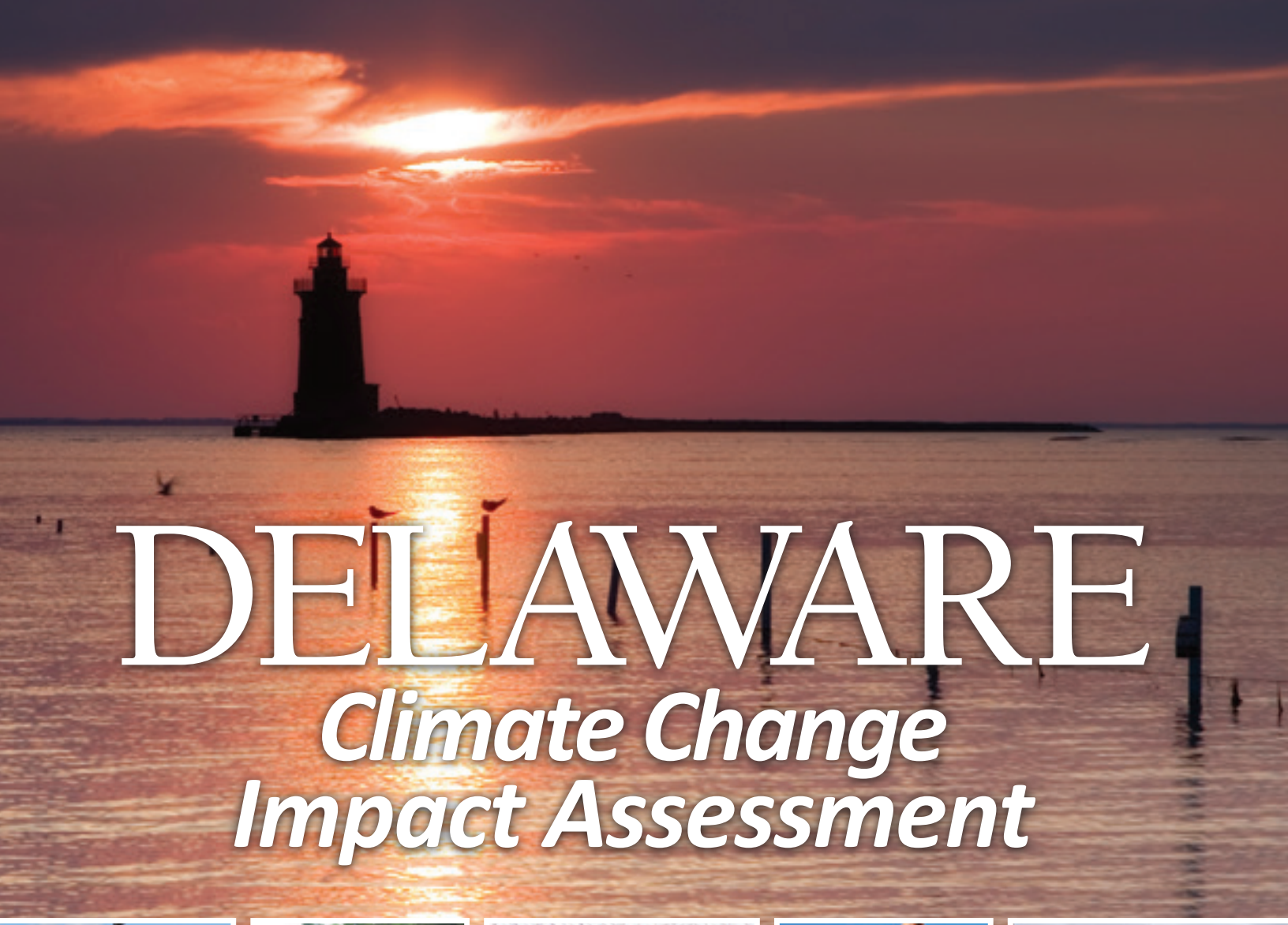

DELAWARE

Climate Change Impact Assessment

PREPARED BY

Division of Energy and Climate

Delaware Department of Natural Resources and Environmental Control

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Climate Change Impact Assessment

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Division of Energy and Climate

Delaware Department of Natural Resources and Environmental Control

February 2014

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- **Withered corn:** Ben Fertig, Integration and Application Network, University of Maryland Center for Environmental Science
- **Farmer sweating:** Photos.com
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Section 1: Summary and Introduction

Table of Contents
Executive Summary
Chapter 1 – Introduction

Section 2: Delaware's Climate

Chapter 2 – Delaware's Historic Climate Trends
Chapter 3 – Comparison of Observed and Modeled Trends
Chapter 4 – Delaware's Future Climate Projections

Section 3: Delaware's Resources

Chapter 5 – Public Health
Chapter 6 – Water Resources
Chapter 7 – Agriculture
Chapter 8 – Ecosystems and Wildlife
Chapter 9 – Infrastructure

Appendix:

Climate Projections – Data, Models, and Methods
Climate Projection Indicators

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December 20, 2013

Dear Fellow Delawareans:

Delaware's long-term competitiveness will be determined in many ways by our ability to improve the state's resiliency to climate impacts. Existing challenges from inland and coastal flooding, heat waves, and intense precipitation events will be exacerbated and significantly impact our citizens, economy and quality of life, and critical infrastructure and services. As the lowest-lying state in the union, preparing now is critical to ensure that Delawareans and our economy are resilient. Our quality of life will continue to be challenged and the window for action is narrowing.

The systems that we depend on day-to-day will continue to be impacted. Our food and water systems, our transportation and commerce networks, and the habitats that support our wildlife and ecosystems are not immune. The decisions that we make now will have lasting impacts on Delaware's future, but to make these decisions we have to understand the best available science. The Delaware Climate Impact Assessment provides that foundation–a report based on the best available science specific to Delaware. We have gathered Delaware's leading scientists and practitioners, the Climate Change Steering Committee, to understand the science and the potential impacts on five key sectors: public health, water resources, agriculture, ecosystems and wildlife, and infrastructure. Their work along with the scientific analyses conducted by Dr. Daniel Leathers, Delaware State Climatologist, and Dr. Katharine Hayhoe, atmospheric research scientist, has built a strong scientific foundation for moving us forward.

Solutions require actions on both reducing our emissions and adapting to the changes that we are already experiencing. The State of Delaware is taking action. Governor Markell is implementing Executive Order 41–*Preparing Delaware for Emerging Climate Impacts and Seizing Economic Opportunities from Reducing Emissions*. This executive order directs state agencies to improve resiliency by recognizing the risks of flooding and sea level rise, developing implementable strategies for adaptation and preparedness, and setting goals for greenhouse gas reductions. Governor Markell has also been appointed by President Obama to serve on as White House task force on Climate Preparedness. This task force will provide recommendations on how the Federal Government can increase climate preparedness, remove barriers and create incentives, and support local efforts on building resilience to climate change. I currently serve as the Chair of the Regional Greenhouse Gas Initiative, an innovative cap-and-trade market based program that is reducing carbon emissions in the power sector and creating jobs through investments in clean energy and energy efficiency projects. Through this and other efforts we have reduced greenhouse gas emissions more than any other states over the past few years and there are many more examples of Delaware's leadership on reducing the impacts of climate change, but there is more work to be done.

Delaware's Good Nature depends on you!

December 20, 2013
Page 2

As Delawareans, we need to be aware of the challenges that we are facing and have dialogues on the actions we can take here at home. We cannot solve the global challenge alone, but we can take actions locally that will help ensure a high quality of life for us and our children, improve our preparedness and resiliency, and facilitate a strong competitive economy. The Delaware Climate Change Impact Assessment serves as a tool to guide these conversations. It's time to roll up our sleeves and take the actions necessary to carry us forward.

Sincerely,

Collin P. O'Mara
Secretary

DELAWARE
Climate Change Impact Assessment

PREPARED BY

Division of Energy and Climate
Delaware Department of Natural Resources and Environmental Control

Section 1: Summary and Introduction

Front Matter

Table of Contents
Acknowledgments
Acronyms and Abbreviations
Additional Resources

Executive Summary

Chapter 1 – Introduction

Table of Contents

Section 1 – Summary and Introduction

Front Matter

Figures and Tables xi
Acknowledgments xiv
Acronyms and Abbreviations xvii
Additional Resources xviii

Executive Summary 1

1. Introduction

1.1. Purpose 1-1
1.2. Scope 1-1
1.3. Organization 1-2
1.4. Methodology 1-3
1.5. Climate 101 1-4
1.5.1. Understanding the Language of Climate Science 1-4
1.5.2. Understanding Climate Information 1-7
1.5.3. Types and Sources of Greenhouse Gases 1-10

Section 2 – Delaware's Climate

2. Delaware Climate Trends *(Daniel J. Leathers)*

Key Terms 2-2
Summary 2-3
2.1. Background 2-4
2.2. Data and Methods 2-4
2.2.1. Statewide and Divisional Temperature, Precipitation, and Drought Index Data 2-4
2.2.2. Cooperative Daily Weather Station Data 2-5
2.2.3. Methods 2-6
2.3. Climate Trends Analysis – Temperature 2-6
2.3.1. Statewide Results 2-6
2.3.2. Temperature Summary 2-9
2.4. Climate Trends Analysis – Precipitation 2-9
2.4.1. Statewide Results 2-9

3. Comparing Observed and Modeled Historic Data
(Katharine Hayhoe and Daniel J. Leathers)

Key Terms 3-1
3.1. Can Global Climate Models Reproduce Observed Historical Trends? 3-1

4. Delaware Climate Projections
(Katharine Hayhoe, Anne Stoner, and Rodica Gelca)

Summary 4-1
Key Terms 4-2
List of Graphs for Temperature and Precipitation Indicators 4-4
4.1. Background 4-5
4.1.1. Observed and Projected Future Change 4-6
4.1.2. Implications for Delaware 4-6
4.2. Data and Methods 4-7
4.2.1. Global Climate Models 4-7
4.2.2. Statistical Downscaling Model 4-7
4.2.3. Station Observations 4-8
4.2.4. Higher and Lower Scenarios 4-8
4.2.5. Uncertainty 4-9
4.3. Temperature-Related Indicators 4-9
4.3.1. Annual and Seasonal Temperatures 4-10
4.3.2. Temperature Extremes 4-14
4.3.3. Energy-Related Temperature Indicators 4-19
4.4. Precipitation-Related Indicators 4-21
4.4.1. Annual and Seasonal Precipitation 4-21
4.4.2. Dry and Wet Periods 4-22
4.4.3. Heavy Precipitation Events 4-24
4.5. Hybrid Variables 4-26
4.5.1. Relative Humidity and Dewpoint Temperature 4-26
4.5.2. Summer Heat Index and Potential Evapotranspiration 4-27
4.5.3. Hybrid Temperature and Precipitation Indicators 4-28
4.6. Conclusions 4-28

Section 3 – Delaware's Resources

5. Public Health

Summary 5-2
5.1. Overview of Climate Change and Public Health 5-4
5.2. Direct Impacts on Public Health Related to Climate Change 5-4
5.2.1. Temperature 5-4
5.3. Indirect Impacts on Public Health Related to Climate Change 5-6
5.3.1. Air Quality 5-6
5.3.2. Diseases 5-10
5.3.3. Risk Factors 5-12
5.4. Potential Impacts of Climate Change on Delaware's Public Health 5-14
5.4.1. Climate Projections for Delaware 5-14
5.4.2. Potential Impacts to Public Health 5-14

6. Water Resources

Summary 6-1
6.1. Overview of Delaware's Freshwater Resources 6-3
6.1.1. Freshwater Resources and Uses 6-3
6.1.2. Water Infrastructure 6-5
6.1.3. Water Quality 6-6
6.2. Climate Change Impacts to Water Resources in the United States 6-7
6.2.1. National Overview 6-7
6.2.2. Impacts to Water Supply and Water Quality 6-9
6.2.3. Impacts to Water Infrastructure 6-9
6.3. External Stressors 6-10
6.4. Potential Impacts of Climate Change to Delaware's Water Resources 6-11
6.4.1. Climate Projections for Delaware 6-11
6.4.2. Water Supply – Increasing Demand 6-12
6.4.3. Water Quality – Changes in Salinity and Temperature 6-13
6.4.4. Water Infrastructure – Flooding and Sea Level Rise 6-14
6.4.5. Public Safety – Flooding 6-14

7. Agriculture

Summary 7-1
7.1. Overview of Delaware's Agricultural Resources 7-3
7.1.1. Agricultural Land Use 7-3
7.1.2. Agricultural Economy 7-4
7.1.3. Agricultural Infrastructure 7-5
7.1.4. Trends in Agricultural Land Use and Production 7-5
7.2. Climate Change Impacts to Agriculture in the United States 7-6
7.2.1. Animal Agriculture 7-6
7.2.2. Crop Production 7-7
7.2.3. Forest Management 7-10
7.3. External Stressors 7-10
7.4. Potential Impacts of Climate Change to Delaware's Agriculture 7-12
7.4.1. Climate Projections for Delaware 7-12
7.4.2. Vulnerability to Impacts 7-12
7.4.3. Animal Agriculture – Heat Impacts 7-14
7.4.4. Crop Production – Heat and Changing Rainfall 7-15
7.4.5. Weeds, Diseases, and Insect Pests 7-15
7.4.6. Agricultural Land Use – Sea Level Rise 7-17
7.4.7. Nutrient Management – Climate Impacts 7-17

8. Ecosystems & Wildlife

Summary 8-1
8.1. Overview of Delaware's Ecosystems and Wildlife 8-3

8.1.1. Wildlife Species 8-4
8.1.2. Beach and Dune Ecosystems 8-5
8.1.3. Wetlands and Aquatic Ecosystems 8-7
8.1.4. Forest Ecosystems 8-10
8.2. Climate Change Impacts to Ecosystems and Wildlife in the United States 8-11
8.2.1. Biodiversity and Ecosystem Function 8-11
8.2.2. Responses to Change 8-12
8.2.3. Ecosystem Thresholds 8-12
8.3. External Stressors 8-13
8.4. Potential Impacts of Climate Change to Delaware's Ecosystems and Wildlife 8-14
8.4.1. Climate Projections for Delaware 8-14
8.4.2. Climate Impacts on Species and Ecosystems 8-15
8.4.3. Species Impacts – Changes in Habitat and Hydrology 8-16
8.4.4. Species Impacts – Extreme Weather and Temperature Changes 8-17
8.4.5. Beach and Dune Ecosystems 8-18
8.4.6. Wetlands and Aquatic Ecosystems 8-19
8.4.7. Forest Ecosystems 8-20

9. Infrastructure

Summary 9-1
9.1. Overview of Delaware's Infrastructure 9-3
9.1.1. Natural Infrastructure 9-3
9.1.2. Human-Built Infrastructure 9-6
9.2. Climate Change Impacts to Infrastructure in the United States 9-10
9.2.1. Interdependent Systems 9-10
9.2.2. Transportation Infrastructure 9-11
9.2.3. Energy Infrastructure 9-12
9.3. External Stressors 9-15
9.4. Potential Impacts of Climate Change to Delaware's Infrastructure 9-16
9.4.1. Climate Projections for Delaware 9-16
9.4.2. Vulnerabilities to Impacts 9-17
9.4.3. Structural and Operational Impacts – Extreme Weather Events 9-18
9.4.4. Roads and Dams – Increased Precipitation and Flooding 9-19
9.4.5. Energy Production and Structural Safety – Increasing Temperatures 9-21
9.4.6. Transportation and Energy Facilities – Sea Level Rise 9-21

Appendix

(Katharine Hayhoe, Anne Stoner, and Rodica Gelca)

Climate Projections – Data, Models, and Methods A-2
A.1. Historical and Future Climate Scenarios A-2
A.2. Global Climate Models A-4
A.3. Statistical Downscaling Model A-6

A.4. Station Observations A-8
A.5. Uncertainty A-10
List of Bar Graphs for all Climate Indicators A-13

Excel File Appendix

Note: Excel files are not included in the PDF but can be downloaded separately

Climate Projections Indicators – Bar Graphs (K. Hayhoe, et al) A-13

- Annual and Seasonal Temperature Indicators A-13
- Other Temperature Indicators A-14
- Annual and Seasonal Precipitation Indicators A-14
- Precipitation Indicators A-14
- Humidity Hybrid Indicators A-15

Climate Trends – Indicator Correlations (D. Leathers)

The tables included here show Pearson product-moment correlation coefficients for:

- Statewide temperature and precipitation ("Statewide" tab)
- Station-based climate indicators for the full period of record ("Indicators" tab)
- Four stations used in the comparison with modeled data for the period 1960-2011 ("Indicators 1960-2011" tab)

Figures and Tables

Executive Summary

- Figure 1. Statewide Mean Annual Temperature for Delaware, 1895-2012 2
- Figure 2. Annual Maximum and Minimum Temperatures 3
- Figure 3. Temperature Extremes 3
- Figure 4. Rainfall Extremes 4
- Table 1. Summary of Potential Climate Impacts to Delaware's Resources 5

Chapter 1 – Climate 101

- Figure 1.1. Global Temperatures and Carbon Dioxide Concentrations, 1880-2010 1-7
- Figure 1.2. Tidal Gauge Data, Lewes, Delaware, 1900-2010 1-8
- Figure 1.3. Precipitation in the Lower 48 States, 1901-2012 1-9
- Figure 1.4. Global Greenhouse Gas Emissions by Sector 1-11
- Figure 1.5. Sources of Greenhouse Gases by Sector in Delaware 1-11

Chapter 2 – Delaware Climate Trends

- Figure 2.1. Annual Cycle of Temperature/Precipitation (Mean, Max, Min), 1895-2012 2-3
- Table 2.1. Climate Indicators Calculated 2-5
- Figure 2.2. National Weather Service Cooperative Stations Used in Analysis 2-5
- Figure 2.3. Delaware Statewide Temperatures (Annual and Seasonal), 1895-2012 2-6
- Figure 2.4. Growing Season Length 2-6
- Figure 2.5 Number of Days with Minimum Temperatures <32˚F 2-7
- Figure 2.6 Number of Days with Minimum Temperatures <20˚F 2-7
- Figure 2.7 Number of Days with Minimum Temperatures >75˚F 2-8
- Figure 2.8 Summer Mean Minimum Seasonal Temperatures. 2-8
- Figure 2.9. Delaware Statewide Precipitation (Annual and Seasonal), 1895-2012 2-9

Chapter 3 – Comparing Observed and Modeled Historic Data

- Table 3.1. Climate Indicators Used in the Analysis for the Period 1960-2011 3-2
- Table 3.2. Comparison of Observed and Modeled Trends in Maximum Temperature 3-3
- Table 3.3. Comparison of Observed and Modeled Trends in Minimum Temperature 3-3
- Table 3.4. Comparison of Observed and Modeled Trends in Precipitation 3-4

Chapter 4 – Delaware Climate Projections

- Figure 4.1. Delaware Weather Stations Used in Analysis 4-8
- Figure 4.2. Annual Minimum and Maximum Temperatures 4-11
- Figure 4.3. Seasonal Average Temperatures 4-12
- Figure 4.4. Seasonal Temperature Range 4-13
- Figure 4.5. Minimum and Maximum Temperature Range 4-14
- Figure 4.6. Number of Cold Nights and Hot Days 4-15
- Figure 4.7. Number of Nights with Minimum Temperature < 20˚F and < 32˚F 4-16
- Figure 4.8. Growing Season, Date of Last Spring Frost, Date of First Fall Frost 4-17

- Figure 4.9. Number of Days with Maximum Temperature > 95˚F, 100˚F, 105˚F, 110 ˚F 4-18
- Figure 4.10. Number of Nights with Minimum Temperature > 80˚F, 85˚F, 90˚F 4-19
- Figure 4.11. Longest Sequence of Days with Maximum Temperature > 90˚F, 95˚F, 100˚F, and Number of 4+ Day Heat Waves per Year 4-20
- Figure 4.12. Cooling Degree-Days and Heating Degree-Days 4-21
- Figure 4.13. Annual Average Precipitation 4-22
- Figure 4.14. Seasonal Precipitation 4-23
- Figure 4.15. Change in Winter Precipitation, Precipitation Intensity, and Average Dry Days per Year ... 4-24
- Table 4.1. Indicators of Extreme Precipitation 4-25
- Figure 4.16. Number of Days with Precipitation > 0.5", > 1", > 2" 4-26
- Figure 4.17. Change in Seasonal Dewpoint Temperature 4-27
- Figure 4.18. Change in Seasonal Relative Humidity, Maximum Temperature, and Heat Index 4-28
- Figure 4.19. Seasonal Potential Evapotranspiration 4-29
- Figure 4.20. Number of Hot Dry Days and Number of Cool Wet Days per Year 4-29

Chapter 5 – Public Health

- Figure 5.1. Hot Days and Warm Nights 5-2
- Figure 5.2. Heat Waves 5-6
- Figure 5.3. Size Comparison of Particulate Matter 5-7
- Table 5.1. Mosquitoes and Vector-Borne Diseases in Delaware 5-10
- Table 5.2. Ticks and Vector-Borne Diseases in Delaware 5-11

Chapter 6 – Water Resources

- Figure 6.1. Heavy Precipitation 6-1
- Figure 6.2. Surface Freshwater Withdrawals in Delaware 6-3
- Figure 6.3. Groundwater Withdrawals in Delaware 6-4
- Figure 6.4. Delaware's Impaired Streams 6-7
- Table 6.1. Climate Change Impacts to Water Resources across Sectors in the United States 6-8
- Figure 6.5. Projected Population Growth in Delaware, 2010-2030 6-10
- Figure 6.6. Annual Peak Discharge, Brandywine River, Delaware, 1970-2012 6-15

Chapter 7 – Agriculture

- Figure 7.1. Changes in Growing Season 7-1
- Figure 7.2. Delaware Agricultural Land Use by Crop (Acres Harvested) 7-3
- Figure 7.3. Value of Poultry and Livestock in Delaware 7-4
- Figure 7.4. Value of Crops in Delaware 7-4
- Table 7.1. Trends in Agricultural Land Use and Production 7-6
- Table 7.2. Climate Change Impacts and Nutrient Management 7-18

Chapter 8 – Ecosystems and Wildlife

- Figure 8.1. Number of Cold Nights per Year and Number of Hot Days per Year 8-1
- Figure 8.2. Changes in Precipitation 8-2
- Figure 8.3. Delaware Physiographic Regions 8-4
- Figure 8.4. Delaware Basins and Watersheds 8-8
- Table 8.1. Potential Ecological Impacts in Response to Climate Change 8-13

Chapter 9 – Infrastructure

- Figure 9.1. Cooling Degree-Days and Heating Degree-Days 9-1
- Figure 9.2. Changes in Precipitation 9-2
- Table 9.1. Wetland Ecosystem Services 9-4
- Table 9.2. Potential Climate Change Impacts to Transportation in the United States 9-11
- Table 9.3. Potential Climate Change Impacts to Energy Systems in the United States 9-13
- Table 9.4. Potential Impacts of Sea Level Rise to Human-Built Infrastructure in Delaware 9-22

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Acronyms and Abbreviations

AQI	Air Quality Index
ARRM	Asynchronous Regional Regression Model
BFE	base flood elevation
CAFO	concentrated animal feeding operation
CDC	Centers for Disease Control and Prevention
CMIP3	Coupled Model Intercomparison Project version 3
CMIP5	Coupled Model Intercomparison Project version 5
CO_2	carbon dioxide
CRS	Community Rating System
CSO	combined sewer overflow
DAQ	Delaware Division of Air Quality
DDA	Delaware Department of Agriculture
DDFW	Delaware Division of Fish and Wildlife
DelDOT	Delaware Department of Transportation
DIMS	Delaware Irrigation Management System
DNREC	Delaware Department of Natural Resources and Environmental Control
DOC	dissolved organic carbon
DRBA	Delaware River and Bay Authority
DRIP	Delaware Rural Irrigation Program
DWSCC	Delaware Water Supply Coordinating Council
FEMA	Federal Emergency Management Agency
FIA	Forest Inventory and Analysis (program of the U.S. Forest Service)
FTA	Federal Transit Administration
GCM	general circulation model
GHCN	Global Historical Climatology Network
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
MGD	million gallons per day
MW	megawatts
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
PCB	polychlorinated biphenyls
PCMDI	Program for Climate Model Intercomparison and Diagnosis
RCP	Representative Concentration Pathways
SAP	Synthesis and Assessment Product (report of the U.S. Global Change Science Program)
SEPTA	Southeastern Pennsylvania Transportation Authority
SDI	subsurface drip irrigation
SPI	Standardized Precipitation Index
SRES	Special Report on Emission Scenarios
TMDL	total maximum daily load
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
VBD	vector-borne disease
VMT	vehicle miles traveled
WTP	water treatment plant

Additional Resources

There are a wide range of resources for more information on climate change and climate impacts at the regional, national, and global scale. Included here is a summary of some of the widely used reports and assessments from peer-reviewed academic and government sources. In addition, sources cited in this Assessment are included at the end of each chapter.

Climate Assessments – Pending Updates

Two important resources for information on climate change and its impacts include the global Assessment Report by the Intergovernmental Panel on Climate and the National Climate Assessment by the U.S. Global Change Research Program. For both sources, the existing reports are listed below and referenced throughout the Delaware Climate Change Impact Assessment.

Intergovernmental Panel on Climate Change (IPCC) - Fifth Assessment Report (AR5)

AR5 – due to be final in 2014 – will provide a clear view of the current state of scientific knowledge relevant to climate change. It will comprise three Working Group reports and a Synthesis Report:

Working Group I – Physical Science Basis – was released in September 2013

Working Group II – Impacts, Adaptation, and Vulnerability – will be released in March 2014

Working Group III – Mitigation of Climate Change – will be released in April 2014

Synthesis Report – will be released in October 2014

The Working Group I (WGI) contribution to the IPCC Fifth Assessment Report provides a comprehensive assessment of the physical science basis of climate change in 14 chapters, supported by a number of annexes and supplementary material.

WGI – Summary for Policymakers

http://www.climate2013.org/spm

U.S. Global Change Research Program (USGCRP) – Third National Climate Assessment

The Third National Climate Assessment is scheduled to be completed in early 2014. A draft report was released in early 2013 and can be reviewed here:

http://www.globalchange.gov/what-we-do/assessment

Several technical reports were released in 2012 that provide input to the National Climate Assessment; these are referenced below.

Climate Impacts – Global Assessments:

Intergovernmental Panel on Climate Change (IPCC) - Fourth Assessment Report (2007)

Climate Change 2007: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: The Physical Science Basis
http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

Climate Change 2007: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Impacts, Adaptation and Vulnerability.
http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

Climate Impacts – National Assessments:

U.S. Global Change Research Program - National Climate Assessment (2009)

Global Climate Change Impacts in the United States. (2009). U.S. Global Change Research Program. Cambridge, MA: Cambridge University Press. http://nca2009.globalchange.gov/.

- *Water Resources.* http://nca2009.globalchange.gov/water-resources
- *Energy Supply and Use.* http://nca2009.globalchange.gov/energy-supply-and-use
- *Transportation*. http://nca2009.globalchange.gov/transportation
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Executive Summary

The Climate Change Impact Assessment provides a summary of the best available science on the potential impacts of climate change to people, places, and resources in Delaware. The purpose of the Climate Change Impact Assessment is to increase Delaware's resiliency to climate change by understanding and communicating the current and future impacts of climate change. Delaware's Climate Change Impact Assessment will provide a strong scientific foundation for the development of the state's mitigation and adaptation planning and strategies.

Methodology and Sources

The Climate Change Impact Assessment was developed through the collaborative efforts of the Delaware Department of Natural Resources and Environmental Control (DNREC) and a community of scientists and practitioners from Delaware's state agencies and universities. DNREC's Division of Energy and Climate took the lead role in developing the Assessment, including researching and drafting the sector assessment chapters, coordinating review and editing, and assembling the final document. Information sources include: peer-reviewed scientific literature; national and regional climate assessments; and interviews with technical and subject experts, including scientists and practitioners from Delaware's academic and government institutions.

The chapter on climate trends (Chapter 2) includes an analysis of Delaware's climate trends conducted by the Delaware State Climatologist Dr. Daniel J. Leathers (University of Delaware). This analysis utilized historic temperature and precipitation data from weather stations throughout Delaware.

To develop future climate scenarios for Delaware, the Division of Energy and Climate contracted with Dr. Katharine Hayhoe (ATMOS Research & Consulting). Dr. Hayhoe developed climate projections that provide average, seasonal, and extreme temperature and precipitation projections for the state of Delaware through the year 2100 (Chapter 4). The Assessment includes both a summary of the findings and detailed graphs of 165 climate indicators developed through this analysis. Graphs and technical information can be found in the Appendix.

The potential impacts related to sea level rise were drawn largely from the findings of the Sea Level Rise Vulnerability Assessment by Delaware Coastal Programs (completed in 2012). In addition, other sources of information were referenced to describe potential impacts of sea level rise, including recent reports by the National Oceanic and Atmospheric Administration and the U.S. Climate Change Science Program.

The eleven members of the Climate Change Impact Assessment Steering Committee guided the development of the Assessment, providing content expertise, peer review, and editorial oversight. In addition, more than 50 subject experts were interviewed and consulted for review of draft text. These contributors are listed in the Acknowledgments.

Findings

The Climate Change Impact Assessment is organized in two main sections: 1) Climate, and 2) Resources. The findings include:

- Historic climate trends in Delaware (temperature and precipitation)
- Future climate projections for Delaware (temperature and precipitation)
- Potential impacts of climate change (including temperature, precipitation, and sea level rise) to Delaware's resources in five sectors: public health, water resources, ecosystems and wildlife, agriculture, and infrastructure

Historic Climate Trends

Temperature:

- Annual and seasonal temperatures have increased by approximately 2˚F over the past century. An analysis of Delaware statewide mean annual and seasonal temperatures indicates a modest warming trend in temperatures during the period 1895 through 2012 annually and for all seasons.
- Delaware has experienced an upward trend of 0.2°F per decade for mean annual, winter, spring, and summer season temperatures. Autumn season temperatures have also seen a significant increase, but at a more modest rate of 0.1°F per decade.
- Nine high-quality National Weather Service Cooperative weather stations across Delaware were analyzed for significant trends in temperature extremes for the period 1895 through 2012 (**Figure 1**). Only a few significant trends were identified from these stations, including a decrease in the number of days with temperatures below 32°F and 20°F and an increase in the length of the growing season.
- Heating degree-days showed a significant downward trend annually, and for the spring and autumn seasons. Cooling degree-days showed significant upward trends only annually and during the summer season, mirroring the temperature increases annually and during the summer.

Precipitation:

- Delaware's historic climate shows highly variable precipitation patterns. Analysis of data shows a modest increase in autumn precipitation of 2.7 inches over the past century.
- No significant trends in annual precipitation are indicated. Only the autumn season (September-October-November) evidenced an upward trend in seasonal precipitation, with an increase of 0.27 inches per decade.
- Delaware's precipitation patterns are highly variable (both large inter-annual and intra-annual variability). Although Delaware's average annual precipitation is approximately 45 inches, statewide annual values have varied from as low as 28.29 inches in 1930 to as high as 62.08 inches in 1948.

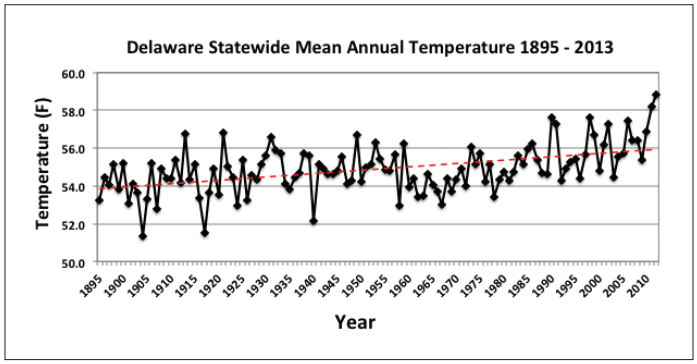

Figure 1. Statewide mean annual temperature for Delaware, 1895-2013. Source: Leathers (2013).

Future Climate Projections

The future climate of Delaware depends on the decisions we make today and in the years to come. To understand the impact of our choices on future climate, we analyzed possible changes in temperature and precipitation that can be expected for the State of Delaware in the near future and over the coming century under two possible future scenarios. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide (CO_2) and other greenhouse (heat-trapping) gases that are causing climate to change so quickly. The ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continues to grow.

Average annual and seasonal temperatures are expected to increase over the coming century.

- By 2020-2039, temperature increases of 1.5 to 2.5°F are projected, regardless of scenario (**Figure 2**).
- By mid-century or 2040-2059, temperature increases under the lower scenario range from 2.5 to 4°F and around 4.5°F for the higher scenario.
- By end of century or 2080-2099, projected temperature changes are nearly twice as great under the higher versus lower scenario: 8 to 9.5°F compared to 3.5 to 5.5°F.
- Slightly greater temperature increases are projected for spring and summer as compared to winter and fall.

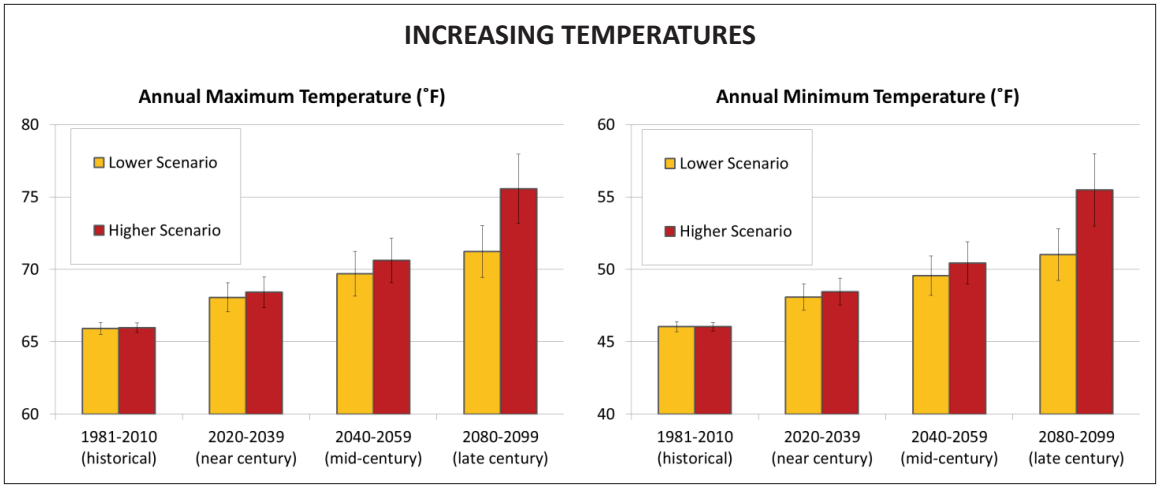

Figure 2. Annual maximum (daytime) and minimum (nighttime) temperatures are projected to increase. (Note difference in temperatures in y-axis.) Changes are average for the State of Delaware, based on individual projections for 14 weather stations. Source: Hayhoe et al. (2013).

- The growing season is also projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost.

Temperature extremes are also projected to change. The greatest changes are seen in the number of days above a given high temperature or below a given cold temperature threshold. By mid-century, changes under the higher scenario are much greater than changes under the lower scenario.

- Heat waves are projected to become longer and more frequent, particularly under the higher versus lower scenario and by later compared to earlier time periods.
- The number of very cold days (below 20°F), which historically occurred on average about 20 times per year, is projected to drop to 15 by 2020-2039, to slightly more than 10 days per year by 2040-2059, and to 10 days per year under the lower scenario and only 3 to 4 days per year under the higher scenario by 2080-2099 (**Figure 3**).
- The number of very hot days (over 100°F), which historically occurred less than once each year, is projected to increase to 1 to 3 days per year by 2020-2039, 1.5 to 8 days per year by 2040-2059, and 3 and 10 days per year under the lower and 15 to 30 days per year under the higher scenario by 2080-2099 (**Figure 3**).

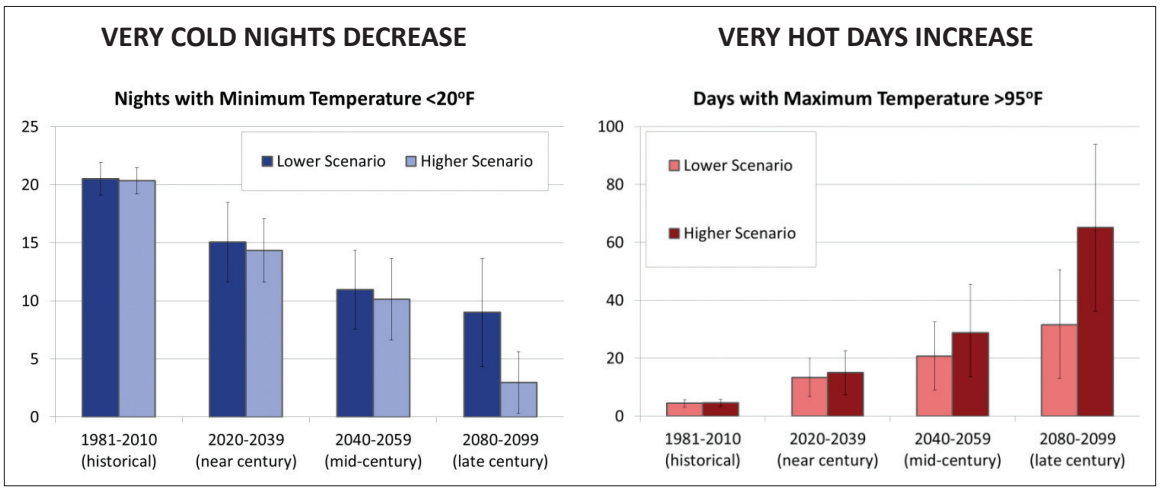

Figure 3. Temperature extremes are projected to change. The greatest changes are seen in the number of days above a given high temperature or below a given cold temperature threshold. Source: Hayhoe et al. (2013).

- Increases in daytime summer heat index (a measure of how hot it feels, based on temperature and humidity) are projected to be larger than increases in maximum temperature alone, due to the nonlinear relationship between heat index, temperature, and humidity.

Average precipitation is projected to increase by an estimated 10 percent by end of century, consistent with projected increases in mid-latitude precipitation in general.

Rainfall extremes are also projected to increase. By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events (**Figure 4**).

Summary of Potential Climate Impacts to Delaware's Resources

The Climate Change Impact Assessment describes potential impacts of climate change to Delaware's resources in five resource areas: public health, water resources, agriculture, ecosystems and wildlife, and infrastructure. The potential impacts relate to the climate projections for Delaware, including increasing annual and seasonal temperatures, increasing temperature extremes, and changes in precipitation patterns, such as more frequent heavy precipitation events. The potential impacts also consider sea level rise, related to the findings of the Delaware Sea Level Rise Vulnerability Assessment. **Table 1** provides a brief summary of the findings of the resource chapters.

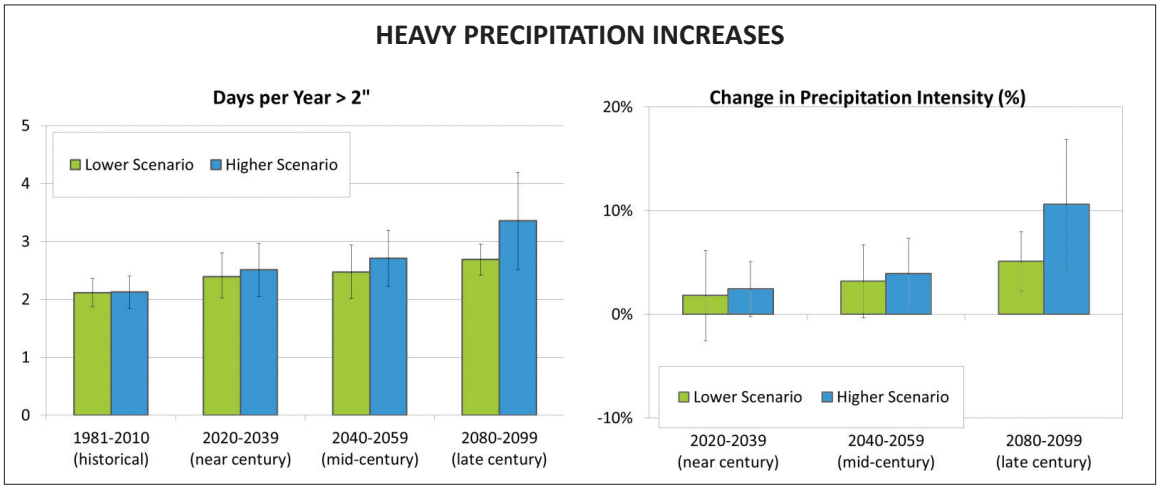

Figure 4. Rainfall extremes are also projected to increase. By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events. Source: Hayhoe et al. (2013).

Table 1. Summary of potential climate impacts by resource in Delaware

Public Health	
Increasing temperatures	*Changes in precipitation: Increasing extreme rain*
Increasing temperatures have direct and **serious impacts on human health,** particularly for vulnerable populations: elderly or very young people, those with underlying health conditions such as asthma or heart disease, and socially isolated individuals with limited access to air conditioning or health care. Increasing temperatures may worsen air quality, exacerbating conditions that produce ground-level ozone.	Flooding may stress the capacity of **stormwater and wastewater** outfalls, causing water to back up and transporting polluted waters to upland areas. Increasing precipitation and sea level rise may lead to failure of septic drain fields as groundwater levels rise. Increasing precipitation and temperatures may lead to conditions that increase exposure to allergens, as well as to pathogenic diseases.

Water Resources			
Increasing temperatures	*Changes in precipitation: Increasing dry days*	*Changes in precipitation: Increasing extreme rain*	*Sea level rise*
Water supply and demand will be affected by rising temperatures and longer periods of dry days, especially in summer months.	**Salinity** increases upstream in coastal rivers and streams during periods of drought, when freshwater inflow decreases. This effect may be magnified with increasing frequency and duration of seasonal droughts, and may be further exacerbated with sea level rise.	**Sewer and stormwater systems** will be increasingly strained to manage peak flows that may exceed their design specifications. Increased flooding associated with extreme rain events may result in structural or operational damage to **dams, levees, impoundments, and drainage ditches**.	**Salinity** in tidal reaches of rivers and streams may be affected by climate change impacts. Sea level rise could increase the tidal influence and salinity levels upriver, although increased precipitation could offset the increasing salinity with additional freshwater inflow.

Agriculture			
Increasing temperatures	*Changes in precipitation: Increasing dry days*	*Changes in precipitation: Increasing extreme rain*	*Sea level rise*
Heat stress resulting from extreme heat days or sustained heat waves can have significant impacts for **poultry and other livestock**. Hotter summers lead to greater heat stress on animal health and reduced feed and growth efficiency, and may require increased **energy usage** for ventilation and cooling in livestock barns and poultry houses. A longer growing season and warmer winter temperatures may provide some benefits for crop production. However, warmer winter temperatures may result in **increased competition from weed species and insect pests**.	Rising temperatures and increased frequency of drought may lead to **crop losses, reduced yields**, impaired pollination and seed development, and higher infrastructure and energy costs to meet irrigation needs. Heat, drought, and extreme weather may affect the dairy industry by reducing **forage supply and quality**, which accounts for more than half of the feed requirements for dairy cows.	Extreme rain events can affect infrastructure and systems that are critical to agriculture. Flooding can impair transportation of crops or livestock to markets or processing facilities, prevent deliveries of feed, or damage processing facilities for poultry and other livestock. Rain events of increasing frequency and intensity will have significant impacts at **critical periods in crop production**, such as delayed planting or post-planting washouts and increases in disease pressure.	Sea level rise may affect soil and groundwater quality in coastal regions and along tidal reaches of streams and rivers.

Table 1. ***continued***

Ecosystems and Wildlife			
Increasing temperatures	*Changes in precipitation: increasing dry days*	*Changes in precipitation: Increasing extreme rain*	*Sea level rise*
Many of Delaware's **wildlife species** will face changes in habitat quality, timing and availability of food sources, abundance of pests and diseases, and other stressors related to changes in temperature and precipitation. Increased temperatures and more frequent droughts will stress **freshwater habitats**, including streams, rivers, and ponds. Higher water temperatures are likely to increase the incidence of harmful algal blooms, which affect the availability of oxygen and light for aquatic species. Extreme decreases in oxygen levels may lead to more frequent fish kills.	Increasing dry days combined with increased air temperatures may lead to higher evapotranspiration and **decreased soil moisture**. These factors are likely to contribute to plant stress, resulting in decreased productivity and greater susceptibility to pests and diseases.	Tidal flooding is likely to increase from both sea level rise and potential increases in heavy rain events. **Tidal wetlands** will be affected by greater storm surges, scouring of tidal creeks and channels, and greater swings in salinity.	**Coastal ecosystems** are already vulnerable to coastal storms; the combined effects of sea level rise and extreme rain events may lead to increased erosion and loss of beach habitat.

Infrastructure			
Increasing temperatures	*Changes in precipitation: Increasing dry days*	*Changes in precipitation: Increasing extreme rain*	*Sea level rise*
Under heat wave conditions, peak **demands for electricity** in summer months increase dramatically and vulnerability to power outages can affect wide regions. Increased heat can accelerate **deterioration of infrastructure**, such as heat stress in structural supports and exposure of pavement to high heat. Buckling or rutting of asphalt may occur on roads or runways. These impacts may require increased maintenance and more frequent monitoring to prevent damage and ensure public safety.	Drought conditions tend to push the salt line up the Delaware River; this increased salinity can affect the **availability and function of cooling water** needed for power generation and other industrial uses.	With potential increases in precipitation falling in more intense storm events, the higher volume and velocity of surface runoff can result in rapid erosion and scouring. This can undermine **structural supports for roads, bridges, culverts, and other drainage structures**. Flooding **impacts to road and rail lines** also affect energy production, particularly for coal-fired power generation that relies on coal transport by rail. Changes in the timing of spring thaw and shifts in seasonal flows and water levels could increase flooding, particularly in urban areas of northern Delaware, where a high percentage of impervious surface area already contributes to severe stormwater runoff problems.	Sea level rise is likely to **affect roads and bridges** throughout the state. In Sussex and Kent Counties, many beach communities may be affected by sea level rise cutting off their primary access roads and evacuation routes. In New Castle County, Delaware City and portions of State Route 9 are also vulnerable to severe flooding from sea level rise. The Port of Wilmington is a major facility that could be significantly affected; an estimated 60 percent of the Port's main facilities could be inundated by 3 feet of sea level rise.

Conclusions

Delaware's climate is changing. Increasing temperatures, shifts in precipitation patterns, and rising sea level are already being experienced across the state. Future climate changes are expected to affect Delaware and the surrounding region by increasing average, seasonal, and extreme temperatures; average precipitation; the frequency of heavy precipitation events; and the total amount of rainfall that falls in the wettest periods of the year.

For all temperature-related indices, there is a significant difference between the changes expected under higher versus lower scenarios by end of century. For many of the changes, this difference begins to emerge by mid-century. In addition, analyses of sea level rise highlight the potential impacts to a wide range of resources, particularly in a low-lying state with extensive ocean and bay shoreline, tidal rivers, and valuable ecosystems.

The projections described here underline the value in preparing to adapt to the changes that cannot be avoided. Changes that likely cannot be avoided would include most changes in precipitation and, at minimum, the temperature-related changes projected to occur over the next few decades, and under the lower scenarios. However, immediate and committed action to reduce emissions may keep temperatures at or below those projected under the lower scenario. Thus, the larger temperature impacts projected under the higher scenarios can be avoided by concerted mitigation efforts.

Delaware faces potential impacts from changes in temperature, precipitation, and sea level rise. State officials, local governments, residents, and businesses must prepare for changing climate conditions that will affect communities and economic sectors throughout Delaware.

The Climate Change Impact Assessment will be a valuable resource for practitioners who make important planning and policy decisions that affect people, communities, and resources across the state. The data and analyses included in this Assessment are a foundation for understanding how climate affects all sectors in Delaware, and will provide a starting point for addressing climate impacts through mitigation and adaptation efforts.

Chapter 1
Introduction

1.1 Purpose

The purpose of the Climate Change Impact Assessment is to increase Delaware's resiliency to climate change by understanding and communicating the current and future impacts of climate change. The Climate Change Impact Assessment will provide a strong scientific foundation for the development of the state's adaptation planning and strategies.

Delaware faces potential impacts from changes in temperature, precipitation, and sea level rise. State officials, local governments, residents, and businesses must prepare for changing climate conditions that will affect communities and economic sectors throughout Delaware.

To address these concerns, the Secretary of Delaware's Department of Natural Resources and Environmental Control (DNREC) directed the Division of Energy and Climate to conduct a comprehensive vulnerability and risk assessment. The Assessment reflects the best available climate science, climate modeling, and projections to illustrate the range of potential vulnerabilities that Delaware may face from the impacts of climate change. Delaware-specific climate projections are a key component to this Assessment. This work builds upon the analysis of DNREC's Coastal Programs, which evaluated impacts from a 1.6 to 4.9-foot (0.5- to 1.5-meter) rise and potential adaptation strategies.

The Delaware Climate Change Impact Assessment is a statewide evaluation of climate change impacts in Delaware. It draws on the best available science – science that is rapidly expanding with new findings from global, national, and regional research. In addition, information on climate impacts in Delaware will continue to evolve as monitoring and data analysis continue. Therefore, future updates to this Assessment will be needed to integrate current information and improve our understanding of current and future impacts of climate change in Delaware.

1.2 Scope

The scope of the Climate Change Impact Assessment covers a wide range of Delaware's resources and potential impacts of climate change. The Assessment is intended to provide a summary and synthesis of the best available information that is scientifically credible, relevant to Delaware, and written for a broad audience.

What is not included in the Assessment is a prioritization of which resources are most vulnerable, or recommendations on how to mitigate the potential vulnerabilities discussed. In addition, the Assessment does not include a quantitative or geographic analysis of potential vulnerabilities, with estimated numbers or locations of affected resources. The one exception to this is that the Assessment does reference the findings of the Sea Level Rise Vulnerability Assessment prepared by DNREC's Coastal Programs, which estimated the spatial impact of sea level rise under several scenarios.

Also important to note is that this Assessment does not include an economic analysis of potential impacts from climate change. In particular, there are several industries important to Delaware that are not included. Tourism, finance and insurance, and petrochemical industries are among those sectors that may be vulnerable to impacts related to climate change. However, to provide a meaningful picture of the impacts, an economic analysis would need to be conducted; this type of report is outside the scope of this Assessment. Instead, this Assessment focuses on the resources on which some of those industries depend. For example, Delaware's beaches are highly important to the state's tourism industry, and these resources are described in the Assessment in terms of their wildlife and ecosystem values, as well as their function as natural infrastructure.

The terms "impact" and "vulnerability" are used throughout the Climate Change Impact Assessment.

In this Assessment, sector chapters include a discussion of "climate change impacts," which is a summary of what published scientific literature says about the observed and anticipated effects of changes in temperature, precipitation, extreme weather events, and sea level rise. This summary is based on peer-reviewed papers, reports, and studies from national and regional sources, and therefore the impacts described are often general to the United States.

The discussion of "potential vulnerabilities" in each sector chapter focuses more directly on Delaware. These are vulnerabilities identified by scientists and practioners within Delaware and the Mid-Atlantic region. Sources of information include reports by state agencies and academic institutions as well as interviews with subject experts. It is important to emphasize that the vulnerabilities described in this Assessment are not necessarily a complete or comprehensive summary. As more information becomes available, and more studies are done in Delaware, our understanding of potential climate change vulnerabilities will expand and improve.

In addition, the sector chapters include story boxes that are intended to provide examples of how climate change impacts are already affecting people and resources in Delaware. These are not presented as recommendations for policy or adaptation responses; they are intended only to illustrate existing vulnerabilities related to climate conditions.

Economic Studies

There are several recent reports on the economic value of Delaware resources; these are referenced in the sector chapters of this Assessment and include:

- **The Impacts of Agriculture on Delaware's Economy.** (2010). University of Delaware, College of Agriculture and Natural Science report. http://ag.udel.edu/deagimpact/index.html
- **Economic Valuation of Wetland Ecosystem Services in Delaware.** (2011). Delaware Division of Water Resources report prepared by Industrial Economic, Incorporated for DNREC. http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Documents/Economic%20Evaluation%20of%20Wetland%20Ecosystem%20Services%20in%20Delaware.pdf
- **Economic Value of the Delaware Estuary Watershed.** (2011). University of Delaware, Water Resources Agency report to Delaware Department of Natural Resources and Environmental Control, Division of Watershed Stewardship. http://www.ipa.udel.edu/wra/research/delawareestuary.html
- **Socioeconomic Value of the Chesapeake Bay Watershed in Delaware.** (2011). University of Delaware, Water Resources Agency report to Delaware Department of Natural Resources and Environmental Control, Division of Watershed Stewardship. http://www.ipa.udel.edu/publications/DelChesapeakeWatershed.pdf
- **The Contribution of the Coastal Economy to the State of Delaware.** (2012). University of Delaware, Delaware Sea Grant report. http://deseagrant.org/products/2012-coastal-economy-appendix

1.3 Organization

The Climate Change Impact Assessment is organized in two main sections:

Section 2 – Delaware's Climate

This section includes:

- **Chapter 2 - Delaware Climate Trends**

Analysis of historic observations from weather stations across Delaware from 1895 through 2012. This provides a summary of trends in Delaware's annual and seasonal temperatures, temperature extremes, and precipitation patterns.

- **Chapter 3 - Comparing Observed and Modeled Historic Data**

Comparison of historic observed data with modeled data for the historic period of 1960 to 2011. This shows that the models were consistent with the observations in identifying trends.

- **Chapter 4 – Delaware Climate Projections**

Analysis of projected future changes in temperature- and precipitation-related climate indicators for Delaware. Statistical downscaling analysis was based on data from 14 weather

stations in Delaware and 13 global climate models.

Section 3 – Delaware's Resources

This section includes five chapters (5 to 9) that focus on resources or sectors in Delaware: public health, water resources, agriculture, ecosystems and wildlife, and infrastructure. Each chapter includes:

- Overview of Delaware's resources in that sector – this summarizes what is potentially at risk to climate impacts;
- Climate impacts to resources – these are generally described on a national or regional scale, based on the best available science sources;
- External stressors that affect resources, such as population growth and land use changes – this adds context to show that climate impacts may add to the effects of other influences; and
- Potential vulnerabilities that may affect Delaware's resources in that sector – based on the review of scientific literature and expert interviews.

1.4 Methodology

Steering Committee

In August 2012, the Secretary of Delaware's Department of Natural Resources and Environmental Control convened a Steering Committee of Delaware's leading scientists and practitioners from academia and state government to provide expertise and peer review in developing Delaware's Climate Change Impact Assessment. The eleven members of the Committee included experts from academic and state government communities. Committee members served as reviewers and provided content and oversight on the development of the draft Assessment.

Information Sources

The Division of Energy and Climate was responsible for researching and drafting the sector assessment chapters. Information sources included: scientific literature (reports, published papers, peer-reviewed journal articles); scientific assessments (conducted by regional, state, and national governmental agencies and international scientific bodies); and interviews with technical and subject experts, including scientists and practioners from Delaware's academic and government institutions.

Climate Trends and Projections

A key component of the Climate Change Impact Assessment is a summary of climate trends and projections for Delaware. The climate section of the Assessment includes an analysis of historic climate data collected in Delaware between 1895 and 2012. This summary, conducted by Delaware State Climatologist Dr. Daniel J. Leathers, focuses on temperature and precipitation data and includes a selection of climate indicators comparable to those developed for climate projections.

To better understand future climate projections, the Division of Energy and Climate contracted with Dr. Katharine Hayhoe, a leading climate statistician, to develop climate projections to understand changes in average, seasonal, and extreme temperature and precipitation.

The projections are based on models using the Coupled Model Intercomparison Project versions 3 (CMIP3) and 5 (CMIP5) data. Four CMIP3 models were selected; these models have a proven track record of adequate performance in previous analyses. Nine CMIP5 models were also used in determining the Delaware-specific projections. The CMIP5 data were released in the summer of 2012 and are the most recent climate modeling data available. The CMIP5 data will be used in the upcoming IPCC 5th Assessment. The Coupled Model Intercomparison Project, established in 1995, involves international scientists and utilizes climate models from around the world. This process has provided consistency and quality control for modeling as well as methods to ensure that the results are reproducible and as transparent as possible.

The Delaware climate projections reflect higher and lower scenarios to the end of this century (2100). The lower scenario represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of CO_2 and other greenhouse gases. The higher scenario represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Average annual and seasonal projections are included for temperature and precipitation. In addition to understanding average and seasonal shifts, the projections also present changes in extremes of temperature and precipitation. Climate change may alter timing, intensity, frequency, and duration of extreme events. The projections also assist in understanding changes in climate patterns, such as length of growing season. The climate projections include analysis of extremes such as:

Temperature-related indicators:
- Number of hot days with maximum temperature above 90˚F, 95˚F, and 100˚F
- Number of hot nights with minimum temperature above 80˚F
- Number of cold nights with minimum temperature below 32˚F
- Growing season length
- Heat wave frequency and duration

Precipitation-related indicators:
- Number of wet days with rainfall greater than 2 inches in a 24-hour time period
- Number of consecutive dry days
- Percent of precipitation coming from heavy precipitation events

Approximately 165 climate indicators were developed with the Delaware climate projection data. A selection of these indicators is presented in Chapter 4. The complete set of indicators is included in the Appendix.

Sea Level Rise

Sea level rise is discussed in the Delaware Climate Change Impact Assessment based on current scientific observations and projections of sea level rise, both globally and regionally. Observations of sea level rise describe historic trends and are measured by the collection and analysis of long-term tidal data. Data are generally collected in tide gauges that track fluctuations in sea level along shorelines of oceans and bays. In the United States, tide gauges are monitored by the National Oceanographic and Atmospheric Administration (NOAA); some tide gauges have been collecting data for more than a century. There are three NOAA tide gauges in Delaware, located at Lewes, Delaware City, and Reedy Point.

Measurements of sea level have been collected by satellite since the early 1990s. Satellite data collection provides new information not detected by tide gauges. Satellite measurements are taken widely across the ocean surface and can identify variations in global mean sea level between and within ocean basins; tide gauges are limited to coastal locations.

Projections of future sea level rise are based on observations (tide gauge and satellite data), general circulation models (GCMs), and methods that utilize both. Estimates of future sea level consider the contributions of ocean warming and melting ice from glaciers and ice sheets. Sea level rise projections are often expressed in scenarios. These do not predict specific sea levels, but describe a range of future potential conditions.

For this Assessment, a number of sources of information were used to describe sea level rise impacts to different resources and potential vulnerabilities to the State of Delaware. The box on the following page provides more information on these resources.

1.5 Climate 101

1.5.1 Understanding the Language of Climate Science

The earth's climate system is complex. Understanding climate science begins with some fundamental concepts and terms that are widely used, but sometimes misunderstood. This section will provide a basic understanding of climate change and the processes related to climate impacts.

Climate Variability

Seasonal variations and even multiyear cycles can result in wetter or drier, hotter or cooler periods across different regions. This natural climate variability can include extremes in climate patterns over temporal and spatial scales beyond short-term weather events, such as periodic droughts or extreme increases in precipitation related to El Niño conditions.[4] However, the rapid rate of climate change observed in recent decades cannot be explained by natural climate variability.

It is also important to understand that climate change does not necessarily occur at a gradual and predictable pace. Year-to-year variations in weather patterns can produce short-term trends that do not follow the long-term warming.[5] Similarly, there are varying rates of change in different parts of the world. For example, the magnitude of temperature change recorded in northern latitudes is higher than the global average. Over the past 50 years, annual average temperatures in Alaska have increased by 3.4˚F – more than twice the average rate of the rest of the United States.[6]

Greenhouse Effect and Global Warming

The greenhouse effect is a natural phenomenon that significantly influences the earth's climate. As energy from the sun reaches the earth, it warms the land and ocean surface. As the earth's surface warms, it radiates some of this energy back toward outer space as terrestrial or longwave radiation. Greenhouse gases in the atmosphere (CO_2, water vapor, and others) absorb some of that outgoing terrestrial radiation, and re-radiate it back toward the earth's surface, creating a "greenhouse effect." One could think of this as an insulating blanket for the earth, maintaining a layer of warmth close to the surface that allows for conditions that support life and liquid water.[7]

Sea Level Rise Resources

- **Preparing for Tomorrow's High Tide: Sea Level Rise Vulnerability Assessment for the State of Delaware.** (2012). Delaware Coastal Programs report and Mapping Appendix. http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx
In Delaware, sea level rise scenarios were developed by Delaware Coastal Programs through its Sea Level Rise Vulnerability Assessment (2012). This Assessment presented three scenarios for sea level rise by 2100 that are based on low, moderate, and high levels of future global warming. The Low scenario is 1.6 feet (0.5 meter), Intermediate scenario is 3.3 feet (1 meter), and High scenario is 4.9 feet (1.5 meters). These scenarios are depicted in a series of maps based on a "bathtub model" that uses two variables: sea level and ground elevation. Inundation is assumed to occur at a constant elevation and does not account for erosion, sediment build-up (accretion), or the effects of tidal action or shoreline protection structures.

- **Global Sea Level Rise Scenarios for the US National Climate Assessment.** NOAA Tech Memo OAR CPO-1. 37 pp. http://www.cpo.noaa.gov/reports/sealevel/
National assessments of sea level rise in the United States have been developed by the National Oceanic and Atmospheric Administration (NOAA). A recent technical report by NOAA presents four scenarios of global sea level rise. The lowest scenario estimates sea level rise of at least 0.7 feet (0.2 meters) by 2100; this is based primarily on the historic sea level rise rate from tide gauge records over the past century. The highest scenario estimates 6.6 feet (2 meters) of sea level rise by 2100; this figure is based on a combination of estimated ocean warming from global models and a projection of the maximum possible extent of glacier and ice sheet melting.

- **NOAA Sea Level Rise and Coastal Flooding Impacts Viewer** http://www.csc.noaa.gov/digitalcoast/tools/slrviewer
NOAA developed this web-based interactive tool that helps users visualize potential future sea levels. Data for the Mid-Atlantic region were made available in early 2013.

- **Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region.** A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. (2009). Synthesis and Assessment Product 4.1. http://www.climatescience.gov/Library/sap/sap4-1/
For a regional perspective, this 2009 report focuses on the Mid-Atlantic region. The U.S. Environmental Protection Agency, U.S. Geological Survey, and National Oceanic and Atmospheric Administration collaborated on this report that discusses the impacts of sea level rise on the physical characteristics of the coast, on coastal communities, and on the habitats that depend on them.

The "enhanced" greenhouse effect occurs when increasing amounts of greenhouse gases intensify the natural or balanced greenhouse effect. Today, humans are amplifying the natural greenhouse effect by increasing the amount of greenhouse gases being released into the atmosphere. There is an overwhelming consensus among scientists that the observed increase in global temperatures over the past century is due, at least in part, to human activities – primarily the burning of fossil fuels that has resulted in rapidly increasing concentrations of CO_2. This increase in CO_2 and other greenhouse gases amplifies the greenhouse effect, thus leading to "global warming."[8]

Key Terms and Definitions

Weather describes atmospheric conditions at a particular place in terms of air temperature, pressure, humidity, wind speed, and precipitation. Weather varies from place to place and across the globe and is measured in short time periods (days, weeks, years).[1]

Climate describes long-term patterns of temperature, precipitation, and other weather variables. It is often described in terms of statistical averages or extremes over decades, centuries, or even millennia. Climate is generally described in a global or regional context rather than in specific locations.[2]

Climate change describes any significant change in the measures of climate persisting for an extended period of time – decades or longer. Many climate models project that future climates are likely to increase beyond the range of variability experienced in the past. Historical data and trends may no longer be reliable indicators for future climate conditions.[3]

Global warming describes an average increase in temperatures near earth's surface and in the lowest layer of the atmosphere. Increases in temperature in the atmosphere contribute to changes in global climate patterns. Global warming can be considered part of climate change, along with changes in precipitation, sea level, etc.

Greenhouse gases are gaseous compounds that absorb infrared radiation, trap heat in the atmosphere, and contribute to the greenhouse gas effect. These include: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)).

Climate Forcings and Feedbacks

Climate is affected by many factors, technically termed "forcings." Forcings are the factors that influence the climate, or the factors that "drive" the climate to behave in a certain manner. Climate forcings include variations in solar output, volcanic eruptions, and greenhouse gas concentrations.[9]

These forcings cause the earth's temperature to cool or warm. These warming or cooling trends can increase or decrease. The increase or decrease of the initial forcing is called a climate feedback. Climate feedbacks can be positive or negative. Positive climate feedbacks amplify or increase the initial change in the same direction. Negative feedbacks decrease the forcing, causing the change to go in the opposite direction.

An example of a positive feedback is the albedo (reflectivity) effect. Ice and snow have a higher albedo (or reflectivity) than vegetation, soil, or water. As more of the land surface is covered by ice or snow, more solar radiation is reflected to space, less is absorbed by the surface, and temperatures decrease. Cooler temperatures lead to more ice growth, more reflection of solar radiation back to space, and even cooler temperatures – a positive feedback. But positive ice-albedo feedbacks can work in the opposite direction as well. Once ice begins to melt and uncover land or water, more solar radiation will be absorbed by the surface, raising temperatures and causing even more ice to melt.

Sea Level Rise

Global warming affects surface temperatures over both land and ocean. Although global sea levels have varied greatly throughout Earth's history, they have been relatively stable over the past 2,000 years. However, since the end of the last glacial period, sea levels have been rising in most parts of the world. As the climate warms, global average sea level rises as a result of two primary causes: thermal expansion and melting ice. Thermal expansion occurs as warmer water expands and increases in volume. As global temperatures rise, warmer air increases ice melt in continental glaciers, and warmer water increases melting of ice sheets, which contributes water to the oceans.[10]

In addition to these larger, global processes, there are a number of factors that can influence local and regional patterns of sea level rise. Vertical land movement can raise or lower the relative rate of sea level rise. Subsidence (land sinking to a lower elevation) can be caused, in some areas, by compaction of sediments from groundwater pumping or extraction of oil or gas. Subsidence can also be triggered by "glacial rebound," a change in the earth's crust. At the end of the last glacial period (Ice Age), lands that were depressed from the weight of glacial ice began to rise, or rebound, as the weight was removed from the land surface. As this rebound effect occurs in northern parts of North America, land to the south – including much of the Mid-Atlantic region – begins to sink or subside in response to the rebound in the north. This results in a higher rate of sea level rise, as the land is sinking while the sea surface is rising.[11]

1.5.2. Understanding Climate Information

Understanding climate science requires a basic understanding of how scientists use climate observations to develop models and projections of future climate conditions. This section will provide an introduction to how climate data collection and analysis informs our understanding of climate change.

Observations

Observations of environmental conditions are essential to understanding the earth's climate system. Scientists use a wide range of monitoring and measuring methods and tools – including satellites, weather stations, buoys, and tide gauges – to collect weather and climate data. Historical data from ice cores, tree rings, and sediment samples also provide important information about past climate changes. Observational data show that climate-related changes have already been observed in the U.S. and worldwide. Measured increases in air and water temperatures are related to a number of trends, including reduced snow cover, glaciers, permafrost, and sea ice; a longer ice-free period on lakes and rivers; lengthening of the growing season; and increased water vapor in the atmosphere.[12]

• CO_2 levels are increasing

The U.S. EPA states, "Heat-trapping greenhouse gases are now at record-high levels in the atmosphere compared with the recent and distant past."[13] CO_2 levels are higher today than at any other time in the past 800,000 years, and much of the increase in CO_2 has occurred in the past 30 to 40 years.

CO_2 is the principal greenhouse gas contributing to global warming. Historic records show a clear correlation between CO_2 concentrations and global temperatures. This graph (**Figure 1.1**) from the U.S. Global Change Research Program's 2009 assessment shows global annual average temperature (as measured over both land and oceans). Red bars indicate temperatures above and blue bars indicate temperatures below the average temperature for the period 1901-2000. The black line shows atmospheric CO_2 concentration in parts per million (ppm).[14]

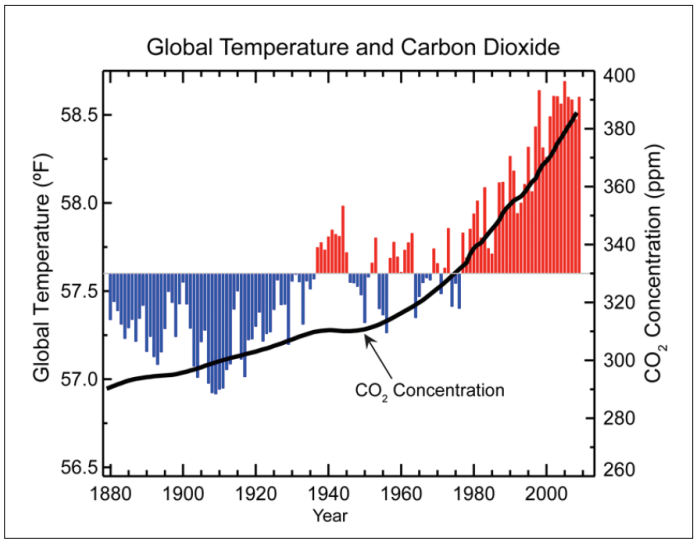

Figure 1.1. Global temperatures and carbon dioxide concentrations. Source: U.S. Global Change Research Program.

• Global temperatures are increasing

Since 1900, the global average temperature has increased by about 1.5˚F. Global warming over the 21st century is projected to be significantly greater than over the last century. By 2100, global average temperatures could increase by 4 to 9°F (1.1 to 4.8˚C), according to the latest estimates from the IPCC.[15] In the United States, average temperatures have risen approximately 2˚F over the past 50 years, a rate higher than the global average. Average temperatures are likely to increase more

than the global average over this century, with regional and seasonal variability. For example, over the past 30 years, temperatures have risen faster in winter than in any other season. Average winter temperatures have increased more than 7˚F in the Midwest and northern Great Plains region.[16]

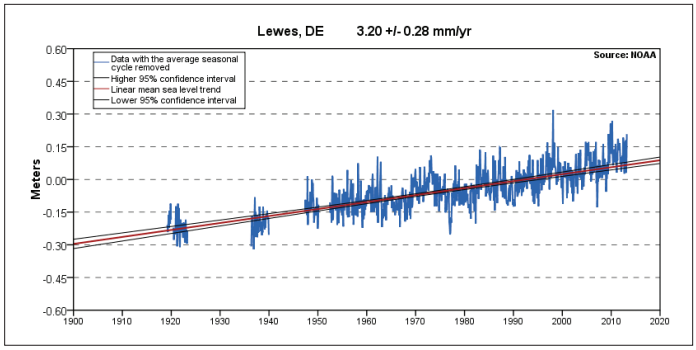

Figure 1.2. Tidal gauge data for Lewes, DE, 1900-2010. Source: National Oceanic and Atmospheric Administration.

Increasing temperatures are observed in extremes as well as in averages. The Center for Energy and Climate Solutions reported trends of extreme temperatures over the past 50 years, with increased frequency of heat waves and decreasing frequency of cold days, cold nights, and frosts. Their report cited data from the U.S. National Climatic Data Center indicating that the 27 warmest years since 1880 all occurred in the 30 years from 1980 to 2009.[17]

• Changes in oceans and coasts are occurring

Tide gauge measurements of sea level taken over the past century show that the global average sea level has risen approximately 0.07 inches per year, or a global average of 7 inches since 1900. Observations of sea level in the past 20 years have shown that the global rate of sea level rise has increased to 0.12 inches per year.[18] Recent satellite data also show an accelerated rate of global mean sea level rise; however, this may be attributed in part to different methodologies between tide gauge and satellite measurements, as well as the distribution of measurement locations.[19] However, these are global averages, and there is a wide range of regional variability.

The Mid-Atlantic coast has experienced a higher-than-global-average rate of sea level rise over the past century, ranging from 0.09 to 0.17 inches per year, or 9 to 17 inches since 1900.[20] This higher rate of sea level rise is due largely to land subsidence (described above). In Delaware, sea level has risen approximately 13 inches during the past century, as shown in this graph (**Figure 1.2**) based on NOAA tide gauge measurements.[21]

Rates of sea level rise have been increasing along the U.S. Atlantic coast. Accelerated rates of sea level rise are being observed in the Mid-Atlantic region, which already has higher-than-global average rates. A recent study identified a "hotspot" of accelerated sea level rise along a 620-mile stretch of the eastern U.S. coast north of Cape Hatteras, North Carolina. Over the past 60 years, sea level rates in this region were estimated to be three to four times higher than the global average.[22]

Sea level rise has direct and indirect effects in coastal regions. Extreme weather events are a key driver of impacts. For example, coastal storms that produce high waves and storm surge cause significant damage when they occur during high tides. Rising sea levels amplify high tides, resulting in greater frequency, duration, and extent of coastal flooding. Even relatively small increases in sea level over the past several decades have contributed to higher storm surge and wind waves.[23]

The chemistry of ocean water is also changing as a result of increasing concentrations of CO_2 in the atmosphere. Oceans absorb CO_2, causing the water to become more acidic; the trend toward increasing acidity is already affecting coral reefs and the complex food webs they support. Studies show that higher levels of acidity can negatively affect other calcifying marine animals, including oysters and clams. These species are important food sources and contribute to local and regional economies; in addition, as filter-feeders, they also provide important water quality benefits.[24]

• Precipitation patterns are changing

Climate records show that changes are already being observed in the amount, intensity, frequency, and type of precipitation. Since 1900,

global precipitation has increased at an average rate of 1.9 percent per century, while precipitation in the lower 48 states (**Figure 1.3**) has increased at a rate of 6.4 percent per century.[25] There are distinct regional differences in global precipitation patterns, with increases in precipitation in eastern North America, southern South America, and northern Europe. Most parts of Africa and southern Asia have experienced decreasing precipitation. In the United States, rainfall patterns also vary geographically, with northern areas becoming wetter and southern and western areas becoming drier.

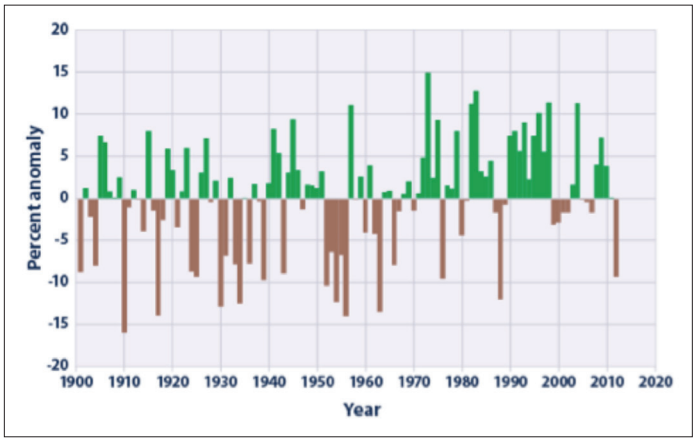

Figure 1.3. Precipitation in the Lower 48 states, 1901-2012. Source: U.S. Environmental Protection Agency (2013).

As global temperatures increase, the warming climate is expected to increase precipitation in many areas, due to increased evaporation and cloud formation. Overall, changes in patterns of drought and flooding are complex; in some regions the extremes of wet and dry climate have a greater impact than changes in average precipitation. Heavy rain events have increased in many areas, even where average or total amounts of precipitation have decreased. The amount of rain falling in the heaviest rain events has increased by roughly 20 percent over the past century; this trend is expected to continue, with the greatest increases in the wettest areas.[26]

Climate Projections

Climate projections are the range of possibilities that could occur based on the findings from climate modeling experiments. Climate projections are not forecasts or predictions for the future; they are examples of possibilities that may occur given a certain set of inputs and assumptions in the climate modeling procedure. Many climate projections project the future under high, medium, and low greenhouse gas scenarios. This provides policy makers and researchers a range of possible futures to understand and evaluate.

Scientists developing climate models use observations, experiments, and theory to construct and refine computer models that represent the climate system. These models help improve our understanding of the complexities of climate change and the many variables that will influence future climate conditions. As new information and climate data are collected, analyzed, and incorporated into computer models, this iterative process will lead to more reliable projections.

Climate models are complex mathematical equations representing the basic laws of physics (conservation of mass, momentum, and energy), fluid motion, and chemistry that represent the physical processes that take place throughout the global climate system.[27] These equations are taken into consideration with factors that influence the earth's climate systems, such as atmosphere, ocean systems, ice and land surface, and others. Because of the complex equations that must be calculated and evaluated, large computers are used to compute and run the models. Researchers are using state-of-the-art models to understand different future climate scenarios around the globe. The models are often referred to as general circulation models, or GCMs. The first climate models were developed in the mid-1970s and specifically examined atmospheric conditions. Over the past 50 years, climate modeling has improved with better technology and improved understanding of the earth's complex systems.[28]

Uncertainty is one of the most commonly confused terms in climate science. To laypeople, uncertainty means not knowing or having limited information. However, the term "uncertainty" as defined by a scientist describes how confidently a subject or

question is known and understood. Many times in science there is not absolute certainty. In fact, any scientific theory is always subject to better data, research, and observations. Scientists create transparent processes to continually increase knowledge and decrease gaps in data. Without careful acknowledgment of the uncertainties, scientific information could be taken out of context and used incorrectly.

In an area of study such as climate, scientists often cannot provide precise certainty or numbers, primarily because the subject of study – the earth's climate – is very complex, all the factors that dictate climate are not fully understood, and the factors change geographically. The U.S. Climate Change Science Program and Subcommittee on Global Change define uncertainty as:

> "An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior."[29]

Likelihood and confidence are terms used in science to describe actions and their outcomes. In complex systems, such as climate change, scientists use a variety of methods to decrease uncertainty, such as rigorously studied and evaluated models, observations, and analyses. The results from these studies are given ranges of uncertainty or likelihoods, therefore providing levels of possible occurrence. These are different concepts and have different meanings, but are often linked in scientific discussions. Confidence is a term used by scientists to describe a range of options and the percentages at which they are likely to occur. Scientists base confidence on established research and statistics.

Some projections of climate change impacts are difficult to measure because of the uncertain rate of response in environmental conditions. For example, currently the greatest uncertainty in estimating future sea level is the rate and magnitude of ice sheet melting in Antarctica and Greenland. Many climate projections have estimated accelerating rates of sea level rise due to increasing ocean temperatures and the potential for greater melting of ice sheets and glaciers. Recent satellite measurements show ice sheet loss contributing more to global sea level rise than previously estimated.[30]

1.5.3 Types and Sources of Greenhouse Gases

Greenhouses gases are defined as "any of various gaseous compounds that absorb infrared radiation, trap heat in the atmosphere, and contribute to the greenhouse gas effect."[31] These include: CO_2, methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)). Greenhouse gases can remain in the atmosphere for varying lengths of time, from a few years to thousands of years. As a result, the concentration of greenhouse gases increases over time.

Water vapor is also considered a greenhouse gas in that it contributes to the warming of the earth, primarily because of the feedbacks related to increasing temperatures. Warmer air is able to hold more moisture, which results in a positive feedback loop. More atmospheric warming increases evaporation, which increases moisture in the atmosphere. Scientists and researchers are working to better understand water vapor in a warming climate, how to correctly quantify its impacts, and the roles that clouds play in the earth's climate system.

Greenhouse gas (GHG) emissions come from a variety of sources (**Figure 1.4**). In their 4th Assessment Report, the IPCC estimated global sources of GHG emissions based on data from 2004:

- Energy supply: Burning of fossil fuels – coal, oil, and natural gas – for electricity and heat.
- Industry: Fossil fuels burned on-site for energy, and other industrial processes.
- Land use change: Deforestation, clearing land for agriculture, and burning or decay of peat soils.
- Agriculture: Soil management, livestock, rice production, and biomass burning.

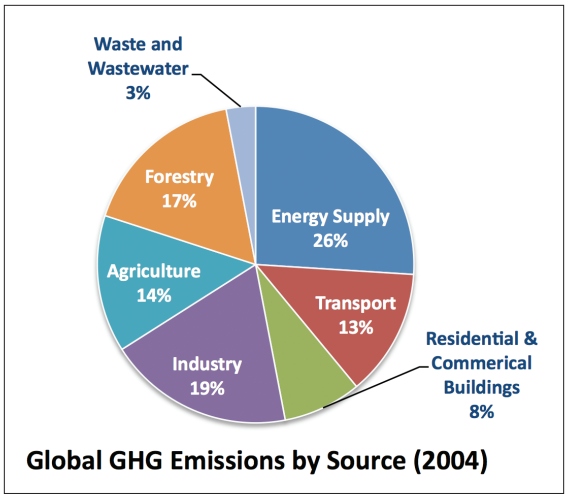

Figure 1.4. Global greenhouse gas emissions by source. Source: U.S. Environmental Protection Agency (Based on 2004 data).

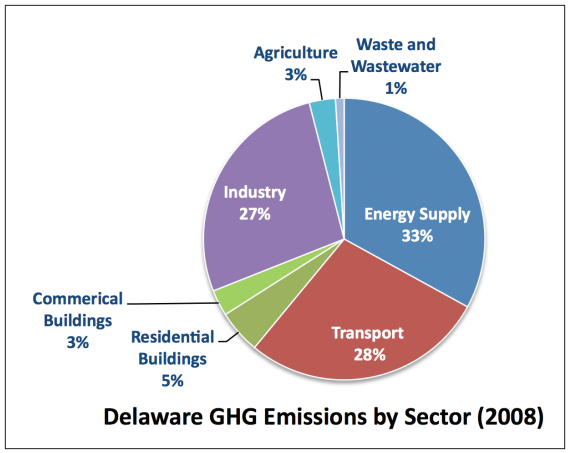

Figure 1.5 Delaware greenhouse gas emissions by sector. Source: Delaware Department of Natural Resources and Environmental Control, Division of Air Quality (Based on 2008 data).

- Transportation: Fossil fuels burned for road, rail, air, and marine transportation – most of which come from petroleum-based fuels.
- Residential and commercial buildings: Energy use for heating buildings and cooking in homes (electricity use not included here is covered in energy supply).
- Waste and wastewater: Methane and other GHGs produced from landfill and wastewater emissions.

In Delaware, greenhouse gas emissions have been estimated based on data from 2008 (**Figure 1.5**). The largest sources of GHG emissions include the power sector, transportation, and industry. Since 2008, the percentage of GHG emissions from the power sector has been reduced, partly due to switching fuels from coal to natural gas.

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