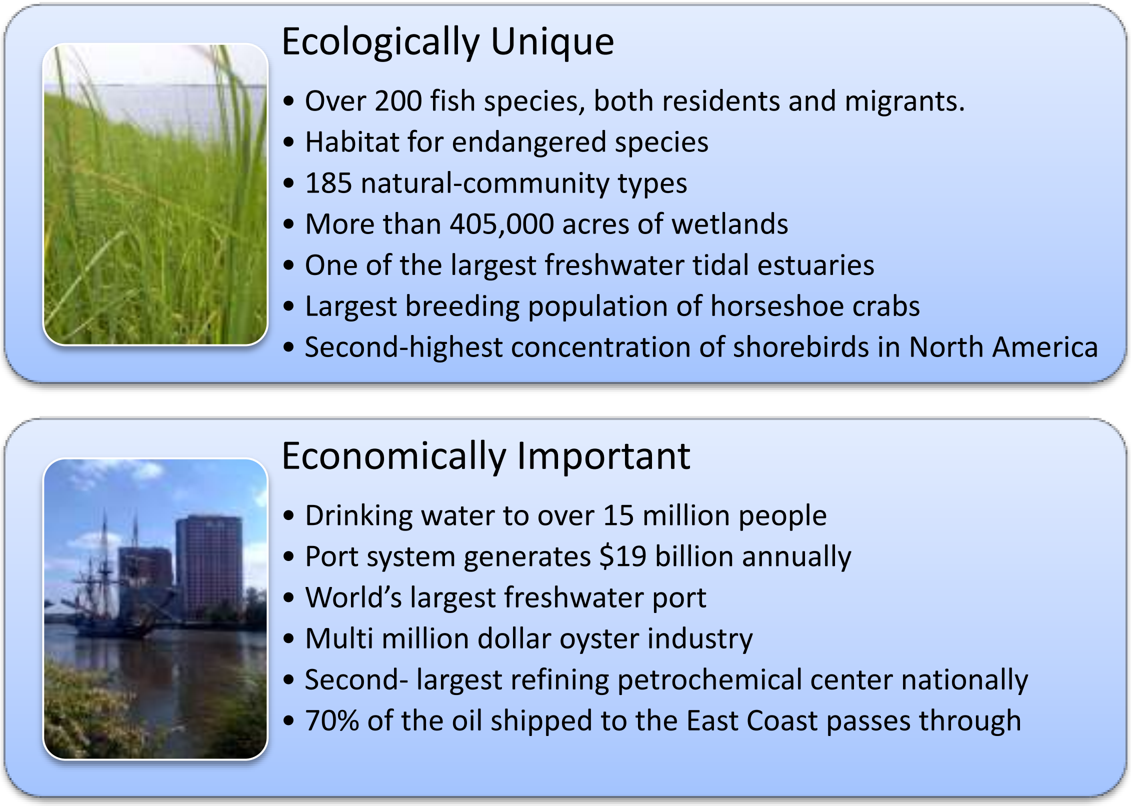
Chapter 1

Introduction

The Delaware River has a duel identity as both a living river and a working river, which makes its Estuary one of many contrasts. It is a principal corridor for commerce that has sustained the region since America's colonial period and reached a zenith during the Industrial Revolution. Today, it continues to be a major strategic port for national defense and economic interests. The Estuary supports the 4th largest urban center in the nation and contains the world's largest freshwater port. The Estuary also sustains a wealth of natural and living resources, such as drinking water for millions of people, extensive tidal marshes that sustain vibrant ecosystems, and world-class habitats for horseshoe crabs, migratory shorebirds, and rare and endangered shellfish (Figure 1-1).



Ecologically Unique

- Over 200 fish species, both residents and migrants.
- Habitat for endangered species
- 185 natural-community types
- More than 405,000 acres of wetlands
- One of the largest freshwater tidal estuaries
- Largest breeding population of horseshoe crabs
- Second-highest concentration of shorebirds in North America

Economically Important

- Drinking water to over 15 million people
- Port system generates $19 billion annually
- World's largest freshwater port
- Multi million dollar oyster industry
- Second- largest refining petrochemical center nationally
- 70% of the oil shipped to the East Coast passes through

Figure 1-1. Examples of ecological and economic features of the Delaware Estuary

Like elsewhere in the United States and world, the Delaware Estuary watershed and its natural resources will face many challenges with climate change. Due to the many unique features of the Estuary, some aspects of changing climate may not be as severe here than in nearby watersheds and estuaries, whereas other changes may be more problematic. Hypothetically for example, modest rises in temperature could lengthen growing seasons or boost productivity for some signature species and help them compete with invasive species or keep pace with sea-level rise. On the other hand, sea-level rise will likely result in greater saltwater (salinity) reaching further up the estuary, threatening the many unique species adapted to our freshwater tidal area, which is the largest of its kind in the world.

Climate changes will occur alongside other changes in the fabric of the watershed. Continued rises in human population will increasingly tax our natural and built infrastructure, with anticipated loss of open space, fragmentation of natural habitats, and rising demands for clean water, as a few examples. Climate change and continued watershed change will interact in complex ways. Environmental resource managers will require new ways to predict climate impacts in order to adapt appropriately.

This report summarizes findings from our first significant effort at climate adaptation planning, whereby the Partnership for the Delaware Estuary worked with dozens of partner entities to characterize the array of issues that confront a few of our key natural resources and to begin to plan for how we might respond, to work proactively to stave off losses and take advantage of opportunities.

1.1 Climate Ready Estuaries – The Delaware Estuary Pilot

Climate Ready Estuaries (CRE) is an EPA program operated by the Climate Change Division and the Oceans and Coastal Protection Division. The mission is to work with the National Estuary Programs to: 1) assess climate change vulnerabilities, 2) develop and implement adaptation strategies, 3) engage and educate stakeholders, and 4) share the lessons learned with other coastal managers. In 2008, EPA funded six National Estuary Programs to create CRE pilots. The Partnership for the Delaware Estuary (PDE) was one of the original six pilots.

Through the CRE pilot funding, the Estuary Programs were given flexibility to design studies and adaptation plans according to the needs of their study areas, and up to 18 months to conduct the pilot. In the large and complex Delaware Estuary (Fig. 1-2,) three case studies were chosen representing major resource areas of concern in the system. These case studies consisted of tidal wetlands as a habitat resource, drinking water as a human/water resource, and bivalve shellfish as a living resource.

For each of the three case study resources, PDE:

- characterized the array of vulnerabilities to climate change using updated climate predictions,
- assessed the potential effectiveness of adaptation options to address those vulnerabilities, and
- developed recommendations for resource managers and stakeholders in the region.

Due to the short timeline and pilot nature of this project, our approach was primarily qualitative, relying principally on best scientific judgment and risk assessment methods. Our findings should therefore be considered preliminary, helping to guide next steps. More detailed, quantitative analyses will be needed to confirm and refine our findings leading to site-specific recommendations.

PDE recognizes that climate change effects are not occurring in a vacuum and must considered with other stressors to the system, Including such activities as dredging, water withdrawals, land use change, new energy development, legacy and emerging pollutants, and environmental hazards. Future refinements to these recommendations will need to consider the added complexity contributed by such ongoing watershed changes. Future adaptation efforts will also need to consider new information on future climate projections, which are frequently updated. Finally, efforts to build on this report will need to consider the multitude of other important natural resources in the Delaware Estuary, and their interactions. "Adaptive adaptation plans" will therefore be needed to build on this first effort.

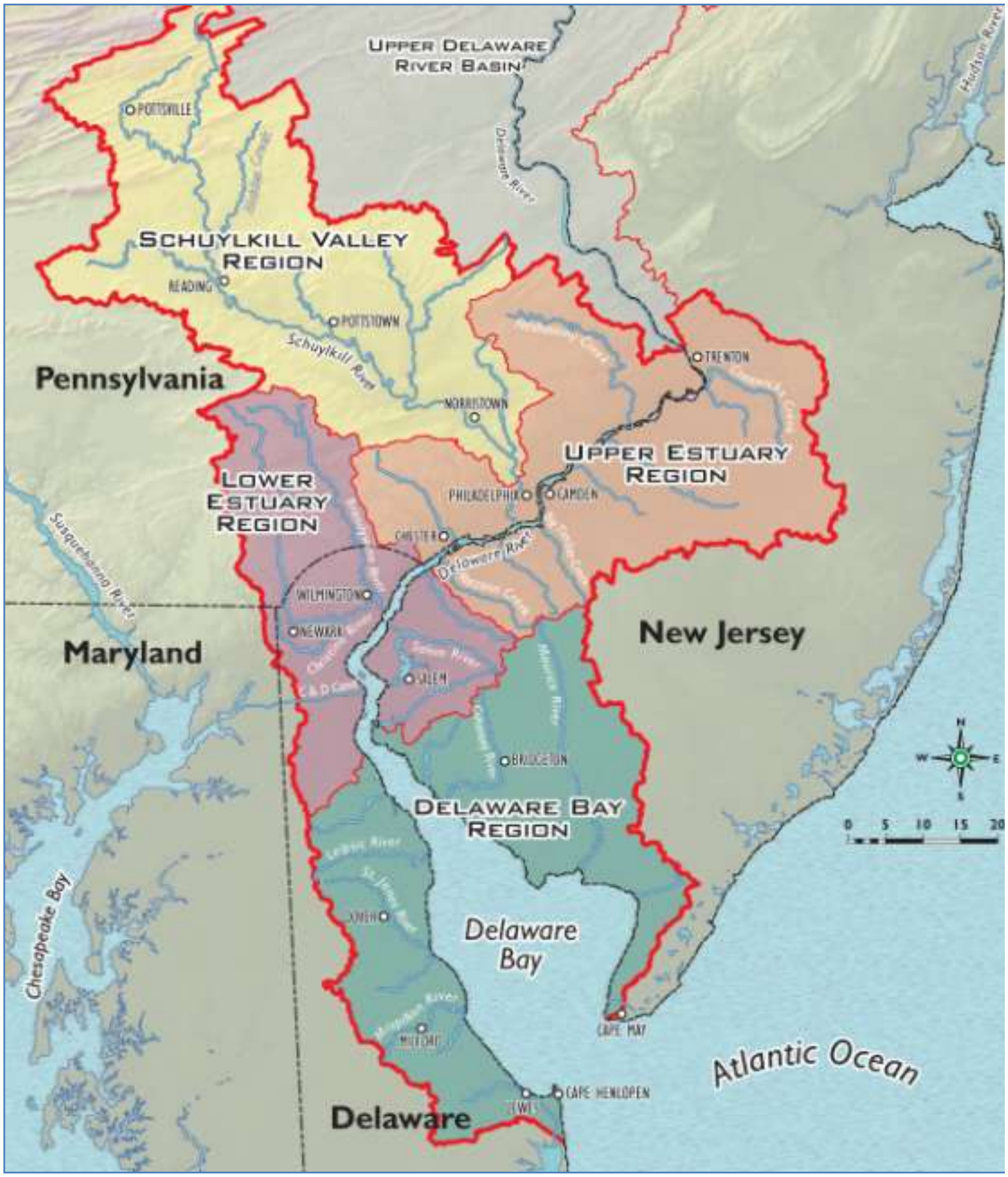


Figure 1-2. Map of the study area of the Partnership for the Delaware Estuary, a National Estuary Program. This comprises the lower 52% of the Delaware River Basin.

1.2 Approach

To assess vulnerabilities of our three case study resources (tidal wetlands, drinking water, bivalve shellfish) to changes in physical and chemical conditions associated with climate change, we first obtained updated and locally relevant predictions for expected changes in key environmental conditions between now and 2100 (Chapter 2.)

We then engaged scientists and managers with expertise in each of the three case study resources to identify and prioritize their concerns related to these expected changes in physical conditions (Figure 1-2). Information was gathered in a special workshop (September 2008), a climate session at the Delaware Estuary Science Conference (January 2009), in workgroup meetings, and through polling using Survey Monkey™. We asked our many partners to also furnish potential adaptation options for each case study resource. To augment the information contributed by these experts, we also performed a literature review for vulnerabilities and adaptation tactics related to the three case studies. This information was compiled into a concise inventory of potential vulnerabilities and adaptation measures.

Survey methods and a risk assessment approach were then used to gauge relative levels of concern (for vulnerabilities) and effectiveness (for adaptation tactics) by additional resource-specific experts in the broader science and management community in the Delaware Estuary or vicinity. This approach was useful in providing a first order ranking of relative concerns and the relative utility of adaptation measures for each of the three case studies based on best available expertise. It also exposed some knowledge gaps.

Potential vulnerabilities and adaptation fixes were then considered in the context of ecosystem goods and services (a.k.a., natural capital). Our eventual goal is to quantify the natural capital "costs" of climate change and "gains" of various adaptation tactics to inform investments in crucial life-sustaining ecosystem services. However, this analysis is only now beginning and this report is limited to some early discussion of future tradeoffs and information for strategic investment, where possible.

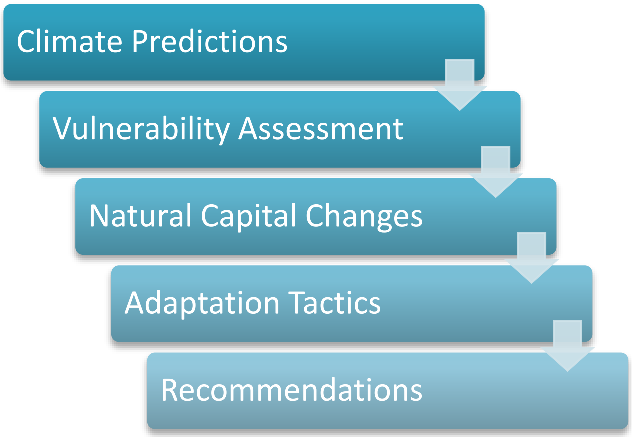


Figure 1-3. Approach for climate adaptation planning for

These activities were performed by multiple teams of experts brought together under a new Delaware Estuary Climate Adaptation Workgroup (CAWG), which was formed as a work group under the PDE Science and Technical Advisory Committee. The CAWG met quarterly. In addition, six subgroups of the CAWG were created to tackle specific tasks and steps in our approach (Fig. 1-3). The subgroups were Tidal Wetlands, Bivalve

Shellfish, Drinking Water, Climate Predictions, Natural Capital, and GIS. Table 1-1 lists the main participants. Although our overall approach was comparable among the three case studies, some methods differed considerably. Additional details on the approach and methods, as well as the results, are provided in the sections below: Predictions (Chapter 2,) Tidal Wetlands (Chapter 3,) Drinking Water (Chapter 4,) and Bivalve Shellfish (Chapter 5.)

Table 1-1. Participants in the PDE Climate Adaptation Workgroup and six subgroups.

Climate Adaptation Workgroup	**(Chair: Dr. Ray Najjar)**
Tidal Wetlands	David Velinsky – Academy of Natural Sciences Kurt Phillip - Wetlands Research Service Tracy Quirk – Academy of Natural Sciences Danielle Kreeger, Angela Padeletti, Priscilla Cole – PDE
Bivalve Shellfish	Danielle Kreeger – PDE John Kraeuter – Rutgers University Priscilla Cole – PDE
Climate Predictions	Raymond Najjar (Chair) The Pennsylvania State University
Drinking Water	Paula Conolly (Chair) –Philadelphia Water Department Raymond Najjar – The Pennsylvania State University Lance Butler – Philadelphia Water Department Carol Collier – Delaware River Basin Commission Chuck Kanetsky - US EPA Region 3 Sue Kilham – Drexel University Chris Linn – Delaware Valley Regional Planning Commission Christine Mazzarella - US EPA Region 3 Amy Shallcross – Delaware River Basin Commission Alysa Suero - US EPA Region 3
Natural Capital Team	Priscilla Cole (Chair) – PDE Anthony Dvarskas – National Oceanographic and Atmospheric Administration Irene Purdy – US EPA Region 2 James Bennett – formerly DVRPC
GIS Team	Priscilla Cole – PDE Andrew Homsey – Water Resources Agency Paula Conolly – Philadelphia Water Department Chris Linn – Delaware Valley Regional Planning Commission James Bennett – Delaware Valley Regional Planning Commission
Other CRE Participants	Jerry Kauffman – Water Resources Agency Jennifer Adkins – PDE Jessica Rittler-Sanchez – DRBC Simeon Hahn - NOAA

1.3 On the road to Adaptation Planning: Next Steps

There is some debate about what it means to be 'climate ready.' The initial Delaware Estuary CRE pilot has come to a close, but the work of climate adaptation planning is an ongoing process. Vulnerability assessments have only been carried out for three of the Estuaries' many resources, and these vulnerabilities could be expanded in further quantitative analysis and modeling. Likewise, the adaptation options and recommendations in this report have not undergone cost benefit analysis, nor have they been vetted through the larger constituent bases or stakeholder bodies necessary to carry them out. This report is the first of its kind for the Delaware system, and it is an important first step for climate adaptation planning. However, this is only the first of many steps that need to take place before the Delaware Estuary is truly Climate Ready.

Table 1-2 provides examples of other regional climate programs in the Delaware Estuary. The CRE pilot fills an important niche by focusing on specific resources at the geographic scale of the Delaware Estuary and watershed. In the future, greater information sharing and collaboration will be needed to link various climate adaptation efforts within the Delaware River Basin and Estuary.

Table 1-2. Examples of regional efforts to examine climate adaptation.

Regional Entities	Climate Change Interests	Mitigation Targets for Greenhouse Gases
Delaware River Basin Commission	Flooding, Inundation, Salinity	N/A
Philadelphia Water Department	Drinking Water, Intakes	N/A
Commonwealth of Pennsylvania	Energy, Forests, Carbon Emissions	30% reduction by 2020 (presented to the Governor Dec 18, 2009)
State of New Jersey	Carbon Sequestration, Air, REGGI Participant	Reduce emissions to 1990 levels by 2020 and 80% below 2006 emissions levels by 2050
State of Delaware	Sea-level Rise, Inundation, REGGI Participant	Stabilize emissions between 2009 - 2015, then reduce incrementally to a 10% reduction by 2019
Partnership for the Delaware Estuary	Natural Resource Adaptation Planning, Climate Predictions, Prioritization Using Natural Capital Analyses	N/A

For updated information, please visit us on the web:
http://www.delawareestuary.org/science_projects_climate_ready.asp

Chapter 2

Climate Predictions

Planning for climate change in the Delaware Estuary watershed first requires an understanding of the most current and locally relevant climate predictions. The Climate Adaptation Workgroup (CAWG) enlisted Dr. Raymond Najjar from The Pennsylvania State University to project changes in temperature, precipitation, sea-level, and a variety of metrics based on these variables (e.g., length of growing season, number of frost days, extreme precipitation, etc.) that can be expected between the present and 2100 under two greenhouse gas emissions scenarios (B1 and A2). Dr. Najjar, an oceanographer, has 10 years of experience in using climate model output for coastal and regional climate impact assessments ((Najjar, 1999; Najjar et al., 2010; Najjar et al., 2000; Neff et al., 2000; Shortle et al., 2009; Wu et al., 2009).

To provide these climate projections for the Delaware Estuary for the 21st century, fourteen different climate models were first contrasted to test their accuracy in predicting past conditions for the region (Appendix A). For this comparison, the geographic extent of the Delaware Estuary and its watershed were regarded as spanning three degrees in latitude and one degree in longitude. Therefore, the climate simulations were averaged over three grid boxes (Fig. 2-1).

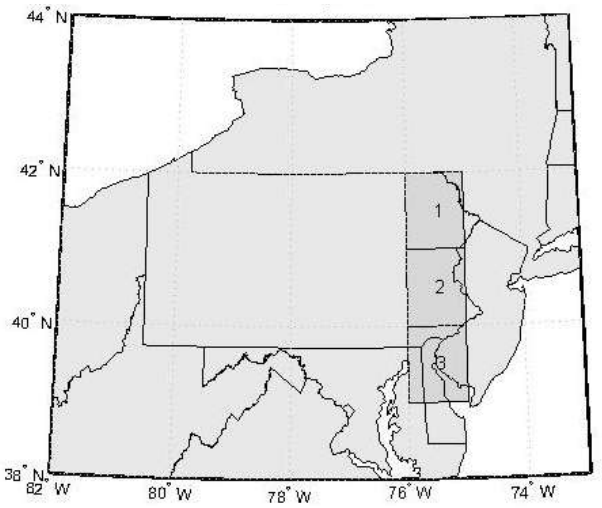


Figure 2-1. For climate modeling, the Delaware River Basin was represented by the three degrees of latitude (39-42°N) and one degree of longitude (75-76°W).

The model comparison indicated that the best past predictions resulted from use of all fourteen model outputs averaged together, rather than from any single model (Appendix A). The multi-model average was considered superior to any individual Global Climate model (GCM) (Appendix A). Therefore, this multi-model approach was used to project future conditions.

Table 2-1 summarizes results of 21st century climate predictions for the Delaware Estuary region. As noted above, models were used to hind-cast climate conditions in the past to expose the models' biases and accuracies. To predict future conditions, these biases (Table 2-1) must be corrected (Appendix A). Sections 2.1 to 2.3 describe expected climate conditions in the Delaware estuary watershed for the key metrics described in Table 2-1. In addition, Dr. Najjar compiled the latest literature on expected sea-level (Section 2.4) and salinity rise (Section 2.5).

Table 2-1. Climate predictions for temperature, precipitation, length of growing season, and number of frost days for the Delaware Estuary watershed during the period from present to 2100. A synopsis of model accuracy and confidence in future projections is provided in columns 3 and 5, respectively.

Climate Condition		Model Evaluation: Biases & Issues	21st Century Prediction	Confidence Levels
Temperature	Monthly Mean	Slight cool bias in winter and summer	Warming: 1.9 – 3.7°C median rise by late century; Substantially greater warming in summer months	High
	Inter-annual Variability	Slightly too much variability, but better with winter than summer		
	Intra-monthly Variability	Models' mean reproduces correctly, but there is a large spread among the individual models		
	Extreme Temp >80° F	Underestimates	Downscaled models show substantial increases	High
Precipitation	Monthly Mean	Wet bias in winter and spring and a dry bias in summer	Increase in Precipitation: 7 - 9% median increase by late century; Substantial increase in winter months	Medium
	Inter-annual Variability	Does not predict summer peak and winter minimum seen in observed conditions		
	Intra-monthly Variability	Mean reasonably captures, but too low in the summer		
Extreme Precipitation	Short Term Drought	Slight low bias	Substantial increases, but less than ¼ of models show declines	Medium
	Heavy Precipitation	Slight low bias		
Growing Season Length		Predicts accurately	Substantial increase by end of century	High
Number of Frost Days		Somewhat high	Substantial decline	High

2.1 Temperature

The models show high confidence that average annual temperatures will increase by the end of the 21st century by 2–4° C (Fig. 2-2). Carbon dioxide emissions will determine whether the lower or higher temperature is realized. More warming is expected in the summer months. The B1 scenario (lower emissions) predicts median summer temperature increases of more than 2° C, whereas the A2 scenario (higher emissions) is predicted to result in summers of about 4.5° C warmer than present by 2100. These conclusions are consistent with predictions by the Union of Concerned Scientists, which estimated that Pennsylvania summer temperatures could increase by 2–7° C depending on the emissions scenario (UCS, 2008; Field et al. 2007). Extreme summer heat days are also expected to rise by the end of the century (UCS, 2009; GCRP, 2009) and southern Pennsylvania could see between 50-70 days per year with temperatures over 90°F (UCS, 2008).

2.2 Precipitation & Extreme Weather Events

Annual mean precipitation is predicted to increase by 7-9% by the end of the 21st century (median projection). Higher increases are expected during winter months (Najjar 2009; GCRP 2009), with more than a 15% increase by 2100 under the high emissions scenario (Appendix A.) Three quarters of the models predict substantial increases in the frequency of extreme precipitation events including heavy precipitation and consecutive dry days. The U.S. Global Climate Research Program (GCRP) also predicted increases in extreme weather events and associated risks from storm surges (GCRP, 2009).

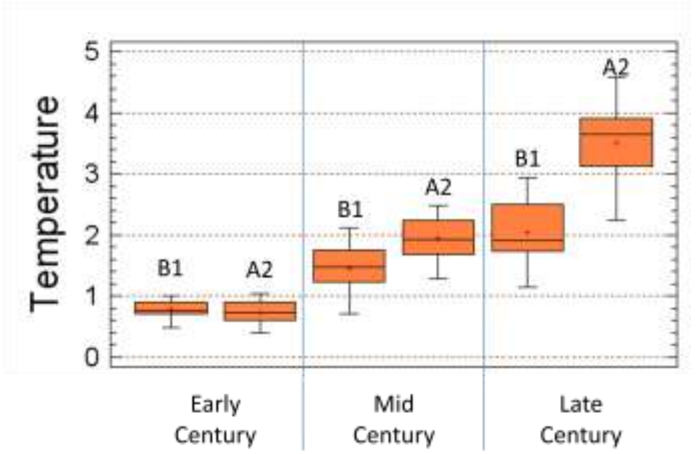


Figure 2-2. Box and whisker plots of temperature rise (°C) for three periods with respect to the late 20th century (1980-1999): 2011-2030 (early century,) 2046-2065 (mid century,) and 2080-2099 (late century) under low (B1) and high (A2) emissions scenarios. The box-and whisker plot shows quartile distributions (minimum, 25th percentile, median, 75th percentile, and maximum) of temperature change among the fourteen models used.

2.3 Other Climate Model Outputs

The length of the growing season will substantially increase: by about 15 days by mid-century and by up to 30 days by 2100 (Appendix A). Approximately 20 fewer frost days per year are predicted by mid-century and 40 fewer frost days by the end of the century under the higher emission scenario (Appendix A). With fewer frost days, Pennsylvania snow packs are expected to decrease and melt earlier (UCS, 2008). The loss of the winter snow pack, combined with higher winter precipitation, will contribute to greater winter flooding and lower amounts of springtime snowmelt runoff. These factors will affect the seasonal timing of freshwater supplies for drinking water and habitats dependent on snow melt.

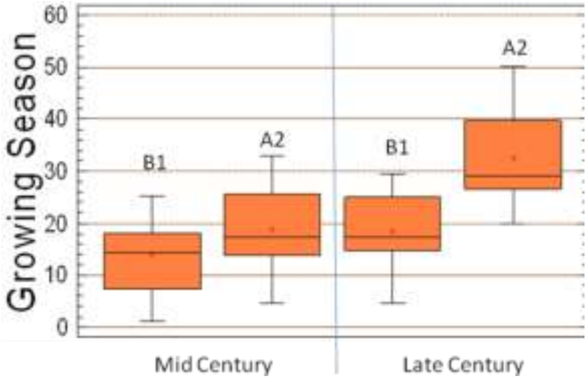


Figure 2-3. Box and whisker plots of growing season length changes for two periods with respect to the late 20th century (1980-1999): 2046-2065 (mid century,) and 2080-2099 (late century) under low (B1) and high (A2) emissions scenarios. The box-and whisker plot shows quartile distributions of the growing season length changes among the fourteen models used.

2.4 Sea-level

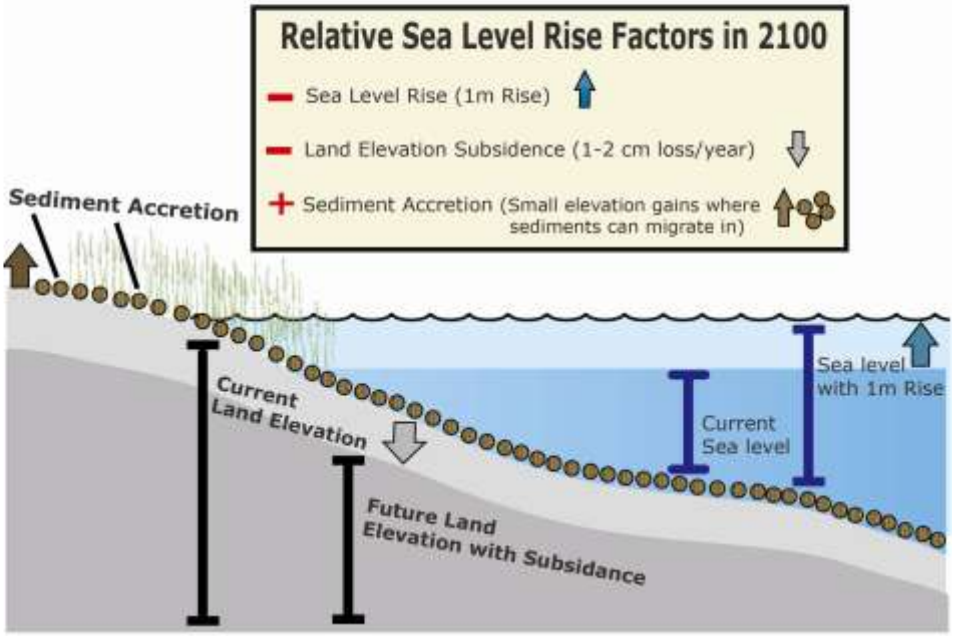


Figure 2-3. The effective rate of sea-level rise experienced at the land-sea surface in the Delaware Estuary is determined by the net elevation change from three factors: the actual rate of sea-level rise, the sinking elevation (subsidence) of the land, and the amount of sediment collected (accretion.)

The Mid-Atlantic States are anticipated to experience sea-level rise greater than the global average (GCRP, 2009). **Absolute sea-level rise** refers to the global rise of water resulting from melting ice sheets and expanding water as it warms. Some regional variation in absolute sea-level will occur because of gravitational forces, wind, and water circulation patterns (Appendix C). In the Mid-Atlantic region, changing water circulation patterns are expected to increase sea-level by approximately 10 cm over this century (Appendix C; Yin et al., 2009). Locally, two other factors contribute to relative sea-level rise: Subsidence and Sediment Accretion (Fig. 2-3.) Post-glacial settling of the land masses has occurred in the Delaware system since the last Ice Age. This settling causes a steady loss of elevation, which is called **subsidence**. Through the next century, subsidence is estimated to hold at an average 1-2 mm of land elevation loss per year (Appendix C; Engelhart et al., 2009). **Sediment Accretion** is a natural process in which suspended sediments in the water settle out and build up along shoreline habitats such as mud flats and wetlands. Accretion cannot occur on hard structures, where erosion is high, or where areas are sediment-starved from diversions. Rates of subsidence and accretion vary in different areas around the Estuary, but the greatest loss of habitat will occur where subsidence is naturally high in areas that cannot accrete more sediments to compensate for elevation loss plus absolute sea-level rise. All three factors must be taken into consideration to determine where habitat will persist, where it will be lost, and where it can be saved (Fig. 2-3) The net increase in sea-level compared to the change in land elevation is referred to as the rate of relative sea-level rise (RSRL). Our best estimate for RSLR by the end of the century is 0.8 to 1.7 m (Appendix C); additional local predictions for RSRL are shown in Table 2-2.

Table 2-2. Predicted rates of relative sea-level rise by 2100 from different sources.

Relative Sea-level Rise Predictions	
State of Delaware	Scenarios = 0.5 m, 1.0 m, 1.5 m
State of Maryland	0.61 m – 1.12 m
State of New York	Considering: Conservative 0.17 m – 0.53 m High Estimates 1.4 m
State of Maine	1.0 m
IPCC AR4, 2007	0.18 m to 0.59 m, excluding accelerated ice discharges from the Greenland and Antarctica ice sheets.
Appendix C, Rahmstorf (2007)	0.8 m – 1.7 m
U.S. Army Corps of Engineers	Planning with scenarios of 0.5m, 1.0m, 1.5m

2.5 Salinity

The Delaware Estuary has the largest freshwater tidal prism in the world. The freshwater tidal region extends about 70 river miles, and the salinity in areas more seaward changes very gradually. This feature makes the Delaware Estuary unique among large American estuaries because of the array of ecosystem services supplied to human and natural communities tied to the extended salinity gradient, such as the supply of drinking water for people and rare natural communities. Increasing sea-level will result in larger tidal volumes that bring more salt water further up the estuary. Sea-level rise could increase the tidal range in the Delaware system (Walters 1992), similar to expectations for the Chesapeake Bay (Zhong et al, 2008). Tidal range changes would also likely increase the salinity range over the tidal cycle (Appendix B).

Increased precipitation could help to offset the salinity rise, at least during cooler seasons. Current literature suggests that modest increases in annual streamflow and more substantial increases in winter streamflow can be expected over the 21st Century, resulting mainly from precipitation (Section 2.2.) However, precipitation is likely to become more variable with the potential for more intense storms and storm surges (Lambert and Fyfe, 2006). All of these factors will likely increase the variability of river flows, perhaps with higher winter runoff and lower or similar summer runoff, leading to increased variability in estuarine salinity (Appendix B).

To understand how river flows affect salinity in the estuary, Dr. Najjar and the CAWG obtained historical salinity data on computer punch cards from Rutgers Haskin Shellfish Research Laboratory. A card-reader was located at Penn State to enable these data, which extend back to 1927, to be digitized. With these data, Dr. Najjar was able to reproduce results from a 1972 Haskin report relating salinity to streamflow, and add more recent salinity data to quantify long term trends in the region (Appendix B). A preliminary analysis suggests that salinity is increasing more than can be explained by streamflow and simple models of the response of salinity to sea-level. This could be a result of other forces in the Estuary, such as successive channel deepening events that occurred during the period of analysis, and which could have also contributed to salinity intrusion upbay due to larger tidal volumes and bathymetric changes (Appendix B).