UCS, 2008). Annual temperatures have risen over the Northeastern U.S. in general (+0.08 ± 0.01˚C/decade; +0.114 ± 0.018 ˚F/decade), especially since about 1970 where rates have been even higher (+0.25 ± 0.01˚C/decade; +0.45 ± 0.018˚F/decade) (Hayhoe et al., 2007; Huntington et al., 2009). Warming was higher during the winter periods, thus leading to a decrease in snow cover and an earlier arrival of spring. Precipitation has also increased over the last century, with additional increases ranging between 5 and 20 percent throughout the state (UCS, 2008). This additional moisture falls in the winter months, while summers have actually seen a slight decrease in precipitation (UCS, 2008). Average annual precipitation increased from 97 to 112 cm (38 to 44 in) throughout the twenty-first century (UCS, 2008). Soil moisture related droughts have also increased due to increased summer temperatures and decreased rainfall. Simulations of the hydrology of the northeastern U.S. over a 50-year period (1950 to 2000) suggest a decline in available soil moisture during the period from June to August over large areas (Sheffield & Wood, 2008). The primary cause of this decline is likely an increase in evapotranspiration during the summer period since rainfall amounts remained relatively stable over the same period. Historically, short-term droughts (lasting one to three months) occurred roughly once every three years over western Pennsylvania and once every two years over eastern Pennsylvania. Medium-term droughts (lasting three to six months) are far less common in Pennsylvania; they have occurred once every ten years in western parts of the state and rarely in most eastern areas. Long-term droughts (lasting more than six months) have occurred on average less than once in 30 years (UCS, 2008). Streamflow has also increased, but to a lesser degree. Milly et al. (2005) calculated that runoff (streamflow) across the northeastern U.S. is expected to have increased between 0 and 5 percent using GCM projections for the 20th century. McCabe and Wolock (2002) found that this increase was mainly in the lower and intermediate flow quantiles for New England and the Mid-Atlantic regions.

Water Resource Change	IPCC examples for North America (AR4)[7]		PA	
1-4 week earlier peak streamflow due to earlier warming-driven snowmelt	↑	U.S. West and U.S. New England regions	↑	Increase in growing season length
Proportion of precipitation falling as snow	↓	U.S. West	↓	Decline
Duration and extend of snow cover	↓	Most of North America	↓	Decline
Annual precipitation	↑	Most of North America	↑	Up in winter months, constant in summer months. Overall increase
Frequency of heavy precipitation events	↑	Most of USA	↑	Increase in heavy precipitation
Streamflow	↑	Most of the Eastern U.S.	↑	Overall increase, but lower in summer and fall
Water temperatures of lakes (0.1-1.5˚C; .18-2.7 ˚F)	↑	Most of North America	↑	Increase
Salinization of coastal surface waters	↑	Florida, Louisiana	↑	Delaware Estuary

[7] The Mid-Atlantic is not part of the New England region. Moreover, the Northeast comprises both the Mid-Atlantic and the New England regions.

Water Resource Change	IPCC examples for North America (AR4)[7]		PA	
Periods of droughts	↑	Western U.S.	↑	Increase of both soil moisture related droughts and decrease in summer / fall low flows

Table 5.1. Observed changes to North American Water Resources during the 20th century Pennsylvania trends are generally typical for the Northern U.S. (Bates et al., 2008, p.102). Note: AR4 refers to the 4th Annual IPCC Assessment.

5.2 Climate Change Implications for the Water Cycle in PA

The complexity of the hydrological cycle with nonlinearities, thresholds and feedbacks makes it hard to model potential future conditions of variables such as soil moisture and streamflow with high reliability. This is particularly true considering the uncertainty already present in the projections of meteorological drivers (i.e. precipitation and temperature). One can probably have high confidence in GCM projections of temperature, moderate confidence in temperature extremes, moderate confidence in precipitation and low confidence in precipitation extremes. This likely translates into moderate confidence in the directional change of hydrological variables and lower confidence in estimates of extreme conditions as discussed in more detail below.

5.2.1 Precipitation – Rainfall and Snow

For Pennsylvania, more than three-quarters of all GCMs analyzed project an increase in precipitation regardless of scenario analyzed (See Chapter 3 in this report and Chapter 5 in the 2009 PCIA). Most of this precipitation increase is projected to occur in the winter months. The uncertainty of precipitation estimates for the summer is likely to be higher as reflected in reduced model consensus during this part of the year. All GCMs analyzed simulate increasing temperatures for Pennsylvania regardless of emission scenario analyzed (See Chapter 3 in this report and Chapter 5 in the 2009 PCIA). Warming projections reach about 4˚C (7.2˚F) for the A2 scenario by the end of the century, while the B1 scenario reaches about half of this value. For Pennsylvania, more than three-quarter of all GCMs analyzed project an increase in precipitation regardless of scenario analyzed. Most of this precipitation increase is projected to occur in the winter months. The uncertainty of precipitation estimates for the summer is likely to be higher as reflected in reduced model consensus during this part of the year. All 21 GCMs analyzed in Chapter 3 of this report simulate increasing temperatures for Pennsylvania regardless of emission scenario analyzed. Warming projections reach about 4˚C (7.2˚F) for the A2 scenario by the end of the century, while the B1 scenario reaches about half of this value. This trend suggests that an increasing fraction of precipitation will fall in liquid form, rather than as snow, which is consistent with historical trends observed over the last 30 years in the region (Huntington et al., 2004). Hydrological modeling studies – necessary due to a lack of historical snow observations – using historical precipitation and temperature data between 1970 and 1999 suggest statistically significant trends for decreasing snow water equivalent (about -3 mm/decade; -.12 in) and for decreasing numbers of snow covered days (about -0.5 days/month/decade) (Hayhoe et al., 2007, Figure 5.1). Snow covered days are defined in Hayhoe et al. (2007) as those days with a snow water equivalent larger than 5 mm (.2 in). Overall, Pennsylvania's precipitation regime is projected to become more extreme, including longer dry periods and greater intensity of precipitation events. Increases in intense precipitation have already been observed for Pennsylvania (Madsen & Figdor 2007). The order of magnitude of change and the direction of change are consistent with other climate change impact studies for the northeastern U.S. (e.g. Hayhoe et al., 2007; UCS, 2008). In general, the confidence in changes to winter climate is higher than the confidence in changes to summer climate.

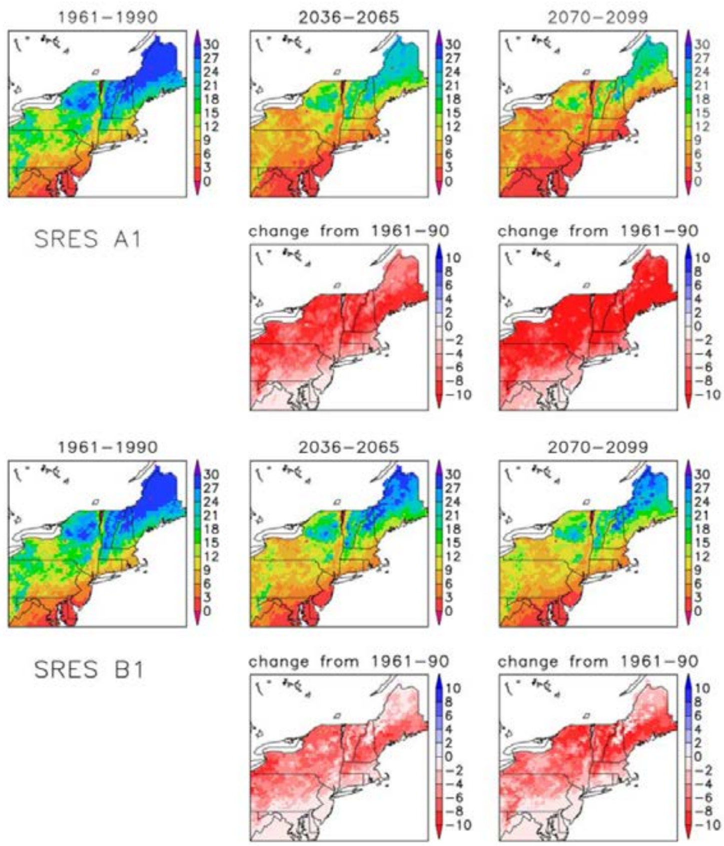

Figure 5.1. Results of HadCM3 and PCM GCM-output driven simulations with the VIC land-surface model. Plots show snow-covered days per month from December to February averaged over 30-year periods. ‘Change’ refers to the difference between the period 1961-1990 and future periods (Hayhoe et al., 2007).

5.2.2 Evapotranspiration

Evapotranspiration is the combined process of evaporation from the soil surface and open water bodies and transpiration from vegetation. The fraction of precipitation that evapotranspires is no longer available as freshwater supply for further use. GCM projections generally suggest an increase in potential evapotranspiration due to increased temperatures throughout the year for both scenarios. Increasing moisture availability, at least in the beginning of the summer, should also lead to increased actual evapotranspiration. Evapotranspiration is generally lower in the winter and is likely to decrease further with a decreasing snow pack and hence reduced sublimation (Hayhoe et al., 2007). The expected lengthening of the growing season (earlier spring and later fall) is likely to result in an additional increase in actual evapotranspiration. Such a lengthening of the growing season has already been observed for the study region and beyond (Christidis et al., 2007).

5.2.3 Streamflow/Runoff

Climate change impact studies performed so far generally suggest a slight increase in runoff across the northeastern U.S. (Milly et al., 2005) across scenarios (Figure 5.2). As a first order estimate of runoff, one can assume that, over a multi-year period, the average runoff is equal to the difference between precipitation and evapotranspiration (assuming no storage change), and thus to the convergence of atmospheric moisture flux (Milly et al., 2005). Sankarasubramanian and Vogel (2003) calculated a precipitation elasticity of streamflow across the northeastern U.S. between 1.5 and 2.5 for most areas based on an analysis of almost 1400 watersheds across the U.S. Elasticity is an index describing the proportional change in streamflow to the proportional change in precipitation. This means that they suggest that for a 1 percent change in precipitation, streamflow will change by 1.5 to 2.5 percent. The non-linearity in this relationship is a function of storage processes within the watershed. The overall increase in precipitation projected is thus likely to result in a slight increase in runoff. Hayhoe et al. (2007) drive a large-scale hydrological model (VIC) with GCM output (precipitation and temperature) for both a historical period (50 years) and for future projections over the northeastern U.S. (see also Figure 5.1). Their results show slight changes in runoff over the historical period, but none of them statistically significant in strength. Future projections show wetter winters and generally warmer temperatures, leading to an overall increase in runoff in the order of 5 percent (Figure 5.2). This runoff increase will likely be in the winter months though, and peak runoff is projected to shift to earlier in the year. While winter months will generally be warmer, frozen ground is still a factor and thus plays a role in increased runoff. Frozen ground prevents infiltration of snowmelt or rainfall, leading to earlier and higher than expected observed spring runoff. Moreover, the snow on top might melt before the soil water does or top soil layers may be warmer than layers also contributing to runoff. For completeness, it should be noted that there is a possibility of increased icing if precipitation freezing on contact with frozen ground (which would decrease winter-runoff/flooding). (Niu & Yang et al., 2006)

Implications of climate change on annual runoff might also be smaller in watersheds that are (or will be) more urbanized (DeWalle et al., 2000). This is because urbanization controls the water balance more than the climate. Hence, climate change has less of an impact in urbanized watersheds. Recent results by Singh et al. (2011) on climate change impact projections across the Eastern U.S. further suggests the streamflow response might be even stronger if it watershed behavior changes are considered under different climatic conditions. Overall, it should be considered that a high degree of uncertainty is still associated with any projections of this kind.

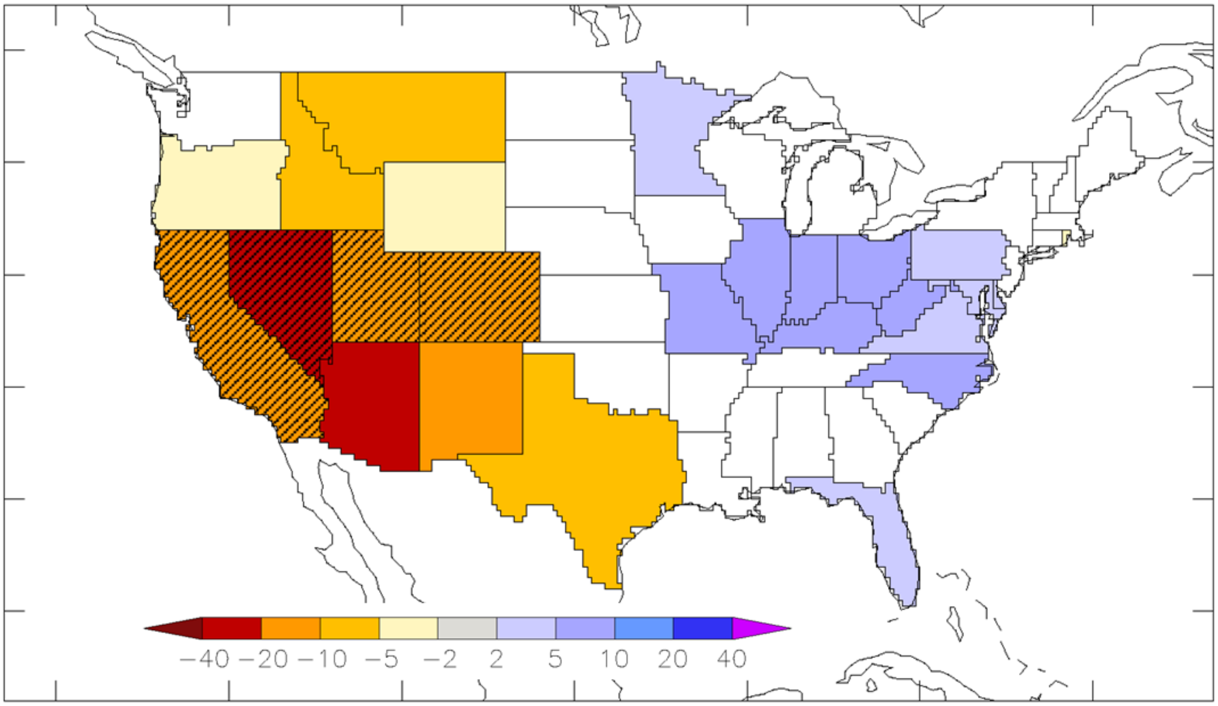

Figure 5.2. Model-projected percentage change in annual runoff for future period, 2041-2060, relative to 1900-1970 baseline (using the A1B scenario projections). Any color indicates that >66 percent of models agree on the sign of change; diagonal hatching indicates >90 percent agreement. (Online supplement to Milly, P.C.D., K.A. Dunne, A.V. Vecchia, Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, 438, 347-350, 2005.)

5.2.4 Soil Moisture

The amount of water in the soil that is available for uptake by vegetation is generally referred to as soil moisture. Hayhoe et al. (2007) suggest a general increase in dry conditions though (with respect to soil moisture) with large spatial variability under future conditions. This drying is mainly caused by increased evapotranspiration due to higher temperatures and decreased summer/early fall precipitation. The study also suggests that spring soil moisture is likely to be much higher (particularly for high emission scenarios) due to higher winter precipitation and earlier snowmelt (Hayhoe et al., 2007). A trend towards decreasing soil moisture in North America has also been shown in a recent study by Sheffield and Wood (2008).

Using a parsimonious soil water balance model developed by and described in detail in Porporato et al. (2004), which represents a stochastic model of the soil moisture dynamics, we can assess the probability distribution of soil moisture under different climatic conditions (Figure 5.3). For typical soil and vegetation characteristics we see that the soil moisture probability density functions (PDF) shift towards drier conditions (to the left) for both the A2 and B1 emission scenarios. A soil moisture value of 1 would mean that the soil is always wet, while a value of 0 indicates that the soil is always dry. The actual modeled values are less reliable than the relative change between time periods and scenarios due to the simplicity of the model used. Differences between the A2 and B1 emissions scenarios are rather small, which is similar to results reported in Boesch (2008) for the state of Maryland. A summer decrease in soil moisture should therefore be considered likely. In how far such drying will result in plant stress will depend, among other things, on the rooting depth of the vegetation. Figure 5.4 shows the variability of the PDF with variation in rooting depth. This result suggests that vegetation with shallow roots will feel more stressed.

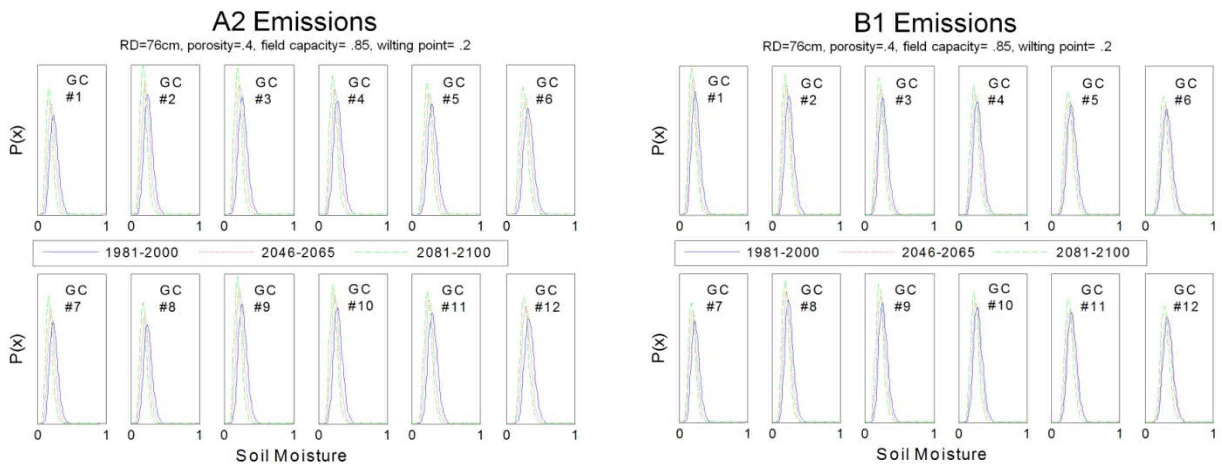

Figure 5.3. Soil moisture probability density functions for different soil and vegetation characteristics (RD: rooting depth) and for different climatic conditions (mainly average temperature, rainfall depth and frequency) during the growing season for control, future 1 and future 2.

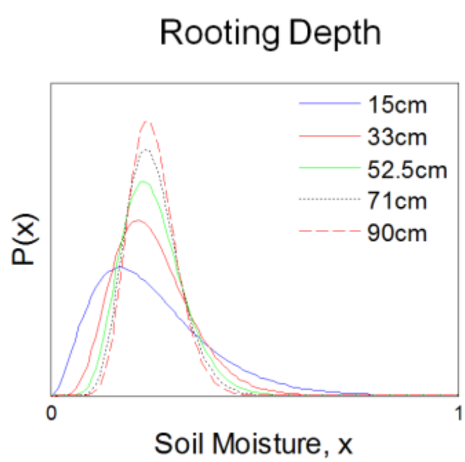

Figure 5.4. Variability of soil moisture probability density functions with variability in rooting depth.

5.2.5 Groundwater

Precipitation that infiltrates into the ground and is not taken up by plants percolates deeper to deeper layers and eventually becomes groundwater. Pennsylvania groundwater characterization is difficult due to the complex geology of the state. Most groundwater, however, is stored in consolidated aquifers that consist of limestone, sandstone, granite or other rock that hold water in interconnected fractures and pore spaces. How much water is contained in an aquifer and how fast it moves depends on the aquifer's specific characteristics. As mentioned earlier, most of the groundwater recharge occurs in the spring, while groundwater levels decline during the remaining year. More than a third of the population of Pennsylvania either uses groundwater from wells and springs as drinking water or for domestic use in general. While higher winter precipitation and warmer temperatures could lead to increased recharge, detailed studies of climate change impacts are not available yet. Any increases in precipitation are unlikely to replace groundwater substantially enough to compensate excessive withdrawals of some aquifers (Boesch, 2008), which means that future population (and thus demand) scenarios are as important for this resource as climate change projections. Moreover, other environmental changes (e.g., increasing urbanization) also have significant impact on groundwater recharge that even exceed the impacts of climate change. Every .4 ha (1 acre) of land that is covered with an impervious surface generates 102 kiloliters (27,000 gallons) of surface runoff instead of groundwater recharge during a one-inch rainstorm (Swistock, 2007).

5.2.6 Stream Temperature

Stream temperature, an important measure of ecosystem health, is expected to be altered by future changes in climate and land use, potentially leading to shifts in habitat distribution for aquatic organisms dependent on particular temperature regimes. The water temperature of streams has important direct and indirect implications for aquatic organisms. Generally, each organism has a particular temperature range, which might change with life stage in which it can survive. In addition, temperature affects water properties (such as dissolved oxygen content and nutrient concentrations) that are important for habitat quality. Stream temperature is strongly correlated with air temperature for many streams unless they receive considerable groundwater influx (Morrill et al., 2005). The relationship between air and stream temperature can thus be used to obtain a first order assessment of the likely implications of air temperature increase for streams. Figure 5.5 shows linear regression relationships between air and stream temperature derived for six streams of different size in Pennsylvania. Stream temperature can be estimated quite well for all but one of the streams (i.e., Big Spring Creek). The water temperature in this spring-fed stream is rather independent of air temperature. In most streams, an increase of 1°C (1.8˚F) in air temperature will lead to about 0.7 to 0.9°C (1.3 to 1.6°F) increase in water temperature. This result is typical for many streams in diverse geographical settings and should be robust even if air-stream temperature relationships can sometimes be slightly non-linear (Morrill et al., 2005). The impact of assuming linearity should be considered minor considering other influences in the data.

To assess the sensitivity of stream temperature to change across Pennsylvania where a temperature shift has the potential to occur, Kelleher et al. (2011) examined the variability of and controls on the direct relationship between air and water temperature across the state. They characterized the relationship between air and stream temperature via linear and nonlinear regression for 57 sites across Pennsylvania at daily and weekly timescales. Both models (linear and nonlinear) showed high performance, with the nonlinear regression performing slightly better. To investigate the mechanisms controlling stream temperature sensitivity to environmental change, “thermal sensitivity,” defined as the sensitivity of stream temperature of a given site to a change in air temperature, was quantified as the slope of the regression line between air and stream temperature. Air temperature accounted for 60-95 percent of the daily variation in stream temperature for sites at or above a Strahler stream order (SO) of 3, with thermal sensitivities ranging from low (0·02) to high (0·93). The sensitivity of stream temperature to air temperature was primarily controlled by stream order (SO) – an indicator of stream size – and baseflow contribution. Together, SO and baseflow index explained 43 percent of the variance in thermal sensitivity across the State (Figure 5.6), and 59 percent within the Susquehanna River Basin. In small streams, baseflow contribution was the major determinant of thermal sensitivity, with increasing baseflow contributions resulting in decreasing sensitivity values (Figure 5.7). In large streams, thermal sensitivity increased with stream size, as a function of accumulated heat throughout the stream network. Riparian buffer plantings that provide stream shading can serve as an effective adaptation strategy to mitigate variation in thermal change, particularly for smaller bodies of water.

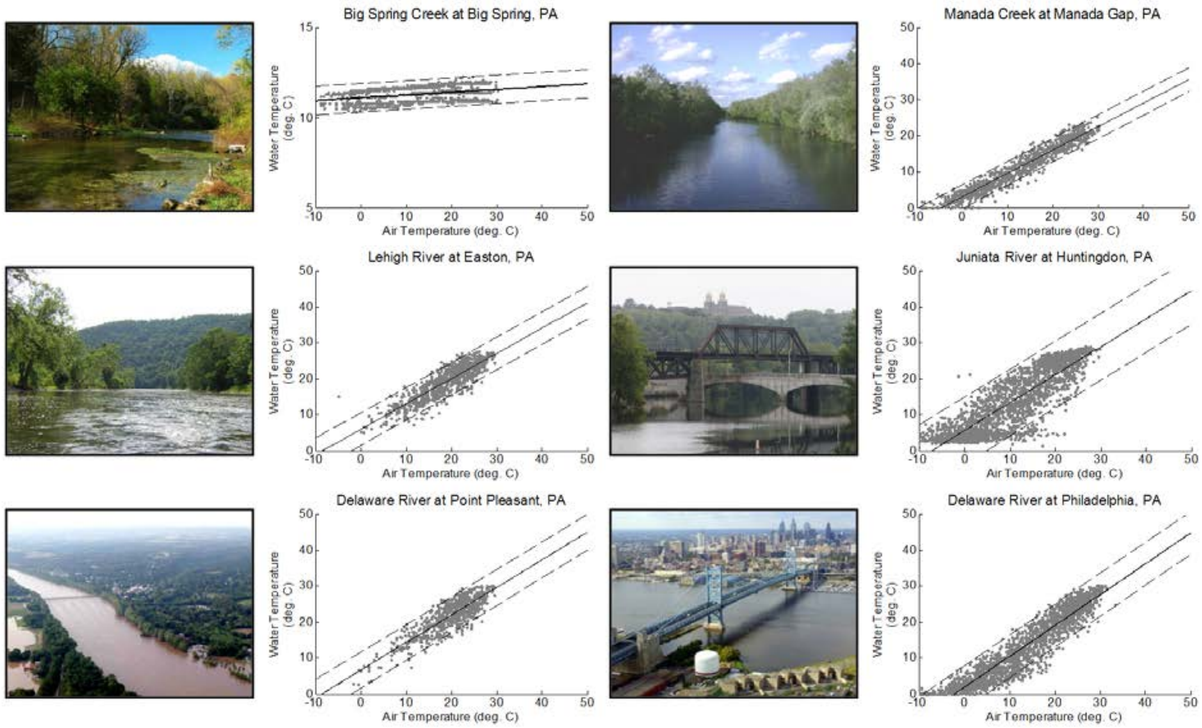

Figure 5.5. Pictures of analyzed rivers and linear regression plots of daily air temperatures versus water temperatures for all six locations. Most streams will see an increase in water temperature with increasing air temperature, though some spring-fed streams might be relatively insensitive to these changes. The combined effect of higher water temperatures and lower summer streamflow is likely to cause problems for aquatic ecosystems and increased competition for freshwater resources. See Appendix 11.1 for further details on this analysis.

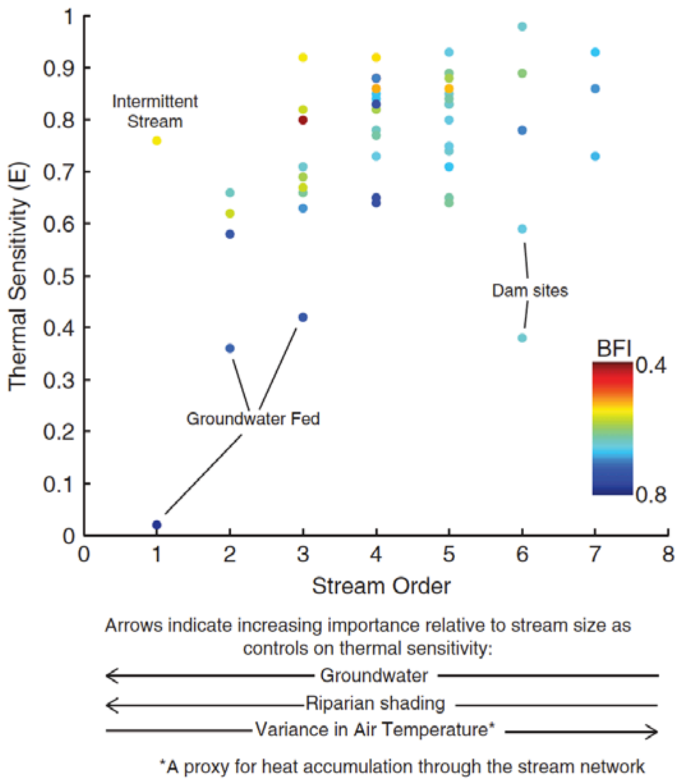

Figure 5.6. Stream order (SO) versus thermal sensitivity, across 57 Pennsylvania streams. Color highlights baseflow contribution, in terms of BFI. Sites where thermal sensitivity is influenced by a unique site condition are noted on the figure. General controls on thermal sensitivity and their influence relative to stream size are conceptualized at the bottom of the figure (Kelleher et al., 2011).

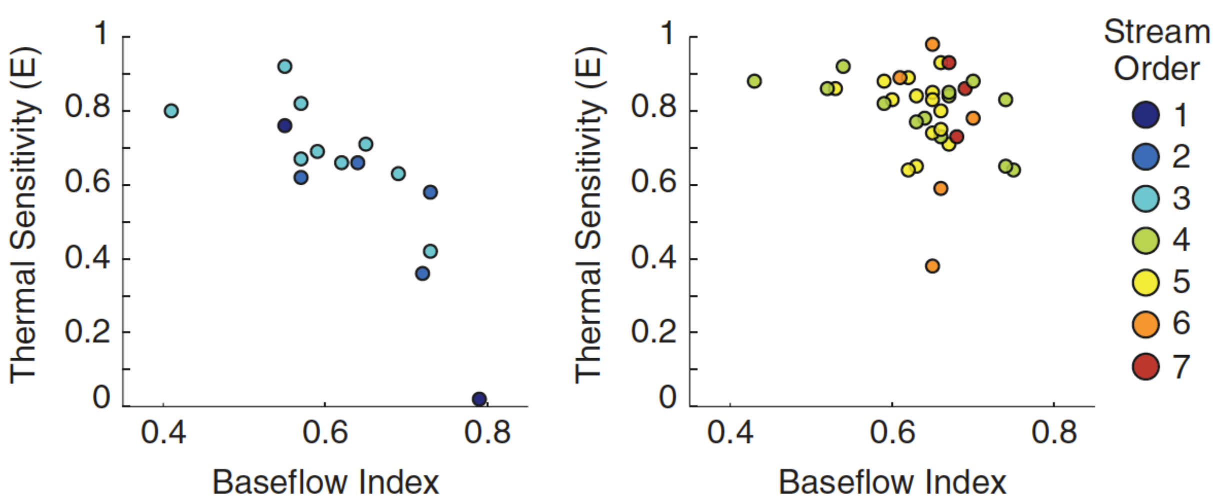

Figure 5.7. Relative influence of BFI on thermal sensitivity in small streams (first through third SO) and in large streams (fourth through seventh SO). (Kelleher et al., 2011)

5.3 Consequences for Pennsylvania Freshwater Services and Disservices

We can define the benefits received by nature (ecosystems) and humans from freshwater resources as services and the negative impacts as disservices (Wagener et al., 2008). This section is based on a mixture of quantitative results and qualitative interpretation of what is currently known or of data that is currently available. Consequently, mitigating factors should be considered before a definitive conclusion is made. Global climate models have particular limitations when it comes to capturing extremes (e.g., in relation to meteorological drivers of floods and droughts) due to their focus on longer term and large scale patterns. At the global scale, a region such as Pennsylvania has to be seen as a low stress region (i.e., based on a ratio of water withdrawals to available water). Potential population increase and urbanization might have impacts on the water cycle that can often exceed the direct impact of climate change, at least in the near future. At the same time, water conservation strategies can significantly reduce water use or maintain constant levels even under growing population (Boesch, 2008).

5.3.1 Floods

Flood events are generally the result of extreme precipitation events. They are as such relatively difficult to predict even under conditions of stationarity of the climatic and the environmental systems. Historically, the frequency of floods with certain magnitudes is typically predicted using statistical hydrology. In this approach, historical records are analyzed to identify a probability distribution that describes the historical occurrence of a flood of a given size. Assuming stationarity, these probability distributions can then be used to calculate design floods. However, the assumption of stationarity is not suitable for climate change impact assessment, and recent papers call for the development of new approaches to replace current techniques (e.g., Milly et al., 2008). Because past analyses of flood frequency were uncertain it is likely that estimates under conditions of climate change are even more unreliable – particularly since precipitation extremes are poorly captured in current GCMs due to the large spatial scales of the grid cells over which they average atmospheric conditions.

Winter floods will likely be impacted by the changes in precipitation type (more rain rather than snow) and by the reduction in snow-cover extent and snow water equivalent. There is a general trend towards higher winter precipitation, which will translate into a tendency for streamflow to be higher in winter and spring. Rain on snow floods can be significant in the Susquehanna River Basin. During such events, large amounts of snow melt quickly during a precipitation event potentially resulting in extreme flood events. The Susquehanna River Basin witnessed an extreme of this flood type in January 1996. The projected reduction in snow pack might lead to a reduction of flood events of this type. Conversely, peak flooding is likely to increase in urban environments due to an increase in impervious areas and higher rainfall variability. A flashier runoff regime and increasing water temperature will likely have negative implications for aquatic ecosystems (Boesch, 2008).

A more detailed investigation of potential future flooding in the Susquehanna River Basin is crucial since it represents one of the most flood prone areas in the whole U.S., experiencing a major devastating flood on average every 14 years (SRBC, 2006). The effectiveness of adaptation measures that reduce the fast runoff response, such as artificial infiltration areas or pervious pavements, has to be investigated.

5.3.2 Droughts

Drought can be defined differently depending on its length and depending on the hydrological variables impacted (Figure 5.8). A meteorological drought is mainly based on lack of precipitation and is generally very short in duration (NWS, 2006). An agricultural drought relates mainly to a deficit in soil moisture with subsequent plant water stress and potential reduction in biomass production (NWS, 2006) – most climate change impact studies for the northeastern U.S. have focused on this kind of drought. Droughts resulting from the longer-term consequences of lack of precipitation and increased evapotranspiration are generally referred to as hydrological droughts. They manifest themselves in reduced streamflow, lower reservoir and lake levels as well as lower groundwater levels (NWS, 2006). As discussed above, increased summer temperatures will likely shift soil moisture distributions to drier regimes, thus increasing plant stress and potentially decreasing plant productivity. The strength of the impact will differ with plant rooting depth and thus moisture availability for individual plants. Pennsylvania will likely see an increased frequency of short-term droughts while the overall annual runoff increases slightly. Lower summer and fall streamflow could provide problems through competing uses, (e.g. power plant cooling versus environmental flows) due to a combination with increased streamflow temperatures (see 5.3.3. Water Quality of this Update). The largest drought on record in Pennsylvania occurred during the period from 1962 to 1965 and will likely remain an extreme event despite increases in future summer air temperatures (Hayhoe et al., 2007). This drought was the consequence of an extended period of low precipitation (Namias, 1966).

At the same time that summer flows might be lower, winter precipitation will likely increase, which could result in fuller freshwater reservoirs at the beginning of the summer and thus allow for an opportunity to reduce any impasses through adjusted water management. Water-supply drought is more heavily affected by periods of low precipitation extending over multiple months, and is most strongly correlated with dry periods persisting through winter and spring when soil moisture, water tables, and reservoir levels would normally experience recharge (Boesch, 2008).

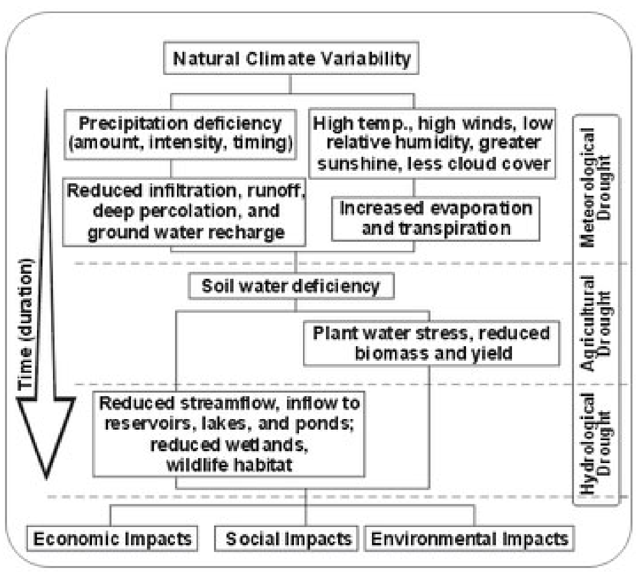

Figure 5.8. Flow chart visualizing the differences between meteorological, agricultural and hydrological droughts (National Drought Mitigation Center, http://www.drought.unl.edu/whatis/concept.htm, Accessed February 2009).

5.3.3 Water Quality

Increased variability in streamflow is likely to occur, which means that there will be a tendency for higher winter and spring flows but lower summer and fall flows. Figure 5.5 suggests that many freshwater streams are well mixed and that their temperature will respond quickly to increasing atmospheric temperatures. Low flows and higher water temperatures are likely to decrease the habitat suitability for aquatic biota since it will lead to a decrease in dissolved oxygen content. Increases to variability of flow, changes to the timing of peak spring flow and changing water temperature will likely negatively impact aquatic ecosystems. Lower summer stream flows could also lead to the loss of small wetlands, thus further impacting water quality throughout the river network negatively. Degraded streams and flashier runoff would further increase water quality impairments in the Chesapeake Bay due to flushing of nutrients and sediments into the estuary (Boesch, 2008).

5.3.4 Salt Water Intrusion in the Delaware Estuary

When one thinks of Pennsylvania, the ocean does not usually come to mind. However, Pennsylvania's connection to the sea, the Delaware Estuary, is one of the state's most valuable economic and ecological resources. The estuary is home to the largest freshwater port in the world, generating $19 billion annually and receiving 70 percent of the oil shipped to the U.S. East Coast. The combined river and estuary system provides drinking water to 15 million people (including many Pennsylvanians), is a source of water for industrial processes, and receives wastes from municipal and industrial wastewater treatment plants. The estuary also supports the largest horseshoe crab population in the world and is one of the world's most important sites for shorebird migration.

Climate change has the potential of altering estuaries through changes in temperature, winds, streamflow, and sea level, which will affect numerous estuarine characteristics, such as circulation, water quality, and ecology. Salinity is an important defining characteristic of the Delaware estuary, regulating floral and faunal distributions and affecting human use of the estuary. A major objective of the Delaware River Basin Commission (DRBC) is to regulate streamflow through the use of reservoirs so as to keep water supplies safe for human consumption and industrial uses. The DRBC attempts to keep potable supplies at sodium concentrations less than 50 ppm, the New Jersey drinking water standard. However, the American Heart Association (AHA) recommends sodium levels less than 20 ppm. The EPA chloride recommended standard is 250 ppm for drinking water and is also the concentration at which water begins to taste salty (EPA, 2012). DRBC salinity controls are also in place to protect groundwater, which is fed in part from the estuary. It has been determined that a chloride concentration at Philadelphia less than 180 ppm will keep well waters potable (Hull et al., 1986).

There is strong evidence that past climate-induced changes in bay salinity have had negative impacts on water supply systems. The drought of 1930 resulted in Delaware River chloride concentrations as high as 500 ppm in Philadelphia, and exceeding 1000 ppm in Chester, Pa. (Mason & Pietsch, 1940). In 1951, Chester changed its water source from the Delaware River to the Susquehanna River Basin because of increases in salinity; it has been suggested that these were caused by sea-level rise (Parker, 1964) and low streamflow (Hull et al., 1986). In 1964, drought conditions resulted in chloride concentrations of 250 ppm in Philadelphia, an emergency declaration by the DRBC, and economic damages (Hull et al., 1986).

Sodium and chloride levels of the Delaware River at Philadelphia have steadily increased from the early 20th century to the present day (Philadelphia Water Department, 2007), likely from changes in land use in the watershed, increased wastewater discharges, but also possibly from the increase in sea level of approximately 0.28 m (1 foot) (Zervas, 2001) that occurred during this time. Current (2003-2005) mean levels of chloride and sodium are 23 ppm and 15 ppm respectively, and extrapolation of recent trends suggests that the mean sodium level will exceed the AHA criterion in 100 years.

Sea level is very likely to keep increasing throughout the 21st Century, which will increase trends of sodium and chloride in the Delaware River and Estuary. Rahmstorf (2007) estimated that global mean sea level will rise by 0.5 to 1.4 m (1.6 to 4.6 feet)by the end of this century, where the range expresses uncertainty in the particular CO_2 emissions scenario and in the response of the climate to CO_2. For the Delaware Estuary, these projections need to be increased to account for local impacts on the relative position of the land and the sea, including land subsidence due to geological processes. Global mean sea level rose at a rate of approximately 1.8 mm per year (0.07 in) during the second half of the 20th Century per year (Hull et al., 1986). At the two locations in the Delaware Bay sampled during this time, Philadelphia, PA and Lewes, DE, sea-level rise was 2.74 ± 0.35 mm per year (.11 ±.01 in) and 3.04 ± 0.29 mm per year (.12 ±.01 in), indicating a local component of sea-level rise of about 1 mm/year (.04 in). Thus sea-level projections for the Delaware estuary should be increased above the global average to 0.6 to 1.5 m (1.9 to 4.9 feet) by the end of this century.

Three modeling studies have been conducted to assess the potential impact of sea-level rise on the Delaware Estuary. Hull and Tortoriello (1979) used a 1-D model to investigate the impact of a 0.13 m (5.12 in) rise in sea level. They ran the model for conditions experienced during the 1964-1965 drought and found that the sea-level increase resulted in a 5-140 ppm (10-21 percent) increase in chloride concentration between river kilometers 129 and 185 (river miles 80 and 115). At Philadelphia's Torresdale water intake (River Mile 110), the chloride increase was 4 ppm. The U.S. Army Corps of Engineers (1997) conducted simulations using a 3-D model and found a 20-ppm chloride increase at River Mile 98 (River km 158) for a sea-level increase of 0.3 m (1 foot). Kim and Johnson (2007) used an updated version of this model to evaluate the impact of a 0.16 m (6.3 in) increase in sea level, finding a chloride increase of 7 ppm (10 percent) at the Ben Franklin Bridge. These studies collectively suggest that, in the vicinity of Philadelphia, chloride increases roughly 3 to 6 ppm for every 0.1 m (4 in) of sea level increase. Thus, sea level projections of 0.6 to 1.5 m (2 to 5 ft) to by the end of this century imply chloride increases of 18 to 90 ppm—anywhere from a doubling to a quadrupling of current chloride levels.

In addition to sea-level rise, salinity of the upper Delaware Estuary is likely to change as a result of climate-induced changes in streamflow. However, the projected change in annual streamflow is uncertain. Nonetheless, streamflow variability is expected to increase, so even though quantitative projections are not possible at this time, it seems likely that drought-induced saltwater intrusion events will increase throughout the 21st century.

5.4 Adaptation Strategies

Any climate change policy must consider some degree of adaptation because – even under the most optimistic emission scenario – we expect some degree of climate change, the consequences of which can already be felt in many regions. Following the IPPC, adaptation can be defined as initiatives and measures to reduce the vulnerability of natural and human systems against actual and expected climate change effects. A wide range of options for adaption exist and some of the more common ones are listed in Table 5.2. Adaptation strategies for water management under potential climate change have to be developed while considering scenarios for future regional population and economic development. As discussed at multiple places within this chapter, population growth, urbanization and other land cover change, and pollution of water bodies could be equal or even more important stressors than climate change at least in the near future. A holistic approach to developing adaptation strategies will be required, while the existing uncertainty in current projections of climate change impacts suggests that "no regret" strategies might be the best option for now. Strategies are classified as "no regret" if they lead to societal benefits regardless of the degree of climate change. Examples of such strategies include water conservation and better monitoring of hydrological and other environmental variables.

Water-use sector	Supply-side measure	Demand side-measure
Municipal water supply	Increase reservoir capacity Extract more water from rivers and groundwater Alter system operating rules Inter-basin water transfer Capture more rain water Desalination Seasonal forecasting	Incentives to use less (e.g. through pricing or rebates) Legally enforced water use standards (e.g. for appliances) Increase use of grey water Reduce leakage Increase use of recycled water Development of non-water-based sanitation systems
Irrigation	Increase irrigation source capacity	Increase irrigation-use efficiency Increase use of drought tolerant plants Alter cropping patterns
Industrial and power station cooling	Increase source capacity use of low-grade water	Increase water-use efficiency and water recycling
Hydropower generation	Increase reservoir capacity	Increase efficiency of turbines, encourage energy efficiency
Navigation	Build weirs and locks	Alter ship size and frequency
Pollution control	Enhance treatment works	Reduce volume of effluents to treat (e.g. by charging for discharges) Watershed management to reduce polluting runoff
Flood management	Increase flood protection (levees, reservoirs) Watershed source control to reduce peak discharges	Improve flood warning and dissemination Curb floodplain development

Table 5.2. List of examples for supply- and demand-side adaptation strategies. (Cooley, 2009)

5.5 Barriers and Opportunities

Main barriers to understanding the potential implications of climate change on Pennsylvania freshwater are mainly twofold: [1] insufficient monitoring of hydrological variables, and [2] lack of state-wide modeling studies to interpret past observations and future projections of climate. Both aspects will be discussed in more detail below.

Any scientifically valid assessment of current and past conditions of the water cycle in Pennsylvania has to be based on observations of the main hydrological variables (streamflow, soil moisture, snow water equivalent, groundwater, water quality) and their meteorological drivers. The river networks of many drainage basins in the eastern U.S. (including Pennsylvania) are characterized by a large fraction of small (low order) streams. It is increasingly recognized that these headwater streams often control water quantity and quality through much of the river network. However, continuous streamflow gauging stations are heavily biased towards larger streams, meaning that for much of the basin we only have observations of the large-scale integrated streamflow response. This issue limits our ability to provide reliable benchmarks of past and current hydrological conditions in most headwater streams. This problem is exacerbated by a lack of soil moisture and snow measurements as well as a lack of coordinated assessments of large scale groundwater dynamics. The monitoring of hydrological variables has to go hand in hand with observations of changes to land cover and population size. The former is important since changes to land cover, (in particular, the extension of impervious areas), is likely to have significant impacts on water flow paths. Population size and residential water use behavior are likely to impact water demand, an important stress on current and future freshwater resources that should be monitored.

The lack of appropriate spatially-distributed data means that hydrological models have to be used to extrapolate hydrological characteristics in space and time. Scientific studies of past and future hydrologic conditions across the state have so far been limited to snapshots often using the output of only a few GCMs, aggregating over large areas, or not providing estimates of confidence in the streamflow (or other) simulations provided. Continuous advancement in watershed-scale hydrologic models and increasing availability of high-performance computing continuously reduces these limitations though. Another barrier related to the use of hydrological models, currently of great interest to the research community, lies in the problem that the hydrological system itself is not stationary. For example, changes in climatic conditions such as temperature and frequency of rainfall impact vegetation and soil characteristics, which in turn alter hydrological flow paths. These changes are often gradual and the evolution of the hydrological system has thus far been ignored, thus assuming that non-stationarity only occurs in the boundary conditions, i.e. the climate. New approaches to include the evolution of the hydrological system itself in our models have to be developed to address this issue.

The redistribution of freshwater resources due to a change in winter precipitation and due to a general warming trend in Pennsylvania might provide opportunities for improved water management strategies (see Table 5.2). Increased availability of precipitation in liquid form during winter and spring months might enable improved groundwater recharge (naturally or artificial) and increased storage of water in reservoirs or the sub-surface to support summer water demands. These water management strategies will in particular have to consider competing summer demands under climate, population and economic change scenarios while considering environmental constraints.

5.6 Information Needs

Information needs are strongly connected to the barriers discussed in the previous section. Improved monitoring and more detailed modeling studies are essential to overcome said barriers. Improved monitoring is necessary to enable better quantification of magnitude and trends in major hydrological variables. In particular the lack of continuous snow and soil moisture measurements limit the direct assessment of climate change impacts and the evaluation of hydrological models. In addition to hydrological variables it is crucial to understand water demand patterns and trends across the state, both agricultural and municipal industrial. The latter is needed since human imposed stresses on

Pennsylvania's freshwater resources are likely to be very important to understand overall water cycle dynamics. The value of some historical data to support the assessment of potential future conditions (using for example statistical analyses) is likely to decrease, though trends in the data might be very important. Statistical approaches – often the basis of current water resources engineering – will have to be replaced with new model-based strategies that allow for the inclusion of the non-stationarity of the system. Regional models have to be implemented and tested to interpret trends in historical hydrological data and to extrapolate hydrologic conditions in space and time. Such modeling studies need to be performed especially to provide better information regarding potential future flooding (rain on snow) and recharge to groundwater. Current studies are generally too coarse in their spatial and temporal resolution. Information about the uncertainty in climate change projections needs to be included in these modeling studies and these uncertainties have to be propagated into ecological and water resources endpoints (e.g. flood frequencies or water temperature ranges).

5.7 Conclusions

Management of Pennsylvania freshwater resources requires a balance between the competing societal and environmental needs placed on the basin's freshwater resources. Humans and ecosystems are embedded in the watershed systems, which exhibit a wide range of characteristics depending on their location and their degree of human activity. Watersheds internal heterogeneity means that we are dealing with complex and uncertain systems. An important task is to support the development of sustainable integrated resource management strategies through environmental models, which enable U.S. to understand these complex systems and to predict their response to future environmental change. This predictive capability is necessary to achieve water security for people (both current and future generations) and the environment in an increasingly non-stationary world (Falkenmark, 2001; Milly et al., 2002; 2005), for which water security can be defined as protection from both water excess and water scarcity (Gleick, 2002). Models of water-driven environmental systems play an important role in understanding human and climate impacts. There is a growing recognition within the scientific community (Reed et al., 2006; National Research Council, 2008; Wagener, 2007) that the management of large scale water resources under uncertainty requires community level advances for developing and evaluating predictive models as well as new frameworks for using these models to enhance monitoring systems. As noted by Dooge (1986) our ability to understand, predict and manage hydrologic systems is dependent on our ability to characterize both the natural and human systems that shape their evolution. The relative uncertainty of these projections in regards to both the results presented in this chapter and to climate change impacts should be noted. Our ability to make such projections at higher spatial and temporal resolutions should not be mistaken for a reduction in uncertainty. It is important to keep this in mind when using the results for actual decision-making. Estimating the uncertainty in projections at decision-making scales is an open research question.

This chapter discussed the current understanding regarding the implications of climate change on Pennsylvania water resources. Throughout this discussion, it is imperative to stress that the IPCC scenarios present potential futures of our world—none of which may actually occur, though all are possible. The process of assessing the implications of these scenarios, through global climate models and local hydrological models of varying complexity, contains uncertainties that have thus far not been quantified. The confidence with which we can make statements about prospective impacts therefore differ for the various elements of the water cycle. Table 5.3 summarizes the main conclusions of this section and also provides a statement of confidence associated with each property.

Property	21^{st} Century Projection
Precipitation	Increase in winter precipitation. Small to no increase in summer precipitation. Potential increase in heavy precipitation events [High confidence for winter, lower for summer]
Snow pack	Substantial decrease in snow cover extend and duration [High confidence]
Runoff	Overall increase, but mainly due to higher winter runoff. Decrease in summer runoff due to higher evapotranspiration [moderate confidence]
Soil moisture	Decrease in summer and fall soil moisture. Increased frequency of short and medium term soil moisture droughts [Moderate confidence]
Evapotranspiration	Increase in temperature throughout the year. Increase in actual evapotranspiration during spring, summer and fall [High confidence]
Groundwater	Potential increase in recharge due to reduced frozen soil and higher winter precipitation when plants are not active and evapotranspiration is low [Moderate confidence]
Stream temperature	Increase in stream temperature for most streams likely. Some spring fed headwater streams less affected [High confidence]
Floods	Potential decrease of rain on snow events, but more summer floods and higher flow variability [Moderate confidence]
Droughts	Increase in soil moisture drought frequency [Moderate confidence]
Water quality	Flashier runoff, urbanization and increasing water temperatures might negatively impact water quality [Moderate confidence]
Salt water intrusion	Increase in salt water intrusion (in estuaries) due to rising sea levels [Moderate confidence]

Table 5.3. Summary of general projections for Pennsylvania water resources.

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6.0 Aquatic Ecosystems and Fisheries

This section updates Chapter 8 of the 2009 ***Pennsylvania Climate Impacts Assessment***, which focused on climate change's impact on ecosystems. The 2009 PCIA came to the following conclusions:

1. Wetlands represent an important ecological part of Pennsylvania's resources and their numbers are depleting and their depletion can be attributed to direct human intervention. However, measuring individual negative impacts are difficult due to the number and complexity of factors affecting wetland survival.
2. The case study for Little Juniata under climate change conditions forecasted decreased water levels, rising (near head water streams) and lowering (throughout the watershed) of the water table, and increased discharge throughout the basin. Because of the lack of research and complexity, it's difficult to predict with high certainty the exact overall effect of these combined conditions. However, individually these impacts (with the exception of rising water tables near head water streams) are expected to have negative consequences, which were discussed in the 2009 PCIA.

Overall, the same conclusions are reached in this update and the 2009 PCIA. This update focuses on expanding the case study for Little Juniata by comparing climate changes impacts to the Little Juniata to Young Woman's Creek. After looking at (past and future) stream flow and groundwater levels for these areas, negative effects were found for both watersheds. These include: increased erosion, loss of native habit (e.g., eastern brook trout), and an increase in invasive species.

6.1 Pennsylvania's Aquatic Resources

Pennsylvania's aquatic resources are primarily freshwater, which represent a significant natural resource. While inventory accounts do not precisely agree, the Pennsylvania State Water Plan (2009) presents the following census:

- *About 138,000 kilometers (86,000 miles) of streams;*
- *Nearly 4000 lakes, reservoirs and ponds;*
- *About 303 trillion liters (80 trillion gallons) of groundwater;*
- *Over 163,000 hectares (404,000 acres) of wetlands;*
- *90 kilometers (56 miles) of coast along the Delaware Estuary and 103 kilometers (64 miles) along Lake Erie.*

While lakes and coastlines present significant and important habitat resources, this discussion will cover the signature resources of the commonwealth (e.g., streams and wetlands). These resources are intertwined and dependent upon one another for ecological integrity. For example, the trout population of a headwater stream is dependent upon wetland habitat along its edge. For that reason, this discussion is based on: the impacts of climate change on wetlands and headwater streams as a riparian ecosystem, and as representative of the majority of the aquatic ecosystems of the commonwealth.

Pennsylvania's streams and rivers are classified into 124,181 segments by Pennsylvania Department of Environmental Protection and Department of Transportation (data from PASDA) and are second only to Alaska in total stream kilometers in any state. The largest area of stream kilometers can be found in the Ridge and Valley eco-region (34,770 km; 21,605 miles), Allegheny High Plateau eco-region (26,596 km;

16,526 miles) and Pittsburgh Low Plateau (23,477 km; 14,588 miles), as reported by the Department of Conservation and Natural Resources (http://www.dcnr.state.pa.U.S./wlhabitat/aquatic/streams.aspx).

Nationally, the United States has destroyed over half of its original wetlands throughout the past 200 years, leaving approximately 40 million hectares (100 million acres), while Pennsylvania has lost an estimated two-thirds hectares of its original wetland area. Estimates of the total amount of current wetland area in the commonwealth vary, and are due either to the inclusion of lakes, ponds, and estuarine habitat under the definition of wetlands, or their placement in a separate category. The National Wetland Inventory data, as reported by the Pennsylvania Game Commission, includes this aquatic habitat under the definition of wetland, and reports a total of 295,232 wetland hectares (729,535 acres) found in more than 160,000 wetlands across the state (http://www.pgc.state.pa.U.S.). These occur in two major categories: [1] a total of 59,414 hectares (146,816 acres) are defined as lacustrine (lakes and ponds primarily), [2] and 165924 hectares (410,009 acres) are defined as palustrine habitat (marshes, etc.). An additional 260 hectares (643 acres) of estuarine habitat are located in the southeastern region along the Delaware River. Most of Pennsylvania's wetlands (97 percent) are palustrine (bogs, fens, swamps, shallow pools). Emergent wetlands (marshes, meadows) and shrub swamps comprise 10-20 percent of state wetlands. Generally, natural wetlands are concentrated in northeast and northwestern counties, with more than 50 percent of the wetlands in the state occurring in these areas (Tiner, 1990).

6.2 Definition and Description of Ecosystem Services

Wetlands and streams are diverse and productive, and provide a number of tangible and intangible benefits to society and the environment. These goods and services have recently been termed "ecosystem services," and the realization that they are critical for human health and well-being (Millennium Ecosystem Assessment, 2005) has heightened the need for assessments that can estimate the level of service provided, detect the impact of human activities (including climate change) on these ecosystem services, and guide U.S. to restoration of these services (Zedler, 2003). The MEA defines four types of ecosystem services: regulating, provisioning, cultural and supporting. These are provided by, or derived from, wetlands and headwater streams (Table 6.1). Many of the ecosystem services most highly valued by society are regulating services, including water quality improvement and flood control, and provisioning services such as production of fish and game are also valuable and are more commonly recognized as "habitat." The freshwater wetlands of Pennsylvania represent critical areas of aquatic ecosystem function, serving as nursery areas, sources of dissolved organic carbon, critical habitat, and stabilizers of available nitrogen, atmospheric sulfur, carbon dioxide and methane (Mitsch and Gosselink, 2000).

Ecosystem Services Provided by or Derived from Wetlands	
Services	**Comments and Examples**
Provisioning	
Food	production of fish, wild game, fruits, and grains
Fresh water[a]	storage and retention of water for domestic, industrial, and agricultural use
Fiber and fuel	production of logs, fuelwood, peat, fodder
Biochemical	extraction of medicines and other materials from biota
Genetic materials	genes for resistance to plant pathogens, ornamental species, and so on
Regulating	
Climate regulation	source of and sink for greenhouse gases; influence local and regional temperature, precipitation, and other climatic processes
Water regulation (hydrological flows)	groundwater recharge/discharge
Water purification and waste treatment	retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	retention of soils and sediments
Natural hazard regulation	flood control, storm protection
Pollination	habitat for pollinators
Cultural	
Spiritual and inspirational	source of inspiration; many religions attach spiritual and religious values to aspects of wetland ecosystems
Recreational	opportunities for recreational activities
Aesthetic	many people find beauty or aesthetic value in aspects of wetland ecosystems
Educational	opportunities for formal and informal education and training
Supporting	
Soil formation	sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients

[a] While fresh water was treated as a provisioning service within the MA, it is also regarded as a regulating service by various sectors.

Source: Ecosystems and human well-being: Wetlands and water – Millennium Ecosystem Assessment / p2

Table 6.1. Ecosystem services provided by wetlands, as per the Millennium Ecosystem Assessment

Pennsylvania's streams provide productive and diverse habitats for fish, shellfish and other wildlife. For instance, upstream freshwater reaches provide critical habitat for eastern brook trout and other resident species, and downstream reaches provide spawning and nursery habitats for migratory fish species such as alewife, Atlantic sturgeon, and the federally endangered short-nose sturgeon. Wetlands also are spawning and nursery grounds for fish. In fact, most freshwater fish feed in wetlands or upon food produced in wetlands. Pennsylvania wetland habitat statistics for other types of are wildlife significant; 84 percent (32 of the 38 amphibian species) find a home in wetlands the majority of the time. 25 percent (11 of the 41 reptile species) spend nearly 99 percent of their life in wetlands. Approximately 122 species of shore and wading birds, waterfowl and some songbirds perform most of their activities in, on or around water.

While stream ecosystem services (primarily "regulating and supporting") have been described on a regional basis (e.g., Roth et al., 2004; U.S. Environmental Protection Agency 2006), the same is not true for wetlands. For example, in the Mid-Atlantic, wetland functional assessments have generally been limited to specific functions and/or a limited number of sites. Habitat functions in wetlands have been described in West Virginia for amphibians and macroinvertebrates (Snyder et al., 2006; Balcombe et al., 2005a, Balcombe et al., 2005b), southeastern Virginia for bog turtles (Carter et al., 1999), and West Virginia and North Carolina for vascular flora (Warren et al., 2004; Rossell & Kesgen 2004). Hydrologic functions are even more rarely described (Moorhead, 2001), but the high level of resources necessary to perform studies of this magnitude make them rare. In addition, characterization of specific ecosystem services (or functions) provided by wetlands has only recently advanced to large-scale surveys (for a review, see Kentula, 2007).

While all wetland types serve valuable roles, headwater wetland and stream systems may contribute a disproportionate share to watershed functioning and the larger drainage areas and regional watersheds into which they drain. Brinson (1993) described how headwater streams tend to set the biogeochemical state of downstream river networks. These low-order headwater streams account for 60-to-75 percent of the nation's total stream and river lengths, making their riparian communities extremely important for overall water quality (Leopold et al., 1964). Lowrance et al. (1997) emphasized the importance of riparian ecosystems along first-, second-, and third-order streams for nutrient abatement, pollution reduction of overland flow, and other ecosystem-level processes in the Bay watershed.

In these systems, the connectivity of the floodplain to the adjacent stream is especially important to the functioning of both communities and all associated downstream systems. Natural patterns of channel and floodplain connectivity sustain resident biota and ecosystem processes such as organic matter accumulation, decomposition, and nutrient cycling (Bayley, 1995; Sheldon et al., 2002). This lateral and longitudinal connectivity is extremely important for the maintenance of viable populations of aquatic organisms in headwater streams. The loss of stream connectivity to the floodplain can lead to the isolation of populations, failed recruitment and even local extinctions (Bunn & Arthington 2002).

While the ecosystems services that are potentially derived directly from wetlands in good condition are obvious, it is important to note that wetlands form the ecotone and interface between human activities in uplands and the streams and rivers of large watersheds, resulting in important indirect services. Due to this unique landscape position, pollutants and fertilizers from managed portions of the landscape accumulate in these systems, impacting and often impairing their condition, and preventing them from functioning at their highest possible level; this has implications for the condition of streams and rivers. Direct modification of wetlands and streams also occur frequently in the context of agriculture or development, altering habitat structure. Direct appropriation of freshwater for human consumption or agriculture displaces the water on which these systems depend; this is likely to become a larger problem as populations increase (Postel, 2000; Vörösmarty et al., 2000). Current and future activity associated with the extraction of natural gas from shales will place additional demand on freshwater, from both surface and groundwater sources. While the full extent of potential activity is yet to be confidently estimated, the Susquehanna River Basin Commission has estimated an additional consumptive water usage in the Basin to be 106 mld (28 mgd) on an annualized basis (SRBC, 2009). This equates to a 19 percent increase in demand attributable to the energy sector. Also, it should be noted that the Susquehanna Basin drains 71,250 km^2 (27,510 mi^2), which covers half the land area of the Commonwealth. SRBC is partnering with state and federal environmental resource agencies, the USACE and the Nature Conservancy to develop flow management recommendations. Unlike regulatory flow thresholds in past policies, the collaboratively recommended flows will offer protection of critical aquatic life and habitat conditions, and have seasonal and aquatic life stage implications.

Chapter 5 of this report presents the impacts of climate change on the provisioning and regulating ecosystem services of floods, drought, and saltwater intrusion. To be complementary, this chapter focuses on changes in hydrological flows at the scale of headwater streams and wetland and stream habitat functions.

6.3 Major Drivers of Aquatic Ecosystem Response to Climate Change

In order to understand the potential impact of climate change on the production of ecosystem services by streams and wetlands, it is imperative to recognize the major drivers in the production of such services. Watersheds and their freshwater elements are defined by a set of inherent physical factors, including climate, soils, geomorphology, topography, and hydrology (Myers et al., 2006; Griscom et al., 2007). Hydrologic processes and patterns, as delivered by regional climate forces and modified by the underlying physical features, fundamentally define and sustain wetlands, streams and lakes. Either directly or indirectly, the ecosystem services provided by these freshwater ecosystems are derived from how water is delivered to and maintained in each type of aquatic resource, as illustrated in Figure 6.1. While temperature and carbon dioxide levels have direct effects of their own, the clear driver in wetlands and streams are the combined effects of temperature, carbon dioxide, and precipitation on the resulting flow regime (for streams) and hydroperiod (for wetlands). Flow regime and hydroperiod are the defining factors in the structure and function of these systems. The amount of water, its rate of flow, and the timing of delivery all significantly determine the type of organisms present, the cycling and removal of nutrients, the occurrence of flooding, the amount of recharge, and the growth and survival of plants and animals. A change in the timing, seasonality, and magnitude of water delivery can severely alter these systems.

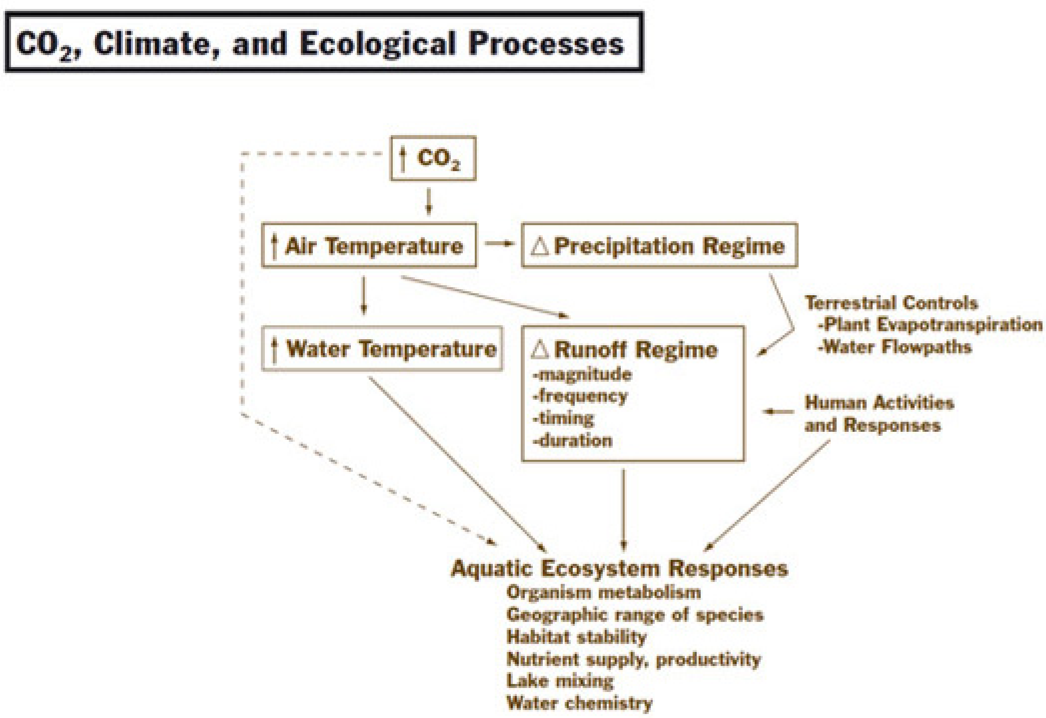

Figure 6.1. Linkages between atmospheric increases in CO2 and environmental drivers of temperature and precipitation that regulate many ecological processes and patterns in inland freshwater and coastal wetland ecosystems. Solid arrows indicate direct responses and dashed arrows indicate direct effects of lesser known importance (Poff et al., 2002).

Situated at the interface of terrestrial and aquatic systems, wetlands are especially vulnerable to changes in soil moisture regime. Alterations in water sources (ground and surface), along with changes in evapotranspiration, affect wetlands. Most wetland processes are dependent on catchment-level hydrology (Gitay et al., 2001). Potential impacts range from extirpation to enhancemen, and include alterations in community structure and changes in ecological function (Burkett & Kusler, 2000).

Evidence suggests that wetlands depending primarily on precipitation for their water supply may be more vulnerable to climate change than those relying on regional groundwater (Winter, 2000). The number and complexity of factors that influence wetland occurrence and type make it difficult to predict the fate of wetlands directly from temperature and precipitation changes alone. Predictions of hydrologic shifts induced by both climate and land cover changes are needed to mitigate the difficulty of analyzing the effect changes have on wetlands. However, as previously stated this can be problematic. For example, hydrologic impacts due to changes in rainfall patterns will depend on the amount and location of impervious surfaces in the watershed. This is information can be cumbersome to collect, but is necessary to describe wetlands as a function of temperature and precipitation.

While hydrology is paramount, the existing condition (i.e., health) of these systems is a second major driver of their ability to provide ecosystem services. The link between the delivery of ecosystem services and condition lies in the assumption that measures of condition reflect wetland ecosystem processes, which in turn drive the delivery of services. For instance, if condition is excellent (i.e., least-disturbed, or equal to reference condition), then the ecological integrity of the wetland is intact and the provision of services characteristic of that wetland type should occur at reference levels. Climate induced impacts to wetlands will be layered onto an already compromised resource. An assessment of wetland condition in the upper Juniata River watershed in Pennsylvania (Wardrop et al., 2007a) reported that over 68 percent of the total wetland area was in medium or low condition, correlating with increased agricultural and urban land use in the watershed. Two regional assessments of wetland condition found that the ability of wetlands in both the Upper Juniata (Pennsylvania) and Nanticoke (Delaware) watersheds to perform valuable functions, such as removal of inorganic nitrogen and retention of inorganic particulates, is already significantly reduced (Wardrop et al., 2007a; Whigham et al., 2007). The majority of these wetlands are functioning below standard reference levels. These impacts are expressed primarily by modification of supporting hydrology (Brooks et al., 2004). Climate-induced hydrologic regime changes may additionally stress these systems, further decreasing their capacity to serve important ecotone functions. The condition of streams shows similar patterns; an in-depth stream assessment conducted through most of Pennsylvania by EPA using a systematic statistical sampling in 1993 and 1994 revealed that 27 percent of streams were in poor condition based on fish and insect populations (Mid-Atlantic Highlands Stream Assessment 2000). Additional baseline assessment of stream condition will be forthcoming for the Susquehanna River Basin; in 2010, the Susquehanna River Basin Commission (SRBC) initiated a network designed to remotely monitor water quality conditions within smaller rivers and streams throughout the portion of the basin experiencing natural gas development (SRBC previously operated and maintained such a system only on the mainstem of the Susquehanna River http://mdw.srbc.net/remotewaterquality/). The network consists of 50 monitoring stations in the Pennsylvania and New York portions of the Susquehanna basin which continuously monitor and record the following five parameters: temperature, pH, conductance, dissolved oxygen, and turbidity. In addition, water depths are recorded to establish a relationship with stream flows at select stations.

6.4 Potential Climate Change Impacts to Pennsylvania Aquatic Ecosystems

While future scenarios related to climate change remain uncertain, the most significant effects predicted for stream and wetland communities are increased water temperature and increased hydrological variability. The latter of which may be reflected by changing seasonal patterns of water levels, reduced stream flows during dry periods, larger floods and longer droughts (Moore et al., 1997; Rogers & McCarty 2000). Some surface-water wetlands, which are believed to be the most vulnerable to these changes, may disappear completely. This loss of water to the system will stem mainly from greater runoff during severe storm events, longer drought periods, and increased evaporation and transpiration, rather than decreased precipitation (Moore et al., 1997). More severe storm events and extensive dry periods will create substantially altered flow patterns, essentially eliminating the flow pulse (below bankfull flood events) and resulting in major changes in channel morphology and aquatic habitat (Poff et al., 1996; Tockner et al., 2000; Amoros & Bornette 2002). In addition, water quality in streams is expected to decline due to increased flushing of contaminants from adjacent lands during runoff and production of higher sediment loads to downstream reaches through runoff and erosion of stream banks during more intense storm flows (Moore et al., 1997; Rogers & McCarty 2000).

Such changes in temperature, water quantity and water quality will most certainly affect stream and wetland biological communities. Climate change impacts across a number of natural systems at the global scale have shown significant range shifts averaging 6.1 km per decade (3.8 miles per decade) towards the poles; (Parmesan & Yohe 2003) this includes fish. The largest negative impact may be in lost biodiversity (Fisher 2000; Tockner et al., 2000), the effects of which are exacerbated by human disturbance (Moore et al., 1997; Rogers & McCarty 2000). Habitat fragmentation from agriculture and urban development creates migration barriers that will prevent many species from moving to colder climates to offset warming temperature trends (Rogers & McCarty 2000). Although typically considered within terrestrial settings (e.g., forest patch sizes), fragmentation applies to aquatic habitats, as well. Hydrologic modification and stream-bank erosion isolate streams from their floodplains and nearby riparian wetlands, effectively reducing areas for flood refuge, larval development, and oviposition sites (Sedell et al., 1990; Tockner et al., 2000). This loss of hydrological connectivity not only reduces aquatic biodiversity, it also makes it more difficult for species to adapt to altered precipitation and temperature patterns. The predictability of timing and duration of high flow events has been shown to be important in determining the use of floodplain habitats by some fish species (Humphries et al., 1999).

Temperature is a critical component in aquatic systems, executing both physiological and behavioral influence on the survival and growth of nearly all macroinvertebrate and fish species (Sweeney et al., 1991; Ward 1992; Mountain, 2002; Harper & Peckarsky 2006). For example, emergence of mayfly populations is initiated primarily by increases in water temperature (Sweeney et al., 1991; Watanabe et al., 1999; Harper & Peckarsky 2006). Consistently warmer temperatures earlier in the year can have negative consequences for the long-term health of mayfly populations, since early emergence coincides with reduced growth during the larval period, which reduces the size and fecundity of the adult mayfly (Peckarsky et al., 2001; Harper & Peckarsky 2006). Pennsylvania contains a vast multitude of headwater streams that provide high quality habitat for numerous cold-water species, including the brook trout (*Salvelinus fontinalis*) and the majority of intolerant mayfly, stonefly, and caddisfly species. Increased stream temperatures can negatively impact these organisms by exceeding their thermal tolerance levels, lowering dissolved oxygen concentrations, and biomagnifying toxins (Mountain, 2002; Moore et al., 1997). Unlike intolerant species that typically cannot withstand high temperatures, many tolerant species respond to warmer temperatures through increased growth rates and fecundity (Sweeney et al., 1991). In addition, the general tolerance and opportunistic nature of these species will enable them to adjust to shorter and unpredictable hydroperiods. As a result, the commonwealth may see a decline in some of our most valued cold-water communities and a simultaneous increase in the abundance of less desirable biological assemblages, especially invasive species that outcompete and often decimate native populations (Rogers & McCarty 2000; Dukes & Mooney 1999).

Of special concern is the impact of higher temperatures and altered flow regimes on Eastern Brook Trout, not only because of its status as a recreationally and culturally important species, but because it is an indicator of high water quality and may be an early casualty of climate change. A population status assessment of eastern brook trout was performed by the Eastern Brook Trout Joint Venture (Hudy et al., 2008; Hudy et al., 2005) and utilized known and predicted brook trout status to classify eastern U.S. subwatersheds according to the percentage of historical brook trout habitat that still maintained self-sustaining populations. The data for Pennsylvania (among all eastern U.S. states in the native range) identified 143 subwatersheds (10 percent) in which over 50 percent of brook trout habitat was intact; 550 subwatersheds (40 percent) in which less than 50 percent of brook trout habitat was intact; 612 subwatersheds (44 percent) from which self-sustaining populations were extirpated; and 72 subwatersheds (5 percent) where brook trout were absent but the explanation for the absence was unknown (i.e., either extirpation from or a lack of historical occurrence in those subwatersheds). Hudy et al. (2008) utilized this data to assess whether classification of subwatersheds could be reasonably well-predicted by utilizing the five factors of percent total forest, sulfate and nitrate deposition, percent mixed forest in the water corridor, percent agriculture, and road density; the classification was correct 71 percent of the time. The classification model was corroborated by a ranking of threats by resource managers; EBTJV (2006) interviewed regional fishery managers and asked them to rank perturbations and threats for all subwatersheds that historically supported reproducing brook trout populations, according to three categories of severity: [1] eliminates brook trout life cycle component; [2] reduces brook trout population; and [3] potentially impacts brook trout population. Across the entire study area of eastern U.S. states supporting brook trout, the top five perturbations listed as a category 1 or 2 severity for streams were high water temperature, agriculture, riparian condition, one or more non-native fish species, and urbanization; increased stream temperatures were ranked by biologists as the top threat to Appalachian brook trout (EBTJV, 2006). Climate change will exacerbate all of these perturbations, either alone or synergistically with continued land cover change. Increased stream temperature may be the first and most direct impact.

Increases in hydrological variability (larger floods and longer droughts) could have severe long-term effects on both stream and wetland communities (Harper & Peckarsky 2006; Humphries & Baldwin 2003). Larger peak flows will result in higher rates of sedimentation and increased scouring of stream banks and floodplains, both of which decrease survival and reproductive success for fish and macroinvertebrates (Chapman, 1988; Fisher, 2000). Fine sediment reduces stream insect and salmonid spawning habitats, and lowers survival rates of many insect species and salmonid embryos (Chapman 1988; Roy et al., 2003). Large flood events reduce survival rates for eggs laid alongside stream banks and floodprone areas and crush species lacking flood refugia (Karr & Chu 1999; Sedell et al., 1990). The greatest impacts will occur in urban areas with a high percentage of impervious surfaces where runoff is quickly routed to streams (Rogers & McCarty 2000). Furthermore, loss of seasonally predictable flood events and reduced groundwater recharge would affect many species that have adapted their life cycles to coincide with times of high water (Tockner et al., 2000; Amoros & Bornette 2002; Suen 2008). Climate change can negatively impact these populations in a multitude of ways, including mismatched timing of life cycle stages and aquatic habitat availability (e.g., aestivating eggs that rely on inundation to initiate hatching in seasonal wetlands), insufficient duration of inundation (e.g., aquatic life cycle stages dependent on longer hydroperiods), and lack of sufficient habitat refugia (e.g., young insect larvae and fish fry that depend on seasonal backwater areas to escape predation and ensure adequate food supply) (Poff & Ward 1989; Sedell et al., 1990; Firth & Fisher 1991; Sweeney et al., 1991; Bunn & Arthington 2002; Suen, 2008). Hydrological factors are significant variables in structuring fish assemblages; alterations in the hydrology could greatly modify fish assemblage structure (Poff & Allan 1995).

At a larger spatial scale, climate change is likely to alter the biogeochemistry of the Chesapeake watershed via the large contribution of the Susquehanna River to its total freshwater input (51 percent). The direction of change is not well constrained given the uncertainty in flow projections (Najar et al., 2008), as well as the lack of a mechanistic understanding of watershed processes. For example, two studies summarized in Najar et al. (2008) for the Susquehanna River Basin Commission, present estimates of percent change in annual streamflow of 24 percent. Nutrient and sediment loading during winter and spring will likely rise due to the anticipated increase in flow during this time and is due to increased runoff and erosion of stream banks. In addition, large concentrations of nutrients (nitrogen and phosphorus) are stored by benthic biofilms (mostly algae) in the bed of streams through Pennsylvania (Godwin et al., 2009). Once dislodged, this material is transported downstream (Godwin & Carrick 2007; Godwin et al., 2009). Over a longer time frame, the impact of development and other land cover changes could control fluxes of both nitrogen and phosphorous by further altering both hydrology (through an increase in impervious surface) and nutrients and contaminants (contained in runoff).

6.5 A Case Study for Climate Change Impacts to Hydrology: Comparison of the Little Juniata River and Young Woman's Creek Watersheds

In order to provide context for the consideration of potential climate change impacts on aquatic ecosystems, we present estimates and predictions of ecologically-relevant streamflow characteristics for two watersheds, one each in two major physiographic regions of Pennsylvania, during present (1979-1998) and future time periods (2046-2065). While the reporting of general statewide estimates is informative, impacts at the local scale often provide greater understanding of the issue. It is important to note that fine spatial scale assessment of potential impacts is generally lacking for aquatic resources, due to the enormous amount of complexity and site-specificity when predicting hydrologic change resulting from projected climate. Thus, we present this current research as a general example of the potential small-scale variability in effects and not as a general example of future conditions state-wide.

The Little Juniata watershed is a small mesoscale (845 km^2; 513 mi^2) subwatershed of the Juniata River, the second largest tributary to the Susquehanna River, which, in turn, is the largest tributary of Chesapeake Bay (McIlnay, 2002). The Little Juniata watershed is located primarily within the Ridge and Valley physiographic province of central Pennsylvania. However, its headwaters are found in the Allegheny Front, which is the watershed divide and transitional region between the Ridge and Valley Province and the Allegheny Plateau.

Most of the bedrock found in the watershed is sedimentary siliclastic and carbonate rock of alternating layers of sandstone, shale, and limestone. Valley floors can be either shale or limestone. The climate of the region is moderate, with an annual average temperature of 10° C (50°F) and monthly averages ranging from -3°C (26.6°F) in January to 22°C (72.3° F) in July. Average annual precipitation is 102 cm (40 in) and is evenly distributed throughout the year, with substantial amounts of frozen precipitation in winter. It is representative of a Ridge and Valley subwatershed, and provides a relevant window into potential effects of climate change on headwater streams and wetlands.

In contrast, Young Woman's Creek is a southwest-flowing tributary of the West Branch of the Susquehanna River. The Young Woman's Creek Basin is in the Appalachian Plateaus physiographic province in north-central Pennsylvania in an area characterized by high, flat-topped uplands dissected by steep- sided stream valleys. The basin drains 120 km^2 (46 mi^2) of forested terrain. The basin is unglaciated, and the bedrock that underlies it includes primarily sedimentary rocks. The most common formation in the basin (the Pocono Group) is highly permeable gray sandstone with layers of conglomerate and shale.

Climate of the area is characterized as a humid continental type with cold winters and warm summers; average daily air temperatures range from -3.3°C (26.1°F) in January to 22.5°C (72.5°F) in July (Kohler, 1986). Precipitation averages 105 cm (41 in) annually and is fairly evenly distributed throughout the year (Kohler, 1986). Frontal storms are the most common source of precipitation, although thundershowers are prevalent in summer. Average seasonal snowfall is 120 cm (47 in); however, a seasonal snowpack rarely persists through the winter.

Establishing the quantitative relationships among surface water, soil water, and groundwater conditions for dynamic climate scenarios, represents an essential step to understanding the problem of wetland and small stream hydrologic dynamics. For this example of two case studies, a fully coupled and distributed modeling system was applied, which simulates surface water (overland, channel, lake), soil moisture, and groundwater dynamics. The model is referred to as the PIHM (Penn State Integrated Hydrologic Model; Qu & Duffy 2007). The model has shown dynamic interaction between groundwater level and evapotranspiration and local topographic and stream morphology effects on stream aquifer interactions. A simple future climate scenario was constructed by applying a daily temperature and precipitation change, obtained from monthly changes predicted by the model mean of the 21 GCMs under the A2 scenario. The model presented estimates of selected hydrologic metrics for two time periods: present conditions (1979-1998) and predicted conditions under the climate change scenario (2046-2065). Metrics are presented as annual averages over the 19-year run period.

Because of the high level of uncertainty associated with forecasting hydrologic variables with climate change in general and in the Mid-Atlantic in particular, it is important to focus on changes that could be ecologically relevant. Our approach is to use regional models of climate change and to feed the scenarios into an integrated, physically based hydrologic model and generate a range of possible conditions. The questions that we are then investigating as ecologists are: what hydrological changes can we forecast with the most confidence? What potential and plausible hydrologic changes due to climate change could cause changes in the ability of wetlands and streams to provide ecologic services? What can be done to prevent these plausible changes? We answer the first two questions by examining the ecologically-relevant hydrologic metrics associated with stream flows (mean, maximum, and minimum flows, and flow variability), and groundwater levels (average depth to water, time in the growing zone). Management actions to prevent these changes are discussed in Section 6.6.

6.5.1 Stream Flow

Various measures of flow magnitude provide a general measure of aquatic habitat availability and suitability, with monthly means describing daily monthly conditions, and similarity between monthly means describing hydrologic constancy throughout the year. Inter-annual variation for any given month describes contingency, or the extent to which flows vary within any given month from year-to-year. For many aquatic organisms, this predictability in conditions and timing is critical for successful reproduction. Extremes in daily to seasonal water conditions provide measures of environmental stress. For both watersheds there were increases in the magnitude of mean flows under the future scenario, with accompanying increases in the magnitude of maximum flows but a decrease in the magnitude of minimum flows (Figures 6.2a and 6.2b). Forecasted seasonal differences in flow are not evenly distributed: the largest increases occur during the typically wet winters and springs while the summers show slight decreases in mean flows. Overall, an increase in the mean magnitude flows would indicate an increase in flooding events, with a concomitant increase in the duration of inundation in habitats in the floodplain. Additionally, it would indicate an increase in stream power, or the amount of work a stream can do in terms of moving materials. Under these conditions, increased erosion and deposition is likely to occur, especially in areas where stream banks are compromised with little vegetation to hold the soils in place. Increasing stream power can translate into increasing incision of streams and mean less of the small over bank flooding events, which are typically not highly detrimental to humans but very important in forming streamside habitats. Furthermore, an increase in sediment deposition can cause a decrease in the rate of native plant species germination and can fill in troughs and hummocks within a wetland that act as important habitat.

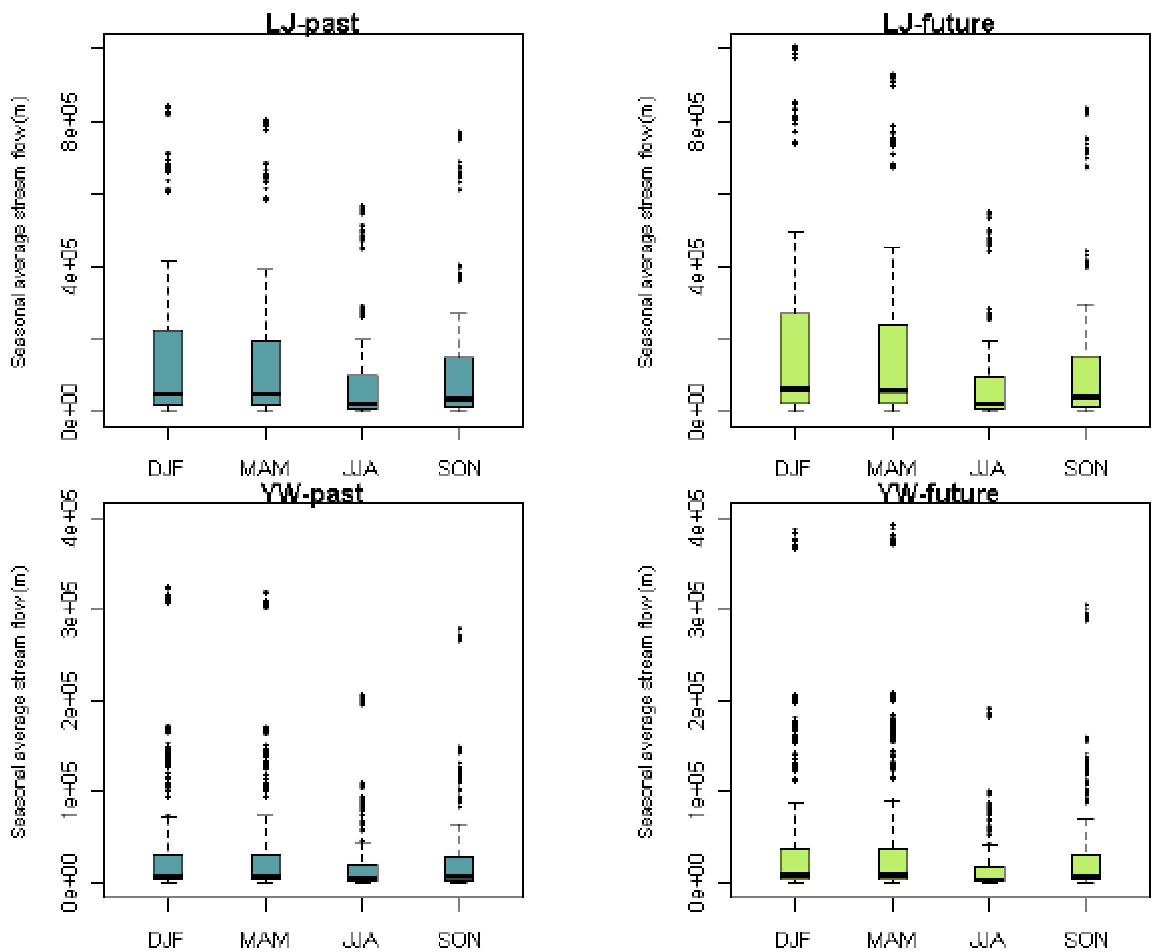

Figure 6.2a. Seasonal stream flow for the Little Juniata and Young Woman's Creek watershed, averaged over present (1979-1998) and future (2046-2065) time periods.

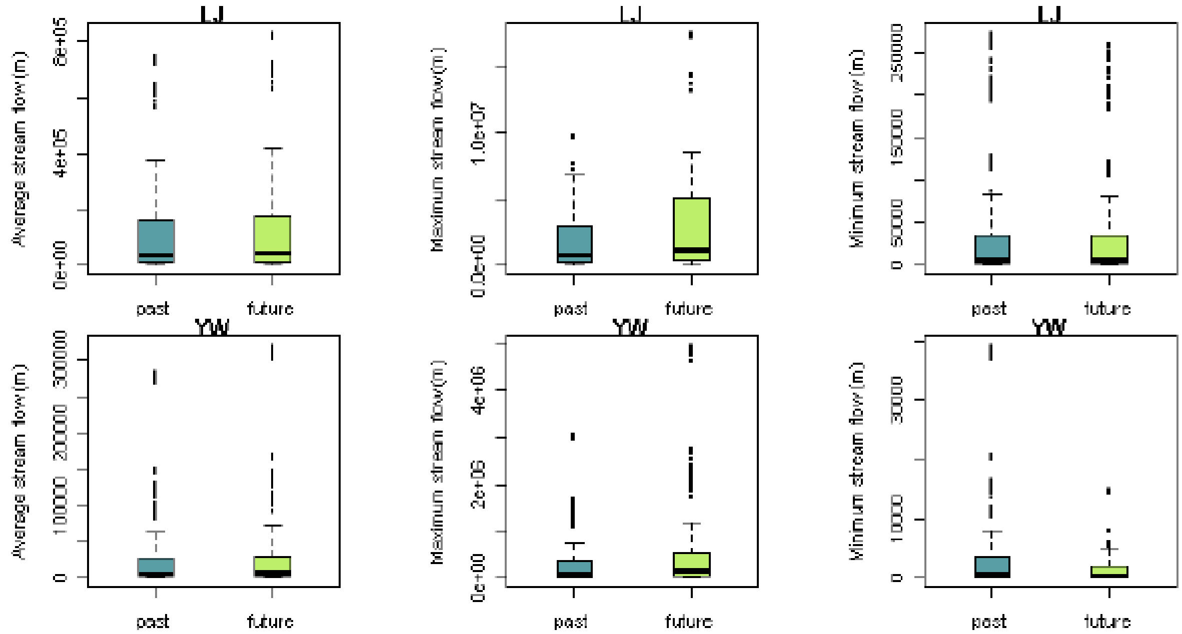

Figure 6.2b. Average stream flow for the Little Juniata and Young Woman's Creek watersheds, averaged over present (1979-1998) and future (2046-2065) time periods.

Another ecologically-relevant metric of stream flow is flashiness. Flashiness has no set definition but is generally associated with dramatic fluctuations in flow, such as high flows immediately following wet weather and a rapid return to pre-rain conditions shortly after the end of the precipitation. This rapidity in response is often the result of faster surface runoff, with a sudden and intense peak flow in the receiving stream, which represents a loss of water storage in soils and vegetation, i.e., water that precipitates will make its way quickly from the land into the stream and be flushed through the system. Two estimates of flashiness are presented in Figure 6.3: the baseflow index (proportion of baseflow to the total flow) (Dunne & Leopold 1979; Chapman & Maxwell 1996) and the Richards-Baker flashiness index (increases with increasing flashiness) (Baker, Richards et al., 2004). The baseflow index is given here because a stream with a lower baseflow index will be more prone to flashiness due to a relatively higher amount of surface water contributing to the overall flow. For both watersheds, the proportion of baseflow goes down in the future scenario. This could have potentially significant consequences for the thermal sensitivity, defined as the sensitivity of stream temperature of a given site to change in air temperature, as discussed in Section 5. Baseflow index is inversely related to thermal sensitivity in smaller streams (Kelleher et al., 2011), but does not appear to influence thermal sensitivity in large streams. Thus, small streams could exhibit an increased thermal sensitivity that will further exacerbate the impact of higher air temperatures, resulting in higher stream temperatures. In addition, the flashiness increases with the future scenario, with a higher probability of lowering stream levels during the critical summer months. All three factors (increased thermal sensitivity, higher air temperatures, and lower stream levels during summer periods) could present significant challenges for cold water fish species such as brook trout.

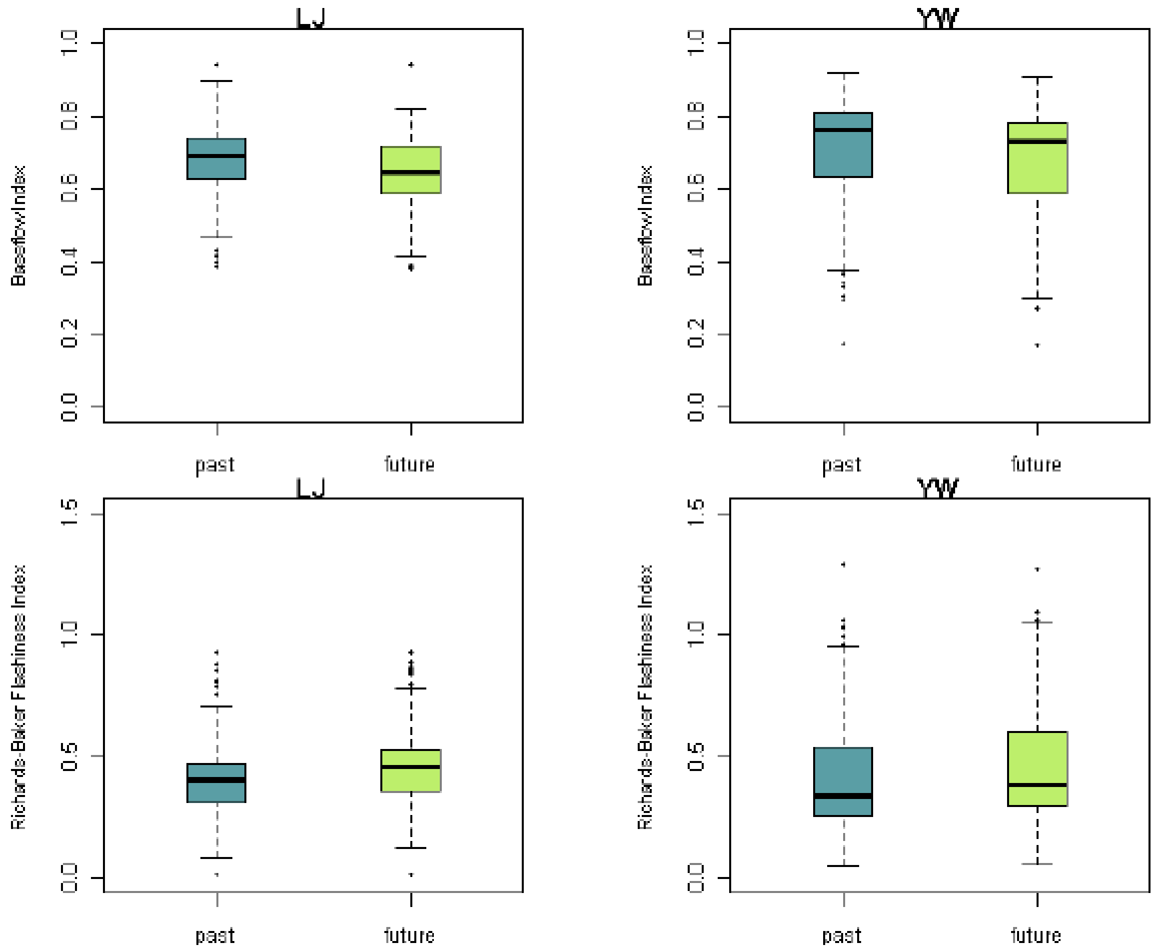

Figure 6.3 Baseflow Index and Richards-Baker Flashiness Index for the Little Juniata and the Young Woman's Creek watersheds, averaged over present (1979-1998) and future(2046-2065) time periods.

6.5.2 Groundwater Levels

Average groundwater levels, expressed as mean depth-to-water (zero is interpreted as ground surface), increase in both watersheds for the future scenario, meaning that average groundwater levels are closer to the surface, resulting in "wetter" conditions (Figure 6.4). An increase in groundwater would influence different types of wetlands differently; wetlands along headwater streams could see possible increases in groundwater driven microhabitats, and there could be a general expansion of these and other groundwater-supported wetlands. In contrast, an increase in inundation can change the vegetation and habitat conditions of other wetlands, with a resulting shift in aquatic communities. Though the overall mean groundwater levels increase in the future scenarios, seasonally there are increases in the winter and spring but decreases during the dry summer months. This may be a critical change in aquatic habitat for macro invertebrates, as suitable habitat in floodplains disappears.

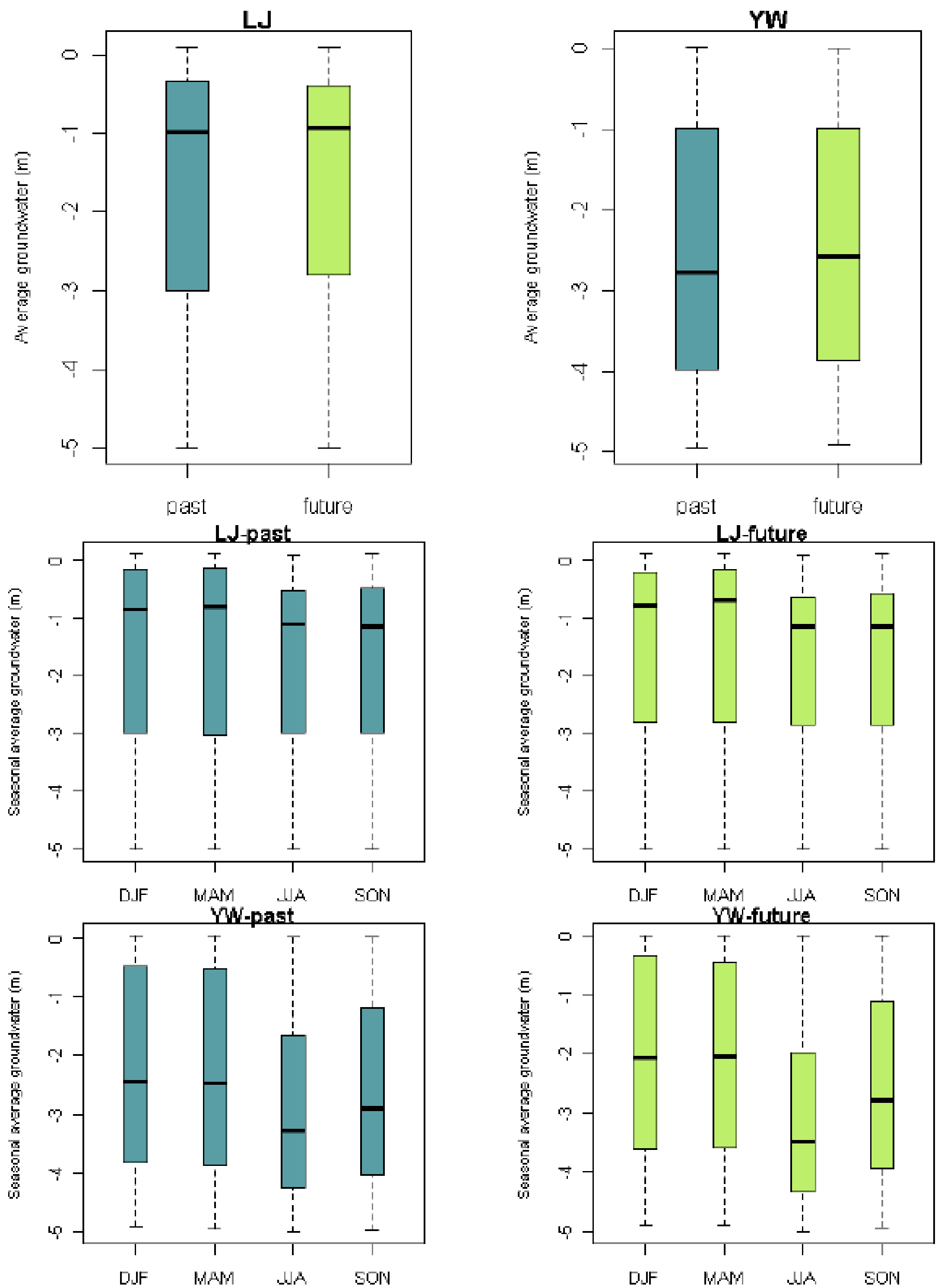

Figure 6.4. Average and seasonal average groundwater levels, expressed as mean depth-to-Water, for the Little Juniata and Young Woman's Creek watersheds, averaged over present (1979-1998) and future (2046-2065) time periods.

Another ecologically-relevant metric for groundwater hydrology is the time that the water table is present in the upper 30 cm (12 in) of soil, which is commonly held to be the average rooting zone for wetland vegetation. This metric has been shown to be related to the wetland type (Cole et al., 2000), as well as the general type of wetland vegetation. Similar to overall groundwater levels, the future scenarios as shown in Figure 6.5 show a marked increase in the percent of time groundwater is in the growing zone (upper 30 cm; 12 in). Seasonally, the increases in time in the growing zone occur in the winter and spring, while there is a decrease in the summer months. While an increase in the percent of time groundwater is in the upper 30 cm (12 in) is generally correlated with a higher quality plant community due to a more stable and constant state of soil moisture, the increased seasonal extremes (wet springs and drier summers) may instead lead to a higher presence of aggressive and invasive species (i.e., more tolerant).

6.6 Summary of Impacts

- The most significant climate change effects predicted for stream and wetland communities are increased water temperature and increased hydrological variability (high agreement, much evidence; high confidence).
- Pennsylvania may see a decline in some of its most valued cold-water communities and a simultaneous increase in the abundance of less desirable biological assemblages, especially invasive species. Eastern Brook Trout will continue to decline as a result of higher water temperatures (high agreement, much evidence; high confidence).
- Wetlands may experience a similar change in habitat conditions, as hydrologic variability changes habitat structure (high agreement, limited evidence). Potential impacts on other ecosystem services cannot be predicted at this time.
- Wetlands and headwater streams in Pennsylvania are already compromised in their ability to provide ecosystem services, due to degraded conditions resulting from modification of hydrology and nutrient enrichment (high agreement, much evidence; very high confidence). These stressors primarily arise from human activities associated with agriculture and development.
- Impacts of climate change on aquatic ecosystems will be difficult to detect because of the continuation of primary stressors to their condition such as development and invasive species (high agreement, much evidence; high confidence).

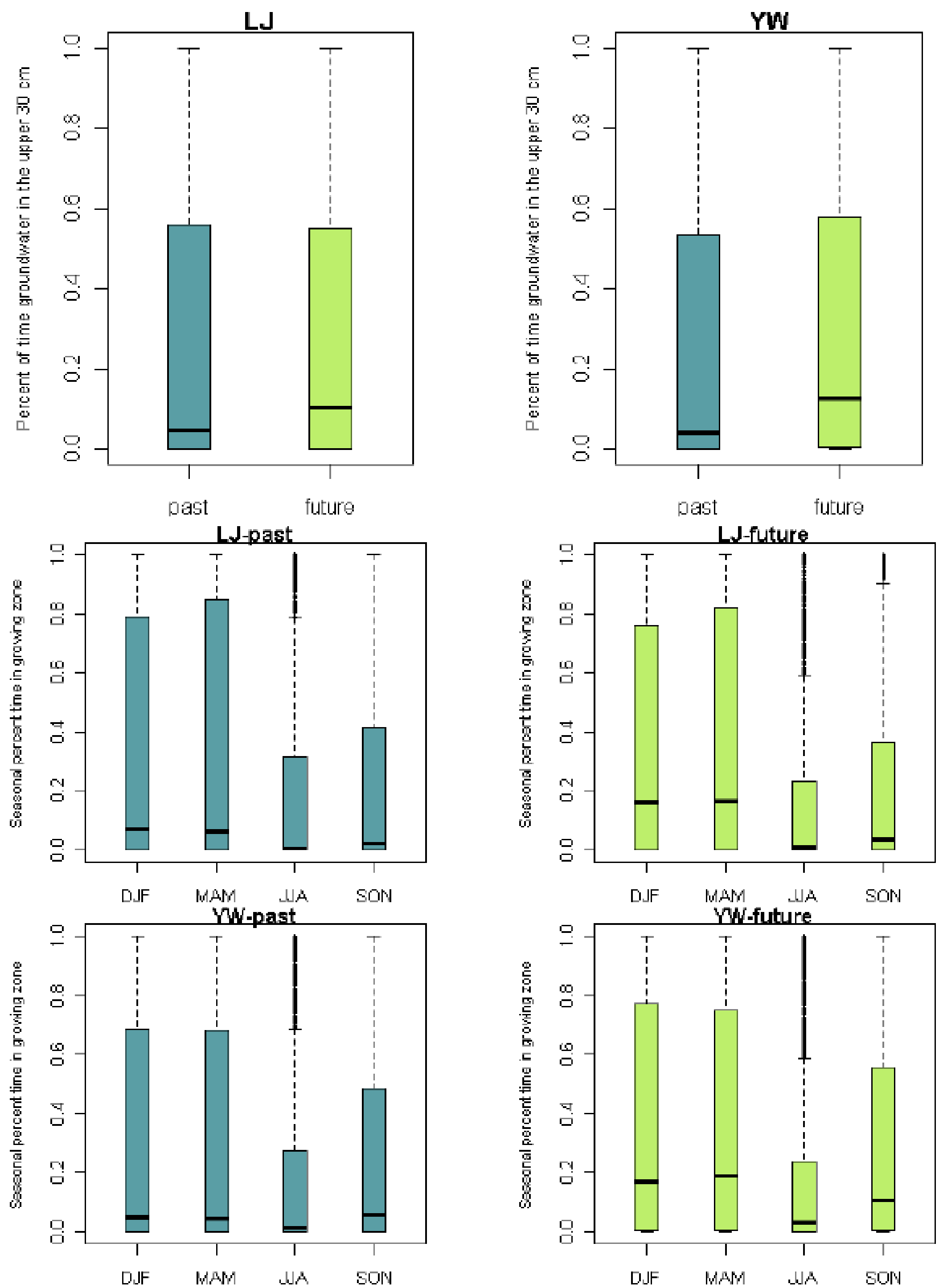

Figure 6.5. Average and seasonal average groundwater levels, expressed as the percent of time groundwater levels are present in the upper 30 cm (12 in) of the soil surface, for the Little Juniata and Young Woman's Creek watersheds, averaged over present (1979-1998) and future (2046-2065) time periods.

6.7 Adaptation Strategies

Strategies to avoid the above impacts from climate change need to center around maintaining and improving the resiliency of aquatic systems through minimization of increased stream temperature, nutrient enrichment, hydrologic modification, habitat fragmentation and degradation, and species loss. Such actions would include:

- Protection of existing stream and wetland habitat, especially intact habitat for identified species of interest, such as Eastern Brook Trout (EBTJV, 2008).
- Consideration of hydrological connectivity within and between stream and wetland habitats.
- Maintenance of riparian forests for moderation of stream temperature and treatment of runoff from adjoining lands
- Implementation of Best Management Practices to reduce nutrient loading
- Restoration of aquatic ecosystems such as streams and wetlands wherever possible
- Minimize groundwater pumping for irrigation, human consumption, etc., that removes water from aquatic and wetland ecosystems.

6.8 Informational needs for Aquatic Ecosystems

- What are the projected increases in temperature in streams of the commonwealth, especially in cold-water habitats?
- What is the projected change in flow rates and hydroperiods in watersheds across the commonwealth?
- What controls the retention of nutrients versus their export to aquatic systems once they are deposited onto the landscape?
- What is the existing condition of streams, lakes, and wetlands across the commonwealth, how will that affect their ability to respond to additional climate change impacts, and how will that affect the production of ecosystem services?
- How will humans continue to interact with aquatic ecosystems under scenarios of climate change, e.g., how will changing patterns of water resource use affect wetlands and streams?

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7.0 Energy Impacts of Pennsylvania's Climate Futures

This section updates Chapter 10 of the 2009 ***Pennsylvania Climate Impacts Assessment***, focusing on possible impacts of climate change on energy production and utilization in Pennsylvania. The 2009 PCIA suggested a few broad implications:

1. Warming in Pennsylvania is likely to increase demand for energy, particularly electric power, during the summer months. This increase is likely to be larger than any decline in wintertime energy consumption. Thus, overall energy utilization in Pennsylvania is likely to increase as a result of climate change.
2. Impacts of climate change on Pennsylvania's energy infrastructure are likely to be focused on the electric power production and delivery system.
3. Some opportunities exist for Pennsylvania to facilitate the adaptation to climate change as well as mitigation of further greenhouse gas emissions, particularly in the areas of CO_2 sequestration and energy efficiency.

These conclusions have not changed significantly since the 2009 PCIA, nor has Pennsylvania's status as a major energy-producing state. This section updates some information from the 2009 PCIA and highlights a few areas where additional information is needed to assess climate impacts. First, the research literature has increasingly focused on location decisions for low-emissions power generation as an important factor in the contribution to reduced greenhouse-gas emissions. Second, there is significant uncertainty regarding likely shifts in the transportation sector. A shift away from gasoline and diesel fuel towards electrified transportation or natural gas transportation is likely to reduce greenhouse gas emissions from this sector, but the rate and direction of transformation is uncertain. Third, we highlight the dependence of Pennsylvania's energy sector on water supplies. Increased seasonal variations on freshwater supplies may impact the ability of Pennsylvania's energy sector to produce reliable supplies under some scenarios.

7.1 Energy Supply in Pennsylvania

Pennsylvania continues to be a major energy-producing state. Based on 2009 production data, the Commonwealth ranks sixth nationally in total energy production. It ranks third in the nation in electric power production, fourth in the nation in coal production, and 19th in the nation in crude-oil extraction (EIA, 2010). Natural gas from the Marcellus Shale has represented the largest energy growth area for Pennsylvania since 2009; gas production in the Commonwealth has increased from under 1 trillion BTU per day (1 billion cubic feet per day) to more than 3 trillion BTU per day (3 billion cubic feet per day) in the past two years.[8] While the Commonwealth continues to be the nation's largest exporter of electric energy and a major exporter of coal, it is largely self-sufficient in natural gas. Pennsylvania continues to import the majority of its crude oil and petroleum products. Overall, the Commonwealth continues to be an energy importer – total energy production in 2009 amounted to 2.6 quadrillion BTU[9] while total energy consumption for all purposes in 2009 was 3.6 quadrillion BTU.

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[8] Natural gas production data after 2009 is from the Pennsylvania Oil & Gas Production Reporting System; www.paoilandgasreporting.state.pa.U.S.

[9] One quadrillion BTU (British Thermal Units) is commonly referred to as a "quad;" official figures after 2009 are not available from the U.S. Energy Information Administration, but the increase in Pennsylvania's natural gas production itself is not enough to make Pennsylvania a net *energy* exporter in 2010 or 2011.

Prices for many energy commodities in Pennsylvania have fallen since 2009, driven in part by the recessionary economic environment. Increased supplies of natural gas are estimated to have played a smaller but still significant role in reducing consumer energy prices in Pennsylvania (Considine, et al., 2011), although natural gas costs in Pennsylvania have remained strong, about 30 percent higher than the national average (as of summer 2011, the citygate price for natural gas in Pennsylvania was around $8 per million BTU (thousand cubic feet) while the national average was around $6 per million BTU (thousand cubic feet)). Presently, virtually all of Pennsylvania is part of a regional electricity market known as the PJM Interconnection, which covers all or part of 13 states plus the District of Columbia. While coal is a major fuel used to supply electricity within the PJM region, electricity prices (particularly during peak periods) are sensitive to the price of natural gas. Petroleum is not a major contributor to electricity generation in Pennsylvania, so the transportation energy sector in Pennsylvania is essentially separated from the electric power, industrial and building energy sectors.

Coal and nuclear power remain the predominant fuels used for generating electricity in Pennsylvania. Pennsylvania's installed capacity mix as of 2010 is shown in Figure 7.1, while utilization of fuels for electric generation is shown in Figure 7.2. Pennsylvania's generation capacity mix is similar to the mix of the U.S. as a whole. The cost of fuels, capital and maintenance all influence how often generating units are used. Thus, there a substantial difference between Pennsylvania's installed generation capacity and the intensity with which generating units or technologies are used to produce electricity. One significant change in Pennsylvania's utilization of fuels for electricity generation is the decline in output from coal-fired power plants to less than 50 percent of the Commonwealth's electric energy mix; this decline has been matched with increases in the utilization of natural gas and renewable energy (primarily wind energy).

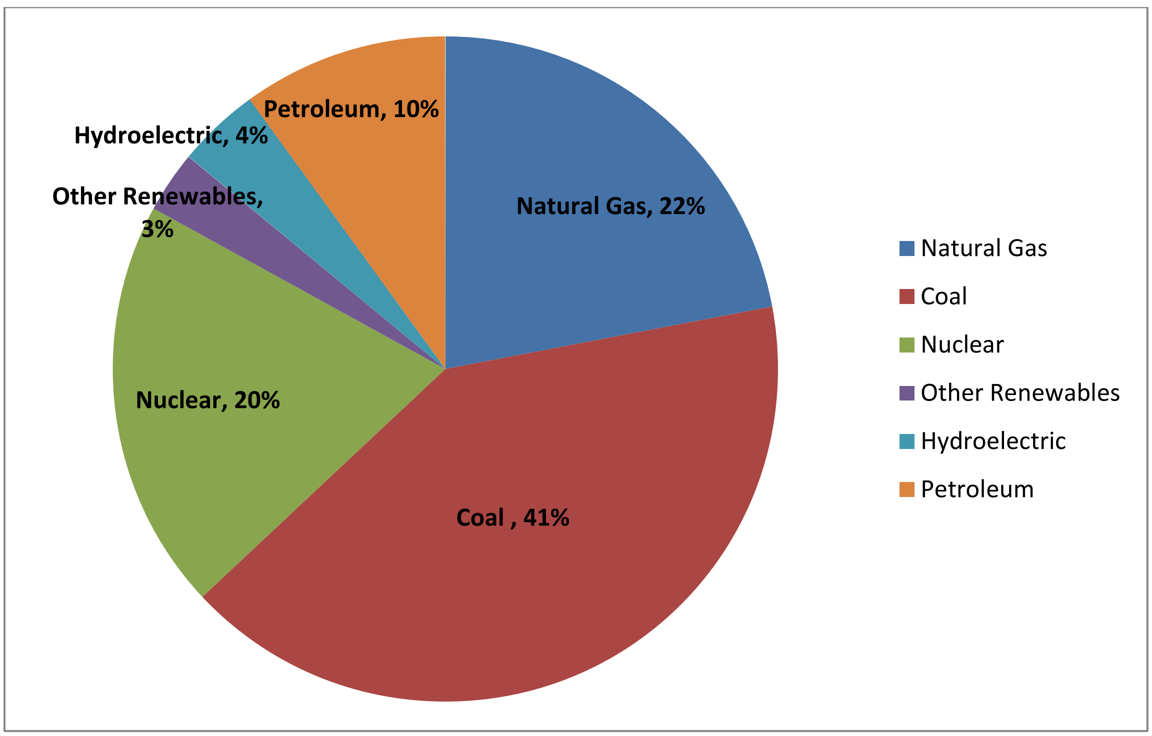


Figure 7.1. Installed capacity mix for electric generation in Pennsylvania, 2009. Source: U.S. Energy Information Administration.

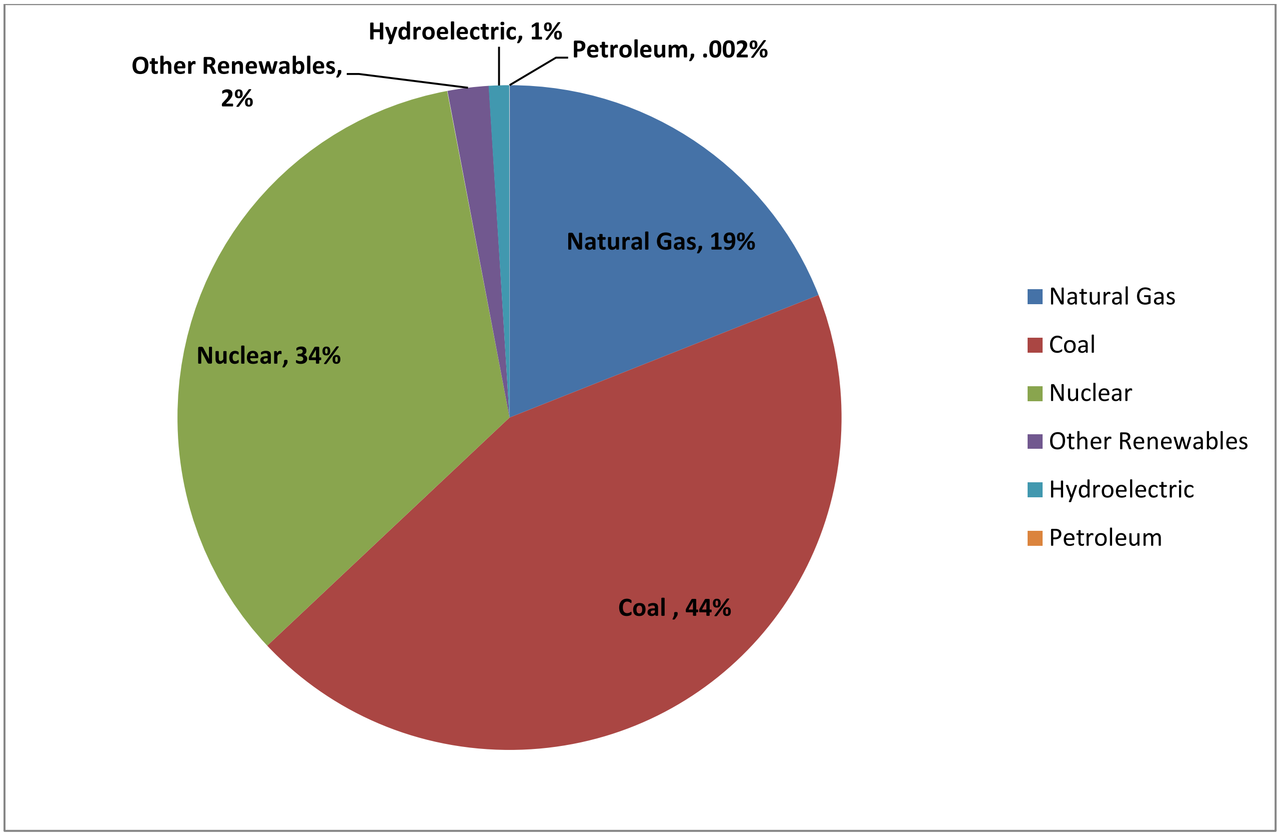


Figure 7.2. Fuel mix for electric production in Pennsylvania, 2011. Source: U.S. Energy Information Administration.

7.2 Energy consumption and pricing in Pennsylvania

Total energy consumption over all sectors and for all uses in Pennsylvania has declined by approximately 10 percent since 2007, to 3.6 quadrillion BTU in 2009. Figure 7.3 shows a breakdown of total energy consumption in Pennsylvania by sector. The industrial and transportation sectors consumed the largest amount of total energy, although industrial energy use declined by the largest amount.

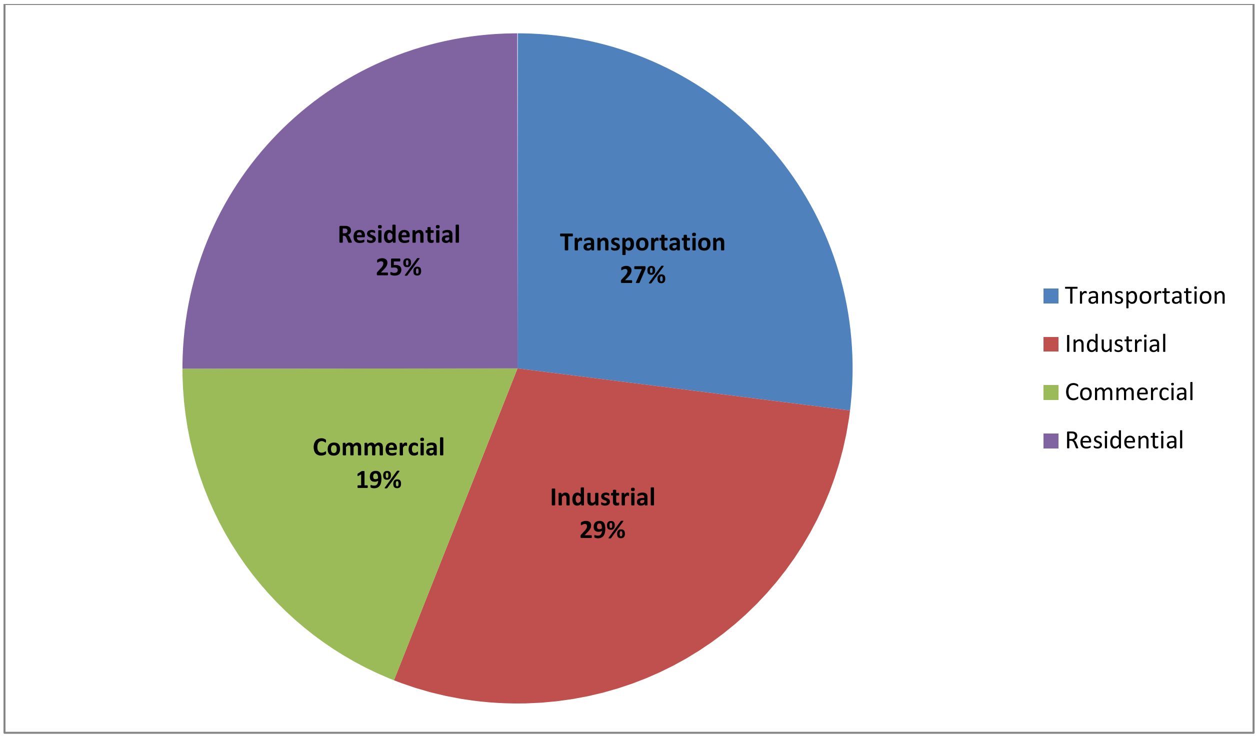


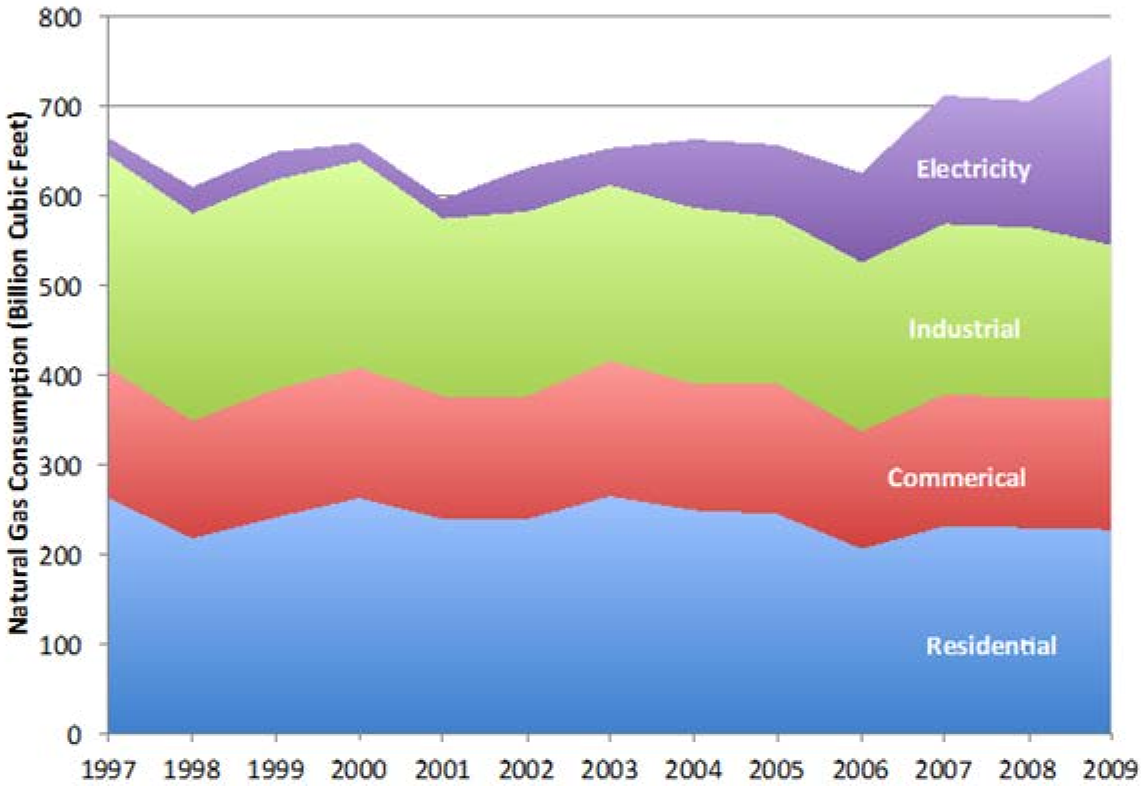
Figure 7.3. Sectoral energy consumption in Pennsylvania, 2009. Total energy consumption in the Commonwealth was 3.6 quads. Source: U.S. Energy Information Administration.

Natural gas consumption in Pennsylvania has largely mirrored national trends, as shown in Figure 7.4. The rate of increase in natural gas usage for electric power generation has increased more rapidly in Pennsylvania than in the U.S. as a whole; the share of Pennsylvania natural gas consumption represented by power generation has risen to 25 percent in 2009 from 10 percent in the late 1990s. At the same time, industrial use of natural gas has declined in Pennsylvania, particularly with the onset of recession beginning in 2008.

Figure 7.4. Sectoral natural gas consumption in Pennsylvania, 1997-2009. Source: U.S. Energy Information Administration.

Wholesale electricity pricing in Pennsylvania is primarily determined by market outcomes in the PJM electricity market, whose footprint encompasses nearly the entire state (Pike County in northeastern Pennsylvania participates in markets run by the New York Independent System Operator). Prices in the PJM electricity market have been falling steadily since 2008, in part due to the recession and in part due to declining natural gas prices (Kleit, 2011).

As of 2011, virtually all electricity customers in Pennsylvania are free to choose their own electric generation supplier, at prices that are largely deregulated. Consumers who do not make an explicit choice of electric generation supplier are assigned to a “default” supplier, usually the regulated distribution utility. The prices charged for so-called “default service” are determined by a series of auctions overseen by the Public Utility Commission. Since the auctions determine long-term contract prices for electricity, consumers in Pennsylvania choosing default electric service may not pay prices that are representative of current wholesale market conditions, as shown in Figure 7.5 (Kleit et al., 2011).



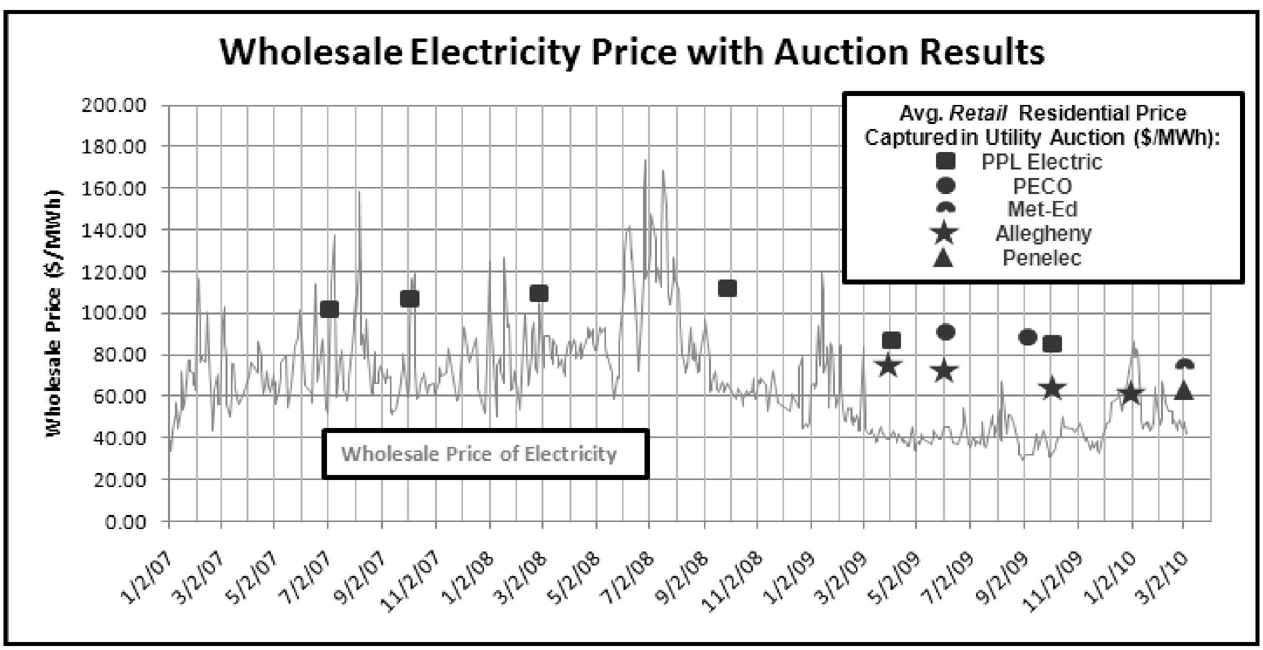


Figure 7.5. Contract prices for default electric service in Pennsylvania. Source: Kleit et al., (2011) from data provided by the Pennsylvania Public Utility Commission and PJM.

Natural gas prices have remained high in Pennsylvania relative to the national average, owing to the amount of pipeline capacity able to transport natural gas from the Marcellus Shale to markets in New

York and New England. In gas-producing states with lower demand and less pipeline infrastructure, such as Wyoming, natural gas prices have fallen to levels not seen since the 1990s (Blumsack, 2010). The emergence of regional electricity markets, such as PJM, in the wake of electricity deregulation in the 1990s has strengthened the link between natural gas and electricity prices. The build-out in natural gas generation that occurred during the mid-1990s increased the utilization of natural gas as a power generation fuel in the U.S., followed by natural gas price increases and increased volatility (Figure 7.6).

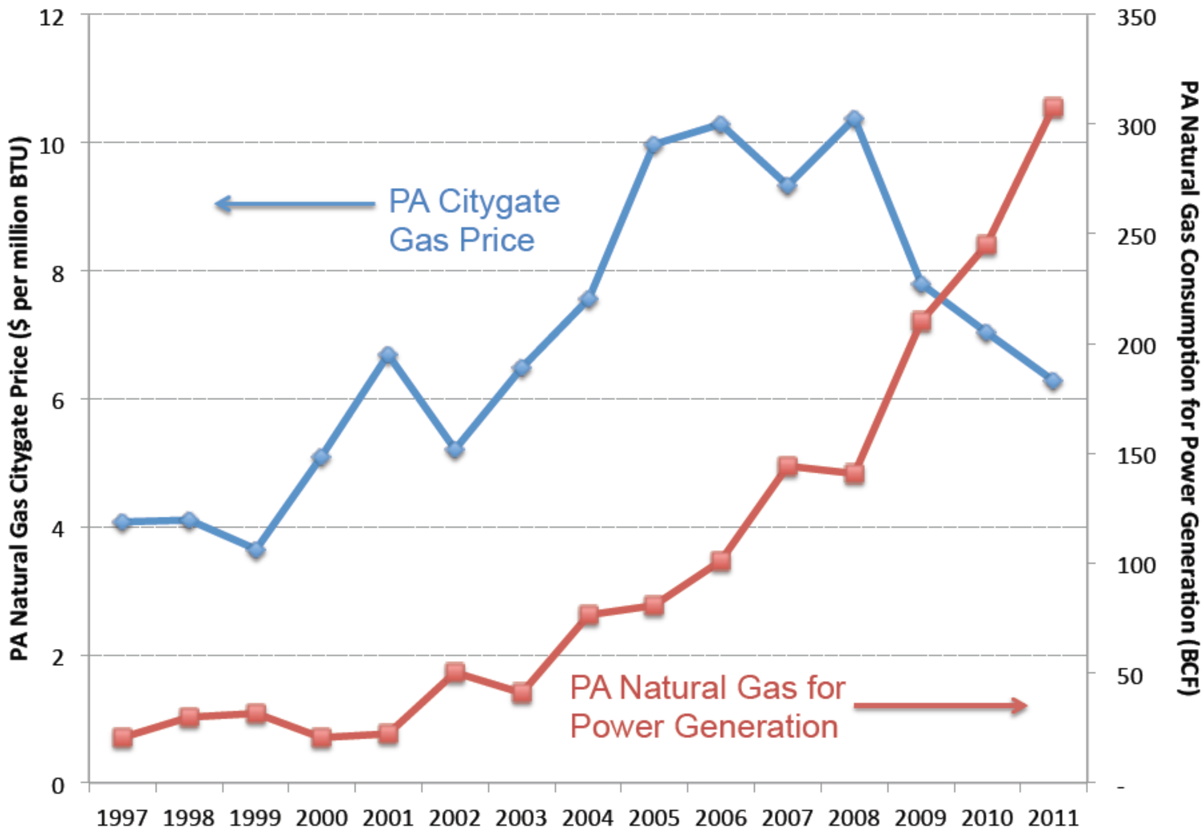


Figure 7.6. The increase in the use of natural gas for power generation has been accompanied by increased price levels and volatility in Pennsylvania gas markets. This trend is similar for the U.S. as a whole (Blumsack, 2010).

The future price of natural gas in Pennsylvania is uncertain, and regional price projections are sensitive to the assumed balance between supply and demand. Blumsack (2010) suggests a significant difference between scenarios where the rate of growth of Marcellus gas production is halted (i.e., there are few or no new Marcellus wells drilled within the next decade) and scenarios where Marcellus development continues, even if the pace of development is not rapid. These price projections are shown in Figure 7.7. In both of the latter cases, natural gas prices in the Mid-Atlantic fall through the 10-year projection period even if the demand for natural gas increases due to increased reliance on gas for power generation. Even moderate growth in the development of Marcellus shale gas will result in significant quantities of “stranded” gas in the Mid-Atlantic if pipeline projects do not proceed as currently scheduled.

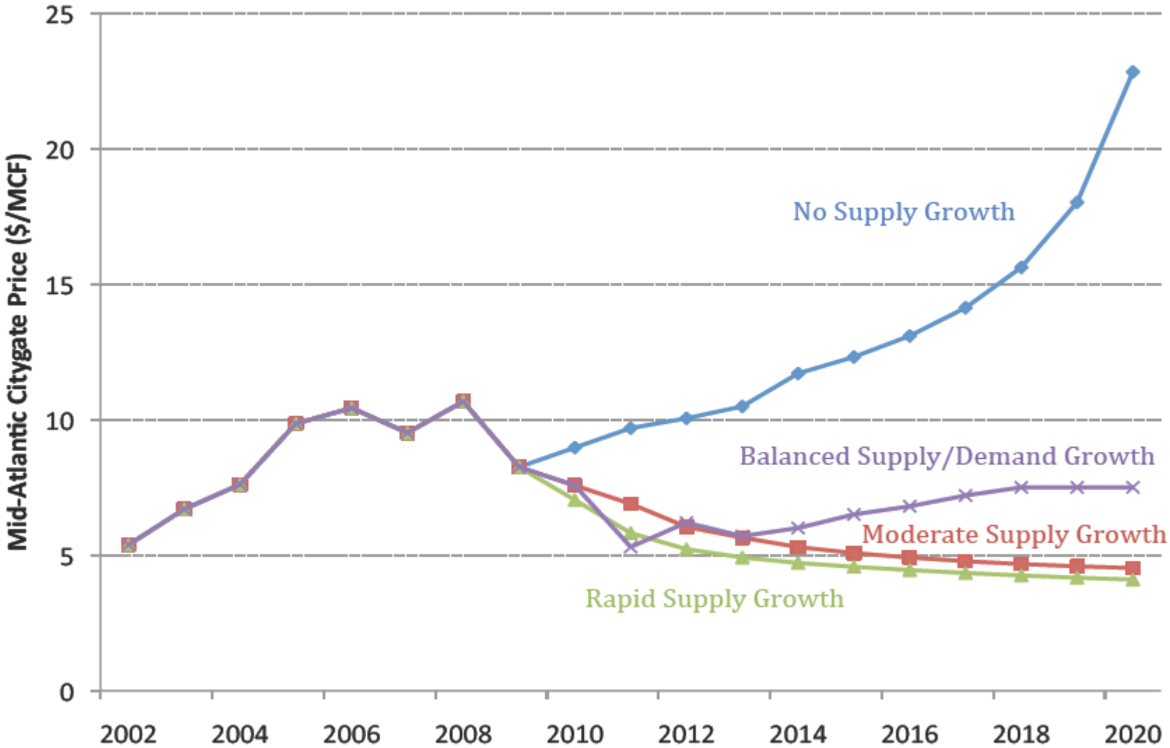


Figure 7.7. Price projections for natural gas in the Mid-Atlantic region. The figure assumes a moderate rate of growth in natural gas demand of 0.3 percent per year. Blumsack (2010).

7.3 Greenhouse-gas impacts of energy production and consumption in Pennsylvania

The primary sources of energy-related greenhouse gas emissions in Pennsylvania continue to be associated with the electric power, transportation and industrial sectors. The burning of fossil fuels for space conditioning in homes or commercial buildings also contributes, but these effects are small by comparison, particularly since the majority of homes in Pennsylvania use natural gas for heating. Table 7.1 shows average and total carbon dioxide emissions from the burning of fossil fuels for various consumptive uses, including the generation of electricity. The figures for electricity generation are based on data specific to Pennsylvania, from the U.S. Energy Information Administration and the Emissions and Generation Resource Integrated Database (eGRID) available through the U.S. Environmental Protection Agency.[10] The figures for home heating from fuel oil or natural gas are taken from Blumsack et al. (2009).

[10] http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

Source	Average CO2 Emissions (lb/per-unit)	Total for PA, 2009 (tons CO2)
*Electric Generation**		
Coal	2,280 lb/MWh	102,205,193
Natural Gas	1,142 lb/MWh	12,028,681
Petroleum	2,637 lb/MWh	976,398
Transportation	180 kg/L	48,922,529
Home Heating		
Natural Gas**	117 lb/mmBTU	22,876,115
Heating Oil	164 lb/mmBTU	6,179,904

Table 7.1. Average and annual CO_2 emissions from energy use in Pennsylvania. Annual figures are based on 2009 data. Blumsack (2009), from U.S. Energy Information Administration data.
*Electric Generation includes consumption for residential heating and cooling.
**Natural Gas includes cooking fuel.

The electric generation sector continues to be the largest source of greenhouse gas emissions in the Pennsylvania economy. As Table 7.1 demonstrates, Pennsylvania's coal plants emit on average more than one ton of CO_2 per megawatt-hour generated, while natural gas emits half as much CO_2. The burning of refined petroleum for electricity is more carbon-intensive than burning coal, but oil-fired generation accounts for only a small portion of the Commonwealth's electric-sector emissions.

The emissions figures in Table 7.1 are limited to greenhouse-gas emissions from the actual production of electric power. Viewed from a life-cycle perspective, the role of coal-fired power generation is even more apparent, as shown in Figure 7.8 (taken from Blumsack, et al., 2010). The figure shows how different stages of the life-cycle of power generation from different fuels contributes to overall greenhouse gas emissions from Pennsylvania's electric generation sector. While no fuel is "carbon-free" from a life-cycle perspective (even renewables, as in Fthenakis & Kim, 2006), the combustion of coal accounts for nearly 85 percent of Pennsylvania's total life-cycle greenhouse gas emissions associated with electricity generation. More broadly, any assessment of the greenhouse-gas implications of energy utilization in Pennsylvania (or other U.S. states) is driven largely by the combustion of fossil fuels. Changes in upstream practices (resource extraction, processing and transport) may be environmentally beneficial but are likely to do relatively little to reduce energy-related greenhouse gas emissions (Jaramillo et al., 2007).

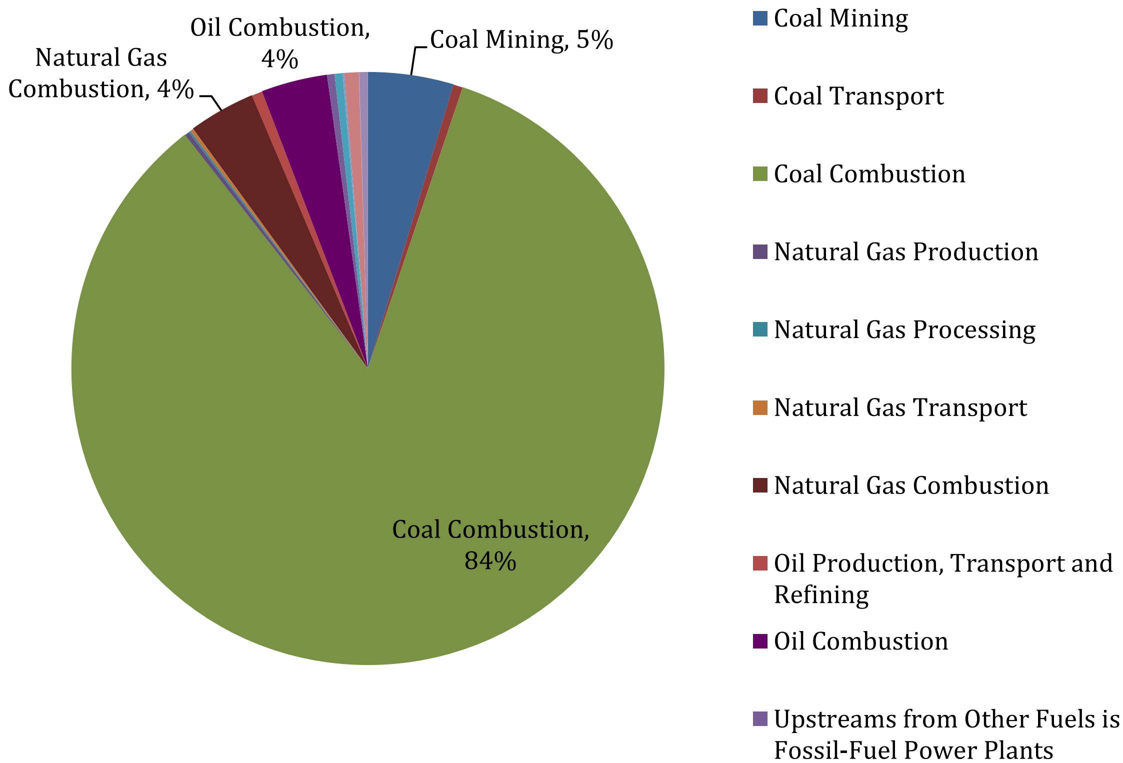


Figure 7.8. Contribution of different life-cycle phases of fossil fuels to the overall greenhouse-gas impact of Pennsylvania's electricity sector (Blumsack et al., 2010).

Pennsylvania's role as the nation's largest exporter of electricity to other states suggests that some portion of greenhouse-gas emissions produced by the power sector in Pennsylvania effectively serve electricity consumers in other states. Emissions leakage, across state borders has been an important governance issues in regional emissions compacts, particularly involving border states that lie outside the emissions management region. Pennsylvania, for example, adjoins several states that participate in the northeastern Regional Greenhouse Gas Initiative (RGGI) but is not itself bound by RGGI's greenhouse-gas reduction targets. Pennsylvania's role as an exporter of fossil-fired electric generation to states participating in the RGGI agreement thus creates some accounting issues in evaluating the impacts of greenhouse-gas management policies. Blumsack et al. (2010) attempt to bound Pennsylvania's exports of greenhouse gases based on generator performance, location and transmission data. Their analysis, summarized in Figure 7.9a and 7.9b, suggests that 25 to 40 percent of total greenhouse-gas emissions from Pennsylvania power plants are produced to satisfy electric demands in Maryland (and the Washington, D.C. metropolitan area) and New Jersey. Weber et al., (2010) have also noted that the measured carbon-intensiveness of an electric power system (and thus mitigation or adaptation policy recommendations) is highly sensitive to the choice of system boundary (state, regional, or broader) and the correct choice for analysis is not clear.

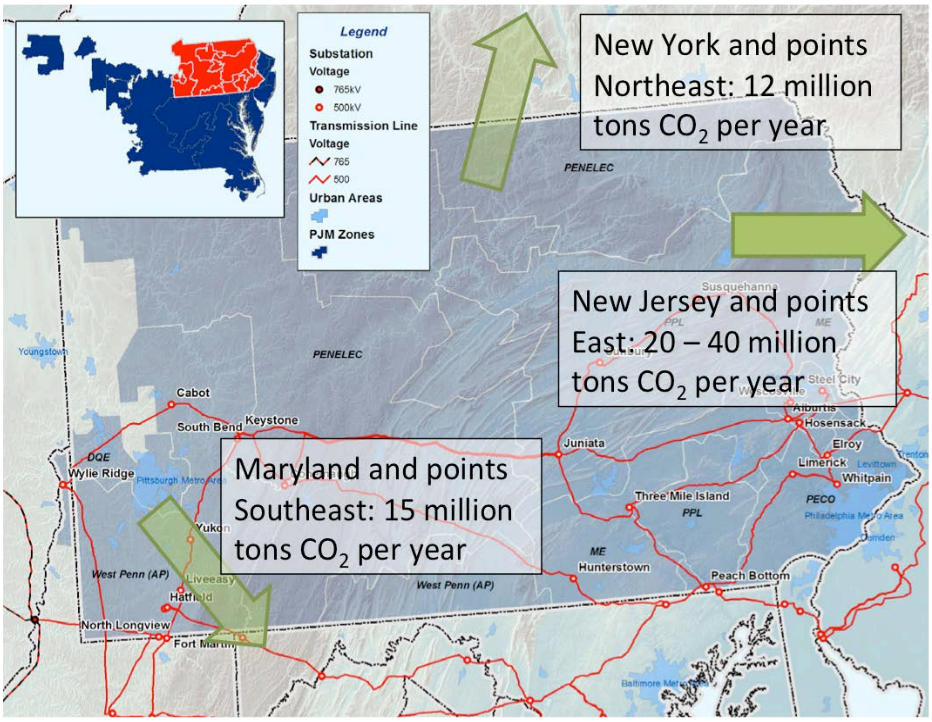


Figure 7.9a. Estimated carbon dioxide exports from Pennsylvania, based on 2009 data (English Units). The figure is suggestive of how fossil-fired generation in Pennsylvania is utilized to satisfy electric demands in other states. Blumsack, et al. (2010), based on data from PJM Interconnection.

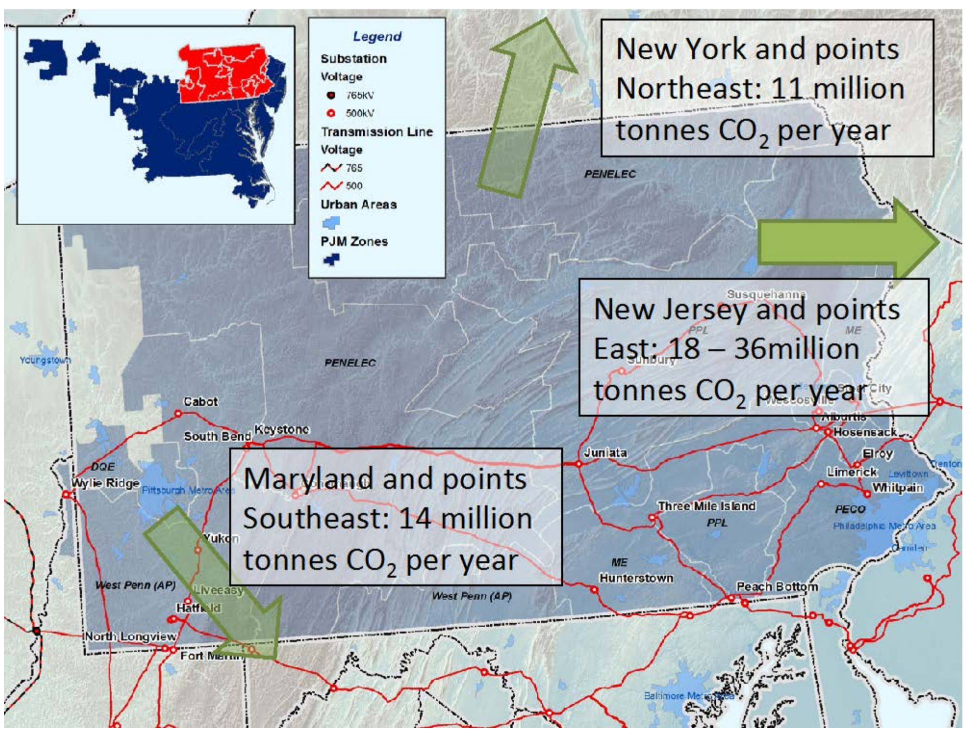


Figure 7.9b. Estimated carbon dioxide exports from Pennsylvania, based on 2009 data (Metric Units). The figure is suggestive of how fossil-fired generation in Pennsylvania is utilized to satisfy electric demands in other states. Blumsack, et al. (2010), based on data from PJM Interconnection.

Extraction of natural gas from deep shales – such as the Marcellus and Utica represents – alongside growth in the wind energy industry, probably the most significant change in Pennsylvania's energy sector over the past few years. The size of the resource and proximity to nearby markets suggest that the role of natural gas as an energy source in Pennsylvania is likely to increase. The reduction in air emissions of conventional pollutants (oxides of sulfur and nitrogen; mercury; particulate matter) achievable through a shift away from the combustion of coal and petroleum and towards natural gas can be substantial, although Katzenstein and Apt (2009) suggest that the magnitude of the emissions reduction is sensitive to the efficiency of the combustion process; the inefficient utilization of gas combustion engines may *increase* NO_x emissions under some scenarios.

The combustion of natural gas releases approximately half of the carbon dioxide as the combustion of an equivalent amount of coal or petroleum. However, this may be offset by methane produced by the natural gas extraction process as methane is a more powerful greenhouse-gas than carbon dioxide. The direct atmospheric venting of methane (as opposed to flaring) at the wellhead, or significant leakage of methane from natural gas infrastructure, may reduce the overall greenhouse-gas reduction potential of substituting natural gas for other fossil fuels. Very little data from actual well or infrastructure operations is available that suggests the rate at which methane is vented into the atmosphere or escapes from pipelines, compressor stations or other infrastructure. Measuring the greenhouse-gas impacts of Marcellus or Utica shale development, as well as the potential greenhouse-gas reductions, involves significant uncertainties. Under scenarios where large amounts of methane are vented, or fugitive methane emissions from the gas transportation system are high (as has been found for one area of Colorado, as described in Tollefson (2012)), the life-cycle climate impacts of natural gas power generation may be on par with coal-fired power generation (Howarth et al., 2011). This conclusion also rests on assumptions regarding the timing of climate impacts over which there is additional uncertainty. Three other studies (Jiang et al., 2011; NETL, 2011; Cathles, 2011) question the assumptions used by Howarth et al. (2011) and collectively draw three broad conclusions regarding the greenhouse-gas impacts of gas-shale development:

- *The reduction in life-cycle greenhouse-gas emissions from the increased utilization of shale-gas for power generation are sensitive to the efficiency of combustion and the operational scenarios. Natural gas base-load generation reduced greenhouse-gas emissions by approximately 40 to 50 percent compared to base-load coal generation. Generating electricity with natural gas in older or less-efficient plants may decrease this benefit to as little as 20 percent.*
- *Shale-gas does have a slightly higher greenhouse-gas footprint than conventional gas production, though the literature suggests less than 5 percent higher. The differences in greenhouse-gas footprint can be traced to methane venting or flaring; and differences in transportation requirements. The greenhouse-gas footprint of Marcellus Shale production and utilization is similar to that of liquefied natural gas (Jiang et al., 2011; Jaramillo et al., 2007).*
- *Where direct capture is technologically infeasible or economically unattractive, policies to encourage flaring of natural gas rather than venting can reduce greenhouse-gas emissions associated with gas shale development.*

7.4 Climate-related policy drivers affecting Pennsylvania's energy sector

Most economic research has focused on regulating greenhouse-gas emissions through price-based or market mechanisms, such as taxes on greenhouse gases or establishing a system of tradable permits for greenhouse-gas emissions. To date, Pennsylvania has not adopted these types of policies, though it acts as an “observing state” in the Regional Greenhouse Gas Initiative for trading of carbon dioxide credits in the northeastern U.S. Pennsylvania has adopted different types of policies that are relevant to the reduction of greenhouse gas emissions.

7.4.1 Pennsylvania’s Alternative Energy Portfolio Standard

Like a large number of U.S. states, Pennsylvania has adopted a “portfolio standard” that sets quantity-based targets for specific alternative energy technologies. Pennsylvania’s portfolio standard, the Alternative Energy Portfolio Standard (AEPS), defines quantity targets for a suite of electric generation technologies that have the potential to reduce air emissions of greenhouse gases or conventional pollutants, or solve other environmental problems (such as the monitoring and remediation of waste coal piles). The specified technologies generally have higher costs than existing power generation facilities, but may be relatively under-provided by the market since many environmental costs of conventional power generation technologies are not directly borne or “internalized” by generation facility owners.

Policies such as AEPS typically provide subsidies for generation resources that have high costs on an average-cost basis. In other words, the levelized cost of energy from subsidized resources is generally higher than from conventional power plants. However, many technologies subsidized through AEPS have high capital costs but very low marginal or operating costs (i.e., fuel from the wind and sun is free at the margin). The subsidies are justified economically if the integration of technologies covered under the portfolio standard provides the desired level of emissions reduction when integrated into the electrical system.[11] Determining the level of avoided emissions associated with renewable electricity generation technologies is difficult, due to the complexity in electrical system operations. One megawatt of an alternative resource, for example, may not exactly displace one megawatt of a conventional (higher-emissions) resource (Apt et al., 2007; Katzenstein & Apt 2009).

[11] The importance of matching subsidy levels to efficient levels of emissions avoidance is not fully discussed here, although it is easy to over-subsidize technologies when multiple regulatory authorities are involved. Blumsack et al. (2011) discuss this issue using ground-source heat pumps as an example.

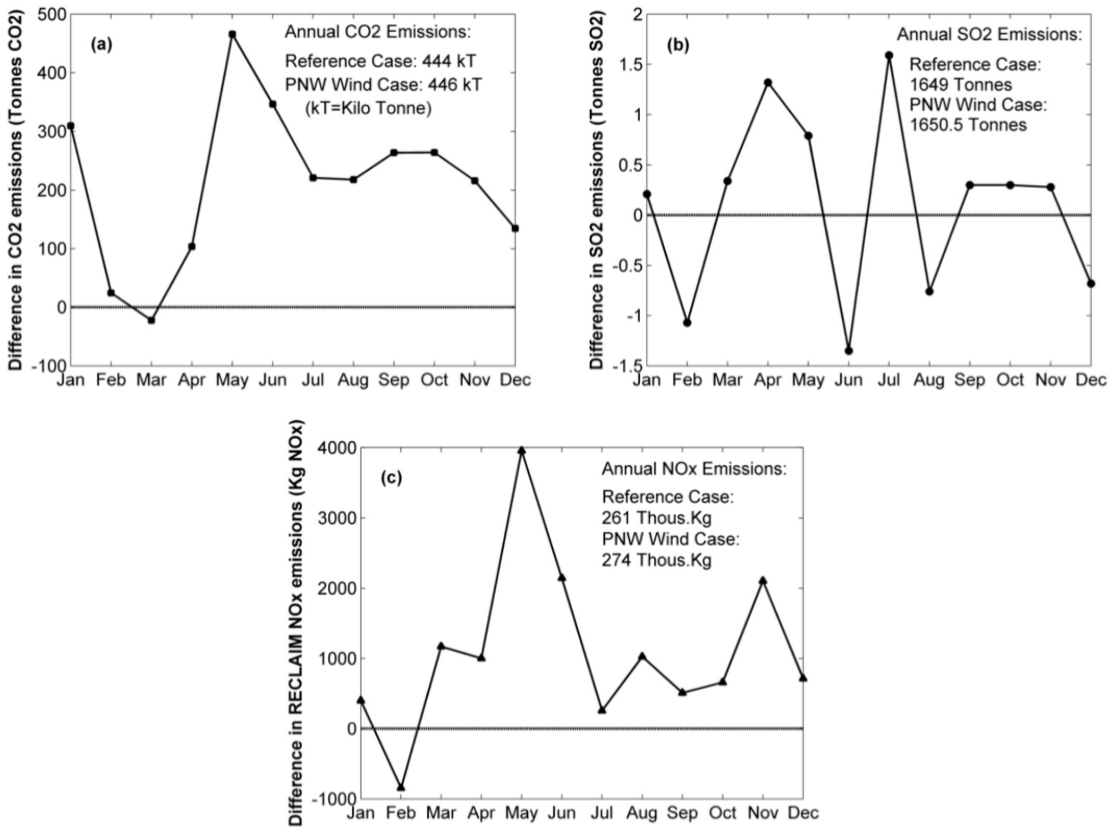


Figure 7.10. In some cases, locational decisions for renewable electricity generation may increase overall system emissions. The figure illustrates the impacts of location a large amount of wind energy in the Pacific Northwest on annual emissions of: (a) carbon dioxide; (b) SO_2; and (c) NO_x emissions under California's RECLAIM program.

Location decisions appear to be a crucial part of utilizing portfolio-standard type policies to achieve environmental goals. Choudhary et al. (2011) finds that locating wind energy facilities in the most profitable areas is not the same decision as locating facilities in areas that are best for the system as a whole. Ruiz and Rudkevich (2010) and Rudkevich and Ruiz (2011) have devised a method of screening the emissions impacts of incremental generation location decisions. Perhaps surprisingly, they find that locating zero-emissions generation assets in some areas may increase emissions in other areas at the margin. This finding is echoed by Blumsack and Xu (2011), who studied wind energy location choices in the Western U.S. As shown in Figure 7.10, they confirmed that emission of carbon dioxide and some criteria pollutants in the Western power grid as a whole may increase slightly based on location decisions.

The impacts of renewable portfolio standards on energy prices are also uncertain. While the direct subsidy costs for technologies covered under AEPS are transferred to Pennsylvania ratepayers via electricity bills, the integration of large-scale alternative energy resources may serve to *lower* prices on wholesale electricity markets (such as PJM) if sufficient resources with higher marginal costs can be displaced (Fischer, 2010). Coupling conventional and renewable electricity generation may also lower average costs of producing energy (Richardson & Blumsack, 2011).

7.4.2 Energy conservation through Pennsylvania's Act 129

Pennsylvania's Act 129, passed in 2008, requires electric retailers in Pennsylvania to reduce annual and peak-time electricity demand. The reduction targets originally laid out in Act 129 specify a performance year of 2013 for meeting those targets. Whether Act 129 will be extended (and in what form) past 2013 is still uncertain. Moreover, the Act does have implications for greenhouse-gas emissions from Pennsylvania power generators, even over the short performance period. Kleit et al. (2010) and Sahraei-Ardakani et al. (2011) have modeled the impact of Act 129 on electricity pricing, fuels utilization and greenhouse-gas emissions in Pennsylvania. They find that successful implementation of Act 129 will primarily affect the so-called marginal fuels or generation technologies – those that serve incremental electricity demand. Base-load generators (which operate more or less continuously) will see their operations affected less than other generation technologies. Since natural gas is often the marginal fuel during periods of peak electricity demand, and since greenhouse-gas emissions from natural gas are lower than from coal, the emissions impacts of Act 129 are estimated to be smaller than might be expected. The influence of Act 129 on coal-fired generation is estimated to be relatively small, although coal is estimated to play a larger role in electricity price formation in Pennsylvania.

7.5 Uncertainties and Informational Needs in Assessing Climate-Change Impacts on Pennsylvania's Energy Sector

Separating mitigation from adaptation in the energy sector is inherently difficult, as many strategies aimed at allowing individuals to adapt to climate change (such as increased use of air-conditioning) may be coupled with shifts in energy systems or the use of higher-efficiency technologies that also provide mitigation services. The impacts of climate change on the energy sector, or impacts of energy-sector shifts on mitigation efforts, are highly uncertain in some areas. This section identifies and briefly discusses specific areas where significant further research is needed.

7.5.1 Uncertainties Related to Natural Gas Impacts

As discussed in Section 7.3, growth in the natural gas industry has the potential to induce substantial energy-sector change, both in Pennsylvania and elsewhere in the U.S. There is still uncertainty, however, in the speed and direction of the substitution of natural gas for other fuels across all sections of Pennsylvania's economy. Two sources of uncertainty in particular deserve to be highlighted here, representing areas where additional information and research are needed to address impacts with a higher degree of certainty.

First, the manner in which natural gas replaces other fuels needs to be assessed using a systems-level approach. The introduction of natural gas into energy utilization and delivery systems (e.g., electric power or transportation) is more complex than just making calculations based on replacing one BTU of another fuel with a BTU of natural gas. For example, while it is true that burning a BTU of natural gas in a power plant releases less CO_2 than burning a BTU of coal or fuel oil in a power plant, the BTU-to-BTU comparison can be misleading. The greenhouse-gas impacts of additional investments in natural gas fired power generation will depend on the efficiency with which natural gas is utilized in the plant, the costs of utilizing the natural gas plant versus other technologies, and the location of the natural gas plant (i.e., the ability of the electric transmission system to bring the gas-fired power generation to market). A more valid comparison in this case would incorporate these system effects to compare the impacts of additional gas-fired power generation on a kWh-basis, not a BTU-basis. Such an approach has been lacking in the existing literature, with a few exceptions (e.g., Jiang, et al., 2011; Dowds, et al., 2012).

Second, life-cycle comparisons of greenhouse-gas emissions from the natural gas sector are subject to uncertainties due primarily to lack of data, but also due to other modeling assumptions. Differences in greenhouse-gas implications of Marcellus shale development largely come down to assumptions made over vented and fugitive CH_4 emissions and the relevant time frame for life-cycle analysis. As discussed in Section 7.3, Howarth et al. (2011) assume high levels of vented CH_4 and fugitive emissions; these estimates are viewed as unrealistically aggressive in other studies (Jiang et al., 2011; NETL, 2011; Cathles, 2011). Direct measurement of CH_4 venting and fugitive emissions is rare and expensive. The recent study described in Tollefson (2012) based on measurement of a gas field in Colorado, finds that methane releases to the atmosphere are more in line with Howarth, et al. (2011) than with other studies. While the Colorado study represents only a single data point, it is suggestive of the high degree of uncertainty that exists in current estimates of direct methane releases from natural gas drilling.

7.5.2 Uncertainties Related to the Transportation Sector

Pennsylvania currently has an energy sector dominated by the use of fossil fuels; even a relatively aggressive alternative energy policy is unlikely to change this characteristic of energy utilization in the Commonwealth. The largest potential shifts are likely to occur in the substitution of natural gas in place of other energy commodities, particularly coal (for power generation) and potentially petroleum (for power generation and transportation). The use of natural gas as a transportation fuel can reduce greenhouse-gas emissions from the transportation sector and provide more local health benefits through reduction in other pollutants, such as particulate emissions from heavy-duty diesel vehicles (buses and trucks). Retrofitting Pennsylvania’s transportation energy infrastructure to utilize natural gas on a wide scale (i.e., for light-duty and heavy-duty fleets) would involve substantial costs and would likely need large public investments. As Jiang et al. (2011) reports, natural gas transportation may be most socially beneficial if limited to fleets of buses and some trucks, although the greenhouse-gas reduction impacts would not be that large.

Electrified transportation represents another option to reduce greenhouse-gas emissions from Pennsylvania’s energy sector. Based on analysis of emissions factors from electric generation in Pennsylvania and the broader PJM region, powering light-duty vehicles using grid electricity is likely to result in lower carbon emissions than fueling this same class of vehicles on gasoline or diesel (Samaras and Meisterling, 2008; Stephan and Sullivan, 2008). The rate of adoption of plug-in hybrid electric vehicles (PHEV) is extremely uncertain and further research is necessary to understand factors likely to lead to widespread adoption. Previous research on hybrid electric vehicles (HEVs such as the Toyota Prius) over the past decade has suggested that consumer decisions to purchase plug-in electric vehicles are likely to be made on the basis of factors besides economics. For example, Maclean and Lave (2001) reported that hybrid gas-electric vehicles were unlikely to pay for themselves without a multi-year period of sustained high gasoline prices (more than \$4-\$5 per 3.8 liters; 1 gallon) even if the social benefit value of emissions reductions are incorporated into the cost-benefit calculation. Yet, within three years after publication of that article, sales of the Toyota Prius alone increased by nearly 500 percent. As costs have declined over the past five years, sales of the Prius have again increased by a factor of four. Even in scenarios where the electricity stored in plug-in hybrid electric vehicles could be sold to the grid during peak demand periods, virtually no scenario shows the fuel savings and “energy arbitrage” activity paying off the increased costs of plug in hybrid-electric vehicles (Peterson et al., 2010; Lemoine et al., 2010). Experience with the market for HEVs suggests that any growth in sales of PHEVs and fully-electric vehicles will likely be spurred by non-economic factors (including early technology adopters) or by significant declines in vehicle prices.

7.5.3 Uncertainties related to coupled energy and water systems

Electric power generation is the largest use of water in Pennsylvania, primarily in steam turbines for cooling. More than 70 percent of all withdrawals from major river basins in Pennsylvania are made to supply the water needs of a number of fossil-fired and nuclear power plants. Not all of this water use is purely consumptive, although the quality of return water may be an issue for maintaining downstream ecosystem health.

While climate change does not have the same drought implications for Pennsylvania as for southwestern areas, as discussed in Chapter 5, under some scenarios streamflows are projected to decline during the summer seasons. In some southeastern regions, increased population pressures have led to highly constrained freshwater systems during below-normal (but still not unusually low) drought years (Wishunt et al., 2008). Whether similar constraints could arise during summer seasons in the future in Pennsylvania, and its implications for energy systems is highly uncertain. The potential for increased frequency of low-flow conditions during the summer season represents a potential threat to electric reliability. If withdrawals are limited due to low-flow conditions, elevated stream temperatures or other reasons having to do with maintaining watershed ecosystem health, forced curtailments could result at nuclear facilities or fossil energy plants that require water for cooling (i.e., those that utilize steam generators burning coal, oil or natural gas). Recent droughts in the southern and southeastern U.S. have strained the ability of power plants to operate normally (Associated Press, 2011; Averyt, 2011).

Whether streamflow-induced plant curtailments could occur at Pennsylvania's major generating facilities, and how often, is highly uncertain and represents a strong need for further research. Current planning practices for the electricity system in Pennsylvania do not currently consider water-related curtailments that power plants could experience over longer time frames. It is also unclear how or whether incorporating hydrologic constraints (or climate-induced uncertainty in the hydrologic cycle) would lead to different system planning decisions than those currently made.

Recent research suggests that increased demands on river systems could increase the cost of mitigating greenhouse-gas emissions from electricity production. Variable electricity generators (such as wind and solar energy) require some sort of system back-up to smooth out fluctuations in output. Hydroelectricity can be used as a source for providing fill-in power, as output can be changed rapidly to accommodate fluctuations. Hydro power has been used as a "load-following" resource because of this operational flexibility. Fernandez et al. (2011) have investigated the financial implications (opportunity costs) associated with utilizing hydroelectric dams to mitigate fluctuations in wind energy output over a range of hydrologic conditions (from wet to drought years). When river flows are unconstrained by other demands, the opportunity costs associated with providing fill-in power for intermittent wind energy is on par with providing load-following services (the costs of which are shared among all customers in the PJM region, and are small relative to the cost of actually producing electricity). During droughts, or when other policy objectives govern release patterns from the dam, the costs of using hydroelectricity to facilitate renewable energy integration increase dramatically. Kern et al. (2011) report that operating hydroelectric dams as "run-of-river" rather than tailoring operations to capture peak prices in deregulated electricity markets reduces operating profits significantly.

7.6 Conclusions

Broadly, the likely impacts of climate change on energy production and utilization in Pennsylvania have not changed significantly from the 2009 PCIA. Warming in Pennsylvania is likely to increase the demand for electricity for cooling in the summertime, and can be expected to decrease demand for heating fuels in Pennsylvania, the primary fuels used for heating are natural gas, fuel oil and electricity. The increase in cooling demand is likely to outweigh the decline in heating demand, implying that electricity consumption is likely to increase as a result of climate change. Perhaps more notably, peak-time electricity demand is likely to increase. Meeting peak-time electricity demand without sacrificing reliability is challenging and costly (Spees & Lave 2008), although recent policy initiatives to increase demand-side participation in regional electricity markets may help to reduce costs and impacts on electric reliability (Walawalkar et al., 2008; Blumsack & Fernandez 2011).

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8.0 Forests

Chapter 7 of the 2009 ***Pennsylvania Climate Impacts Assessment*** on climate change in Pennsylvania (Shortle et al. 2009) listed six key conclusions related to climate change and Pennsylvania's forests:

1. Suitable habitat for tree species is expected to shift to the north. This will reduce the amount of suitable habitat in Pennsylvania for species that are at the southern extent of their range in Pennsylvania, and the amount of habitat in the state that is suitable for species that are at the northern extent of their range in Pennsylvania will increase.
2. The warming climate will cause species inhabiting decreasingly suitable habitat to become increasingly stressed. Mortality rates will increase and regeneration success will decline for these species, resulting in declining populations of those species in the state.
3. Longer growing seasons, warmer temperatures, possibly higher rainfall, and a phenomenon termed "CO_2 fertilization" may increase overall forest growth rates in the state, but the increased growth rates may be offset by increased mortality (see conclusion 2 above).
4. The state's forest products industry will need to adjust to a changing forest resource. The industry could benefit from planting faster-growing species and from salvaging dying stands of trees. Substantial investments in artificial regeneration may be needed if large areas of forests begin to die back due to climate-related stress.
5. Forests can contribute to the mitigation of climate change by sequestering carbon. It would be difficult to substantially increase the growth rates of Pennsylvania hardwoods, so the best opportunities most likely lie in preventing forest loss.
6. Forests can also be a significant source of biomass to replace fossil fuels.

Since the 2009 PCIA, climate scientists and forest biologists have continued to improve our understanding of how climate change is affecting and will likely affect Pennsylvania's forested ecosystems. However, none of the above conclusions are contradicted by recent research on the impacts of climate change on the forests of the eastern U.S. As discussed below, research continues to support the expectation that suitable habitat for the tree species currently found in the state will shift northward, but recent research has more accurately quantified expected habitat shifts. Recent research does not show observed increases in tree mortality in the eastern U.S. due to climate change, nor have growth rates been shown to increase as a result of climate change. Nevertheless, these effects are still expected to occur as climate change progresses. There has been little, if any, new research on how the forest products industry of the northeastern U.S. is likely to adapt to changed forests in the future, so no research on that topic is discussed in this update. There is little doubt that forests play a key role in the Earth's carbon cycle. Considerable research has been done in the past two years on how forests can be managed to sequester more carbon. However, none of this research contradicts the basic conclusion of the 2009 PCIA that the best strategy for managing the carbon stored in the hardwood forests of the northeastern U.S. is to minimize forest loss. Some new research has raised doubts about the efficacy of replacing fossil fuels with forest biomass. This literature is discussed later in this chapter.

The 2009 PCIA listed four strategies for managing Pennsylvania's forests to help them adapt to climate change. They are:

1. Management for healthy, resilient forests with a high degree of biodiversity.
2. Conduct research to better predict the impacts of climate change on the forests in the Commonwealth.
3. Monitor the health and productivity of the forest resource to identify and detect the effects of climate change.
4. Recognize potential climate-change induced stresses when planning forest management activities.

This update supports the importance of each of these adaptation strategies. With regard to the first adaptation recommendation, this update emphasizes the importance of minimizing additional fragmentation of the state's forest resources.

This chapter of the update is organized as follows. The rest of the introduction provides an overview of the key issues related to the impacts of climate change on Pennsylvania's forests. The next section reviews various ways climate change is expected to affect forests, including shifts in tree species ranges, impacts on tree regeneration and mortality rates, changes in the timing of key biological events (called phenology) such as leafing out and flowering, impacts on tree growth rates, interactions of climate and pollution and the resultant effects on trees, changes in insect and disease dynamics, and impacts on forest animals. The following section discusses how forests can be managed to mitigate climate change. This section discusses strategies for managing forests to increase carbon storage and the debate about whether substitution of woody biomass for fossil fuels is a useful strategy for reducing carbon emissions. The final section discusses ways to help forests adapt to climate change. The section focuses primarily on the so-called "assisted migration" debate, in which some have advocated actively relocating species that are most threatened by climate change.

Current and projected changes in the state's climate affect forests directly through increases in average, maximum and minimum temperatures, longer growing seasons, increased average rainfall, decreased winter snow cover, more intense weather events, and longer periods of drought (Hayhoe et al., 2007, 2008). These direct effects will change the suitability of areas within the state to support the species that are currently found there, causing increased stress and mortality in mature trees, changes in the regeneration rates of tree species, and ultimately changes in stand structure and species composition. Changing atmospheric concentrations of various gases also directly influence plant chemistry and growth. These changes will also indirectly affect forests in many different and less predictable ways, including changes in soil chemistry (Campbell et al., 2009), changing population dynamics of pests and organisms that cause disease (Dukes et al., 2009), changes in rates of growth and spread of invasive species (Dukes et al. 2009), and changes in both competitive and symbiotic relationships among species, both plant and animal. How all these changes will play out on the forested ecosystems of the state is difficult to predict, but evidence from around the world and from the region already show some consistent signs of how these ecosystems are likely to respond. Species' ranges are shifting poleward (Chen et al., 2011), in many areas (although not necessarily the northeast U.S. (Dietze & Moorcroft 2011)) mortality is increasing (Allen et al., 2010), and rates of regeneration are shifting (Woodall et al., 2009). By changing the relative competitiveness of different tree species, climate change is likely to shift the species composition of Pennsylvania's forests. Trees and other plants are also responding to changing climate by leafing out earlier, flowering earlier, and through other phenological changes (Bertin 2008).

In the long run, whether species thrive or decline under changing climate regimes depends on [1] their ability to adapt to a wide range of conditions, [2] their ability to migrate to locations with more favorable climates and to compete with the other species that they encounter as they migrate, [3] their ability to compete with other species that migrate into their ranges, [4] changes in the distribution and phenology of species with which they have symbiotic relationships, such as pollinators, and [5] changes in the distributions and vigor of the pest species that target them, such as insects and diseases (Aitken et al., 2008). As a general rule, climate change will tend to favor generalist species with shorter reproductive cycles, greater mobility, and greater genetic diversity. Climate change is a greater threat to species with small populations that occupy narrow, geographically isolated ecological niches, and with limited genetic diversity (Aitken et al., 2008).

As forests represent significant pools of carbon, they can play a role in mitigating climate change. Globally, loss of forestland is a significant contributor to climate change, but Pennsylvania's forests have been growing and therefore represent a carbon sink. However, this trend could be reversed by increasing losses of forestland to development and through increased mortality rates.
Modern forested landscapes have been fragmented by agriculture, development and transportation corridors, making them less capable of adapting to climate change today than in the past. This is primarily because fragmentation reduces the ability of species – both plant and animal – to migrate across the landscape. One of the most useful things humans can do to help forests adapt to climate change is by reducing and even reversing the trend toward greater fragmentation (Krosby et al., 2010). Nevertheless, it is unlikely that the majority of forest plant species will be able to migrate as fast as will be necessary to keep up with changes in the climate (Loarie et al., 2009). Because of this, some authors have suggested that we should actively move some species to new habitats that are currently or are projected to be more suitable for those species (Hewitt et al., 2011). Others have argued against this notion, for a variety of reasons (Hewitt et al., 2011).

Changes in forest ecosystems' composition and health will also affect communities and industries that depend on these natural resources. These changes will influence the ability of the state's forest ecosystems to provide forest products, clean water, carbon sequestration, recreational opportunities, wildlife habitat, and maple syrup production. Furthermore, other trends, such as the development of the Marcellus shale for gas production, are also affecting these ecosystems. Natural gas development is bringing jobs and wealth to Pennsylvania communities, but at the same time this development may make the forest ecosystems of Pennsylvania less resilient to changes in climate. In addition, the recession that started in 2008 has had a devastating effect on the state's forest products industry. New wood products industries, such as those that would utilize woody biomass for energy production have not yet grown significantly, but have the potential to do so in the coming decade. Much has changed since the 2009 PCIA on potential impacts of climate change on the state. This update reviews new literature relevant to understanding the potential impacts of climate change on Pennsylvania's forests and wildlife.

8.1 Climate Changes' Effects on Pennsylvania Forests

Anticipated changes in the climate of Pennsylvania are likely to alter Pennsylvania's forest ecosystems through [1] range shifts, including expansions and contractions, of tree species, birds and mammals, [2] increased mortality and extinction rates, [3] changes in ecosystem productivity and phenology, and [4] increases in insects, pathogens and invasive species.

8.1.2 Tree Species Range shifts

Evidence continues to accumulate that climate change is altering forest ecosystems through shifts, including expansions and contractions, in the ranges of tree species and the other fauna and flora associated with those ecosystems. In a seminal study based on three data sets, (British birds, Swedish butterflies, and Swiss alpine plants) Parmesan and Yohe (2003) estimated that species were migrating poleward at an average rate of 6.1 km per decade (3.8 miles per decade). A more recent study by Chen et al., (2011) updates these estimates based on 53 studies, which included "23 taxonomic group × geographic region combinations for latitude, incorporating 764 individual species responses and N = 31 taxonomic group × region combinations for elevation, representing 1367 species responses" (Chen et al., 2011, p. 1024). Chen et al. (2011) estimate that the median latitudinal migration rate is 16.9 km/decade (10.5 miles/decade) and that the median altitudinal (upslope) migration rate is 11.0 m/decade (36 feet/decade). Chen et al. (2011) suggest that the primary reason they estimated faster migration rates is that their datasets cover more recent time periods than those used by Parmesan and Yohe (2003). This is consistent with the observation that temperatures have increased about four times as fast since 1970 than between 1900 and 1970 (IPCC 2007). The study found that the latitudinal shifts were consistent with expected shifts based on observed regional temperature changes but that elevation shifts were generally less than expected. Bertin (2008) also reviews numerous studies showing poleward and upslope range shifts for dozens of plant species in response to climate change.

In the northeastern U.S., Beckage et al. (2008) identified a 91-110 m (299-361 feet) upslope shift in the northern hardwood–boreal forest ecotone along elevation transects in the Green Mountains of Vermont over the 43-yr. period between 1962 and 2005. This translates into a 21.2-25.6 m (70-84 feet) decadal altitudinal migration rate, approximately double the average rate found by Chen et al. (2011). Based on climate data, Beckage et al. (2008) estimated an expected shift of 208 m (682 feet), suggesting a lag in the rate of migration.

Models of tree species envelope shifts project that boreal hardwood species such as birch and aspen are likely to decrease dramatically in abundance in Pennsylvania during the 21st Century as their climate envelopes shift northward (McKenney et al., 2007; Mohan et al., 2009; Iverson et al., 2008). Similarly, northern hardwoods, such as American beech, red and sugar maples, black cherry, and American basswood, and common northern conifers, including hemlock and white pine, are also likely to decline in abundance in the state as the habitat in the state becomes increasingly less suitable for those species. On the other hand, species that are currently in the northern extent of their climate envelopes in Pennsylvania, such as oaks, hickories, silver maple, eastern red-cedar, and loblolly and shortleaf pine, will find increasingly suitable habitat conditions In Pennsylvania in the coming century and are likely to increase in abundance (McKenney et al.; 2007; Mohan et al., 2009; Iverson et al., 2008). In addition to a general northward shift of species' ranges, species will likely shift upslope to higher elevations during the coming century.

Models used to predict species shifts based on the predictions of atmosphere-ocean global circulation models (AOGCMs) are being refined and validated. McKenney et al. (2007) projected on average that the climate envelopes of 130 North American tree species would shift north by 700 km (435 miles) by the end of the century, and that the average climate envelope would shrink by 12 percent. Under a scenario where tree species climate envelopes were assumed to not migrate northward, the average northward shift was only 330 km (205 miles), but future potential ranges were projected to be 58 percent smaller, on average, than today (McKenney et al., 2007). (Note, the centroid of the climate envelope moves north even though the northern boundary is not allowed to advance because of shrinkage of the envelope along its southern extent.) A more recent article by McKenney et al. (2011) compares how different AOGCMs influence predictions of shifts in species' climate envelopes over the course of the century. While McKenney et al. (2011) found large differences between the predicted climate envelope shifts based on different AOCGMs, the predictions from more recent versions of the models (2008-2010) were more consistent than the predictions from older versions of the models (2003-2005), suggesting that improvements in the AOCGMs are reducing this source of uncertainty in climate envelope projections.

8.1.2 Tree Regeneration

Seed germination is affected by temperature and moisture (Walck et al., 2011). In general, each species has an optimal temperature and moisture regime for seed germination, so deviations in either direction from this optimum can be expected to lead to lower regeneration rates. Furthermore, increased CO_2 levels have been found to increase (Farnsworth & Bazzaz 1995; LaDeau & Clark 2001, 2006) and decrease (Farnsworth & Bazzaz 1995; Thomas et al., 1999) seed production, and to cause it to occur earlier (Farnsworth et al., 1996). Woodall et al. (2009) found that for northern tree species, seedling density relative to tree biomass was nearly 10 times higher in northern latitudes compared to southern latitudes. However, no such relationship was found for southern tree species. For northern species, this suggests that conditions for regeneration are more favorable at the northern limits of their ranges than at the southern limits. Increases in regeneration rates in species' northern ranges and decreases in regeneration rates in their southern ranges is one mechanism by which climate change shifts species composition and ultimately produces a northward shift in the species' ranges.

8.1.3 Tree Mortality

As climactic factors such as temperature and rainfall shift, at least some trees that were previously well-adapted to the climate in their current location will become less well adapted. This maladaptation to the changed climate will result in physiological stress that could directly kill trees or increase their susceptibility to other causes of mortality such as fire, insects and diseases (Allen et al., 2010). Furthermore, warmer temperatures and longer growing seasons will increase rates of evapotranspiration by plants, (Huntington et al., 2009) exacerbating the effect of longer periods of drought as rainfall becomes more sporadic in the region. Higher mortality has been observed with higher temperatures and lower precipitation rates in many regions of the world (Allen et al., 2010) and in the Western U.S. (van Mantegem et al., 2009). At least at present, however, there is little evidence that climate factors have significantly increased mortality rates in the eastern U.S. Dietze and Moorcroft (2011) evaluated four categories of tree mortality drivers in the eastern and central U.S.: [1] climate, [2] air pollutants, [3] topography, and [4] stand characteristics. They found that air pollutants (e.g., acidification and nitrogen deposition and ozone) and stand characteristics (stand age and density) were the most important drivers of mortality. Climate factors were a distant third in significance, and varied with different species and portions of their range. For many eastern species, mortality declined with increased temperatures, and increased mortality was not always more pronounced in the southern parts of species' ranges. Similarly, warmer winters were associated with increased mortality in some species but lower mortality rates in others (Dietze & Moorcroft 2011). For some species, hemlock for example, higher mortality rates associated with warmer winter temperatures were likely linked to greater winter survival of insects and pathogens (Paradis et al., 2006).

Increased tree mortality could also occur if climate change increases the intensity of storms in Pennsylvania. Although there is considerable uncertainty about how climate change will affect the intensity and frequency of major storms in the region, Huntington et al. (2008) and Emanuel (2005) derived an index of potential hurricane destructiveness and found that it has been increasing over the past 30 years. In addition, longer periods of drought can lead to more fires and associated tree mortality (Huntington et al., 2009).

8.1.4 Phenological Mistiming

Climate change is altering the timing of a variety of events in the life cycles of plants (i.e., their phenology). Spring events, including leafing out and flowering, have moved up on average by 4-5 days for each degree Celsius of warming (Bertin, 2008). Fall events are typically delayed, but less consistently compared to spring events (Bertin, 2008). Phenological impacts are easier to observe than range shifts because it takes longer for plants to shift their ranges than to adjust the timing of events in their life cycles. As a result, there are an overwhelming number of studies documenting shifts in the life cycles of plants in response to climate change (Bertin, 2008). Plants rely on animals, such as bees and squirrels, for a variety of critical ecosystem services (i.e., pollination and seed dispersal). These animals also respond to climate change by shifting critical events in their life cycles, but not necessarily at the same rates as the plants with which they interact. As climate change shifts the timing of events such as when forest plants flower, disperse pollen, and produce seed, these events could become out of sync with the life cycles of the animals they depend on to support these functions. Such "de-coupling" of these events can reduce reproductive success of both plant and animal species (Bertin 2008; Mohan et al., 2009). In some cases, plants could benefit from mismatching of pest phenology with the timing of key events in the plants' life cycles. (e.g., winter moths' eggs hatching later than the timing of the oak buds on which they feed) (Bertin, 2008; Visser & Holleman 2001).

8.1.5 Growth impacts

Climate change could lead to increased growth rates due to [1] longer growing seasons (Hayhoe et al., 2007; Campbell et al., 2009), [2] increased CO_2 levels (Huang et al., 2007), and [3] increases in soil nitrogen due to increased mineralization and nitrification (Bertin, 2008; Campbell et al., 2009). Growing seasons in Pennsylvania are projected to increase by 29-43 days during the 21st century (Hayhoe et al., 2007). Many studies have looked at the impact of elevated CO_2 levels on plant growth and reproduction. Huang et al. (2007) reviewed the literature on the hypothesis that CO_2 increases plant growth. While many free-air CO_2 enrichment (FACE) experiments have found that trees grow faster under elevated CO_2 conditions, most of these studies are relatively short-term compared to the full life cycle of trees and have focused mostly on young trees (Ainsworth & Long 2005). Attempts to detect the effect of elevated CO_2 on tree growth from tree ring analysis have been less conclusive, and Huang et al. (2007) concluded that the CO_2 fertilization hypothesis is only well supported by tree-ring analysis in semi-arid or arid conditions where nitrogen is not limiting. This is not surprising, since it is well established that CO_2 increases water use efficiency (Huang et al., 2007). In other cases, results are less clear because it is hard to separate the CO_2 effect from the effects of warmer climate and anthropogenic atmospheric deposition (e.g., nitrogen) (Huang et al., 2007). However, in an analysis of 49 studies, Boisvenue and Running (2006) found that climate change has generally increased forest growth rates, except on water-limited sites, over the past 55 years.

8.1.6 Atmospheric Impacts

The effects of increased atmospheric CO_2 are complicated by other man-made atmospheric changes, such as increased ozone (O_3) and deposition of nitrogen (N) and sulfates (S), whose negative effects could more than offset any increase in productivity due to the potential growth-enhancing effects of nitrogen deposition and enriched atmospheric CO_2 (Ollinger et al., 2002; Campbell et al., 2009; Mohan et al., 2009). Sulfate deposition causes soil acidification in Pennsylvania and other industrialized areas, but sulfate aerosols also scatter solar radiation and reduce temperatures (Campbell et al., 2009). Nitrogen deposition can improve soil productivity, stimulating greater forest growth and carbon sequestration, or it can contribute to acidification (Campbell et al., 2009)

8.1.7 Insects, Pathogens and Invasive Species

Climate change will indirectly affect forests by influencing the populations, ranges and activity of various "nuisance species," including both native and exotic insects, tree diseases, and invasive species (Dukes et al., 2009). These species affect forests by stressing and killing trees and by interfering with key processes such as regeneration. Pennsylvania forests host a large number of forest insect pests, including elm spanworm, emerald ash borer, forest tent caterpillar, gypsy moth, hemlock woolly adelgid, and two-lined chestnut borer (Dukes et al., 2009). While we cannot say with certainty how climate change will affect these and other insect pests, a few general observations are possible. Insect metabolic rates tend to double with an increase of 10°C (18°F) (Clark & Fraser 2004). Like other species, insect ranges tend to shift northward with warming climate (Logan et al., 2003; Parmesan, 2006). On the other hand, while insect ranges are often limited by minimum winter temperatures, lack of winter snow cover may reduce overwintering survival rates for some species (Ayres & Lombardero 2000). Longer warm seasons have allowed some insect species to go through more generational cycles within each season, greatly increasing potential population growth rates (Logan & Powell 2009). Wetter climates are generally better for insects, but longer periods of drought can be detrimental to insect populations. In general, insects are likely to be more adaptable to changing ecological conditions because their short reproductive cycles allow for faster rates of genetic adaptation. Dukes et al. (2009) discuss an example of how climate change can influence the impact of an insect pest that is important in Pennsylvania's forest ecosystems: the hemlock woolly adelgid. The adelgid has had a devastating effect on one tree species in Pennsylvania, particularly in the eastern and southern part of the state. However, the insect's expansion into the northwestern part of the state has been limited by the region's cold winters (Paradis et al., 2006). A warming climate could therefore allow the insect to expand its range within the state.

Pennsylvania's forests are also affected by a number of tree pathogens, including: armillaria root rot, elm yellows, beech bark disease, chestnut blight, dogwood anthracnose, Dutch elm disease, and oak wilt, among others (Dukes et al., 2009). Given the wide variety of pathogens and their ecological characteristics, few generalizations are possible. On one hand, many diseases, such as rust fungi, will benefit from wetter conditions (Dukes et al., 2009; Lonsdale & Gibbs 1994; Vanarsdel et al., 1956), but others, such as powdery mildew, do not (Lonsdale & Gibbs 1994). As with insects, warmer winter temperatures tend to increase overwinter survival (Coakley et al., 1999), but lack of snow cover can be detrimental to other species (Ayres & Lombardero 2000). Increased mechanical damage to trees resulting from more intense storms can create more opportunities for both diseases to infect trees (Shigo, 1964). Like insects, pathogens are likely to be more adaptive to changing environmental conditions because of their short reproductive cycles relative to trees (Brasier, 2001). In general, as trees are stressed by climate change, they can become more susceptible to insects and diseases. Armillaria root rot, for example, is a tree disease that is common in Pennsylvania. Because it tends to infect and kill mainly trees that are already stressed by some other factor, armillaria root rot is not currently a major cause of mortality in Pennsylvania's forests. However, if a large number of trees are stressed by climate change, this currently minor disease could become a significant driver of tree mortality in the state (Dukes et al., 2009).

Invasive plant species affect Pennsylvania's forest ecosystems by competing with native trees and understory species for space, interfering with regeneration processes, and, in the case of vines, by climbing, breaking and killing trees. Some non-native invasive species that affect Pennsylvania's forests are oriental bittersweet, purple loosestrife, Japanese knotweed, Japanese stiltgrass, Japanese and European barberry, Russian olive, Japanese and Amur honeysuckle, multiflora rose, mile-a-minute vine, kudzu, Norway maple, and tree-of-heaven. While changes in climate can potentially affect these species in both negative and positive ways, the fact that these species are invasive is an indication of their ability to compete in new environments and to migrate quickly into new habitats. These species tend to have potential for rapid evolutionary change (Maron et al., 2004; Schweitzer & Larson 1999) and broad environmental tolerances (Qian & Ricklefs 2006). Thus, these species are likely to thrive under changing climatic conditions (Dukes et al., 2009), and climate change will likely exacerbate problems caused by these species.

8.1.8 Fauna

Climate change will affect the animals that inhabit forest ecosystems in many different ways. As with plants, some species will benefit from these changes and others will be affected negatively. Climate change affects animals through direct effects from changes in temperature and rainfall regimes and indirect effects through changes in habitat and interactions with other species, including predators, prey, competitors, parasites and diseases. Rodenhouse et al. (2009) review the potential impacts of climate change on mammals, birds, amphibians and insects in the northeastern U.S. The 59 species of mammals in the northeastern U.S. vary in size from the smallest, the pipistrelle bat (3.5-6 g; .12-.21 oz), to the largest, the moose (315-630 kg; 694-1,389 lbs). Smaller mammals tend to be more susceptible to colder temperatures due to their relatively high surface area-to-mass ratios. Smaller mammals, therefore, generally need to find cover during the winter. (e.g., underground in the case of small rodents such as mice and voles, or in caves or under tree bark in the case of bats). In general, one would expect these species to benefit from less harsh winter conditions, but this is not necessarily always the case. In the case of small rodents, snow cover provides additional insulation, so reduced snow cover can result in higher winter mortality. Bats are very sensitive to hibernation conditions, and warmer temperatures can decrease their survival due to more frequent arousals even though the duration of the hibernation period is decreased (Rodenhouse et al., 2009). Large mammals find thermal cover under coniferous trees, so reductions in the number and distribution of hemlock and white pine can have a negative effect on their winter survival. Shorter, warmer winters with less snow cover can also result in greater parasite populations, such as ticks (Rodenhouse et al., 2009).

Birds are affected by climate change in many ways. Warmer weather has resulted in earlier arrival and breeding dates for migrants (Rodenhouse et al., 2009). Rodenhouse et al. (2009) also found that the populations of 15 out of 25 bird species that are permanent residents of the North Atlantic Forest Bird

Conservation (NAFBC) have increased in abundance, 5 species have decreased, and 5 species have shown no discernible trend. The ranges of most bird species found in the northeastern U.S. (27 out of 38, Rahbek et al., 2007) have shifted northward. Rodenhouse et al. (2008) model shifts in the bioclimatic envelopes for 150 bird species. They projected declining bird species richness in Pennsylvania and western New York, but increasing species richness in Maine and New Hampshire. Different groups of bird species were projected to be affected differently, with more temperate migrants declining than increasing, no net changes in neotropical migrants (declines approximately equaling gains), and with most resident species gaining from warming temperatures. In addition to temperature changes, changes in rainfall can affect bird populations. Increased rain can result in reduced survival of eggs, nestlings and adults and less food for aerial insectivores (Rodenhouse et al., 2009). Furthermore, migrants are affected by changes in climate in their wintering areas and can experience greater mortality during migration as a result of storms (Rodenhouse et al., 2009).

Amphibians are an important component of the fauna of temperate forests, often comprising a greater proportion of the faunal biomass than all other faunal species combined (Rodenhouse et al., 2009). Furthermore, amphibian populations are already stressed, with 25 of the 32 species found in northeastern forests under some type of protected status (Rodenhouse et al., 2009). Amphibians are particularly susceptible to climate change because they are sensitive to desiccation, their habitat is often dispersed, and they are susceptible to disruption of phenological relationships with their prey (Rodenhouse et al., 2009). Warmer temperatures and higher rates of evapotranspiration will likely lead to faster desiccation and even loss of the vernal pools that are crucial habitat for some amphibians. Amphibians are also likely to be negatively affected by the increased variation in streamflows and soil moisture in riparian areas that is projected under climate change.

8.2 Mitigation

Forests play a significant role in the carbon cycle of the Earth. Worldwide, they store about two times the amount of carbon in the atmosphere, and each year they sequester an amount of carbon approximately equal to 30 percent of all emissions from burning fossil fuels and deforestation (Canadell & Raupach 2008). In the U.S., net CO_2 sequestration in U.S. forests and forest products was 790 million metric tons (Heath et al., 2011), offsetting 12-19 percent of the nation’s fossil fuel emissions (Ryan et al., 2010). As Pennsylvania’s forests have recovered from heavy exploitation around the beginning of the 20th Century, they have increased in volume and acted as a net carbon sink (McWilliams et al., 2007). In spite of this important role, it is not always obvious how forests can be managed to best mitigate climate change. Ryan et al. (2010) discuss several strategies for [1] increasing forest carbon storage, [2] reducing the loss of carbon stored in forests, and/or [3] offsetting fossil fuel consumption. However, each of the strategies has trade-offs and risks. The least risky strategy is reducing deforestation. When forests are lost, much of the carbon stored in them is also lost. Moreover, it should be noted forests provide many ecosystem and social benefits in addition to carbon storage and sequestration, which is why forest management is imperative. There are also no direct costs of mitigating deforestation, only the opportunity costs of not developing the forestland. Similarly, afforestation is a relatively low risk strategy, but in this case, costs are direct – land must be acquired and planted. Decreasing harvests retains more of the carbon stored in the forest, but foregoes forest products and harvest revenue that could have been obtained, and may simply shift harvests to another location. Furthermore, harvested wood and its associated carbon that ends up in forest products may represent another long-term carbon storage pool, and young (regenerating) forests grow faster and sequester more carbon per acre than older forests. Increasing growth rates of existing forests by management intensification sequesters more carbon and produces more forest products, but such treatments may be expensive and can lead to loss of biodiversity if natural forests are replaced with planted forests. In Pennsylvania's forests, few cost-effective management intensification options are available. Using woody biomass from the forest for energy in place of fossil fuels can, in the long run, decrease carbon emissions, but in the short run this strategy reduces the amount of carbon stored in the forest and results in higher emissions. This option is discussed in more detail below. Using wood products in place of concrete and steel reduces net emissions, but reduces carbon stored in forests. Finally, increased planting and better management of urban forests can increase the amount of carbon stored in urban ecosystems (Ryan et al., 2010). All of these options can potentially be applied to some degree in Pennsylvania. Further analysis of the costs and benefits of each should be done.

Woody biomass is considered by many to be "carbon neutral." However, this is a complex issue. Harvesting more wood biomass for energy production will, at least in the short run, inevitably lead to less carbon stored in forests and emission of this carbon to the atmosphere. Furthermore, because the energy content per metric ton of carbon emitted by burning wood is less than for coal, and significantly less than for natural gas, replacing these fossil fuels with biomass energy will in the short run require emitting more carbon into the atmosphere per unit of energy produced. Assuming that the harvested wood eventually grows back, this "carbon debt" will be offset over time by the regrowth of the forest, ultimately resulting in a net carbon benefit. But the time required achieving a net reduction in atmospheric carbon by substituting woody biomass for fossil fuels ranges from a few years to more than a century (Manomet 2010; McKechnie et al., 2011). The length of time needed to offset this carbon debt varies with four variables.

1. The efficiency of the process used to convert the wood to energy,
2. The type of fossil fuel technology that is replaced,
3. Whether the wood used is from standing trees (that presumably would not have been harvested or died anyway) or whether it is from harvest residues (which would have eventually released their carbon through decomposition),
4. The rate of regrowth of the harvested forest (McKechnie et al., 2011). Thus, each woody biomass bioenergy application should be analyzed carefully to determine the time profile of the carbon benefits, if indeed there are any.

8.3 Adaptation

Whether or not tree populations successfully adapt to climate change will depend on [1] their ability to migrate to more suitable habitats, [2] the genetic variation in populations and their ability to adapt and thrive in a variety of conditions, [3] their ability to compete with other species in the context of the changed climate (Clark et al., 2011), and [4] their susceptibility to existing and new mortality agents, such as fire, drought, insects and diseases (Aitken et al., 2008). Several strategies have been discussed in the literature for enhancing ecosystems' ability to adapt to climate change, including [1] increasing landscape connectivity (Heller & Zavaleta 2009; Krosby et al,. 2010), [2] assisted migration (Hewitt et al., 2011). The purpose of improving landscape connectivity is to facilitate the migration of populations of organisms across the landscape so they can colonize new areas that have more suitable habitat conditions as climate change makes the areas they currently inhabit less suitable (Krosby et al., 2010). This can be done by maintaining or restoring corridors of natural landscape, increasing the number and proximity of stepping-stone reserves, and by making the matrix between reserves more suitable for migration of species if not colonization (Krosby et al., 2010). The diversity of habitat requirements for different species makes this difficult to accomplish in practice, but corridors of natural landscapes can be used by a wide variety of species (Gilbert-Norton et al., 2010). In Pennsylvania, a key challenge in the coming decades will be maintaining forest habitat connectivity in the more heavily forested parts of the Marcellus Shale region where natural gas development is likely to result in expansion of existing roads, development of new roads, and development of pipeline corridors, all of which will contribute to further fragmentation of the landscape.

Loarie et al. (2009) estimate that, on average, some plants and animals will have to migrate at a rate of 420 m/year (1/4 mile/year) in response to climate changes projected under the IPCC A1B emissions scenario. This is consistent with Hughes (2000), who estimated that eastern North American trees will have to migrate at rates of 3000-5000 m/decade. Fossil pollen studies suggest that when the Laurentide ice sheet melted in the late Quaternary-early Holocene North American trees migrated at rates up to 100-1000 m/decade(328 -3280 feet/decade) (Davis, 1981; Delcourt & Delcourt 1987; MacDonald et al., 1993). However, Dyer (1995) estimated early-Holocene migration rates of only 136 m/decade (446 feet/decade) or less. Petit et al. (2008) suggest that past migration rates may have been even slower than this because the role of small refugia has been ignored in most pollen studies. Furthermore, migration rates could be much slower in modern, fragmented landscapes. Under current rates of climate change, mobile species have been observed to be migrating at rates of more than 1 km/yr (.62 miles/year) (Chen et al., 2011), and AOGCMs are predicting migration rates of 1 km/year (.62 miles/year) or higher (Malcom et al., 2002). In contrast, Iverson et al. (2004) estimate that most tree species may only be capable of migrating up to 100-200 m/year (328-656 feet/year), which is less than one tenth of the rate that may be required to keep up with changing climates. Species with very specific habitat requirements, that tend to be found in small, isolated populations and that take longer to reach sexual maturity will be least able to adapt by migrating to new habitats.

To address the challenge that at least some species will not be able to migrate fast enough to keep up with changing habitat conditions, several authors (Appell, 2009; Hewitt et al., 2011) have proposed a strategy of assisted migration. Some are even putting the practice into place. For example, Marris (2009) reports on efforts in British Columbia to identify which Douglas fir seedlings, including those from seed sources from as much as 500 km (311 miles) to the south, will grow best in various locations. Some researchers have opposed assisted migration (Hunter, 2007; Davidson & Simkanin, 2008) for a variety of reasons. Key concerns with assisted migration are [1] the huge logistical challenge of assisting more than a few key species, [2] the fact that one would ideally like to conserve entire communities, to the extent possible, rather than manage for the conservation of individual species, and [3] the bioethical issues related to replacing communities that are currently in a given location with communities from another location (Hewitt et al., 2011). At a minimum, research is needed to identify species most susceptible to extinction from climate change, and seed transfer guidelines should be developed for these species (Aitken et al., 2008).

8.4 Conclusions

Climate is currently and will continue to affect Pennsylvania’s forests in the coming decades. Key changes that are likely to occur include species composition shifts, shifts in tree regeneration rates, greater tree stress, changes in the phenology of forest ecosystem species, changes in tree chemistry and growth rates, greater insect, disease and invasive species activity, and shifts in faunal populations. Many of these shifts have already begun to occur, and while many may be expected to lead to greater tree mortality, at least for the present, increases in mortality that can be attributed to climate change have been minor. Furthermore, while one might expect longer growing seasons and the CO_2 fertilization effect to increase tree growth rates, this has not yet been observed in Pennsylvania’s forests, and these effects could potentially be offset by the negative effects of pollutants such as ozone and sulfate deposition. On the whole, it is important to keep in mind that all of these effects will interact in very complex ways, making highly specific projections of future forest conditions difficult.

As a significant reservoir of carbon, Pennsylvania's forests can contribute to mitigating future climate change, but these effects are not likely to be large, as the growth rate of Pennsylvania's forests is relatively slow and difficult to accelerate. The most promising forest management strategies for mitigating climate change in Pennsylvania are to reduce rates of conversion of forestland to non-forest uses and to plant trees in areas where they are not currently found, for example, abandoned strip mines and some urban areas.

As climate change is already happening and is, to some extent, irreversible, forest managers need to think about how to help the state's forests adapt to climate change. A key strategy for accomplishing this is to maintain or increase forest connectivity. This may be a significant challenge in areas where road and pipeline networks are being built and expanded to develop natural gas from the Marcellus Shale and other promising geological strata. For some key species that are particularly vulnerable to climate change, assisted migration may be an option, but accomplishing this in practice for very many species will be difficult.

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9.0 Human Health Impacts of Climate Change in Pennsylvania

Chapter 11 of the 2009 ***Pennsylvania Climate Impacts Assessment*** identified five pathways through which human health could be affected by climate change where there is sufficient research to project how climate change could impact future human health. These are:

1. Mortality from temperature stress (heat and cold)
2. Respiratory and heart disease caused by air quality pollution
3. Mortality and injuries associated with extreme weather events
4. Changes in the geographical distribution and prevalence of vector-borne diseases
5. Changes in water and air-borne infectious disease

This chapter will summarize new knowledge of these pathways that has been developed since the 2009 PCIA.

A consistent finding highlighted by several recent studies on the impacts of climate change on human health is that health impacts will vary within the population, with some identifiable groups more vulnerable to health impacts from climate change than others. For each climate change health impact discussed, this chapter will summarize what is known about which subpopulations are more vulnerable, and discuss how those vulnerabilities could be reduced.

9.1 Temperature-related mortality

The 2009 PCIA reviewed what was known about the impact that short term temperature anomalies (heat waves and cold snaps) have on human mortality. The previous review revealed that mortality is lowest when temperatures are moderate, and that high and low temperatures are both associated with increased mortality rates, due to increased stress on the body.

A new study of 107 U.S. communities (Anderson & Bell 2009) confirmed that the impact of temperature on mortality is U or J shaped. That study found that heat-related mortality occurs relatively quickly (within one to two days of the high temperatures), while cold-related mortality can continue for up to three weeks after the cold snap has ended. This difference is related to the difference in the physiological consequences of excess heat and cold. Heat waves are more likely to cause cardiovascular deaths, while cold snaps are more likely to cause deaths through respiratory conditions.

New research has shown that mortality from heat waves can be quite substantial. Hayhoe et al. (2010) projected potential heat-related deaths in Chicago (a city with summer temperatures similar to those in Pittsburgh and slightly cooler than those in Philadelphia). They found that heat related mortality is projected to increase from 2.6 deaths per 100,000 residents to 7.1 - 19.9 deaths per 100,000 residents by the end of the century. If similar increases occur in the Pittsburgh metropolitan area and the Pennsylvania counties of the Philadelphia metropolitan area, with current population, that would imply an additional 300 to 1200 heat-related deaths per year.

In Pennsylvania, more excess deaths are associated with cold weather than with hot weather. Even so, it is difficult to predict whether the effect of climate change will be a net increase in temperature-related mortality or a net decrease. The 2009 PCIA cited studies that came to opposite conclusions. Studies published since the 2009 PCIA continue to reach ambiguous conclusions.

Two recent studies for New York City project that the net impact of climate change would lead to an increase in annual temperature-related mortality. Li, Horton and Kinney (2011) find that by the year 2080, heat-related deaths will increase by 31-56 percent while cold-related deaths will decrease by 44-67 percent, with the net effect an increase in annual temperature-related mortality. Nicholls (2009) projects that a 2°C (3.6°F) temperature increase in New York City would increase summer mortality and decrease winter mortality for senior citizens aged 75 years and above, with a net increase of a 2.6 percent in total annual mortality. Deschenes and Greenstone (2011) project the net impact of climate change on total mortality for each state in the United States. They find that climate change would result in an additional 63,000 temperature-related deaths nationwide, but that the net impact for cooler states, including the Mid-Atlantic States, is not statistically different from zero.

Susceptibility to temperature-related mortality varies across and within communities. Balbus and Malina (2009) review the literature on vulnerable subpopulations. They find that heat-related mortality risk is highest for infants and children, the elderly, the poor, and those with chronic medical conditions. More recent research confirms some of these conclusions. Anderson and Bell (2009) find that communities with higher unemployment, higher population, and more urban character experienced higher heat-related death rates, while communities with a higher proportion of homes with air conditioning experienced lower heat-related death rates. Within communities, the elderly were most at risk for heat-related mortality. Community characteristics were not strongly correlated with susceptibility to cold-related mortality. Deschenes and Greenstone (2011) find that the impact of climate change on annual mortality was highest for infants (who have poorly-developed temperature regulation), but also elevated for the elderly over 65 years of age.

9.2 Air quality and health

In the 2009 PCIA, we identified three potential linkages through which climate change could affect air quality, and subsequently human health. [1] Higher increased summer temperatures increase the rate of formation of ground-level ozone. [2] Climate change could affect the concentration of small airborne particulates. [3] Pollen and mold concentrations could increase as a consequence of climate change.

9.2 1 Ground-level ozone

Ground-level ozone is a respiratory irritant that has been linked through epidemiological studies to higher rates of respiratory symptoms (coughing, sneezing, wheezing), aggravation of asthma, and higher rates of respiratory infections. Ozone exposure has also been linked to increased mortality. Ground-level ozone concentrations are highest in summer, when warm temperatures and sunshine facilitate ozone creation from volatile organic compounds. Higher summer temperatures due to climate change would be expected to result in more ozone creation, and higher concentrations. In the 2009 PCIA we concluded that ground level ozone concentrations would increase over the century by 4.5 to 10.5 ppb in southeastern Pennsylvania, and by 7.5 to 13.5 ppb in southwestern Pennsylvania. Smaller increases are projected for the rest of the state. We calculated that such increases would result in approximately 800 additional hospital admissions and approximately 200 additional deaths per year in Philadelphia and Allegheny counties alone.

More recent studies show the difficulty in projecting changes in ozone concentration at fine spatial resolution. Dawson et al. (2009) project that climate change will significantly increase ground level ozone concentrations in the Southeast by 2050, but do not project statistically significant changes for the Northeastern U.S. Their models project little impact on ozone concentrations for Pennsylvania. This contrasts with earlier studies such as Hogrefe et al. (2004). Hogrefe et al. (2004) also project larger increases in ozone concentrations for the Ohio River valley than for Northeastern U.S., but project increases for Pennsylvania that were similar to those in the Ohio River valley, particularly for the southwest portions of the state. Tagaris et al. (2007) project that changes in ground level ozone concentrations due to climate change will be small relative to potential impacts of changes in future emissions of ozone precursors. Wu et al. (2008) project that climate change alone would decrease ozone formation in the eastern U.S., but that projected increases in emissions of ozone precursors would cancel out that effect, so that ozone concentrations are projected to be unchanged.

In 2009, the EPA (Weaver et al., 2009) reviewed available model projections of the impact of climate change on ozone concentrations. Their review showed that individual studies differ in their spatial projections of future ozone concentrations. All of the models reviewed project average national increases in summer ozone concentrations nationwide of between 2 to 8 ppb by 2050. However, the spatial pattern of those increases differed among models. Three of the five models reviewed projected increased ozone concentrations for Pennsylvania, while the other two projected little change for Pennsylvania. The EPA review also points out that ozone formation is affected not only by temperature, but also by cloud cover, precipitation, and the height of the mixed near-surface layer of air, all of which can change as a result of climate change. Spatial variation in the model results was driven primarily by variation in the projected spatial pattern of those drivers.

While recent research has highlighted the difficulty in projecting climate-change-induced changes in ozone concentrations for a specific state, it has also highlighted the fact that future changes in emissions are likely to be more important in determining future ozone concentrations than changes in meteorology due to climate change.

9.2.2 Airborne particulates

Airborne particulates and aerosols can be created by chemical reactions on SO_2 and NO_2 emitted from combustion processes. Small particulates (i.e., less than 2.5 microns in diameter) can cause many of the same respiratory health conditions as ozone exposure, but have also been linked to increased cardiovascular disease. Holding emissions constant, higher temperatures can result in increased rates of particulate creation in the atmosphere, but also increased rates of volatilization, so that the net effect of higher temperatures on particulate concentrations is difficult to project.

Recent research on the impact of climate change on particulate concentrations has demonstrated that, as in the case with ozone, temperature is not the only meteorological driver that affects particulate creation and removal. As with ozone, creation and removal of particulates is affected by cloud cover, precipitation, and mixing. Tagaris et al. (2007) project that climate change will only have a small effect (less than 3 percent) on concentrations of small particulates (PM2.5). However, they project that emission control policies will lead to reduced future SO_2 and NO_2 emissions, resulting in much lower PM2.5 concentrations than today. Nationwide, they project a decrease in PM2.5 concentrations of 35 percent by 2050.

In contrast, Dawson et al. (2009) project that climate change would increase summer PM2.5 concentrations by over 10 percent in the Ohio and Lower Mississippi river valleys, but project decreased PM2.5 concentrations in the Northeastern U.S., due to better mixing of the air. They project little impact of climate change on PM2.5 concentrations in Pennsylvania.

As is the case with ozone, it is difficult to project what impact climate change will have on particulate concentrations in Pennsylvania. As was also the case with ozone, emissions control policy will probably have a larger effect on future PM2.5 concentrations than will climate change.

9.2.3 Pollen and mold

The 2009 PCIA discussed several different mechanisms through which climate change could affect pollen and mold exposure. There is experimental evidence that plants grown under higher CO2 concentrations produce more pollen. Higher temperatures will also lengthen the pollen season, and change the geographic distribution of pollen-producing plants. Increased precipitation could lead to more favorable conditions for mold, and increased variability in precipitation could lead to higher rates of mold dispersal, as spores are carried on dust particles during dry periods.

New research confirms and strengthens the conclusion that climate change is expected to lengthen the pollen season and increase allergen loads (Cecchi et al., 2010; Reid & Gamble 2009; Scheffield, Weinberger & Kinney 2011). This research also points out that allergic response to pollen is stronger in the presence of other irritants such as ozone and particulates, which themselves may be affected by climate change.

9.2.4 Vulnerable populations

Because children respire at a faster rate than adults, they are more vulnerable to health impacts from ground-level ozone and small particulates (Balbus & Malina 2009). Children also spend more time outdoors, and spend more time in vigorous activity, increasing their exposure to outdoor air pollutants. Children are also more prone to develop allergies and asthma when exposed to pollen, mold and irritants than adults (Pawanker et al., 2012). The elderly are also more susceptible to health effects of ozone and particulate pollution, as are persons with pre-existing heart and lung disease and persons who work outdoors (Balbus & Malina 2009). Finally, lower income families are more susceptible to health effects of air pollutants for several reasons; they have less access to health care, more often live in areas with higher pollutant loads, and experience poorer indoor air quality (Deguen & Zmirou-Navier 2010).

9.3 Extreme weather events

Extreme weather events such as floods and winter storms can cause property damage, injury and mortality. In the 2009 PCIA, we summarized what was known about how climate change would change the frequency or intensity of extreme weather events. We concluded that Pennsylvania is likely to experience more intense winter rainfall events, but fewer rain-on-snow flood events. The impact of climate change on tropical storms and non-tropical cyclones that reach Pennsylvania was deemed to be uncertain. It was also concluded that there would be fewer snowstorms, but that the impact of climate change on ice storms was uncertain. Although extreme weather events are dramatic, their health impacts in Pennsylvania are small relative to those from, for example, exposure to air pollution.

Recent research has shown that the extreme weather event that is most clearly linked to climate change is wildfires in the western U.S. There, a climate signal can already be detected, as wildfire intensity and frequency has increased as a consequence of recent warming. Extreme weather events of more concern to the Mid-Atlantic region include floods and hurricanes. There is evidence that heavy rainfall events have become more frequent in Pennsylvania (Madsen & Figdor 2007). However, it is difficult to determine whether the frequency or intensity of extreme events such as floods and hurricanes has increased in response to recent warming (Mills, 2009).

Models that project the future incidence of tropical storms and hurricanes tend to predict fewer storms, but more intense storms. Garner et al. (2010) project that while higher sea surface temperatures will favor formation of tropical storms, increased wind shear will hamper their formation. They project a net decrease in the number of tropical storms. Knutson et al. (2010) also project that the frequency of tropical storms will decrease or remain the same but that the intensity of storms will increase, with the net result that the frequency of high intensity tropical storms will likely increase.

While tropical storms can and do produce damaging floods in Pennsylvania, a more frequent concern is extra-tropical cyclones. In Pennsylvania, extra-tropical cyclones include both rain and snow storm systems that track through the state from the west to the east as well as nor'easters. Several studies have found that extra-tropical cyclone frequency has decreased in North America, but their intensity has not changed (Ulbrich, Leckebusch, & Pinto 2009). Models of future climate give variable projections, but tend to predict fewer total storms but possibly more intense storms (McDonald, 2010).

Whether a particular storm involves rain, snow, or mixed precipitation depends on the temperature and position of the storm track. Temperatures are projected to increase, so that fewer snowstorms are expected to occur. Lambert and Hansen et al. (2012) project that freezing rain events will shift northward as a consequence of climate change and that Pennsylvania will experience less freezing rain. Increased rates of freezing rain are projected for Eastern Canada.

Regardless of whether extreme weather events increase or decrease as a consequence of climate change, the economic impact of those events has been rising, due to increased population and infrastructure in vulnerable areas (Bouwer, 2011).

Populations particularly at risk for injury or death from extreme weather events would include those who live in flood prone areas, because they are at greater physical risk, and those with lower socio-economic status, who are both more at risk from extreme weather events and have less resilience to recover from such events (Morss et al., 2011).

9.4 Vector-borne disease

The prevalence of vector-borne diseases depends on several factors, each of which can be influenced by climate. These include the spatial distribution and density of vector species and alternative hosts as well as the duration and frequency of exposure between humans and the vector species.

Two vector-borne diseases of particular concern in Pennsylvania are Lyme disease and West Nile virus. Other less-common vector-borne diseases include Ehrlichiosis and St. Louis encephalitis. These have similar life cycles to Lyme disease and West Nile, respectively, and will likely respond to climate change in similar ways. While it is possible that climate change will affect the distribution and prevalence of malaria in some developing countries, malaria has long been eradicated from Pennsylvania, and is not likely to return.

Lyme disease is caused by bacteria that are spread to humans by the blacklegged deer tick. Alternative hosts that serve as reservoirs for the disease include small mammals and birds. One such host that is of particular importance is the white-footed mice. The prevalence of Lyme disease in ticks therefore depends on the population of white-footed mice. Contrary to popular notion, deer abundance is not correlated with Lyme disease incidence. While deer serve as a host for ticks, deer do not infect ticks, and deer population control is not an effective means of reducing Lyme disease prevalence.

Recent research has revealed that the dynamics that affect Lyme disease prevalence are very complicated. For example, because of the importance of mice in its life history, Lyme disease has been found to be higher in years following larger than normal acorn crops (Ostfeld et al., 2006). As an another example, it has been found that some tick hosts (e.g. opossums and squirrels) kill a high proportion of the ticks that attempt to feed on them (Keesing et al., 2009). Climate change could have differential impacts on the relative abundance of mice versus other alternative hosts, which would affect tick abundance. As a third example, it has been found that areas with more honeysuckle have higher tick populations with higher disease prevalence, due to higher density of alternative hosts (Allan, 2010). Because white-footed mice, deer, and blacklegged ticks are all adapted to a fairly broad range of climates, climate change will impact Lyme disease prevalence through these types of complicated interactions with host species food sources and habitats. It is challenging to project how these interactions might change in response to climate change.

West Nile disease was first reported in North American in 1999. Between 2006 and 2011, there was an average of 11 human cases of West Nile disease in Pennsylvania, according to the Centers for Disease Control. It is transmitted by mosquitos, with birds serving as alternate hosts. Many different bird species carry West Nile virus. It is not lethal for most birds, but is lethal for crows. For this reason, dead crows are routinely examined to track the geographic distribution of the West Nile pathogens.

Many broadly-distributed species of birds serve as alternative hosts for West Nile. If climate change is to affect the distribution or prevalence of West Nile, it will most likely do so through the mosquito vector. Mosquito abundance is strongly affected by temperature, with an early season peak and decrease in late summer (Gong, DeGaetano & Harrington 2010). Short-term weather events that are favorable to mosquito production (warm temperatures and high precipitation) have been found to be associated with higher infection rates (Soverow et al., 2009). This finding suggests that warmer, wetter conditions with climate change would be more conducive to mosquito production, and therefore result in higher incidence rates of West Nile virus. However, the impact that climate change will have on mosquito abundance is complicated. Wang et al. (2010) find that West Nile infections are higher in years following relatively dry years, possibly because dry years reduce the abundance of mosquito predators, and concentrate birds in wet areas in close proximity to mosquitos. There are other explanations for this phenomenon, but more research is needed on the complicated interactions among birds, mosquitos and climate before we can confidently predict whether climate change will affect the prevalence of West Nile disease.

Recent research demonstrates that the distribution, prevalence and severity of outcomes associated with vector-borne disease can be influenced by climate, but that other factors play a larger role. Such factors include alteration and fragmentation of habitat, residential construction in the urban/wildland fringe that increases exposure of humans to vectors, and human influence on the availability of mosquito breeding sites play a larger role (Ostfeld, 2009).

Persons at greater risk for Lyme disease and West Nile disease are those who spend more time outdoors in areas where they can come into contact with ticks and/or mosquitos. One way in which climate change will likely affect the prevalence of these diseases is through increasing the number of months during which people are active outside and potentially in contact with disease vectors.

Lyme disease is usually treated successfully with oral antibiotics. Failure to treat Lyme disease can lead to more severe chronic illness that is more difficult to treat. For this reason, persons with limited access to health care face greater risks for adverse outcomes from Lyme disease. West Nile is a virus, and will not respond to antibiotics. Most people infected with West Nile virus recover within a few days or weeks. Treatment involves rest, fluids, and pain medication to reduce discomfort. More serious cases can involve encephalitis or meningitis. Treatment in these cases can require hospitalization. Again, persons without access to health care are at greater risk of adverse outcomes.

9.5 Water and air-borne disease

In the 2009 PCIA, we discussed the potential risk for increased air-borne and water-borne disease as a consequence of climate change. For water-borne disease, the most important concern was the potential increase in water-borne pathogens due to increased precipitation. Heavy rain events can result in runoff from livestock operations and sewage overflows, increasing pathogen loads in waterways. With proper well construction for private water supplies and proper treatment of public water supplies, increased human illness should not result, though it should be noted that well protection and water treatment are not infallible. A greater risk of water-borne illness also exists for recreationists who engage in water-based recreation (e.g., swimming).

Recent research has confirmed that rates of gastroenteritis among recreational swimmers are higher during rainy periods than during dry periods (Semenza & Menne 2009). Similarly, rates of infection cryptosporidiosis are positively related to river flow (Lake et al., 2005), suggesting that increased intensity of storm events would result in higher disease incidence. As an example, high fecal coliform counts following heavy rains have resulted in beach closures at Gifford Pinchot State Park in each of the last three summers. However, an analysis of drinking-water disease outbreaks showed that both high rainfall and low rainfall are associated with higher probability of a disease outbreak (Nichols et al., 2009). High rainfall increases the chances for contamination from livestock operations and sewage treatment plants, while low flow periods provide less dilution to pathogen loads from, for example, sewage treatment plants. Unfortunately, climate change is expected to increase both high flow and low flow events.

In the 2009 PCIA, we concluded that the role of climate in air-borne disease is poorly understood. Respiratory diseases such as pneumonia and influenza show a seasonal pattern, with higher rates of incidence during winter months, and their incidence could decrease as a consequence of warmer temperatures. There is evidence that the season for respiratory syncytial virus, a common childhood infection, has shortened and the severity of cases has decreased as temperatures have warmed (Ayres et al., 2009). However, warming might not decrease the rate of incidence of influenza. Warmer regions do not experience lower total influenza incidence than colder regions. In fact, recent research has shown that influenza shows a seasonal pattern even in tropical regions as well (Tamerius et al., 2011), suggesting that seasonality is an inherent characteristic of influenza's virology, and not dependent on the existence of a cold season and a warm season. The impacts that climate change might have on air-borne respiratory disease are still poorly understood.

Persons most at risk for water-borne and air-borne infectious disease are those with greater exposure and those who might experience worse outcomes after infection. For water-borne disease, exposure is greatest for those who engage in water-borne recreation and those with private drinking water supplies.

Persons with weakened immune systems, children, pregnant women, and persons without access to health care are at higher risk of more severe outcomes if infected.

9.6 Adaptation Strategies

For each of the health risks identified here, adaptation strategies to minimize the adverse consequences of climate change can be targeted at reducing exposure to the risk at increasing access to and quality of medical care after exposure.

For heat and cold related stress, the most effective adaptation strategy is to reduce exposure to extreme temperatures. This can involve education (e.g., heat wave warnings) or provision of shelters during extreme temperature events. It can also involve assisting households with limited resources to assure that they have adequate heat and cooling at their homes. Finally, it can involve changes to urban environments in order to reduce heat island effects.

For air pollutants, changes in emissions levels will play a more important role in determining pollutant concentrations than will climate change. SO_2 and NO_x emissions levels are expected to continue to decline, as new technologies allow tighter regulation of these pollutants. Climatic conditions will likely be more favorable to formation of ozone and particulates in the future. The most effective way to counter this tendency is by aggressive reductions in pollutant emissions. There are also ways that households can protect themselves from ozone and particulate exposure. Public education and warnings can help at-risk individuals reduce their exposure during periods with poor air quality. Air conditioning can also reduce indoor particulate concentrations and associated health impacts (Bell et al., 2009).

Flood risk could be higher in Pennsylvania as a consequence of climate change. The evidence suggests that both tropical and non-tropical rain events could become fewer but more intense as a consequence of climate change. Adaptation strategies to reduce health impacts from flood risks include improved monitoring and warning systems, discouraging building in flood-prone areas, and careful consideration of changing rainfall patterns when constructing hydrologic infrastructure such as reservoirs, storm water systems, and bridges over rivers.

It is not clear whether climate change would increase or decrease vector-, water- and air-borne infectious disease risks. Regarding water-borne disease, the most effective adaptation strategy is to prevent pathogens from reaching surface waters by controlling runoff from livestock operations and controlling sewage outflows, coupled with drinking water protection through private well protection, inspection and testing and careful management and monitoring of public drinking systems.

For all climate-related health risks, risks are highest for those who do not have access to health care. For example, in most cases, Lyme disease is easily treated with early use of antibiotics. However, early treatment is less likely for those who do not have access to health care. Untreated, Lyme disease can cause serious, chronic disease that requires expensive medical treatment.

9.7 Information Needs

Recent research on the health impacts of climate change conducted has incorporated more complex models and more mitigating factors. This research gives a more realistic picture of the potential impacts of climate change on health, and also highlights the uncertainties involved.

Research conducted to date has firmly established that both high and low temperatures are associated with increased mortality. Whether the net effect of climate change (reduced cold-related mortality and increased heat-related mortality) is positive or negative is less well established.

It is well established that higher ozone concentrations and higher particulate concentrations are associated with adverse health outcomes. What is less well understood is the impact that climate change will have on ozone and particulate concentrations, particularly for a specific region such as Pennsylvania. Climate change could improve or worsen air quality. It is well established that emissions policy will have a larger impact on air quality than will climate change.

Uncertainties regarding the impact of climate change on extreme weather events are mostly uncertainties over meteorology and hydrology. Improved down-scaled climate models should provide more guidance over how storm events will change as a consequence of climate change. Of more immediate importance is to maintain and improve monitoring and forecasting systems to help identify and notify individuals at risk from flooding events. The United States Geological Survey (usGS) has been scaling back on its river and stream monitoring efforts, as a consequence of budget cuts.

The links between climate change and infectious disease are poorly understood. Recent research has shown the potential links between rainfall and water-borne disease. Additional research there would help identify when risks are highest, allowing public education and increased monitoring of drinking water supplies. For vector-borne disease, recent research has shown that the factors that determine disease distribution and abundance are complex, and that climate change is probably not as important in determining the spread of these diseases as other factors such as habitat modification. Continued monitoring of the distribution and incidence of diseases such as Lyme disease and West Nile are critical for public health provision, regardless of whether these diseases are expected to increase as a consequence of climate change.

9.8 Conclusions

This chapter identifies several different pathways through which climate change could affect human health in Pennsylvania. A consistent finding is that the impact of climate change on human health is uncertain, but likely to be small. Of the pathways discussed in this chapter, the pathways with the largest potential climate change induced impacts on health are changes in temperature-related deaths and health consequences from changing ozone and small particulate concentrations.

Research has consistently shown that warming temperatures will result in increased heat-related deaths and decreased cold-related deaths. The net effect is uncertain, though recent research suggests that the increase in heat-related deaths will be larger than the decrease in cold-related deaths, so that total temperature-related deaths will increase. Adaptation strategies to reduce heat-related deaths include warning systems, provision of emergency shelters during heat waves and cold snaps, assistance to low income households to assure adequate heating and cooling in the home, and changes to building codes to reduce urban heat island effects.

Of the health impacts considered here, air pollution has the largest current impact on human health, both in terms of morbidity and mortality. However, research on the impact of climate change on ozone and particulate concentrations is ambiguous. Warmer summer temperatures favor ozone and particulate creation. However, pollution concentrations depend on other factors as well, such as cloud cover, precipitation, and air mixing, all of which are potentially affected by climate change. Regardless of whether climate change will increase or decrease pollution concentrations, other factors will have a larger effect on local air quality. Primary among these other factors is policies to reduce emissions of volatile organic compounds, SO_2, and NO_2.

Research on extreme weather events suggests that Pennsylvania will be subject to more and more severe rainfall events. Pennsylvania is likely to experience fewer snowstorms and fewer freezing rain events. However, as pointed out in the 2009 PCIA, traffic fatalities are not necessarily higher when roads are slippery. There is some evidence that Pennsylvania will experience fewer rain events, but more intense rain events, so that flood risk may increase. River monitoring is critical for effective warning and emergency response. Careful hydrologic and land use planning can reduce flood risk and reduce the number of buildings at risk of flooding.

As more research is conducted on the potential impacts of climate change on infectious disease, two things have become increasingly clear. First, our understanding of the biology and ecology of infectious disease is insufficient to project with confidence what impact climate change might have on its distribution or prevalence. Second, factors other than climate change, such as habitat disturbance, human behavior, and health care access, will have a larger impact on disease incidence and outcomes than will climate change.

The health impacts of climate change will fall disproportionately on vulnerable subpopulations. These include the very young, the elderly, those with low socio-economic status, those with chronic medical conditions, and those without access to health care. Cost-effective adaptation strategies would be targeted to those at-risk groups.

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10.0 Outdoor Recreation and Tourism

Chapter 12 of the 2009 ***Pennsylvania Climate Impacts Assessment*** reviewed available information on the potential impacts of climate change on outdoor recreation and tourism in Pennsylvania. That review concluded that climate change would affect outdoor recreation in several ways. The most important impacts identified were:

1. Higher spring and fall temperatures will lengthen the outdoor recreation season resulting in a general increase in outdoor recreation participation;
2. Higher summer temperatures will particularly increase demand for water-based recreation;
3. Higher summer temperatures will decrease the amount of habitat suitable for trout in Pennsylvania, but total participation in recreational fishing may increase, because of the longer season;
4. Reduced summer streamflows could negatively affect sport fish populations;
5. Higher winter temperatures and reduced snowfall will negatively impact snow-based recreation such as skiing and snowmobiling.

In this chapter we review research that has been conducted since the 2009 PCIA. Little research on the impact of climate change on outdoor recreation has been conducted specific to Pennsylvania. This review focuses, when possible, on research conducted in the Mid-Atlantic region and in neighboring states.

10.1 Winter Recreation

The 2009 PCIA stated that snowmobiling and cross country skiing depend on natural snow and on cold temperatures to maintain snow cover. Downhill ski resorts in Pennsylvania rely heavily on artificial snowmaking, but require consistent cold temperatures to make and keep snow cover.

10.1.1 Evidence of winter climate change in Pennsylvania

The Pennsylvania State Climatologist publishes data on seasonal snowfall for 10 climate divisions (shown in Figure 10.1), as well as data on average monthly temperature. A statistical analysis[12] of this data was conducted for this report. That analysis shows that, over the period 1950-2010, average winter temperature (December – February) increased by .1°C /decade; standard error = 0.039 (0.18°F/decade; standard error = 0.07) and average seasonal snowfall declined by 2.09 cm/decade; standard error = 0.36 (0.82 inches/decade; standard error = 0.37).

While, for the state as a whole, snowfall has declined while winter temperatures have risen, for a specific location there is not a simple year-to-year relationship between temperature and snowfall. Warmer winter temperatures make it more likely that a given storm event will occur as rain instead of as snow. However, total seasonal snowfall also depends on the location of storm tracks through the winter season. Winter storms in Pennsylvania often follow a track from southwest to northeast, along a boundary between cold air pushing in from the northwest and warmer air to the southeast. If the boundary is located further east, then western Pennsylvania can experience cold temperatures but little

[12] For both snowfall and average winter temperature, panel data regressions were estimated, with fixed effects for climate divisions.

snow. If the track is further west, then western Pennsylvania can experience warmer temperatures but more snow. Unfortunately, it is difficult to predict how storm track location might change as a result of climate change.

Northwestern Pennsylvania (Climate District 10) is unique because of the influence of lake effect snow. Lake effect snows can occur when colder winds from the west travel over warmer open water in Lake Erie. Warmer winter temperatures will reduce the amount of time that Lake Erie is covered by ice, and therefore increase the amount of time that lake effect snows can occur. However, those same warmer temperatures will reduce the frequency of occasions when atmospheric conditions are conducive to lake effect snow formation. Kunkel, Westcott & Krostovich (2002) project that climate change will result in more frequent lake effect rain events and less frequent lake effect snow events.

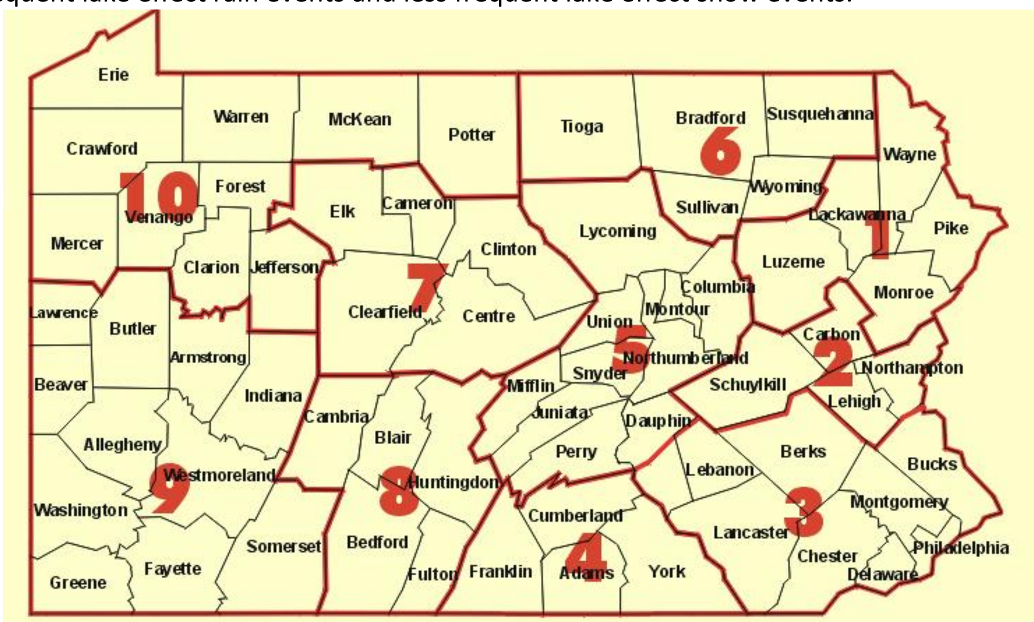

Figure 10.1. Pennsylvania Climate Divisions. Source: PA State Climatologist Office

Still, we can learn something about the relationship between winter temperatures and snowfall by comparing across climate divisions. Figure 10.2a and 10.2b shows average winter temperature and average seasonal snowfall for all ten Pennsylvania climate divisions. A clear pattern emerges. Across the climate divisions located in southern Pennsylvania is a clear negative relationship between average winter temperature and average seasonal snowfall. A similar relationship exists for divisions in central and northern Pennsylvania. Climate Division 10 (which includes northwestern counties) is something of an outlier, likely due to the unique influence of lake effect snow. Simple linear regressions (excluding counties in climate division 10) show that a 1°C increase in winter temperature is associated with a decrease in snowfall of 25.2 cm; standard error=0.68 (1°F increase in winter temperature is associated with decrease in snowfall of 5.5 inches; standard error = 0.15) for central and northern counties, and a decrease of 31.9 cm; standard error=0.84 (7.0 in; standard error = 0.18) for southern counties.

This analysis ignores the influence of location on snowfall. For example, the Piedmont region in Southeastern Pennsylvania experiences weather systems that follow different storm tracks than those that affect the Appalachian Plateau. This analysis also does not take into account an anticipated increase in winter precipitation from climate change. Still, it does provide a rough approximation of the impact that an increase in winter temperatures will have on snowfall in Pennsylvania. Based on this analysis, a projected 2°C (3.6°F) increase in temperature by 2050 would result in a decrease in snowfall of 50-64 cm (20-25 in). Decreases of that magnitude would have serious negative consequences for activities that depend on natural snow, such as cross country skiing, sledding, and snowmobiling.

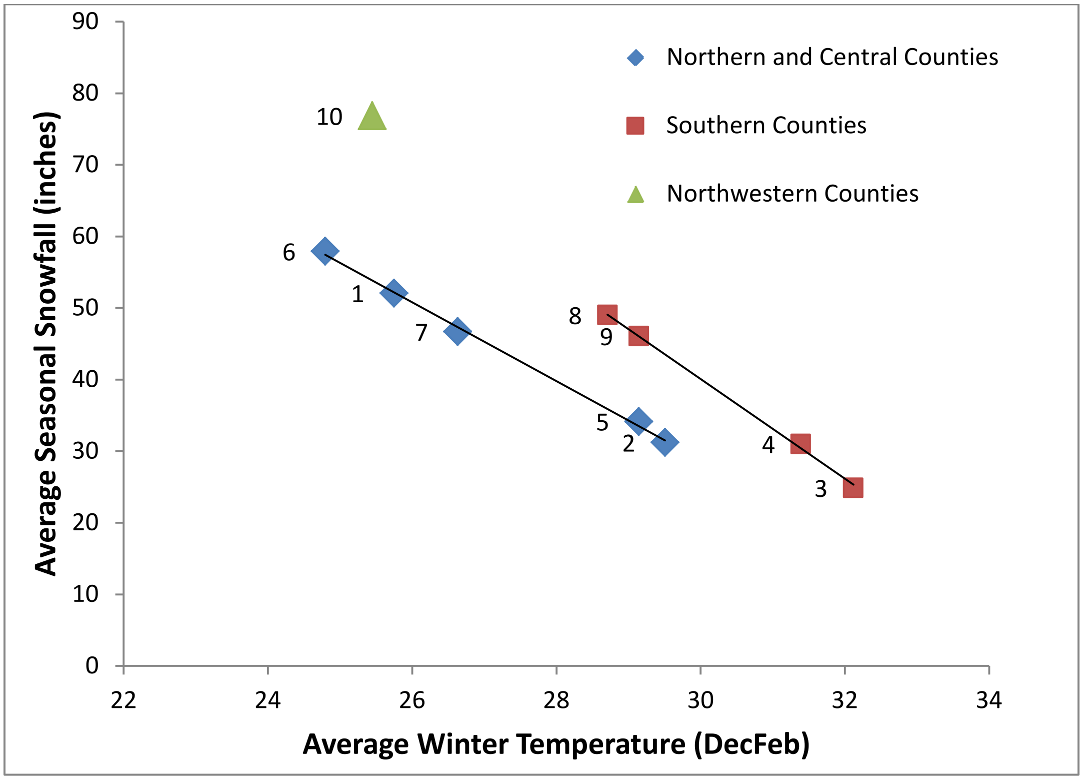

Figure 10.2a. Average Snowfall versus Average Winter Temperature for ten PA climate divisions. (Source: Analysis for data from 1950-2010 from PA State Climatologist Office)

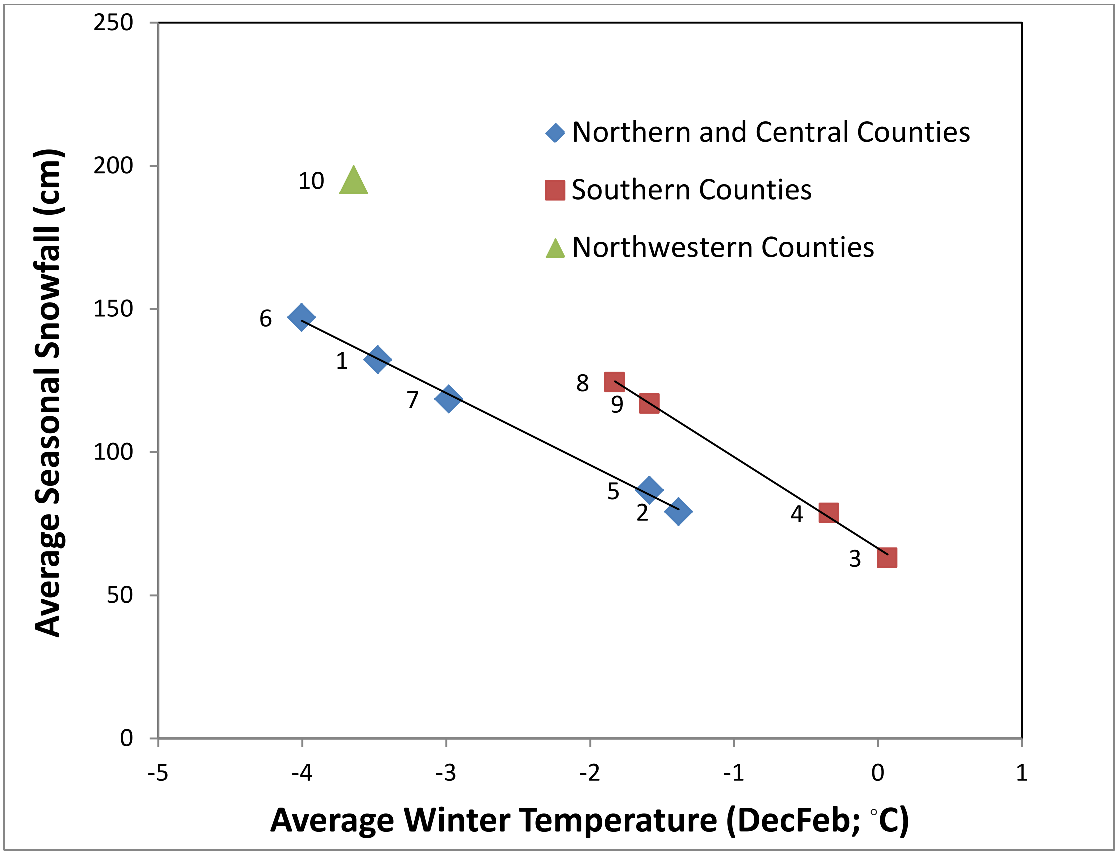

Figure 10.2b. Average Snowfall versus Average Winter Temperature for ten PA climate divisions. (Source: Analysis for data from 1950-2010 from PA State Climatologist Office)

Caution should be used in using a simple analysis like this one to project impacts outside the range of the data. For example, the analysis predicts that snowfall in southeastern Pennsylvania (climate district 3 including Philadelphia, Reading, and Lancaster) would average below 13 cm/year (5 in/year) in 2050, which is well outside the range of the data here. Still, such an outcome is possible. A year-round increase in temperatures of 2°C (3.6°F) would make winter temperatures in southeastern Pennsylvania similar to those found in Gaithersburg, MD, which averages 15 cm (6 in) of snow per year, or Dover, DE, which averages 10 cm (4 in) of snow per year.

10.1.2 Recent research on the impact of climate change on downhill skiing

Downhill skiing is less reliant on natural snowfall, but still requires cold temperatures to make and retain snow. Research published since the first Pennsylvania Climate Impacts assessment has attempted to predict the impacts of climate change on downhill skiing, taking into account adaptation through snowmaking. Unfortunately, little research has been conducted on downhill skiing specific to Pennsylvania.

A consistent result in the literature on the impact of climate change on downhill skiing is that large, high elevation, more northern resorts will be able to compensate for higher winter temperatures through increased snowmaking, but that southern, lower elevation, smaller resorts (such as those in Pennsylvania) will reach a point where artificial snowmaking to sustain resort operation is not financially feasible.

Dawson, Scott and McBoyle (2009) analyzed ski resort response to colder and warmer winters in New York and New England states. The warmer winters had average temperatures similar to those expected as a result of climate change. They found that, compared to seasons with temperatures close historical average, warmer seasons were associated with 40 percent less natural snowfall, more hours spent making snow with consequently higher energy use, and 3-11 percent shorter season length. The impacts were greatest for the smallest ski resorts, which in Pennsylvania would include resorts such as Tussey Mountain, Ski Sawmill and Tanglwood. For small resorts, resort profits were 28-40 percent lower in warm winters than in average winters. The impact of climate change on small resorts could be even larger in Pennsylvania than in the more northerly states studied in that research. However, since no research has been specifically conducted for Pennsylvania, we cannot say with certainty which climate divisions within the state will be most affected.

Pickering and Buckley (2010) analyzed the potential for adaptation to climate change through snowmaking for ski resorts in Australia. They found that higher altitude ski resorts would be able to adapt, though such adaptation would involve more snowmaking and higher energy costs, but that lower altitude ski resorts would not be able to compensate for higher temperatures and reduced natural snowfall. Similarly, Steiger (2010) modeled ski resort operations for three resorts in Austria, and found that while snowmaking could compensate for higher temperatures and reduced snowfall for a few decades, such adaptation could not sustain skiing past mid-century.

Even if a ski resort is able to stay open through snowmaking, the depth of the snow base is an important determinant of skier participation. Shih, Nichols and Holecek (2009) found that lift ticket sales were associated with greater snow depth on the slopes, but not with total natural snowfall, suggesting that it is total snow depth that matters to skiers, not natural snowfall. They also found that, controlling for snow depth, lift ticket sales were lower when temperature was higher. This suggests that the problem facing ski resorts is not just maintaining adequate snow cover to remain open. Reduced snow depth and higher temperatures will lead to lower lift ticket sales even if resorts are open.

As smaller, lower elevation and more southern resorts close due to their inability to maintain adequate snow cover, larger, higher elevation, more northern resorts may actually benefit, through displacement of skiing activity. Dawson and Scott (2010a) found that as a consequence of climate change, resorts in Connecticut and Massachusetts will be less likely to be open during the important Christmas to New Year’s period, but that more northern resorts that can adapt to climate change could experience increased skier traffic due to substitution. In a survey of New England skiers Vivian (2011) found that while most skiers and snowboarders will respond to a shorter ski season at their usual ski resort by skiing fewer days or by quitting skiing, 31-41 percent of respondents would react by travelling to resorts located further north or outside of New England.

10.2 Recreational Fishing

Climate change could affect both the demand for and the quality of recreational fishing in Pennsylvania. However, both relationships are difficult to establish. Warmer spring and fall temperatures could lengthen the fishing season. Consistent with this hypothesis is that the average Pennsylvania angler fishes more days than the average New York angler, according to the (National Survey of Fishing, Hunting and Wildlife-Associated Recreation). However, it is not the case that states located south of Pennsylvania have even higher fishing rates. Such a comparison is complicated by the differences in fishing resources in the different states.

While it may be the case that warmer spring and summer temperatures could increase total fishing trips, the relationship could be reversed in summer if temperatures are high enough to make fishing uncomfortable. Hailu and Gao (2010) found that during the warmest months of the year, anglers are more likely to go to cooler areas to fish, and during the colder months anglers are more likely to go to warmer areas, suggesting that anglers do change their behavior to avoid fishing on the hottest and coldest days. It is difficult to establish whether higher temperatures are associated with more spring and fall fishing, or less summer fishing, because consistent data on fishing participation (trips or days) is not systematically collected. There does not appear to be any relationship between temperature and fishing license sales, even when considering average temperature through the season or when considering temperature during the spring only (when many anglers are making their license purchase decision). Information is not available that would tell U.S. reliably whether higher temperature will increase the demand for recreational fishing (holding constant angling quality).

The direction of the impact of climate change on angling quality is known with more confidence, but the magnitude is uncertain. Higher temperatures and decreased summer stream flows will reduce available habitat for trout. Both stocked and wild trout are important to sport anglers in Pennsylvania. About two thirds of who purchase a trout stamp. In the 2009 PCIA, we noted that little research has been conducted on the specific impact that climate change will have on trout habitat in Pennsylvania. Since that report was written, there have been several studies examining the potential impact of climate change on cold-water sport fish species in other regions. Many of these studies find that fish habitat is sensitive to temperature, but to other external drivers as well. Wenger et al. (2011) find that in addition to temperature changes, changes in stream flow will affect trout habitat. They also forecast a 47 percent reduction in suitable trout habitat by the year 2080 for the interior western United States. Steen, Wiley and Schaeffer (2010) find that in addition to temperature, land cover change will affect the distribution of fish species. They project a decrease in cold water fish abundance and distribution in Muskegon River in Michigan, and an increase in cool- and warm-water fish. Their findings suggest that careful management of land cover change can offset to some extent the impact of temperature rise on fish populations.

Recent research has also highlighted that higher air temperatures will affect different stream stretches in different ways. Trumbo et al. (2010) found that higher air temperatures do not affect all streams in the same way, and that climate change will not affect all stream stretches the same way. Their findings suggest that some trout habitat will remain even after temperatures have risen by an amount that would make the average stream stretch an unsuitable habitat. The challenge is identifying these stream stretches.

While there has been research on the potential loss of cold-water fish habitat from climate change, less attention has been directed toward the possible increase in warm-water fish habitat. Here, it is not necessarily the case that a decrease in one will lead to a corresponding increase in the other. Small streams that are suitable for trout may not provide suitable habitat for desired warm-water species as air and water temperature rises.

10.3 Water-Based Recreation

As discussed in the 2009 PCIA, the demand for water-based outdoor recreation (e.g., swimming and boating) is anticipated to increase as a consequence of climate change (Dawson & Scott 2010). Swimming and boating participation are strongly temperature sensitive. Higher temperatures will result in a longer water-based recreation season and hotter days within the season, both of which will increase demand for water-based recreation.

One issue that was not addressed in the 2009 PCIA was the vulnerability of water-based recreation resources to climate change. As discussed in Chapter 5 of this report, climate change is expected to result in higher winter and spring stream flows, but lower summer and fall flows. So, while the summer demand for water-based recreation will be higher as a consequence of climate change, the water available to support that recreation will be scarcer.

Water level is an important determinant that determines the quality of water-based recreation. Low flows in streams and rivers can result in problems with poor water quality and decreased water depth. Reservoir-based recreation is particularly sensitive to water level. Low water levels can result in loss of access to the pool at boat launches (Daugherty, Buckmeier & Kokkanti 2011). Variation in reservoir levels will constrain both the quantity of water-based recreation and the value to recreationists (Lienhoop & Ansmann 2011). Even if water levels are maintained, reduced summer inflows can have negative consequences on reservoir recreation. Because reservoirs tend to be located higher up in watersheds than similarly-sized natural lakes, water quality in reservoirs is more sensitive to changes in inflow volumes (Brooks et al., 2011).

10.4 Outdoor Sports and Exercise Activities

In the 2009 PCIA, we presented evidence that outdoor sport and exercise participation (e.g., golf, jogging, bicycling, team sports) are temperature-sensitive, and that a general increase in temperature would result in an increase in these activities. This is important, because outdoor recreation conducted close to home is the most common form of outdoor recreation. Higher temperatures would lengthen the outdoor sports and exercise season, but could discourage participation in the hottest months. While it is clear that increases in temperature in Spring and Fall increase outdoor activity, an important question is whether increased temperatures in the hottest part of summer decrease participation due to excess heat.

Ziven and Neidell (2010) employ an innovative research approach that provides evidence that the upper threshold, beyond which increasing temperature decreases outdoor activity, is rather high. They analyze data on time use collected from 24 hour diaries kept by 40,000 individuals. They matched these to weather records for the same date and location, and analyzed the relationship between outdoor temperature and time spent engaged in outdoor recreation. They find that time spent engaged in outdoor leisure increases up to 24.44-26.68°C (76-80°F), and then is fairly constant as temperature rises further, but falls when temperature exceeds 37.78°C (100°F). This suggests that climate change in Pennsylvania would tend to increase outdoor leisure during Fall, Winter and Spring, but would have little impact on outdoor leisure during summer, except on the very hottest days.

While higher summer temperatures alone may not discourage outdoor activities except at very high temperatures, ozone formation may them. As detailed in the 2009 PCIA, ozone formation is greater on days with higher temperature. Zivin and Neidell (2009) find that, after controlling for temperature, visitation at outdoor attractions is lower on days when ozone exceeds alert thresholds. Therefore, for days with high temperatures above 32.22°C (90 °F) but below 37.78°C (100°F), outdoor exercise may be limited more by ozone exposure than by direct effects of heat alone.

10.5 Adaptation Strategies

Climate change will have positive and negative impacts on outdoor recreation in Pennsylvania. Adaptation strategies would include both strategies aimed at mitigating negative consequences and ameliorating strategies aimed at capitalizing positive outcomes.

Climate change will have a clear and dramatic negative effect on winter recreation. Climate change is projected to result in higher winter temperatures and reduced natural snowfall. There are few available adaptation strategies to moderate the anticipated negative consequences for dispersed winter recreation (cross-country skiing and snowmobiling). In Scandinavian countries, where participation rates in cross country skiing are much higher, artificial snowmaking is used to supplement natural snowfall on cross country ski tracks. The level of participation in cross country skiing is not high enough to justify that kind of investment in Pennsylvania.

Artificial snowmaking can sustain downhill ski area operations for some time. But most downhill ski resorts in Pennsylvania will become economically marginal eventually. One adaptation strategy that is currently being adopted by ski resorts (both within Pennsylvania and elsewhere) is to develop revenue-generating summer uses that take advantage of their unique facilities. Examples include dry slope tubing, forest canopy tours and zip lines, and downhill mountain biking. Increased summer revenue can help offset higher snowmaking costs and decreased ski ticket sales, so that ski resorts can be financially feasible with a shorter winter season.

It is important to remember that artificial snowmaking is a relatively new technology, having first been used in the 1950's. It is only recently that the technology for making snow has advanced beyond the original technology. It is difficult to project what technological advances in snowmaking might occur in the future. Still, no technology will be able to make snow if temperatures rise too high.

However, two new technologies could provide similar experiences. Indoor slopes are currently cost prohibitive due to high construction and energy costs. None have yet opened in the United States, though one facility has been under construction in Meadowlands, NJ, for several years. The indoor slope business model is primarily based on teaching customers to ski in small facilities, so that the customers can then travel to large, outdoor resorts located in colder climates. Artificial snow is a plastic mat material that simulates snow. It has been installed at several hills in Great Britain, and a small artificial snow ski slope has been built in Virginia. Current products are good for some uses such as terrain park skiing (performing jumps and tricks on constructed features), but do not match the feel of snow for downhill skiing. As with indoor slopes, all artificial slopes built to date have been small, due to the cost of purchasing and installing the material. Advances in artificial snow that improve quality and decrease cost could make year-round skiing feasible and less sensitive to climate.

Recent research on the impact of climate change on cold-water fish distribution and abundance has demonstrated that temperature is not the only factor that determines cold-water fish habitat suitability. Factors such as stream flow regimes and land use change also have a role to play. These findings suggest that the anticipated decrease in cold-water fish habitat from climate change can be slowed by careful management of stream flows and land use change. Recent research has also pointed out that some stream stretches are more resilient to climate change than others. Resources should be directed towards identifying and protecting these stream stretches, so that they can serve as refuges for cold-water fish species.

Climate change will increase the demand for water-based recreation, but will decrease the summer water flows that support that recreation. Careful water resource management can help maintain summer flows to some degree in water systems with storage infrastructure (reservoirs). Construction of new reservoirs could provide more sites for water-based recreation and more storage in river systems, but is difficult, costly, and introduces other environmental concerns.

Perhaps the most important category of climate-sensitive outdoor recreation, in terms of participation rates statewide, is outdoor sports and exercise undertaken at parks and green spaces close to home. Higher temperatures will result in longer seasons for outdoor sports and recreation and higher participation rates, though participation on the hottest days may be constrained by poor air quality from ozone creation. The most important adaptation strategies in this area are to provide adequate parks and green spaces for this increased demand. Cities and counties should plan for an increase in the demand for developed (eg., ball fields) and undeveloped (eg., green spaces) recreation areas and other recreation infrastructure such as walking and biking corridors. An added benefit from such recreation infrastructure is that provision of these spaces is associated with improved health and decreased obesity (Nielsen & Hansen 2007; Maas et al., 2006). When planning such spaces, consideration should be made to provide shade during the hottest summer days.

10.6 Information Needs

The outdoor recreation activity that is most climate sensitive is winter sports. There is limited information on participation in winter sports, particularly for dispersed sports such as cross country skiing and snowmobiling. However, there is little that can be done to adapt to climate change for these activities, so information generated on these activities would not be useful for public decisions.

Information does exist on lift ticket sales at ski resorts, though that information is not always readily available. Adaptation in this area involves primarily private investment, which will be based on privately-generated information. If there were to be consideration of using public resources to support downhill skiing, then information would need to be generated on the demand for downhill skiing and the cost of making and maintaining snow cover, to evaluate the financial viability of such investments.

Information is of more use for recreational activities that depend on public provision of recreation opportunities such as recreational fishing, water-based recreation and outdoor activities such as sports and exercise that depend on public parks, paths, and green spaces.

With regards to recreational fishing, there is little information on either how climate change will affect the demand for fishing or on how climate change will affect recreational fishing quality specifically in Pennsylvania. With regards to angler behavior, little is known about how climate affects fishing behavior independent of fishing quality. Would a year-round increase in temperature, and longer frost-free season, induce anglers to fish more often? Do high summer temperatures depress fishing activity? With regards to fishing quality, research is needed specific to Pennsylvania on the potential decrease of cold-water fish habitat and survival as a consequence of climate change and on the potential expansion of warm-water fish habitat. This research needs to incorporate projected changes in stream flow regimens and land use as well as projected temperature changes.

10.7 Conclusions

The main conclusions are similar from those in the 2009 PCIA. The outdoor recreation activity that will be most affected by climate change is winter recreation. Snowfall is expected to decline and winter temperatures are expected to rise. Both trends work against snow depth, which is the critical factor for snow-based recreation. There are few opportunities for adaptation for dispersed winter recreation such as cross-country skiing and snowmobiling. Downhill skiing can adapt at least for some time through increased and improved snowmaking. Ski resorts that develop summer revenue sources can remain financially viable longer. As temperatures continue to rise through the latter half of the century, the only available adaptation approach for downhill skiers will be to travel to other regions located farther north or at higher elevations.

Participation in water-based recreation and outdoor sports and exercise is expected to increase as the warm season lengthens. This effect is expected to occur throughout the warm season for water-based recreation, but is expected to be most prominent during spring and summer for outdoor sports and exercise. Higher temperatures during mid-summers are not likely to increase participation in outdoor sports and exercise, though available evidence is that outdoor activity is restricted only at very high temperatures. State and local governments should plan for increased demand for recreational facilities such as beaches and river access points and local parks, bike paths, and green spaces.

While it is clear that climate change will have a negative impact on recreational fishing for cold-water species (e.g., trout) in Pennsylvania, the magnitude of that impact is not well known. Research is needed specific to Pennsylvania on the potential impact of climate change on the abundance and distribution of both cold-water and warm-water fish species. Nor is there much information on the ways in which recreational anglers will change behavior in response to climate change or on the ways in which anglers will change behavior in response to changes in fish abundance and distribution that result from climate change.

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11.0 Appendix

11.1 Locations of Stream Temperature Measurements

River	Water Temperature Location	Air Temperature Location	Period of Record	A (mi^2)	Q (ft^3/s)	Δt	Y-Intercept A	Slope B	NSE	N
Big Spring Creek	Big Spring, PA	State College, PA	2005-2007	3.41	27.8	D	11.11	.02	.13	1092
						W	11.11	.02	.12	156
						M	11.10	.02	.12	36
Manada Creek	Manada Gap, PA	Harrisburg, PA	2005-2007	8.59	17	D	3.11	.65	.93	1010
						W	2.87	.67	.96	153
						M	2.70	.68	.98	36
Juniata River	Huntingdon, PA	Harrisburg, PA	1997-2003	960	1110	D	5.68	.80	.17	2482
						W	4.92	.88	.55	362
						M	4.37	.93	.77	84
Lehigh River	Easton, PA	Allentown, PA	2002-2006	1364	2850	D	5.99	.70	.93	891
						W	3.57	.83	.96	140
						M	5.61	.74	.98	38
Delaware River	Point Pleasant, PA	Allentown, PA	2002-2006	6570	10800	D	6.65	.77	.88	705
						W	3.83	.91	.95	121
						M	4.18	.91	.97	33
Delaware River	Philadelphia, PA	Philadelphia, PA	2002-2007	7993	11800	D	1.19	.86	.88	2053
						W	0.99	.92	.95	306
						M	0.56	.95	.97	72

A: Drainage Area, Q: Mean Annual Discharge, Δt: Time Step of Data, D: Daily, W: Weekly, M: Monthly, NSE: Nash-Sutcliffe Efficiency Measure, N: Number of Data Points

11.2 IPCC Emissions Scenarios

The IPCC scenarios are intended to address uncertainty over demographic development, socio-economic development, and technological change. Scenarios are based on one of four storylines with all scenarios within each storyline part of that storyline "family." The scenario families are A1, A2, B1, and B2. There are three scenario groups within A1 and one in each of the others, creating a total of six scenario groups.

A1 Storyline

The A1 scenario is characterized by high rates of economic growth. Population growth increases until mid-century and declines afterwards. The scenario also assumes a rapid introduction of new and more efficient technologies. This results in and enables relatively energy intensive lifestyles. The major themes characterizing the A1 scenario include: convergence among regions, capacity building, increased cultural and social interactions, and reduced regional differences in per capita income. Economic convergence is facilitated by technological development, increased international cooperation and national regulatory changes.

The A1 storyline is divided into three scenario groups (A1F1, A1B and A1T) with each assuming an alternative energy technology mix. The A1F1 group assumes a fossil fuel intensive energy mix. A1B assumes a balanced energy mix and thus does not rely too heavily on any one energy source. It is assumed that technological changes apply evenly to all energy types and supply sources. Finally, A1T assumes a primarily non-fossil fuel energy mix.

A2 Storyline

The A2 storyline assumes a very heterogeneous world. As a result, it is characterized by themes of self-reliance and preservation of local identities. Population growth rates are continuously increasing because of slow convergence of fertility patterns across regions, creating the largest population of all of the storylines. Economic development is primarily at the regional level. This results in varied rates of economic growth across regions. As a result, the world is characterized by significant income inequality, particularly between the developed and developing world. Technological development follows a similar pattern and new technologies are diffused slowly. Both economic growth and technological change are slower than in the other storylines. The heterogeneous nature of the A2 storyline also presents itself in more varied governments across regions. Environmental concerns are locally based, with little global cooperation in environmental policy. Regional resource availability determines the energy mix utilized within regions.

B1 Storyline

A convergent world characterizes the B1 storyline. Worldwide, the population grows through mid-century and declines afterwards. Major themes are increased levels of global integration and more concern for economic, social, and environmental sustainability. As a result, development becomes more socially and environmentally 284 conscious. The structure of the economic system transitions quickly to a service and information oriented economy, with a resulting decrease in the consumption of material goods. There are efforts to decrease income inequality. However, these socially and environmentally conscious efforts may compromise economic efficiency and distort markets. Rapid technological innovation combined with an effective global institutional structure to diffuse these technologies results in expanded use of cleaner and more energy efficient technologies. These factors contribute to a high level of environmental quality in the B1 storyline. Oil and gas use decline as the world makes a relatively smooth transition to alternative energy use.

B2 Storyline

The B2 storyline is characterized by an emphasis on local solutions to economic, social, and environmental sustainability. The global population increases continuously, but at a rate lower than in the A2 storyline. As a result of a local emphasis, international institutions become less important. There are intermediate levels of economic development. Incomes converge at the local level. Though there is some convergence in incomes worldwide, an emphasis on local solutions results in a slower convergence than in storylines characterized by high levels of global integration. Technological change is less rapid and less diffused globally but more regionally diverse than in the B1 and A2 storylines. Environmental policy is focused at the local and regional level, with global environmental initiatives less important. Energy use is heterogeneous, with resource endowments influencing the regional energy mix. Globally, energy use transitions alternative energies, but this transition is gradual and the global energy system relies primarily on fossil fuel energy sources.