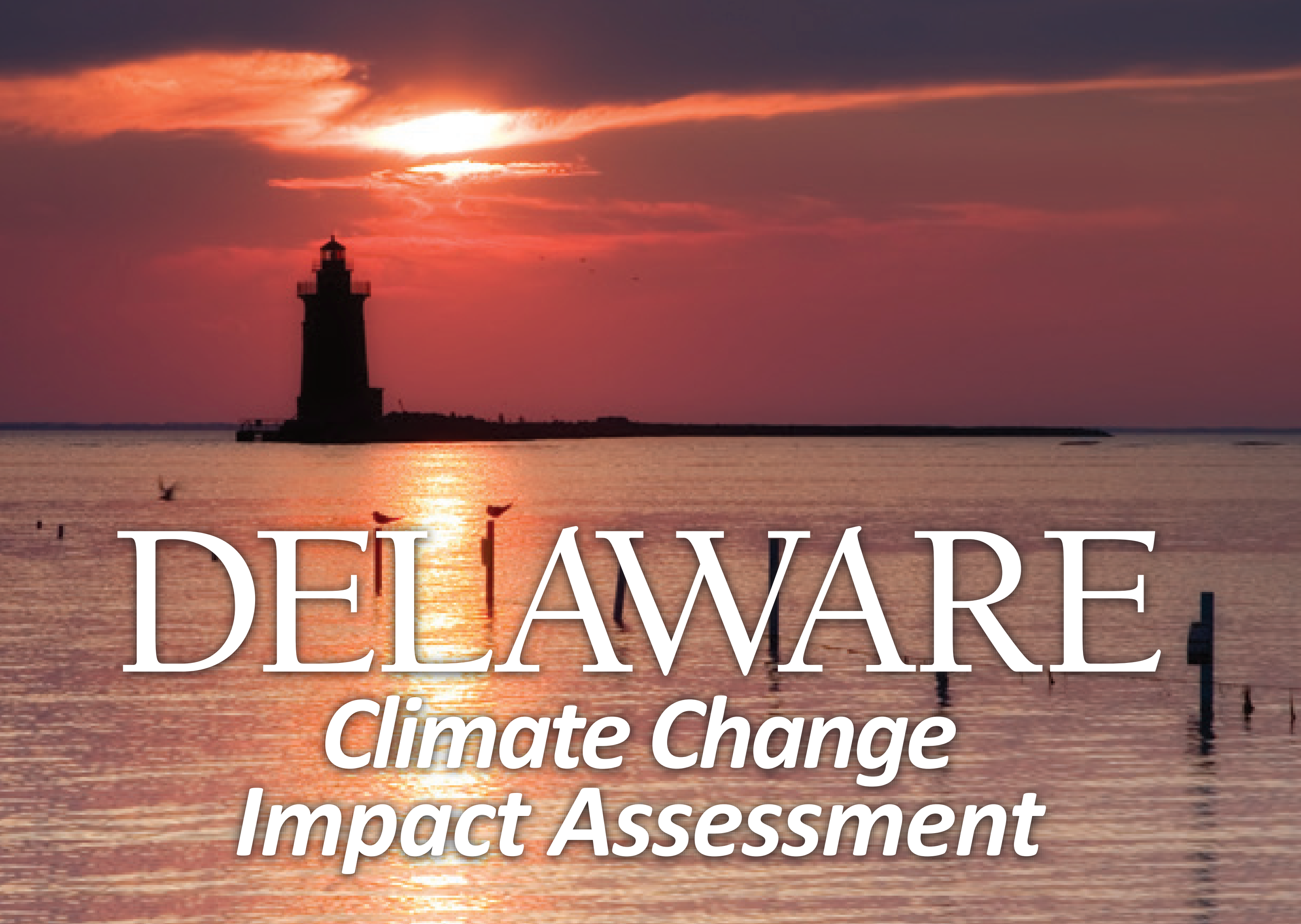

# DELAWARE
## Climate Change Impact Assessment

PREPARED BY


**Division of Energy and Climate**

Delaware Department of Natural Resources and Environmental Control

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February 2014

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- **Beach house with waves:** Wendy Carey, Delaware Sea Grant

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STATE OF DELAWARE
DEPARTMENT OF NATURAL RESOURCES
AND ENVIRONMENTAL CONTROL
89 KINGS HIGHWAY
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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!*

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

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



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## 5. Public Health

## Excel File Appendix

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



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

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## Chapter 8 – Ecosystems and Wildlife



## Chapter 9 – Infrastructure

# Acknowledgments

Lead authors and editors of this report are Jennifer de Mooy and Morgan Ellis of the Division of Energy and Climate, Delaware Department of Natural Resources and Environmental Control. Final editing was provided by Joy Drohan, Eco-Write, LLC.

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**Dr. Katharine Hayhoe,** ATMOS Research & Consulting

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**Dr. Rodica Gelca,** ATMOS Research & Consulting

We are grateful for the guidance and expertise of the Climate Change Impact Assessment Steering Committee and for the input and review provided by numerous experts within Delaware's academic and practitioner communities.

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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
- *Agriculture.* http://nca2009.globalchange.gov/agriculture
- *Ecosystems.* http://nca2009.globalchange.gov/ecosystems
- *Human Health*. http://nca2009.globalchange.gov/human-health
- *Society.* http://nca2009.globalchange.gov/society
- *Northeast Region.* http://nca2009.globalchange.gov/north

*Coastal Impacts, Adaptation and Vulnerability: A Technical Input to the 2013 National Climate Assessment.* National Oceanic and Atmospheric Administration & U.S. Geological Survey. http://www.noaanews.noaa.gov/stories2013/20130125_coastalclimateimpacts.html

*Global Sea Level Rise Scenarios for the US National Climate Assessment*. (2012). National Oceanic and Atmospheric Administration. NOAA Tech Memo OAR CPO-1. 37 pp. http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf

*Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. (2012).* Cooperative Report to the 2013 National Climate Assessment. http://www.globalchange.gov/what-we-do/assessment/nca-activities/available-technical-inputs

*Climate Change and Infrastructure, Urban Systems, and Vulnerabilities*. (2012). U.S. Department of Energy, Science Office. Oak Ridge National Laboratory. Technical Report for the U.S. Department of Energy in Support of the National Climate Assessment. http://www.esd.ornl.gov/eess/Infrastructure.pdf

*Climate Literacy: The Essential Principles of Climate Science.* U.S. Global Change Research Program brochure dated March 2009. http://www.globalchange.gov/resources/educators/climate-literacy

### U.S. Climate Change Science Program – Synthesis and Assessment Products (SAP reports)

*The Effects of Climate Change on Agriculture, Land Resources, Water Resources and Biodiversity in the United States.* United States Climate Change Science Program, Synthesis and Assessment Product 4.3. http://www.climatescience.gov/Library/sap/sap4-3/final-report/

*Effects of Climate Change on Energy Production and Use in the United States.* United States Climate Change Science Program, Synthesis and Assessment Product 4.5. http://www.climatescience.gov/Library/sap/sap4-5/final-report/default.htm

*Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region.* (2009). United States Climate Change Science Program, Synthesis and Assessment Product 4.1. http://library.globalchange.gov/products/assessments/sap-4-1-coastal-sensitivity-to-sea-level-rise-a-focus-on-the-mid-atlantic-region

## Other National Reports:

*National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate.* (2011). Interagency Climate Change Task Force. http://water.epa.gov/scitech/climatechange/federalcollaborations.cfm

*Potential Impacts of Climate Change on U.S. Transportation*. (2008). National Research Council. Transportation Research Board Special Report 290. http://www.trb.org/Main/Blurbs/156825.aspx

*Climate 101: Understanding and Responding to Global Climate Change. (2011).* Center for Energy and Climate Solutions. http://www.c2es.org/science-impacts/climate-change-101

## Regional and Statewide Assessments:

*Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. (2007). Synthesis report for the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (USC). http://www.climatechoices.org/ne/resources_ne/nereport.html

*Preparing for Tomorrow's High Tide: Sea Level Rise Vulnerability Assessment for the State of Delaware.* (2012). Delaware Department of Natural Resources and Environmental Control. Delaware Coastal Programs report. http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

*Striking a Balance: A Guide to Coastal Dynamics and Beach Management in Delaware.* (2006). Delaware Department of Natural Resources and Environmental Control & Delaware Coastal Programs Division of Soil and Water Conservation, Shoreline and Waterway Management Section Report. http://www.deseagrant.org/products/striking-balance

*Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning.* (2010). Partnership for the Delaware Estuary Report. Report No. 10-01. June 2010. http://delawareestuary.org/climate-ready-estuary-workgroup-data-products-reports

# 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.

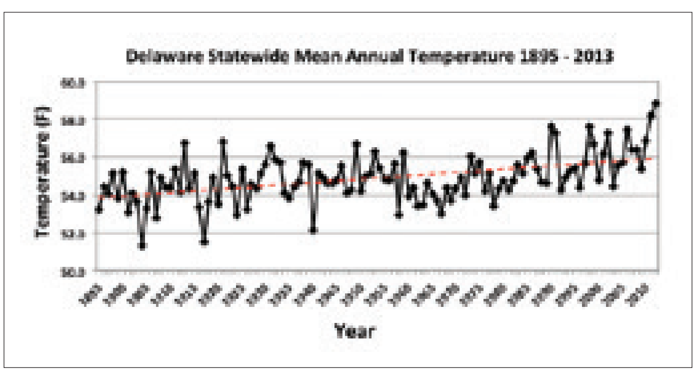


**Figure 1.** Statewide mean annual temperature for Delaware, 1895-2013. Source: Leathers (2013).

# 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.

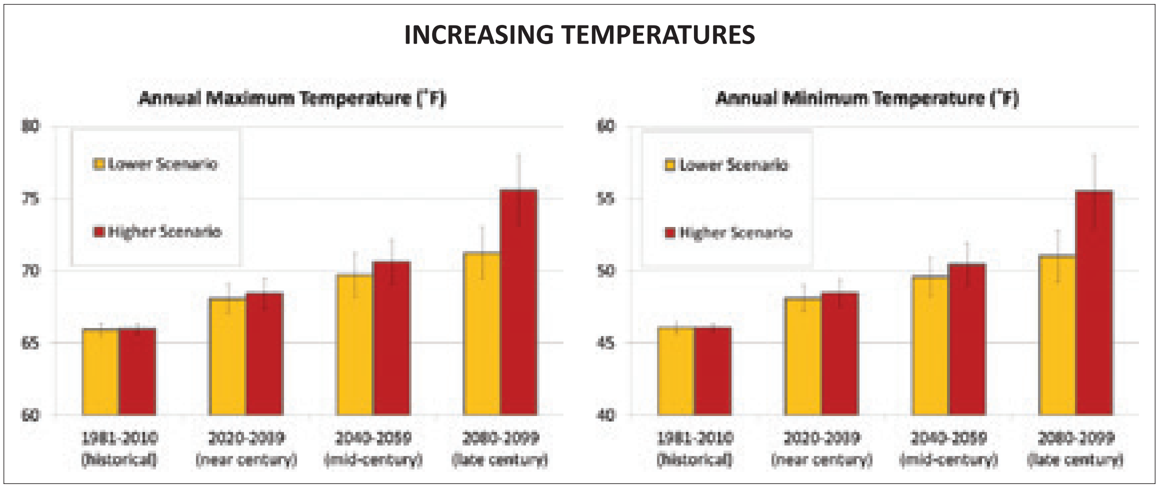


**Figure 2.** Annual maximum (daytime) and minimum (nighttime) temperatures are projected to increase. (Note difference in temperatures in y-axis.) Changes are average for the State of Delaware, based on individual projections for 14 weather stations. Source: Hayhoe et al. (2013).

- 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**).

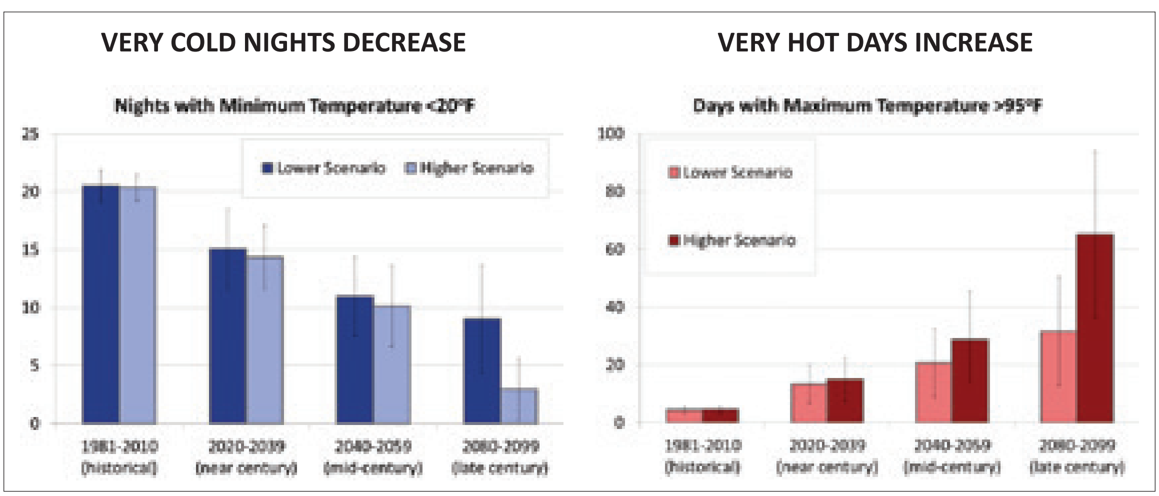


**Figure 3.** Temperature extremes are projected to change. The greatest changes are seen in the number of days above a given high temperature or below a given cold temperature threshold. Source: Hayhoe et al. (2013).

- 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.

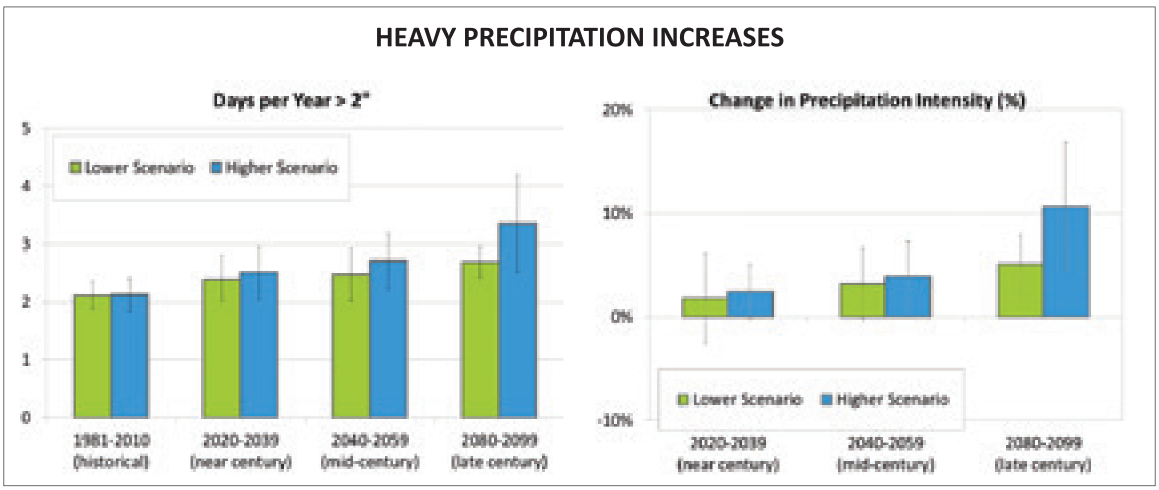


**Figure 4.** Rainfall extremes are also projected to increase. By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events. Source: Hayhoe et al. (2013).

**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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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**.<br><br>Flooding **impacts to road and rail lines** also affect energy production, particularly for coal-fired power generation that relies on coal transport by rail.<br><br>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.<br><br>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]

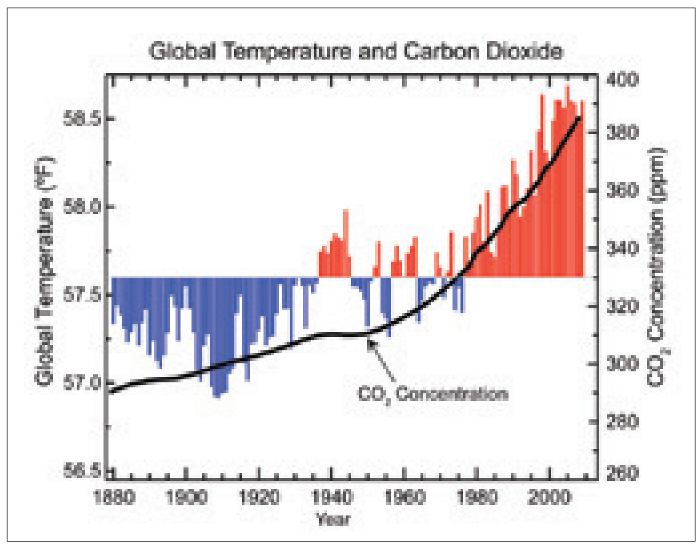


**Figure 1.1.** Global temperatures and carbon dioxide concentrations. Source: U.S. Global Change Research Program.

### • 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]

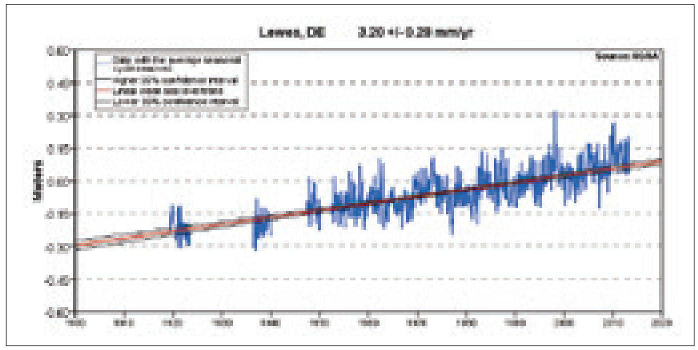


**Figure 1.2.** Tidal gauge data for Lewes, DE, 1900-2010. Source: National Oceanic and Atmospheric Administration.

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.

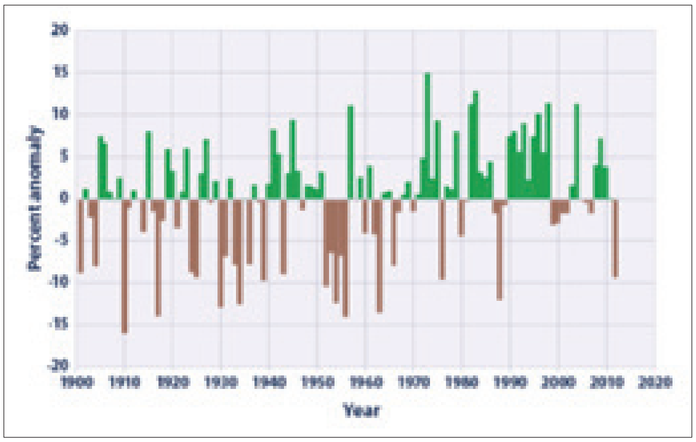


**Figure 1.3.** Precipitation in the Lower 48 states, 1901-2012. Source: U.S. Environmental Protection Agency (2013).

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.

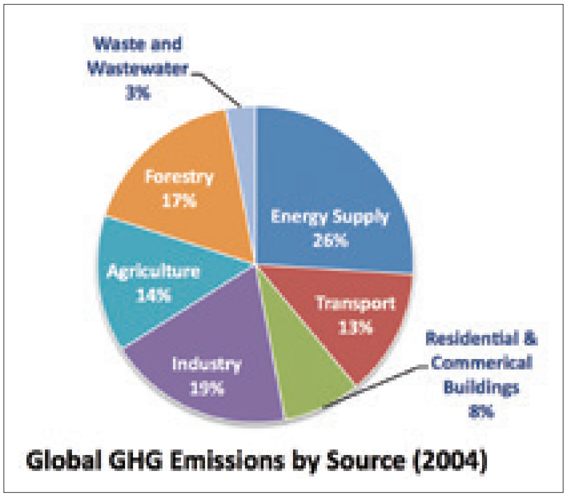


**Figure 1.4.** Global greenhouse gas emissions by source. Source: U.S. Environmental Protection Agency (Based on 2004 data).

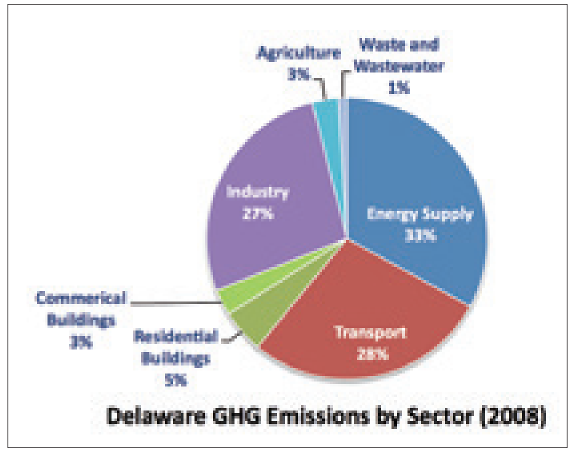


**Figure 1.5** Delaware greenhouse gas emissions by sector. Source: Delaware Department of Natural Resources and Environmental Control, Division of Air Quality (Based on 2008 data).

- 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.

## Sources – Climate 101
### (Endnotes)


1 National Aeronautics and Space Administration. (2012). *NASA Climate change web page.* Retrieved on June 13, 2012. http://www.nasa.gov/mission_pages/noaa-n/climate/climate_weather.html

2 National Oceanic and Atmospheric Administration. (2012). *NOAA Education sources web page.* Retrieved on June 13, 2012. http://www.education.noaa.gov/Climate/

3 U.S. Environmental Protection Agency. (2012). *Adaptation strategies guide for water utilities.* EPA report, January 2012. Retrieved from http://water.epa.gov/infrastructure/watersecurity/climate/

4 U.S. Agency for International Development. (2007). *Adapting to climate variability and change: A guidance manual for development planning.* USAID report, August 2007. Retrieved from http://pdf.usaid.gov/pdf_docs/PNADJ990.pdf

5 U.S. Global Change Research Program. (2009). *Global climate change impacts in the United States.* Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

6 U.S. Global Change Research Program. (2009). *Global climate change impacts in the United States.* Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

7 U.S. Global Change Research Program. (2009). *Climate literacy: The essential principles of climate science.* USGCRP brochure, March 2009. Retrieved from http://www.climatescience.gov/Library/Literacy/

8 Center for Energy and Climate Solutions. (2011). *Climate 101: Understanding and responding to global climate change.* Retrieved from http://www.c2es.org/global-warming-basics/climate_change_101

9 National Oceanic and Atmospheric Administration. (2012). *NOAA Satellite and Information Services web page.* Retrieved on June 13, 2012 from http://www.ncdc.noaa.gov/paleo/globalwarming/gw-forcing.html

[10] Anderson, K. E., Cahoon, D. R., Gill, S. K., Gutierrez, B. T., Thieler, E. R., Titus, J. G., & Williams, S. J. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* U.S. Climate Change Science Program. Synthesis and Assessment Product 4.1.

[11] Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., … Weiss, J. (2012). *Global sea level rise scenarios for the US national climate assessment.* NOAA Tech Memo OAR CPO-1. 37 pp. Retrieved from http://www.cpo.noaa.gov/reports/sealevel/

[12] U.S. Global Change Research Program. (2009). *Global climate change impacts in the United States.* Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

[13] U.S. Environmental Protection Agency. (2010). *Climate change science facts.* EPA fact sheet, April 2010. Retrieved from http://www.epa.gov/climatechange/downloads/Climate_Change_Science_Facts.pdf

[14] U.S. Global Change Research Program. (2009). *Global climate change impacts in the United States.* Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

[15] Intergovernmental Panel on Climate Change. (2013). *Working Group I contribution to the IPCC fifth assessment report, Climate change 2013: The physical science basis, summary for policymakers.* http://ipcc.ch/

[16] U.S. Global Change Research Program. (2009). *Global climate change Impacts in the United States.* Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

[17] Center for Energy and Climate Solutions. (2011). *Climate 101: Understanding and responding to global climate change.* Retrieved from http://www.c2es.org/global-warming-basics/climate_change_101

[18] Burkett, V. R., & Davidson, M. A. [Eds.]. (2012). *Coastal impacts, adaptation and vulnerability: A technical input to the 2012 national climate assessment.* Cooperative Report to the 2013 National Climate Assessment., 150 pp. Introduction and Chapter 1 – FINAL – 1.2.2014 Page 37

[19] Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., … Weiss, J. (2012). *Global sea level rise scenarios for the US national climate assessment.* NOAA Tech Memo OAR CPO-1. 37 pp. Retrieved from http://www.cpo.noaa.gov/reports/sealevel/

[20] Anderson, K. E., Cahoon, D. R., Gill, S. K., Gutierrez, B. T., Thieler, E. R., Titus, J. G., & Williams, S. J. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* US Climate Change Science Program. Synthesis and Assessment Product 4.1.

[21] Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July 2012. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx.

[22] Sallenger, Jr., A. H., Doran, L. S., & Howd, P. A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change.* doi: 10.1038/CCLIMATE 1597

[23] Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., … Weiss, J. (2012). *Global sea level rise scenarios for the US national climate assessment.* NOAA Tech Memo OAR CPO-1. 37 pp. Retrieved from http://www.cpo.noaa.gov/reports/sealevel/

[24] National Oceanic and Atmospheric Administration. (2012). *NOAA PMEL carbon program website.* Retrieved on June 8, 2012 from http://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F

[25] U.S. Environmental Protection Agency. (2012). *Climate change indicators in the United States.* Retrieved on June 8, 2012 from http://www.epa.gov/climatechange/science/indicators/weather-climate/precipitation.html

[26] U.S. Global Change Research Program. (2009). *Global climate change impacts in the United States.* Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

[27] National Oceanic and Atmospheric Administration. (2012). *NOAA Office of Oceanic and Atmospheric Research website.* Retrieved from http://www.research.noaa.gov/climate/t_modeling.html

[28] National Aeronautics and Space Administration. *NASA Goddard Institute for Space Studies website.* Retrieved from http://www.giss.nasa.gov/research/briefs/schmidt_04/

[29] Climate Change Science Program and Subcommittee on Global Change Research. (2003). *Strategic plan for the U.S. Climate Change Science Program, Washington, D.C., p. 199.* Retrieved from http://www.climatescience.gov/Library/stratplan2003/default.htm

[30] Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., … Weiss, J. (2012). *Global sea level rise scenarios for the US national climate assessment.* NOAA Tech Memo OAR CPO-1. 37 pp. Retrieved from http://www.cpo.noaa.gov/reports/sealevel/

[31] Merriam-Webster Dictionary: http://www.merriam-webster.com/dictionary/greenhouse%20gas

# DELAWARE
# Climate Change Impact Assessment

PREPARED BY


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


## Section 2: Delaware's Climate

### Chapter 2 – Delaware Climate Trends
*(Daniel J. Leathers)*

### Chapter 3 – Comparing Observed and Modeled Historic Data
*(Daniel J. Leathers and Katharine Hayhoe)*

### Chapter 4 – Delaware Climate Projections
*(Katharine Hayhoe, Anne Stoner, and Rodica Gelca)*

## Key Terms and Definitions

**Climate indicators** – Represent the state of a given environmental condition over a certain area and a specified period of time, such as the mean annual temperature in Delaware for the period 1895-2011 or 2020-2039.

**Temperature** – Air temperatures over land surface, typically recorded at a height of 2 meters, in degrees Fahrenheit as ˚F.

**Precipitation** – Includes rain and snow, typically recorded as cumulative amount over a given time period ranging from a day to a year, in inches.

**Temperature and precipitation extremes** – Extremes can be measured using fixed thresholds (e.g., days per year over 100˚F) or using percentiles (e.g., number of days colder than the coldest 1 pecent of days).

**Maximum temperature** – The highest temperature value in a given time period (daily, seasonal, or annual). Unless otherwise stated, all daily maximum temperatures in this report refer to values recorded within a 24-hour period, usually (but not always) occurring in the afternoon (also described as daytime temperatures).

**Minimum temperature** – The lowest temperature value in a given time period (daily, seasonal, or annual). Unless otherwise stated, all daily minimum temperatures in this report refer to values recorded within a 24-hour period, usually occurring at night (also described as nighttime temperatures).

**Observations** – Data collected from weather stations, usually daily, with measurement instruments. Data usually consists of temperature and precipitation, but weather stations may also collect data on humidity, wind speed, and other conditions.

**Cooling degree-days and heating degree-days** – An indicator of energy demand for heating and cooling. This represents demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). Degree-days are typically calculated as the cumulative number of hours per year above (for cooling) or below (for heating) a given temperature threshold. For this analysis the threshold value is 65˚F.

**Natural climate variability** – Variation in seasonal, year-to-year, and even multiyear cycles that can result in wetter or drier, hotter or cooler periods than "average" weather measurements. Most natural climate variability occurs over time scales shorter than 20 to 30 years.

**Growing season** – The "frost-free" period between the last frost in spring and the first frost in fall or winter, defined as the last and first time that nighttime minimum temperature falls below 32º.

# Chapter 2 Delaware Climate Trends

***Author:*** *Dr. Daniel J. Leathers, Delaware State Climatologist, University of Delaware*

## Summary

A climate change analysis of historical climate data for Delaware for the period 1895 through 2012 has been completed. The major goal of the project was to identify any statistically significant trends in diverse climate variables for the Delaware region. The variables analyzed included temperature, temperature extremes, precipitation, precipitation extremes, and additional derived variables such as heating- and cooling degree-days, drought indices (PDSI, PDHI, PMDI and Palmer-Z), and commonly studied climate indicators.

- Since 1895, temperatures across Delaware have been increasing at a statistically significant rate of approximately 0.2°F per decade annually and in all seasons.

- Significant increasing trends were found for cooling degree-days annually and during the summer, and significant decreasing trends were found in heating degree-days for all seasons except winter.

- Although both maximum and minimum temperatures have increased over this period, much of the temperature increase in recent decades is associated with warming minimum temperatures, evidenced by a decrease in the number of "cold" nights with minimum temperatures below 32°F, and by an increase in the number of warm nights with minimum temperatures above 75°F.

- Several of the temperature-dependent climate indicators indicated an upward trend in minimum temperatures, especially over the last three decades. Maximum temperatures have also been increasing at several stations, but most of this increase occurred earlier in the 20th century.

- Annual and seasonal precipitation totals across Delaware have remained generally unchanged since 1895, except for a statistically significant increase in autumn season precipitation. No significant trends were found in the value of the four drought indices studied (PDSI, PDHI, PMDI, and Palmer-Z), and no trends were found in precipitation-dependent climate indicators.

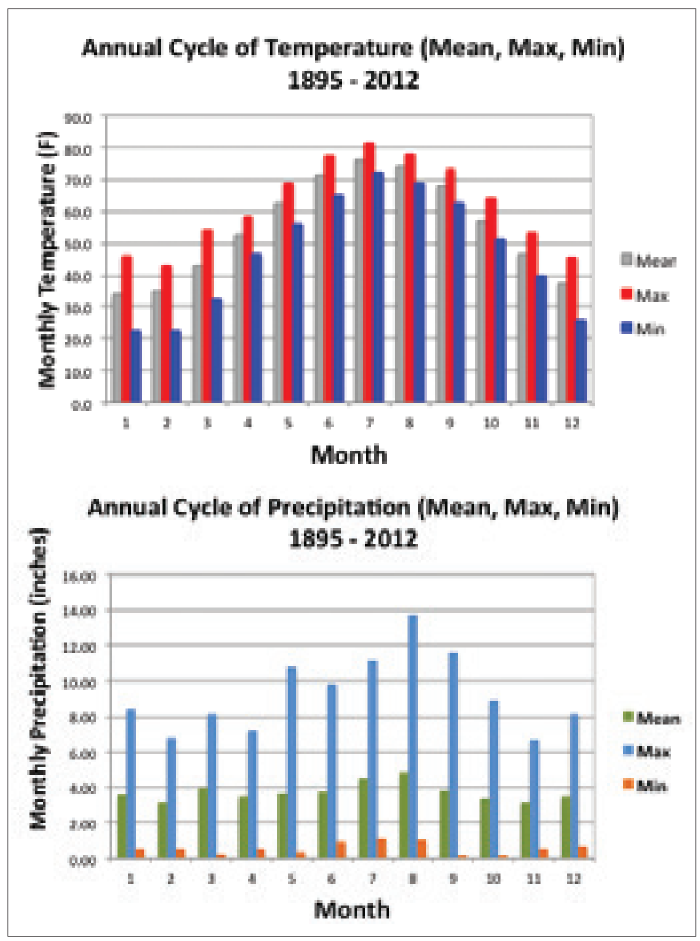


**Figure 2.1.** Annual cycle of mean, maximum, and minimum values of Delaware statewide a) mean monthly temperature, and b) mean monthly precipitation for the period 1895-2012. Note high variability in monthly precipitation totals.

### Graphs for Temperature and Precipitation Indicators

- Statewide mean annual, mean winter, mean spring, mean summer, and mean autumn temperatures
- Growing season length
- Annual number of days with minimum temperatures less than 32˚F
- Annual number of days with minimum temperatures less than 20˚F
- Annual number of days with minimum temperatures greater than 75˚F
- Summer mean minimum seasonal temperature
- Statewide annual, winter, spring, summer, and autumn precipitation

## 2.1. Background

Located along the Atlantic Coast of the eastern United States, the State of Delaware is situated in a transition zone between humid subtropical climate conditions to the south and humid continental conditions to the north. The moderating effects of surrounding water bodies, including the Atlantic Ocean and Delaware Bay to the east, and Chesapeake Bay to the west, lessen temperature extremes compared to nearby interior locations. Even so, the state has a continental climate, with cold winter temperatures, hot summers, and ample but highly variable precipitation throughout the year (**Figure 2.1 a-b**). Delaware's precipitation patterns show great interannual and intra-annual variability. Although the 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.

## 2.2. Data and Methods

Observed climate data can be affected by a number of issues, including observer bias, time of observation bias, station moves, instrument changes, and missing data to name just a few. To ameliorate as many of these difficulties as much as possible, metadata for each data set used in this study were carefully evaluated, and only the most appropriate data for climate studies were used. Missing data are also a substantial problem, especially when daily thresholds in temperature or precipitation are being investigated. Unfortunately, daily precipitation data are more greatly affected, because in many instances observers fail to record any observation on days with no precipitation falling. A lack of observation of precipitation for a given day must then be treated as missing data because the intent of the observer cannot be presumed. For this study, data for a given year were considered complete for temperature when 95 percent of the days in a year were available and when 90 percent were available for precipitation.

### 2.2.1. Statewide and Divisional Temperature, Precipitation, and Drought Index Data

Statewide and divisional temperature, precipitation, and drought index data are available for the period 1895 through 2012 from the National Climatic Data Center.[1] These data are made available by NCDC for the study of climate variability and change. When necessary, observations have been adjusted to account for the effects introduced into the climate record by factors such as instrument changes, station relocations, changes in observer or observing practice, urbanization, etc.[2] Similar data are also available for the state's two climate divisions: division 1 (New Castle County) and division 2 (Kent and Sussex Counties).[3,4] These data are available through both the Office of the Delaware State Climatologist and the NCDC. These data were used in the analysis of temperature and precipitation variability and large-scale drought (PDSI, PDHI, PMDI, and Palmer-Z) for the state as a whole and for each of Delaware's two climate divisions since 1895. Keim et al.[5] discussed some possible problems in the divisional data associated with stations coming into and out of the divisional calculation over time, especially if the station changes

| Temperature | Precipitation |
|---|---|
| Tmax < 32° F | Precip. Days > Trace |
| Tmax > 90° F | Precip. > 0.5" |
| Tmax > 100° F | Precip. > 1" |
| Tmax > 105° F | Precip. > 2" |
| Tmin < 32° F | Precip. > 3" |
| Tmin < 20° F | Precip. > 4" |
| Tmin > 75° F | Precip. > 5" |
| Tmin > 80° F | Precip. > 6 " |
| Tmin > 85° F | Precip. > 7" |
| Absolute Maximum T | Precip. > 8" |
| Absolute Minimum T | Consec. Days with Precip. |
| Consec. Days Tmax > 90 | Max 1-day Precip. |
| First Freeze Date | Max 2-day Precip. |
| Last Freeze Date | Annual Precip. |
| Growing Season Length | Winter Season Precip. |
| Winter Season Tmax | Spring Season Precip. |
| Spring Season Tmax | Summer Season Precip. |
| Summer Season Tmax | Autumn Season Precip |
| Autumn Season Tmax | |
| Winter Season Tmin | |
| Spring Season Tmin | |
| Summer Season Tmin | |
| Autumn Season Tmin | |

**Table 2.1.** Listing of climate indicators calculated from National Weather Service Cooperative station data.


**Figure 2.2.** Spatial distribution of National Weather Service Cooperative weather stations used in the analysis.

include large elevation differences. Given the small elevation differences across Delaware and the small size of the climate division areas, this problem should not be of major concern in this study. The statewide data are calculated from National Weather Service Cooperative Station data from 1931 to the present. Prior to 1931, statewide data are derived from United States Department of Agriculture data.

## 2.2.2. Cooperative Daily Weather Station Data

The DSI-3200 data set, available through NCDC, includes 23 National Weather Service Cooperative stations that have been located in Delaware at some point since the late 19th century (**Figure 2.2**). The DSI-3200 data include daily observations of maximum temperature, minimum temperature, total liquid precipitation, snowfall, and snow cover on the ground. Although the data have been quality controlled, care must still be taken in their use to account for time of observation biases, poor sensor placement, etc. For this study, metadata on all stations were collected and analyzed to ascertain those stations and period of record that are suitable for the investigation of climate variability. The Cooperative station data identified as suitable for further evaluation are used in the analysis of temperature and temperature extremes, precipitation and precipitation extremes, and potential asymmetric changes in temperature (changes in maximum compared to minimum temperatures). Nine stations out of the initial list of 23 possibilities were retained for further analysis. A complete list of the climate change indicators calculated from the cooperative station data is given in **Table 2.1**; **Figure 2.2** shows the locations of the stations used in the analysis. It is important to note that only those climate indicators that showed significant trends at a number of stations are discussed in this report. However, all 41 climate indicators were investigated at all nine stations used in this study (369 separate trends were analyzed). Moreover, four high-quality stations (Wilmington Porter Reservoir, Wilmington NCC Airport, Dover, Lewes), spanning the length of Delaware, are used in this report to illustrate the trends across the state for specific climate indicators.

### 2.2.3. Methods

Arguably, the most common analysis technique used to ascertain the presence of statistically significant trends in climate data is simple linear regression, which describes the linear relationship between two variables. In the case of climate studies, these two variables are typically time and the meteorological variable of interest. Linear regression techniques were used in the current study to ascertain the presence of a statistically significant trend between the independent variable (time) and the dependent climatological variable.[6] A variety of statistical tests were used to ascertain the significance of the relationship between time and the variable of interest.

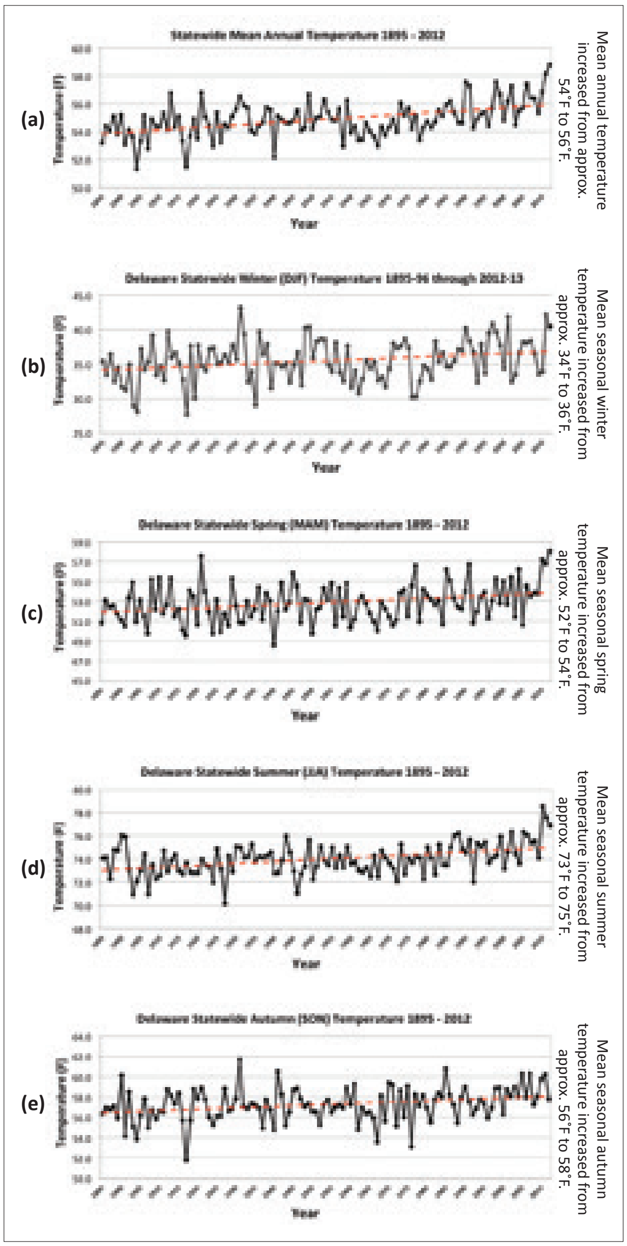


**Figure 2.3.** Delaware statewide a) mean annual, b) mean winter, c) mean spring, d) mean summer, and e) mean autumn temperatures, 1895-2012. Red line indicates linear regression trend line for the period of record.

## 2.3. Climate Trends Analysis – Temperature

### 2.3.1. Statewide Results

An analysis of Delaware statewide mean annual and mean seasonal temperatures using the

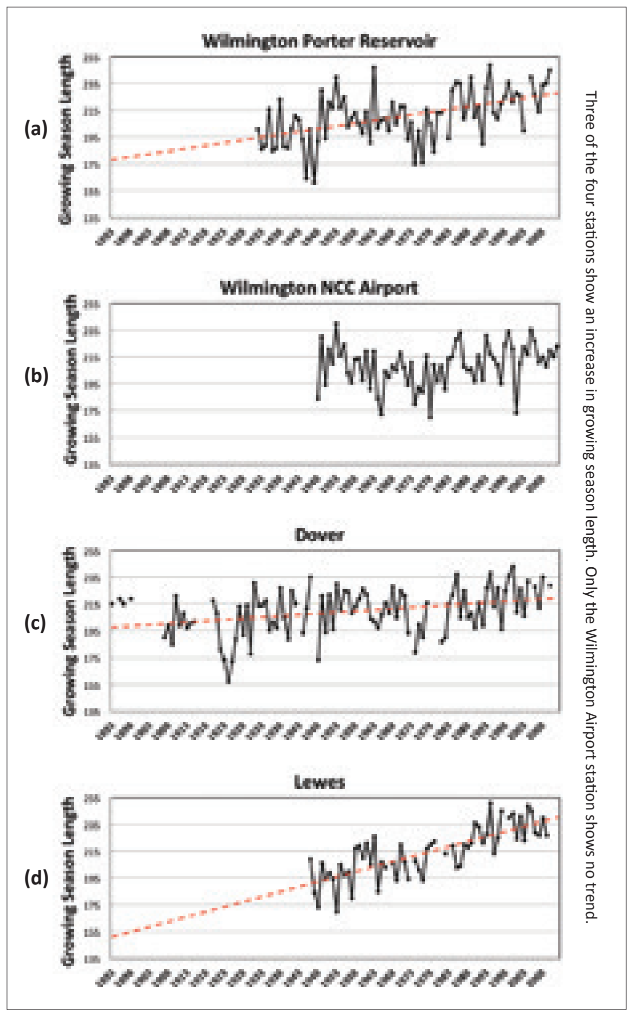


**Figure 2.4.** Growing season length: a) Wilmington Porter Reservoir, b) Wilmington NCC Airport, c) Dover, and d) Lewes. Growing season is defined as number of days between last spring freeze and first fall freeze.

"Climate Division Time Biased Corrected Temperature and Precipitation Data" maintained by the NCDC shows a statistically significant increasing trend in temperatures during the period 1895 through 2012 annually and for all seasons.[7,8] An increasing trend of 0.2°F per decade was identified for mean annual, and mean seasonal winter, spring, and summer temperatures (**Figure 2.3 a-d**). Autumn mean seasonal temperatures have also seen a significant increase, but at a rate of 0.1°F per decade (**Figure 2.3e**). A modest increasing trend in statewide mean annual temperatures is detectable before 1960, with a more apparent trend after that year. The last two years of the record (2011, 2012) have been the two warmest since 1895 for mean annual temperature. Individual seasons show a more monotonic long-term upward trend from 1895 through the present.

Significant increasing trends were found for statewide cooling degree-days annually and during the summer, and significant decreasing trends were found in heating degree-days for all seasons except winter. These results are expected, because cooling- and heating-degree day data are calculated directly from mean temperature statistics.

## Cooperative Station Results

Several temperature-dependent climate indicators also show statistically significant trends during the period of record, including growing season length, the annual number of days with minimum

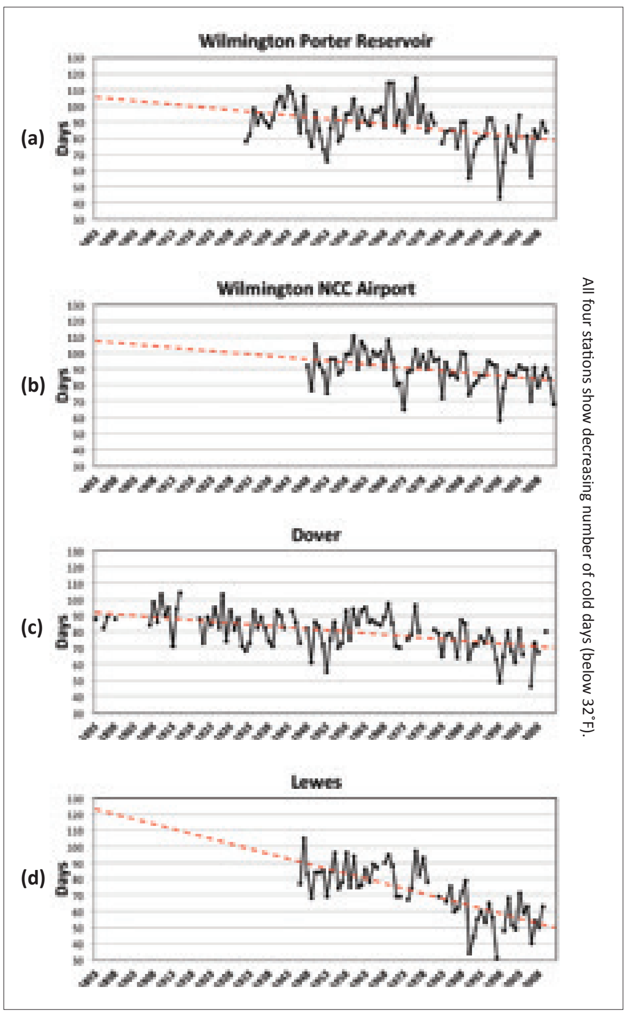


**Figure 2.5.** Annual number of days with minimum temperature less than 32oF a) Wilmington Porter Reservoir, b) Wilmington NCC Airport, c) Dover, and d) Lewes.

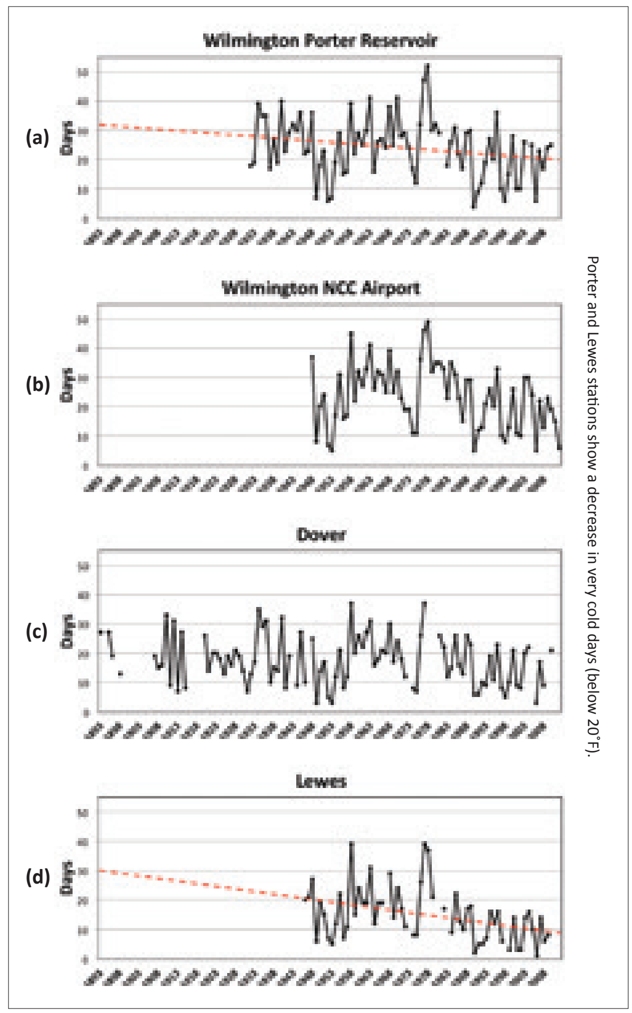


**Figure 2.6.** Annual number of days with minimum temperature less than 20oF a) Wilmington Porter Reservoir, b) Wilmington NCC Airport, c) Dover, and d) Lewes.

temperatures below 32ºF and 20ºF, the number of days annually with minimum temperatures above 75ºF, and seasonal mean minimum and maximum temperatures. Of the four Cooperative stations that have significant data extending into the last decade, three (Wilmington Porter Reservoir, Dover, and Lewes) show significant increasing trends in growing season length associated with an earlier "last freeze" date in the spring and a later "first freeze" date in the fall. However, the Wilmington New Castle County Airport site shows no significant trend in growing season length (**Figure 2.4 a-d**). Examining the number of days per year with temperatures below 32ºF, all four stations (Wilmington Porter Reservoir, Wilmington Airport, Dover, and Lewes) show significant decreasing trends in the number of days with minimum temperatures below freezing (**Figure 2.5 a-d**). Very cold days, with minimum temperatures below 20ºF, have seen significant decreases at both Wilmington Porter Reservoir and Lewes, with decreases at the Wilmington Airport nearly reaching the 95% significance level (**Figure 2.6 a-d**). For minimum temperatures greater than 75ºF, Wilmington Porter Reservoir, Wilmington Airport, and Lewes all show significant increasing trends in the annual number of warm minimum temperatures (**Figure 2.7 a-d**). An analysis of mean seasonal temperatures at the Cooperative stations indicates statistically significant increasing trends in seasonal mean minimum temperatures during the period of record in each season. **Figures 2.8a-d** show mean summer season minimum temperatures for each of the four locations as an example. Increasing

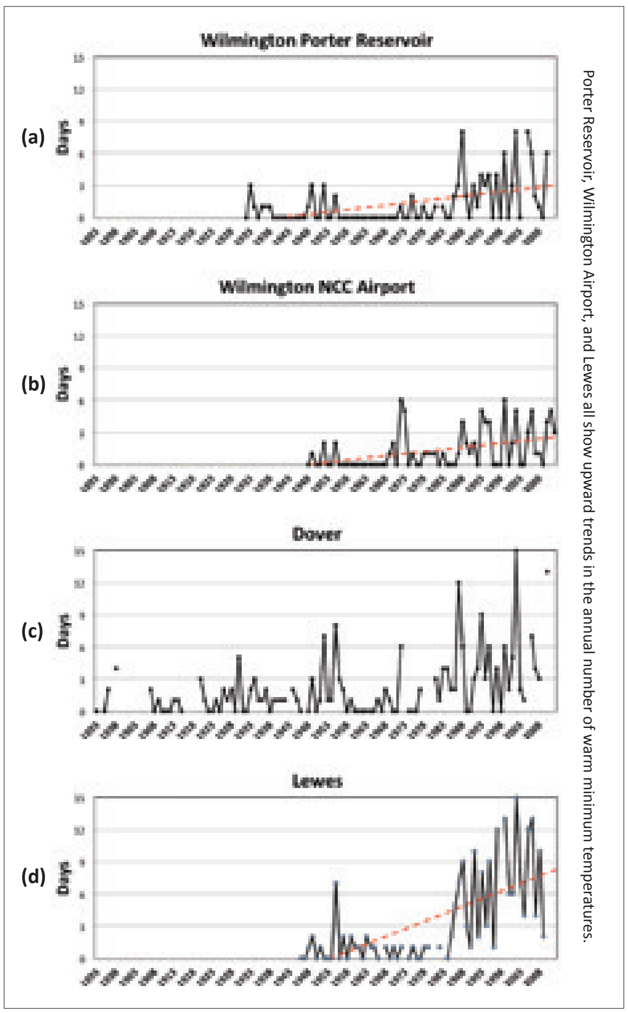


**Figure 2.7.** Annual number of days with minimum temperature greater than 75oF a) Wilmington Porter Reservoir, b) Wilmington NCC Airport, c) Dover, and d) Lewes.

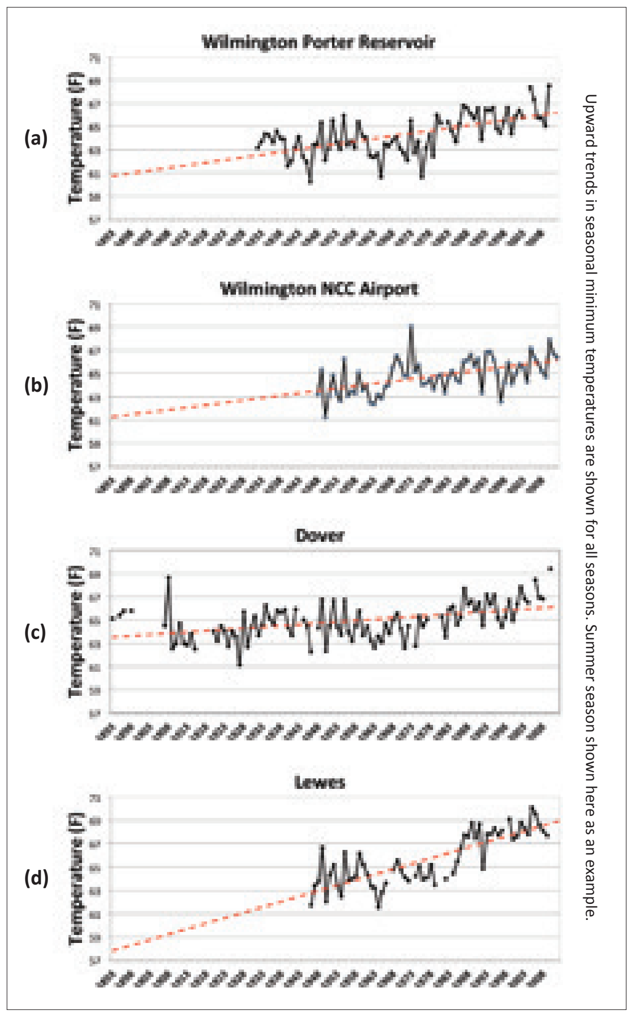


**Figure 2.8.** Summer mean minimum seasonal temperature (JJA) for a) Porter Reservoir, b) Wilmington NCC Airport, c) Dover, and d) Lewes.

trends in seasonal mean maximum temperatures were also found for several stations in diverse seasons. The majority of these increasing trends were associated with temperature increases early in the 20th century, with less warming of maximum temperatures in recent decades. Only Lewes showed a significant increasing trend in days above 90°F (not shown).

## 2.3.2. Temperature Summary

In summary, the analysis of historical temperature data indicates that temperatures across Delaware have been increasing at a rate of approximately 0.2°F per decade since 1895. An analysis of the Cooperative station data, used in the statewide values, suggests that much of the long-term trend in annual and seasonal temperatures is being driven by increasing minimum temperatures, especially later in the period of record. Mean seasonal maximum temperatures have increased at many stations, with the primary period of warming occurring earlier in the 20th century at most locations. The analysis also shows that days with minimum temperatures below 32°F and 20°F (cold nighttime low temperatures) are decreasing, while days with minimum temperatures above 75°F (warm nighttime low temperatures) have been increasing in recent decades. Therefore, nighttime low temperatures are asymmetrically increasing across Delaware compared with daytime maximum temperatures, especially in the later portion of the period of record.

# 2.4. Climate Trends Analysis – Precipitation

## 2.4.1. Statewide Results

"Climate Division Time Biased Corrected Temperature and Precipitation Data" maintained by the NCDC were used to study changes in observed precipitation across Delaware.[9,10] No significant trends were identified in statewide precipitation for the period 1895-2012 annually, or during the winter, spring, or summer seasons (**Figure 2.9 a-e**). Only autumn season statewide precipitation was found to have a statistically significant increasing trend of 0.27" per decade.

During the observational record, the most important characteristic of Delaware precipitation has been large annual and seasonal precipitation variability, with statewide annual values varying between 28.29" in 1930 and 62.08" in 1948. In addition, there has been a tendency for decadal-scale variations in annual precipitation, including a continuously wet period from 1932 through 1939

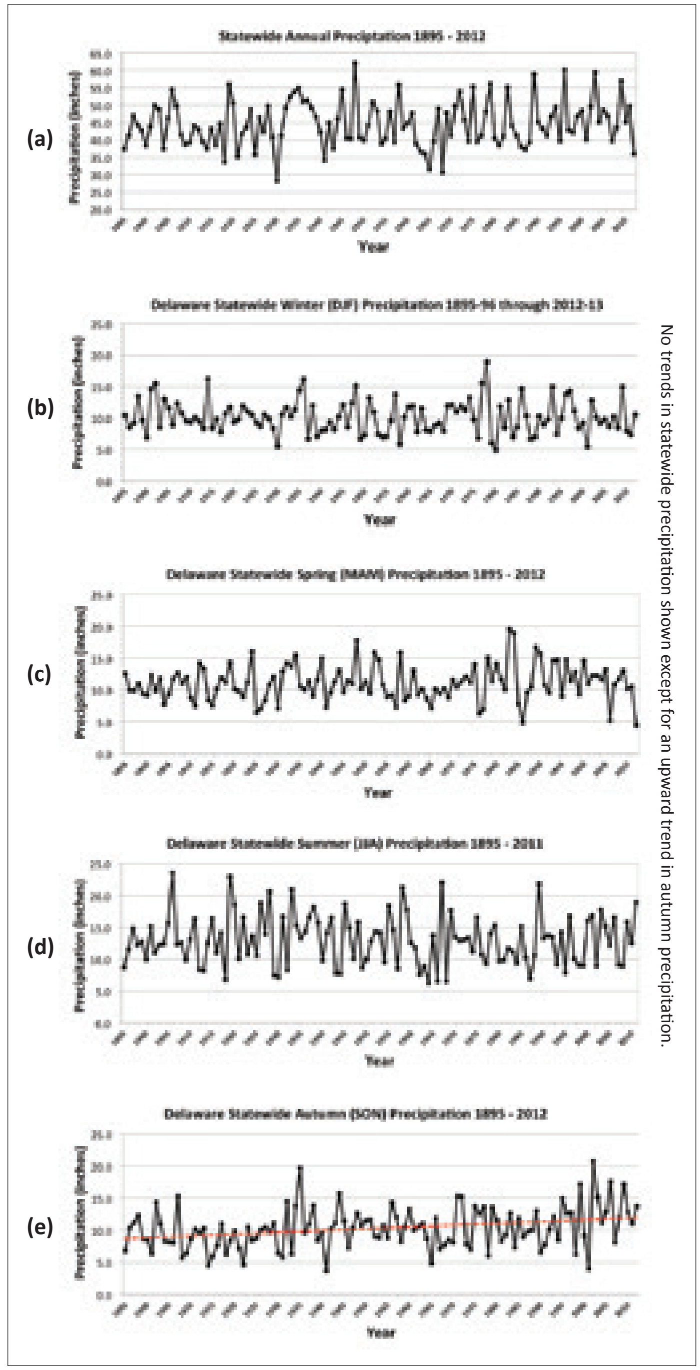


**Figure 2.9.** Delaware statewide a) annual, b) winter, c) spring, d) summer, and e) autumn precipitation 1895-2012. Red line indicates linear regression trend line for the period of record.

and an exceptionally dry period during the 1960s (**Figure 2.9a**).

## Cooperative Station Results

An analysis of Cooperative station results for precipitation show no significant long-term trends in any of the climate indicators based on daily precipitation thresholds (see **Table 2.1**). Only a few of the nine stations for which data were analyzed show any significant trends for any precipitation variable, except for autumn season precipitation. For that variable, three stations of the nine showed significant upward increasing trends in precipitation.

## Precipitation Summary

In summary, Delaware statewide precipitation has shown no significant changes since 1895, except for a significant upward increasing trend during the autumn season. The major characteristic of precipitation across Delaware during this period has been large interannual and intra-annual variability. For example, the two-month period of June through July 2012 saw a statewide precipitation total of only 5.40", the 17th driest on record. One year later, the June through July period of 2013 saw a statewide precipitation total of 16.47", the wettest such period since 1895. An analysis of Cooperative station precipitation data showed no homogeneous trends in precipitation thresholds for the stations analyzed, except for an upward increasing trend in precipitation at several locations during the autumn season.

## Sources


1 National Climatic Data Center. Data can be accessed at http://www.ncdc.noaa.gov/oa/ncdc.html

2 Guttman, N. B., & Quayle, R. G. (1995). A historical perspective of U.S. climate divisions. *Bulletin of the American Meteorological Society,* 77, 2, 293-303.

3 Keim, B. D., Wilson, A. M., Wake, C. M., & Huntington, T. G. (2003). Are there spurious temperature trends in the United States Climate Division database? *Geophysical Research Letters,* 30, 7, 1404, doi:10.1029/2002GL016295.

4 Keim, B. D., Fischer, M. R., & Wilson, A. M. (2005). Are there spurious precipitation trends in the United States Climate Division database? *Geophysical Research Letters,* 32, L04702, doi:10.1029/2004GL021895.

5 See endnotes 3 and 4.

6 Wilks, D. S. (1995). *Statistical methods in the atmospheric sciences.* San Diego, CA: Academic Press, 465 pp.

7 NCDC. (1994). Time bias corrected divisional temperature-precipitation-drought index. Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733. 12 pp.

8 Guttman, N. B., & R. G. Quayle. (1995). A historical perspective of U.S. climate divisions. *Bulletin of the American Meteorological Society,* 77, 2, 293-303.

9 NCDC. (1994). Time bias corrected divisional temperature-precipitation-drought index. Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733. 12 pp.

10 Guttman, N. B., & Quayle, R. G. (1995). A historical perspective of U.S. climate divisions. *Bulletin of the American Meteorological Society,* 77, 2, 293-303.

# Chapter 3

# Comparing Observed and Modeled Historic Data

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## 3.1. Can Global Climate Models Reproduce Observed Historical Trends?

*To assess the robustness of the global climate models used to generate projections of future climate, we compared modeled and observed historical trends from 1960 to 2011. Both models and observations show significant positive (warming) trends in all minimum temperature and most maximum temperature indicators. Models and observations also agree that there are few to no consistent trends in precipitation-related indicators. For minimum temperature and a few maximum temperature indicators, modeled trends tend to slightly underestimate observed warming, while for other maximum temperature indicators, modeled trends tend to slightly overestimate observed warming. Considering*

### Key Terms and Definitions

**Global climate models (GCMs)** – Complex, three-dimensional models that incorporate all the primary components of the earth's climate system, including atmospheric and ocean dynamics. Earlier versions that only modeled the atmosphere and ocean were known as general circulation models. *(See detailed description in Appendix.)*

**Climate projections** – A description of the future climate conditions based on global climate model simulations driven by a range of scenarios describing future emissions from human activities. A climate projection is usually a statement about the likelihood that something will happen over climate time scales (i.e., several decades to centuries in the future) if a given emissions or forcing pathway is followed. In contrast to a prediction (such as a weather prediction), a projection specifically allows for significant changes in the set of boundary conditions, such as an increase in greenhouse gases, which might influence the future climate. As a result, what emerge are conditional expectations (if X happens, then Y is what is expected).

**Observations** – Data collected from weather stations, usually daily, using measurement instruments. Data usually consists of temperature and precipitation, but weather stations may also collect data on humidity, wind speed, and other conditions.

**Climate indicators** – Represent the state of a given environmental condition over a certain area and a specified period of time, such as the mean annual temperature in Delaware for the period 1895-2011 or 2020-2039.

**Temperature** – Air temperatures over land surface, typically recorded at a height of 2 meters, in degrees Fahrenheit as ˚F.

**Precipitation** – Includes rain and snow, typically recorded as cumulative amount over a given time period ranging from a day to a year, in inches.

**Temperature and precipitation extremes** – Extremes can be measured using fixed thresholds (e.g., days per year over 100˚F) or using percentiles (e.g., number of days colder than the coldest 1% of days).

*that global models are expected to be accurate only over geographic regions far larger than the state of Delaware, the correspondence between model and observed historical trends is notable. This comparison establishes the basis for confidence in the use of these models to generate future projections.*

We compared model-simulated trends with observed data for 1960 through 2011, a period when information is available from both sources. We used observed data from the four highest-quality long-term weather stations and compared them with statistically downscaled simulations from global climate models for those same four stations. The stations used in the comparison run from north to south through the state: Wilmington Porter Reservoir, Wilmington New Castle County Airport, Dover, and Lewes. These sites were chosen because of the quality and quantity of observed data during the historical period.

Trends in 17 temperature and 11 precipitation variables were calculated independently from the model simulations and observations at each station (**Table 3.1**). The Mann-Kendall trend test was used to measure the direction and strength of the trend. Results were averaged across all four stations used in the analysis if at least two of the stations had a statistically significant trend above the 90% confidence level. If only one or no stations had a significant trend, then the mean trend value was set to zero, so only trends that were regionally consistent across the state were compared.

For the following tables (**Tables 3.2, 3.3**, and **3.4**), the numbers result from the Mann-Kendall trend test, which ranges from -1 for a very negative trend to 0 for no trend to +1 for a very positive trend. Only trends that are significant at the 90% level or higher ($p<0.10$) are shown. The color shading represents the magnitude of the trends: darker for larger trends, lighter for smaller ones.

For **maximum temperature** (**Table 3.2**), modeled trend values matched observed trends quite well. The mean trend from all models is very similar to the mean trend from the four stations used in the analysis for most variables. Both the observations and the multi-model averages show an upward trend in the majority of maximum temperature indicators. The multi-model mean better replicates some trends than others. For example, modeled trends for summer and autumn temperature and for annual numbers of days above 90°F are generally greater than observed. In contrast, modeled trends for winter and for 5-day maximum temperature are not significant, while observed trends are. Also, certain models better replicate observed

**Table 3.1.** Climate indicators used in the analysis for each station for the period 1960-2011

| *Maximum Temperature (abbreviation used in Tables 3.2-3.4)* | *Minimum Temperature* | *Precipitation* |
|---|---|---|
| Mean Annual (ann) | Mean Annual | Annual |
| Mean Winter (djf, [Dec.-Jan.-Feb.]) | Mean Winter | Winter |
| Mean Spring (mam, [March-April-May]) | Mean Spring | Spring |
| Mean Summer (jja, [June, July, Aug.]) | Mean Summer | Summer |
| Mean Autumn (son, [Sept., Oct., Nov.]) | Mean Autumn | Autumn |
| # Days > 90°F (90d) | # Days < 32°F | Days > 2” (2in) |
| # Days > 100°F (100d) | Coldest Day of the Year (1dx) | Days > 3” (3in) |
| Hottest Day of the Year (1dx) | Coldest 5 Consecutive Days (5dx) | Wettest Day of the Year (1dx) |
| Hottest 5 Consecutive Days (5dx) | | Wettest 5-day Period (5dx) |
| | | Precipitation Intensity (int) |
| | | # of Dry Days (dry) |

trends than others. For example, the CCSM4 and IPSL-CM5A models tend to over-estimate observed maximum temperature trends, while the CNRM-CM5, HadGEM2 and INMCM4 models tend to under-estimate the trends. These differences illustrate why it is important to rely on simulations from multiple climate models. In general, however, the sign and magnitude of observed and multi-model average trends match quite closely.

For **minimum temperature** (**Table 3.3**), the mean of all models (ALLMOD) corresponds closely to the mean of the station observations (OBS) in both sign and magnitude. Here, most model trends are smaller than observed. However, both observations and the multi-model averages show significant trends in every indicator, indicating rising minimum temperatures. It is important to note that both observed and modeled trends in minimum temperature are greater than observed and modeled trends in maximum temperatures, suggesting that the models are able to reproduce the observed asymmetry in recent warming.

For **precipitation** (**Table 3.4**), neither observations nor models show consistent trends for any of the 11 precipitation variables examined. Observations indicate very weak upward trends for annual precipitation, 5-day maximum precipitation, and precipitation amounts greater than 3 inches, and a weak decreasing trend in the number of dry days. One model (MIROC5) shows similar increases in annual precipitation, 5-day maximum precipitation, and precipitation amounts greater than 3 inches. The remaining models have few significant trends. Given the weakness and inconsistency of observed trends, model results correspond well with observations in showing little to no appreciable changes in precipitation-related variables during the analysis period.

In summary, both models and observations show trends toward warmer conditions in the maximum and minimum temperature indicators examined. Both modeled and observed trends are stronger for minimum temperature than for maximum. Multi-model ensemble averages tend to correspond well with observations. While most individual

**Table 3.2.** This table compares observed and modeled trends in **maximum temperature** indicators. The first column lists the indicator (see **Table 3.1** for full names). The second column shows the four-station mean observed trends (OBS). The third column shows the four-station mean of all models (ALLMOD), while the remaining columns show the individual values for each model.

| TMAX | OBS | ALLMOD | CCSM4 | CSIRO | CNRM-CM5 | HadGEM2 | INMCM4 | IPSL-CM5A | MIROC5 | MRI-CGCM3 | MPI-ESM-LR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ann | 0.36 | 0.38 | 0.47 | 0.29 | | | | 0.45 | 0.39 | 0.28 | 0.39 |
| djf | 0.24 | | 0.19 | | | | | | | | 0.25 |
| mam | 0.24 | 0.26 | 0.28 | 0.33 | | | | 0.18 | 0.22 | 0.26 | 0.30 |
| jja | 0.28 | 0.38 | 0.50 | 0.21 | | | | 0.53 | 0.36 | 0.29 | 0.37 |
| son | | 0.35 | 0.42 | | 0.25 | | | 0.48 | 0.32 | | 0.27 |
| 90d | 0.24 | 0.39 | 0.46 | | | | | 0.51 | 0.34 | | 0.25 |
| 100d | | | 0.29 | | | | | 0.30 | | | |
| 1dx | 0.24 | 0.27 | 0.33 | | | | | 0.38 | 0.19 | | 0.19 |
| 5dx | 0.23 | | 0.31 | | | | | 0.43 | | | |

**Table 3.3.** This table compares observed and modeled trends in **minimum temperature** indicators. The first column lists the indicator (see **Table 3.1** for full names). The second column shows the four-station mean observed trends (OBS). The third column shows the four-station mean of all models (ALLMOD), while the remaining columns show the individual values for each model.

| TMIN | OBS | ALLMOD | CCSM4 | CSIRO | CNRM-CM5 | HadGEM2 | INMCM4 | IPSL-CM5A | MIROC5 | MRI-CGCM3 | MPI-ESM-LR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ann | 0.57 | 0.36 | 0.46 | 0.31 | 0.24 | 0.30 | 0.26 | 0.50 | 0.41 | 0.34 | 0.45 |
| djf | 0.31 | 0.21 | 0.19 | | | | | | | 0.16 | 0.28 |
| mam | 0.39 | 0.26 | 0.22 | 0.37 | | | | 0.17 | 0.16 | 0.28 | 0.35 |
| jja | 0.51 | 0.34 | 0.42 | 0.33 | 0.22 | 0.18 | 0.19 | 0.54 | 0.41 | 0.34 | 0.48 |
| son | 0.36 | 0.34 | 0.33 | 0.21 | 0.35 | 0.26 | | 0.48 | 0.41 | | 0.32 |
| 32d | -0.43 | -0.25 | -0.24 | -0.21 | | | -0.27 | -0.22 | | -0.27 | -0.33 |
| 1dx | 0.28 | 0.22 | | | 0.16 | | | | | 0.18 | 0.33 |
| 5dx | 0.25 | 0.20 | | | | 0.21 | | | 0.17 | | 0.21 |

**Table 3.4.** This table compares observed and modeled trends in **precipitation** indicators. The first column lists the indicator (see **Table 3.1** for full names). The second column shows the four-station mean observed trends (OBS). The third column shows the four-station mean of all models (ALLMOD), while the remaining columns show the individual values for each model.

| PR | OBS | ALLMOD | CCSM4 | CSIRO | CNRM-CM5 | HadGEM2 | INMCM4 | IPSL-CM5A | MIROC5 | MRI-CGCM3 | MPI-ESM-LR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ann | 0.22 | | | | | | | | 0.17 | | |
| djf | | | | | | | | | | | |
| mam | | | | | | | | | | | |
| jja | | | | | | | | | | | |
| son | | | | | | | | | | | |
| dry | -0.21 | | | | | | | | | | |
| 2in | | | | | | -0.18 | | | | | |
| 1dx | | | -0.21 | | | | | | | | |
| int | | | | | | | | 0.19 | 0.20 | | |
| 5dx | 0.18 | -0.07 | -0.22 | | | -0.21 | | | 0.20 | | |
| 3in | 0.18 | | | | | | | | 0.22 | | |

model trends are consistent with the observed, some are typically greater or less than observed for maximum and minimum temperature variables. Neither observations nor models show a consistent and robust signal in any of the precipitation indicators that were assessed. Thus, the models were consistent with the observations in showing little if any significant changes in precipitation during the period of analysis.

# Chapter 4
# Delaware Climate Projections


## ***Authors:*** *Dr. Katharine Hayhoe, Dr. Anne Stoner, and Dr. Rodica Gelca, ATMOS Research & Consulting*


## Summary


This chapter of the Climate Change Impact Assessment documents projected future changes in temperature- and precipitation-related climate indicators for the state of Delaware. The chapter provides a summary of the data and methods used for this analysis and a detailed discussion of the findings. The findings include projections for average annual and seasonal temperature and temperature extremes; seasonal precipitation, drought, and heavy precipitation; and indicators that combine temperature, precipitation, and/or humidity.

Future projections were developed for two very different types of scenarios, to span a range of possible changes over the coming century. A ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide and other greenhouse (heat-trapping) gases that are causing climate to change so quickly. A ***higher scenario*** represents a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow.

Future projections are based on simulations from nine CMIP5 global climate models and four CMIP3 global climate models.[a] Most of the projections dicussed here are based on the more recent CMIP5 simulations, unless there are important differences between what is simulated by the older CMIP3 versus the newer CMIP5 models.

Data from 14 long-term weather stations in the region are used in this analysis: Bear, Bridgeville, Dover, Dover AFB, Georgetown, Georgetown Sussex Airport, Greenwood, Lewes, Middletown, Milford, Newark University Farm, Selbyville, Wilmington Porter Reservoir, and Wilmington New Castle County (NCC) Airport. Statistical downscaling of global model projections to each of the 14 weather stations was performed using the Asynchronous Regional Regression Model.

Over the coming century, climate change is expected to affect Delaware by increasing **average** and **seasonal temperatures**.

- By near-century (2020-2039), annual average temperature increases of 1.5 to 2.5°F are projected, regardless of scenario.
- By mid-century (2040-2059), annual average temperature increases under the lower scenario range from 2.5 to 4°F and around 4.5°F for the higher scenario.
- By late-century (2080-2099), annual average temperature is projected to change by nearly twice as much under the higher as compared to 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.
- The range of spring temperature (between daytime maximum and nighttime minimum temperature) is projected to increase, while the range in fall temperature is projected to decrease.
- The growing season is projected to lengthen, with slightly greater changes in the date of last spring frost as compared to first fall frost.


[a] CMIP3 and CMIP5 are two groups of global climate models developed by the Coupled Model Intercomparison Project (CMIP).

**Temperature extremes** are also projected to change. The greatest changes are seen at the tails of the distribution, 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 greater than changes under the lower scenario.

- The number of very cold days (below 20°F), which historically occur 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.

## Key Terms and Definitions

**Climate indicators** – Represent the state of a given environmental condition over a certain area and a specified period of time, such as the mean annual temperature in Delaware for the period 1895-2011 or 2020-2039.

**Climate projections** – A description of the future climate conditions based on global climate model simulations driven by a range of scenarios describing future emissions from human activities. A climate projection is usually a statement about the likelihood that something will happen over climate time scales (i.e., several decades to centuries in the future) if a given emissions or forcing pathway is followed. In contrast to a prediction (such as a weather prediction), a projection specifically allows for significant changes in the set of boundary conditions, such as an increase in greenhouse gases, which might influence the future climate. As a result, what emerge are conditional expectations (if X happens, then Y is what is expected).

**Higher and lower scenarios** – Scenarios are used to describe a range of possible futures. Studies of future climate projections are often based on two or more possible future scenarios. In this analysis, the lower scenario represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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.

**Observations** – Data collected from weather stations, usually daily, using measurement instruments. Data usually consists of temperature and precipitation, but weather stations may also collect data on humidity, wind speed, and other conditions.

**Global climate models (GCMs)** – Complex, three-dimensional models that incorporate all the primary components of the earth's climate system, including atmospheric and ocean dynamics. Earlier versions that only modeled the atmosphere and ocean were known as general circulation models. *(See detailed description in Appendix.)*

**CMIP3 and CMIP5** – Two groups of global climate model simulations archived by the Coupled Model Intercomparison Project (CMIP). CMIP3 simulations were used in the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). The more recent CMIP5 simulations are used in the Fifth Assessment Report of the IPCC. *(See detailed description in Appendix.)*

**Natural climate variability** – Variation in seasonal, year-to-year, and even multiyear cycles that can result in wetter or drier, hotter or cooler periods than "average" weather measurements. Most natural climate variability occurs over time scales shorter than 20 to 30 years.

**Statistical downscaling** – A method used to combine higher resolution observations with global climate model simulations in to obtain local- to regional-scale climate projections. Statistical downscaling models capture historical relationships between large-scale weather features and local climate. *(See detailed description in Appendix.)*

**Multi-model or scientific uncertainty** – Different models in a climate analysis may yield different results. In this report, the range of results, or outputs, from multiple models is expressed in the black "whiskers" (error bars) shown on the bar graphs, while the colored bar represents the multi-model mean. *(See detailed description in Appendix.)*

**Standard deviation of temperature** – Assesses the day-to-day variability in daily maximum and minimum temperatures.

**Temperature** – Air temperatures over land surface, typically recorded at a height of 2 meters, in degrees Fahrenheit as ˚F.

- The number of very hot days (over 100°F), which historically occur 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 by 3 and 10 days per year under the lower and 15 to 30 days per year under the higher scenario by 2080-2099.
- Heat waves are projected to become longer and more frequent, particularly under the higher as compared to lower scenario and by later compared to earlier time periods. For example, heat waves with at least 4 consecutive days warmer than the 1-in-10 historical average are expected to occur on average between 1 to 3 times per year by 2040-2059,

**Precipitation** – Includes rain and snow, typically recorded as cumulative amount over a given time period ranging from a day to a year, in inches.

**Temperature and precipitation extremes** – Extremes can be measured using fixed thresholds (e.g., days per year over 100˚F) or using percentiles (e.g., number of days colder than the coldest 1% of days).

**Maximum temperature** – The highest temperature value in a given time period (daily, seasonal, or annual). Unless otherwise stated, all daily maximum temperatures in this report refer to values recorded within a 24-hour period, usually (but not always) occurring in the afternoon (also described as daytime temperatures).

**Minimum temperature** – The lowest temperature value in a given time period (daily, seasonal, or annual). Unless otherwise stated, all daily minimum temperatures in this report refer to values recorded within a 24-hour period, usually occurring at night (also described as nighttime temperatures).

**Temperature range** – The range between highest and lowest temperature value in a given period (daily, seasonal, or annual).

**Heat wave events** – A period of prolonged, unusual heat. There is no single standard definition of a heat wave. Different measures can be used to assess the frequency and severity of heat events, such as the length of consecutive days with maximum daytime temperatures exceeding a specific threshold temperature (e.g., 90˚F, 95˚F, 100˚F). Another definition of an extreme heat wave is at least four consecutive days during which average temperatures (daytime plus nighttime temperatures) exceed the historical 1-in-10 year event.

**Growing season** – The “frost-free” period between the last frost in spring and the first frost in fall or winter, defined as the last and first time that nighttime minimum temperature falls below 32°F.

**Cooling degree-days and heating degree-days** – An indicator of energy demand for heating and cooling. This represents demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). Degree-days are typically calculated as the cumulative number of hours per year above (for cooling) or below (for heating) a given temperature threshold. For this analysis the threshold value is 65˚F.

**Precipitation intensity** – Total precipitation over a season or year, divided by the number of wet days (where wet days are defined as days with more than 0.01 inches of rain in 24 hours) that occurred in that same season or year. Higher values of precipitation intensity tend to suggest that, on average, precipitation may be heavier on any given wet day; lower values, that precipitation may be lighter on average.

**Annual dry days** – The number of days per year with no (or trace) precipitation (falling as either rain or snow).

**Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI)** – Measurements of drought with negative values indicating dry (drought) conditions and positive values indicating wet conditions.

**Dew point temperature** – The temperature to which the air must be cooled to condense the water vapor it contains into water.

**Relative humidity** – The percentage of water vapor actually present in the air compared to the greatest amount of water vapor the air could possibly hold at the same temperature.

**Heat index** – A measurement that combines temperature and humidity, which affects evaporation and cooling. Sometimes referred to as the “apparent temperature”, the Heat Index is a measure of how hot it really feels to the human body.

and an average of 3 times per year under a lower and 10 times per year under the higher scenario by 2080-2099.

- Daytime summer heat index (a measure of how hot it feels, based on maximum temperature and average humidity) is projected to increase by approximately twice as much as projected changes in maximum temperature alone, due to the nonlinear relationship between heat index, temperature, and humidity.

**Average precipitation** is projected to increase an estimated 10 percent by late-century, consistent with projected increases in mid-latitude precipitation in general. CMIP3 and CMIP5 models do not show the same seasonality: CMIP3 shows increases in winter, spring, and summer, while CMIP5 simulations show increases primarily in winter alone.

**Rainfall extremes** are also projected to increase. By late-century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events. This increase is consistent over a very broad range of definitions of "heavy precipitation": accumulations ranging from 0.5 to 8 inches over anywhere from 1 day to 2 weeks.

All simulations show large increases in potential evapotranspiration and in the number of hot and dry days per year. Smaller to no significant changes are projected for relative humidity and for the number of cool and wet days per year.

There is *greatest certainty* in projected increases in annual and seasonal temperatures, high temperatures, increased evaporation, precipitation intensity, and the frequency of heavy precipitation, all of which show greater increases under the higher as compared to lower scenario and by late-century as compared to more near-term projections. There is *moderate certainty* in projected changes in cold temperatures and an increase in annual precipitation on the order of 10 to 20 percent. There is *less certainty* in projected changes in seasonal precipitation, specifically which seasons are likely to see the greatest increases in precipitation and in moderate precipitation amounts (0.5 to 1 inch in 24 hours).

## List of Graphs for Temperature and Precipitation Indicators

Future projections are summarized for three future time periods, relative to a historical baseline of 1981-2010: near-century (2020-2039), mid-century (2040-2059) and late-century (2080-2099). The results are discussed in the following sections. A complete list of graphs for all indicators can be found in the Appendix.

### TEMPERATURE

### Annual and Seasonal

- Maximum temperature
- Minimum temperature
- Average temperature
- Temperature range (average maximum minus average minimum)
- Standard deviation of maximum and minimum temperature

### Extremes

- Cold nights: days per year with minimum temperature below 20°F and 32°F or below the 1st and 5th percentile of the historical distribution
- Hot days: days per year with maximum temperature above 90, 95, 100, 105, and 110°F or above the 95th and 99th percentile of the historical distribution
- Warm nights: days per year with minimum temperature above 80, 85, and 90°F
- Number of heat wave events lasting 4 or more days (as defined by Kunkel et al., 1999[1])
- Longest stretch of days with maximum temperature over 90, 95, and 100°F

### Other

- Date of last frost in spring and first frost in fall
- Length of frost-free growing season
- Annual cooling degree-days
- Annual heating degree-days

## PRECIPITATION

### Annual and Seasonal

- Seasonal and annual cumulative precipitation
- Cumulative precipitation for 3-, 6-, and 12-month running means, beginning in each month of the year

### Extremes

- Precipitation intensity: annual precipitation divided by the number of wet days per year
- Heavy precipitation days: days per year with cumulative precipitation exceeding 0.5, 1, 2, 3, 4, 5, 6, 7, and 8 inches in 24 hours
- Extreme events: amount of precipitation falling in the wettest 1, 5, and 14 days in 1, 2, and 10 years
- Number of future events exceeding the historical wettest 2, 4, and 7 days

### Other

- Total number of dry days each year (precipitation < 0.01 inches)
- Longest dry period
- Standardized Precipitation Index (a measure of wetness and drought)

## HUMIDITY and HYBRID INDICATORS

### Annual and Seasonal

- Dew point temperature
- Relative humidity
- Summer heat index

### Other

- Percentage of precipitation falling as rain versus snow
- Number of hot and dry days per year (precipitation < 0.01" and maximum temperature > 90°F)
- Number of cool and wet days per year (precipitation > 0.01" and maximum temperature < 65°F)

# 4.1. Background

Since the Industrial Revolution, atmospheric levels of heat-trapping gases such as carbon dioxide ($CO_2$) and methane ($CH_4$) have been rising due to emissions from human activities. The main source of heat-trapping gases is the combustion of fossil fuels such as coal, oil, and natural gas.[2, 3] Other activities, such as agriculture, wastewater treatment, and extraction and processing of fossil fuels, also produce carbon dioxide, methane, nitrous oxide, and other gases.[4]

$CO_2$ and other heat-trapping gases exist naturally in the atmosphere. However, artificially increasing the amounts of these gases in the atmosphere affects the energy balance of the planet. As levels increase, more of the heat given off by the earth that would otherwise escape to space is trapped within the earth's climate system. This extra heat increases the temperature and the heat content of the atmosphere, ocean, and land surface.

Over short timescales, of years to more than a decade, natural variability has a strong effect on global and regional temperatures. Some patterns of natural variability increase the ocean's share of the heat uptake compared to the atmosphere's. Over the last 150 years, average surface temperatures in the Northern Hemisphere have risen by 1.5°F. At the global scale, each decade has successively been warmer than the decade before. The heat content of the ocean has increased by more than 20 times that of the atmosphere.[5, 6]

## 4.1.1. Observed and Projected Future Change

In the United States, average temperature has increased by 1.5°F over the last century, with most of the increase occurring in the last 30 years.[7] Warmer temperatures are driving many changes in average climate conditions in the United States and around the world. Observed changes highlighted by the Third U.S. National Climate Assessment include:

- More frequent heavy precipitation events, particularly in the Northeast and Midwest
- Increasing risk of heat waves, floods, droughts, and wildfire risk in some regions
- Decreases in Arctic sea ice, earlier snow melt, glacier retreat, and reduced lake ice
- Stronger hurricanes, rising sea level, and warming oceans
- Poleward shifts in many animal and plant species, as well as a longer growing season

In the past, climate variations were caused entirely by natural forces. These include changes in amount of energy the earth receives from the sun, natural cycles that exchange heat between the ocean and atmosphere, or the cooling effects of dust clouds from powerful volcanic eruptions, amplified by natural feedbacks within the earth-ocean-atmosphere system. Today, however, the climate is being altered by both natural and human causes.[8] Recent studies have concluded that human influence, specifically the increases in emissions of $CO_2$ and other heat-trapping gases from human activities, is responsible for most of the warming over the last 150 years, and as much as all of the warming over the last 60 years.[9,10,11]

Over the coming century, climate will likely continue to change in response to both past and future emissions of heat-trapping gases from human activities.[12] At the global scale, average temperature increases between 2°F and 9°F are expected by late-century, accompanied in many regions of the United States by increases in extreme heat and heavy precipitation events. These future projections are consistent with observed trends.[13, 14]

Future changes depend on heat-trapping gas emissions from human activities. For many impacts, higher emissions are expected to result in greater amounts of change; lower emissions, in comparatively smaller amounts of change. The 2011 U.S. National Research Council report "Climate Stabilization Targets" quantified many of the impacts that would be expected to increase per degree of global warming. For example, each degree-Celsius (almost 2°F) increase in global temperature might be expected to:

- Shift the amount of precipitation that falls in many regions around the world by 5 to 10 percent
- Increase the amount of rain falling during heavy precipitation events by 3 to 10 percent
- Shift the amount of streamflow and runoff in river basins by 5 to 10 percent (with increases in the northeastern United States and decreases in the southwestern United States)
- Shrink annual average Arctic sea ice area by 15 percent (by 25 percent, for the September minimum)
- Reduce yields of common crops, including wheat and maize, by 5 to 15 percent worldwide
- Increase the area burned by wildfire in the western United States by 200 to 400 percent

## 4.1.2. Implications for Delaware

Delaware's climate – together with that of the rest of the United States – is already changing. What might the future hold?

Future climate depends on the impact of human activities on climate, and the sensitivity of climate to those emissions. This report describes projected changes in Delaware's climate under two possible scenarios: a higher scenario in which fossil fuels continue to provide most of humankind's energy needs, and a lower scenario in which global carbon emissions peak within a few decades, then begin to decline.

Future projections are based on simulations from two groups of global climate models: the older models used in the 2007 Northeast Climate Impacts Assessment, and the newer set of models used in the upcoming Third U.S. National Climate Assessment.

Global model projections were translated down to the local scale using a statistical downscaling model. This model relates modeled variability and changes in large-scale climate to observed conditions at 14 long-term weather stations in Delaware, then uses this relationship to estimate how the regional manifestations of global climate change might affect local conditions in the future.

Assessing the potential impacts of climate change on a given location is a challenging task. Future projections are uncertain, due to the difficulties in predicting human behavior; understanding the response of the earth's climate to heat-trapping gases produced by human activities; and predicting the variability of natural cycles within the earth system that have a strong influence on local climate.

Although challenging, it is important to assess climate impacts because the information generated can be valuable to long-term planning or policies. For example, projected changes in heating- or cooling degree-days can be incorporated into new building codes or energy policy. Shifts in the timing and availability of streamflow can be used to redistribute water allocations or as incentive for conservation programs. Projected changes in growing season and pest ranges can inform crop research and agricultural practices.

The information generated by this analysis, and summarized in this report, is intended to inform such studies for the state of Delaware and relevant sectors by providing state-of-the-art climate projections that can be incorporated into future planning.

## 4.2. Data and Methods

A detailed discussion of the methods and the assessment framework used for the climate projections analysis can be found in the Appendix. The detailed methodology section describes the specific data sets and methods used to assess projected changes in Delaware climate in response to human-induced global climate change. These datasets, models, and methods include future scenarios, global climate models, long-term station records, and a statistical downscaling model.

### 4.2.1. Global Climate Models

Global climate models (GCMs) are complex, three-dimensional models of the atmosphere, oceans, and earth's surface that are used to better understand historical climate as well as to study how future climate might change in response to human emissions of $CO_2$ and other heat-trapping gases. The climate projections produced by this analysis are based on simulations from four older CMIP3 models and nine newer CMIP5 models. All of the bar charts shown in this chapter show the all-model average (colored bar), as well as the range of values simulated by the different models (thin black lines, or whiskers). Unless otherwise indicated, the results shown in this report are based on the newer CMIP5 simulations only. (See Appendix for complete description of models used in this analysis.)

### 4.2.2. Statistical Downscaling Model

This project used the statistical Asynchronous Regional Regression Model. It was selected because it is able to resolve the tails of the distribution of daily temperature and precipitation to a greater extent than other more commonly used methods, but is less time-intensive and therefore able to generate more outputs as compared to a high-resolution regional climate model.

### 4.2.3. Station Observations

This project used long-term station data from the Global Historical Climatology Network and the National Climatic Data Center Co-op Observing Network, supplemented with additional station data provided by the Delaware State Climatologist. All station data was quality controlled to remove questionable data points before being used to train the statistical downscaling model. Projected future changes are consistent across all 14 stations; unless otherwise indicated, plotted values in this report correspond to the average value across the 14 stations (**Figure 4.1**).

To train the downscaling model, the observed record must be of adequate length and quality. After the quality control and filtering process was complete, there were 14 usable stations for Delaware for maximum and minimum temperature and precipitation.


**Figure 4.1.** This report generated future projections for 14 weather stations in Delaware with long-term historical records. Weather stations that did not have sufficiently long and/or complete observational records to provide an adequate sampling of observed climate variability at their locations were eliminated from this analysis.

### 4.2.4. Higher and Lower Scenarios

Future scenarios depend on a myriad of factors, including how human societies and economies will develop over the coming decades; what technological advances are expected; which energy sources will be used in the future to generate electricity, power transportation, and serve industry; and how all these choices will affect future emissions from human activities.

The Intergovernmental Panel on Climate Change (IPCC) has released two families of future scenarios: the 2000 Special Report on Emission Scenarios (SRES) and the 2010 Representative Concentration Pathways (RCP). In contrast to the SRES scenarios, RCPs are expressed in terms of $CO_2$ concentrations in the atmosphere, rather than direct emissions. This analysis uses the higher and lower scenarios from each family: RCP 8.5 (higher) and 4.5 (lower) concentration pathways and SRES A1fi (higher) and B1 (lower) emission scenarios.

- The higher scenario represents a world with fossil fuel-intensive economic growth. In these scenarios, emissions continue to increase and atmospheric $CO_2$ concentrations reach nearly 1,000 parts per million by 2100, more than triple preindustrial levels of 280 ppm.
- In the lower scenario, a shift to less fossil fuel-intensive industries and the introduction of clean and resource-efficient technologies cause emissions of greenhouse gases to peak around mid-century and then decline. Atmospheric $CO_2$ concentrations approximately double by 2100 compared to preindustrial levels.

In the near term, most projections do not show a great difference between the higher versus lower scenario. This is because the climate is currently responding to the greenhouses gases already in the atmosphere. By the second half of the century, however, there is a noticeable difference between projected changes for most climate indicators under a higher as compared to a lower scenario. The difference is due to the much greater concentrations of greenhouse gases if emissions continue to increase. The substantial difference between the higher and lower scenario used here provides a good illustration of the potential range of changes that could be expected over the coming century, and how much these depend on future emissions and human choices.

### 4.2.5. Uncertainty

Uncertainty in future climate change projections at the global to regional scale is primarily due to three different causes: (1) *natural variability* in the climate system, (2) *scientific uncertainty* in predicting the response of the earth's climate system to human-induced change, and (3) *scenario uncertainty* in predicting future energy choices and hence emissions of greenhouse gases from human activities.[15]

In the near term – over timescales of years to one or two decades – *natural variability* is the most important source of uncertainty. In developing climate projections, this uncertainty can be addressed by always averaging or otherwise sampling from the statistical distribution of future projections over a climatological period – here, 20 years.

By mid-century, *scientific uncertainty* is the largest contributor to the range in projected temperature and precipitation change. This can be addressed by using multiple global climate models that simulate the response of the climate system to human-induced change in slightly different ways. The climate models used in this analysis cover a range of climate sensitivity.

By the end of the century, *scenario uncertainty* is most important for temperature projections, while scientific (or model) uncertainty continues as the dominant source of uncertainty in precipitation. Scenario uncertainty can be addressed by comparing climate projections for multiple futures: for example, a "higher" future in which the world continues to depend on fossil fuels as the primary energy source (RCP 8.5), as compared to a "lower" future focusing on sustainability and conservation (RCP 4.5).

It is important to note that *scenario uncertainty* is very different, and entirely distinct, from *scientific uncertainty*. While scientific uncertainty can be reduced through coordinated observational programs and improved physical modeling, scenario uncertainty reflects our fundamental inability to predict future changes in human behavior. It can be reduced only by the passing of time, as societal choices can eliminate or render certain options less likely. In addition, scientific uncertainty is often characterized by a normal statistical distribution, in which a central value is more likely than the outliers. Scenario uncertainty, however, depends on societal choices for economic development, future technologies, and other factors that influence the rate of greenhouse gas emissions from human activity. Hence, scenario uncertainty cannot be considered to be a normal statistical distribution. Rather, the consequences of a lower versus a higher emissions scenario must be considered independently to isolate the role that human choices are likely to play in determining future impacts.

The Data, Models, and Methods section in the Appendix of the Assessment includes a more detailed discussion of types and sources of uncertainty and how they are addressed in climate modeling.

## 4.3. Temperature-Related Indicators

In the future, average temperature and temperature-related indicators across the state of Delaware are expected to increase. Year-to-year variations in temperature are primarily the result of natural variability, or what we often call "weather." Long-term changes, over timescales of 30 years or more, are expected to be primarily driven by increases in global temperature.

The magnitude and rate of global climate change depend on the amount of human emissions, as well as on the sensitivity of the earth's climate system to those emissions. Impacts on Delaware's climate due to global climate change will be modified by local factors, including topography (such as the proximity of the state to the ocean), small-scale feedback processes (such as changes in the type of vegetation that grows in Delaware as climate changes), and land use (including conversion of forests to suburbs, or fields to forests).

This chapter summarizes the changes in temperature and temperature-related secondary indicators that are projected to occur in response to global climate change. Projected changes are consistent across all 14 stations; unless otherwise indicated, plotted values correspond to the 14-station average, across the state.

Projections shown in figures and discussed in the text are averaged across all of the latest generation of CMIP5 climate models for individual scenarios: higher (RCP 8.5) and lower (RCP 4.5). All figures include the scientific uncertainty that results from using multiple climate models. For CMIP3 climate models (not shown here), scientific uncertainty was defined by the difference between the highest and lowest model projection for each scenario and time period. For CMIP5 climate models, because there are more of them, scientific uncertainty was defined by the standard deviation of the all-model ensemble unless the distribution was significantly non-normal, or skewed, in which case the highest or lowest model projection was used to define the range instead.

## 4.3.1. Annual and Seasonal Temperatures

In the future, **annual average temperature** is expected to continue to increase. Over the next few decades, projected temperature changes are expected to be similar regardless of the scenario followed over that time. There is no significant difference between temperature projections from different scenarios over the short term for two reasons. First, it takes some time for the climate system to respond to differences in emissions. Second, emissions among different scenarios are not very different over the short term. This is because of the lags in our socioeconomic and energy systems: installations of fossil fuel or renewable energy take years to design and build, and are typically used for decades. None of the scenarios considered here envision a world in which all fossil fuel use could be eliminated within a decade or two. For these two reasons, the majority of the changes that will happen over the next few decades are the result of heat-trapping gas emissions that have already built up in the atmosphere or are already entailed by our existing infrastructure.

By mid-century, temperature increases are greater under the higher scenario versus the lower, although the scientific uncertainty range (i.e., the temperature change projected by a given model) still overlaps (**Figure 4.2**). By late-century, the multi-model uncertainty range for the higher versus the lower scenario does not overlap: in other words, even the smallest projected change in temperature under the higher scenario is greater than the largest projected change under the lower scenario. Temperature increases are also greater for later time periods as compared to earlier ones. By 2020-2039, annual maximum (daytime) temperature is projected to increase by an average of 2 to 2.5°F and annual minimum (nighttime) temperature by an average of 1.5 to 2.5°F across all scenarios. By mid-century 2040-2059, increases under the lower scenario range from 2.5 to 4°F for maximum temperature and 2 to 3.5°F for minimum temperature. Under the higher scenario, increases average 4.5°F for both maximum and minimum temperature. By late-century 2080-2099, projected temperature changes are nearly twice as great under the higher as compared to lower scenario. Maximum temperature increases by 3.5 to 5.5°F under the lower and 8 to 9.5°F under the higher scenario. Minimum temperature increases by 3 to 5°F under the lower and 8.5 to 9.5°F under the higher scenario.

**Seasonal temperatures** are also projected to increase, sometimes at different rates than the annual average. In general, projected increases for spring and summer are greater than the increases

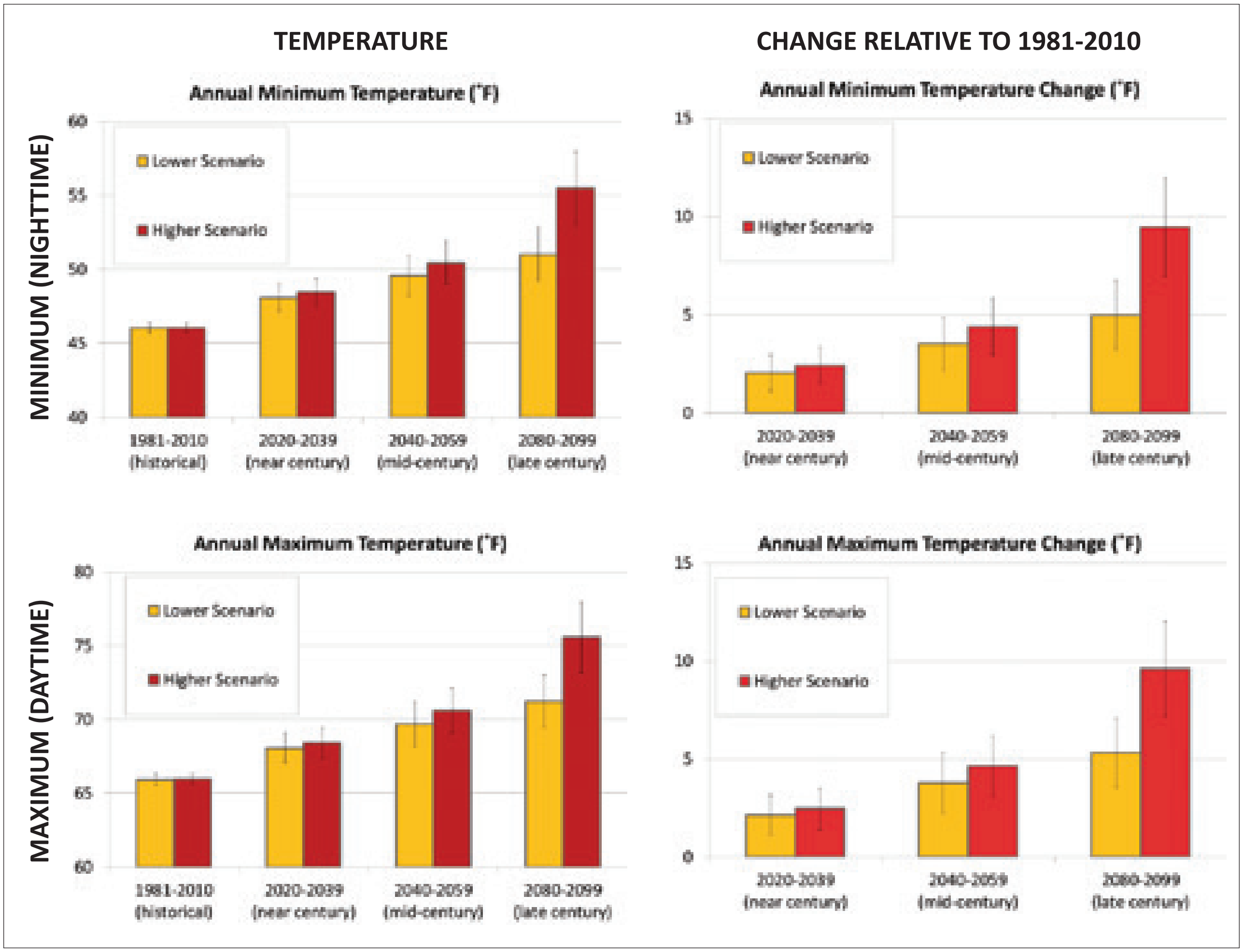


**Figure 4.2.** Projected absolute (left) and change in (right) **annual maximum (daytime) and minimum (nighttime) temperature** compared to 1981-2010 average values. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black "whiskers" indicate the range of scientific uncertainty that results from using multiple climate models.

projected for fall and winter (**Figure 4.3**). By late-century, for example, spring temperature is projected to increase by about 4 to 6°F under the lower and 7 to 11°F under the higher scenario, while summer temperature is projected to increase by 3.5 to 8°F under the lower and 7 to 15°F under the higher scenario. Fall and winter changes are projected to be smaller: 2 to 5°F under the lower and 6 to 10°F under the higher scenario in fall, and 3.5 to 4°F under the lower and 6.5 to 8°F under the higher scenario in winter.

For both seasonal and annual temperature, the increases simulated by CMIP5 models are generally higher than those simulated by CMIP3 models (not shown). This difference may be due to a greater number of models in CMIP5 as compared to CMIP3, and therefore a larger sample size of projected changes. It may also reflect different processes occurring within the models, because the CMIP5 models used in this analysis represent newer and more complex versions of CMIP3 models. Comparing simulations for seasonal temperature, it appears that the SRES A1fi and RCP 8.5 scenarios (both higher) are generally close, with RCP 8.5 (higher) being slightly higher than A1fi in all seasons. In contrast, the SRES B1 and RCP 4.5 (lower) scenarios are nearly identical in winter and spring, but extremely different in summer and fall. SRES B1 multi-model average projections and even the multi-model range are significantly smaller (by more than 3°F) than RCP 4.5 in summer and fall. This suggests that there may be different processes at work in driving summer and fall temperature change in the CMIP5 models compared to CMIP3.

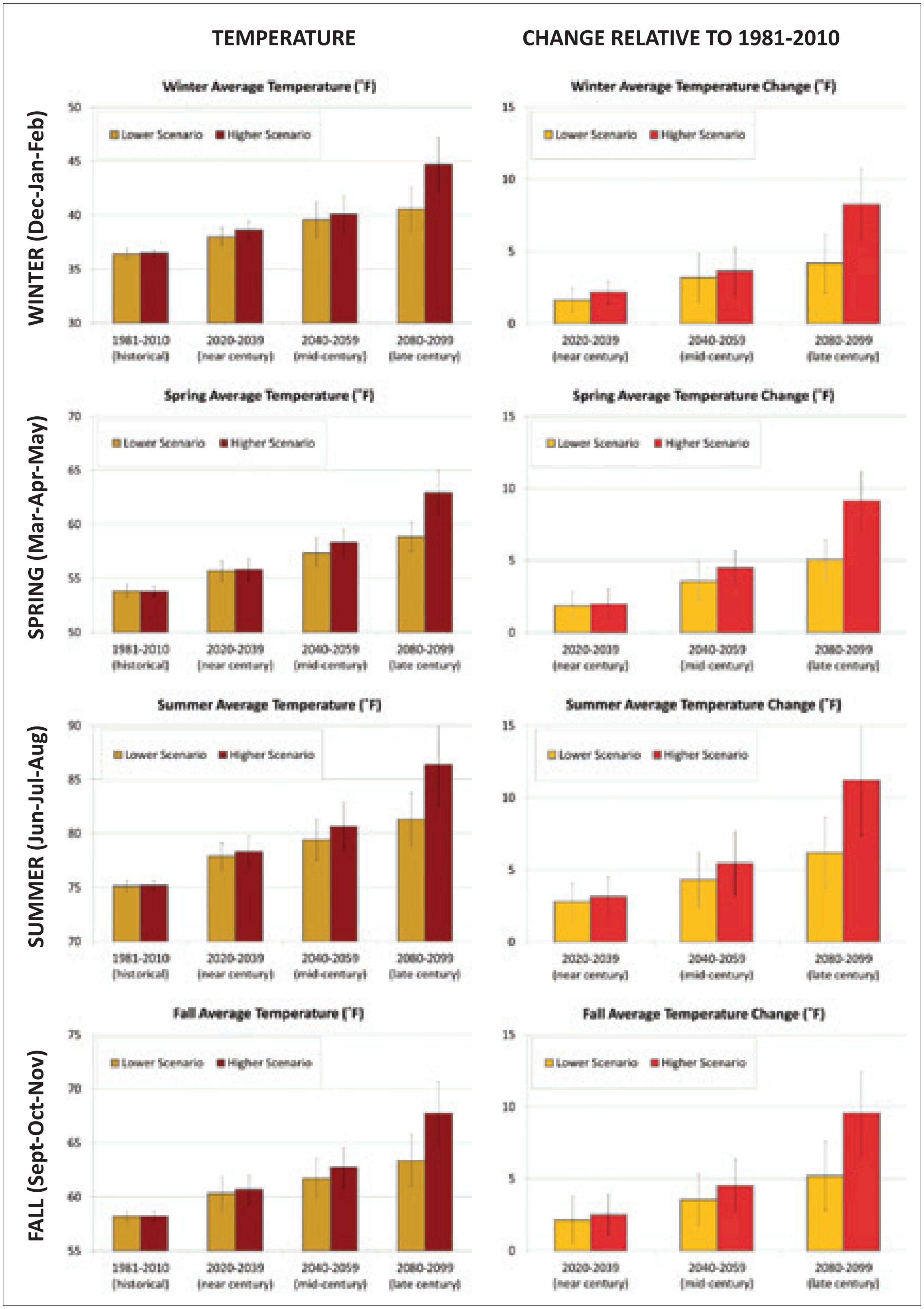


**Figure 4.3.** Projected absolute value (left) and increase (right) in **seasonal average temperature** compared to 1981-2010 for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sept-Oct-Nov). Greater changes are projected for spring and summer as compared to winter and fall. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the range of scientific uncertainty from multiple climate models.

Historical temperature range is smallest for winter (averaging around 17°F) and largest for spring (around 21°F). The **range of temperature** (the difference between the average maximum and minimum temperature for the season) may be changing in spring and fall, but not in winter or summer. For example, increases in minimum temperature tend to be smaller by about 1°F in spring and fall as compared to projected increases in maximum temperature for those seasons (not shown). For winter and summer, changes in maximum and minimum temperature are similar.

**Figure 4.4** shows the historical and projected future range in temperature for each season. The largest and most significant change is in spring, where all models project a consistent increase in the range of temperature. Projected changes for winter and summer are inconsistent, with some models projecting an increase and others, a decrease. For fall, models project either no change or a decrease in temperature range. Projected changes in annual temperature range are negligible (not shown).

The **standard deviation of temperature** is a different type of measure; it assesses the day-to-day variability in maximum and minimum temperatures. Historically, the standard deviation of daytime maximum temperature, averaged across the 14 Delaware weather stations, is almost 18°F, while the standard deviation of nighttime temperature is slightly lower, almost 17°F. In the future, the standard deviation of temperature is projected to change slightly: for maximum temperature, an increase

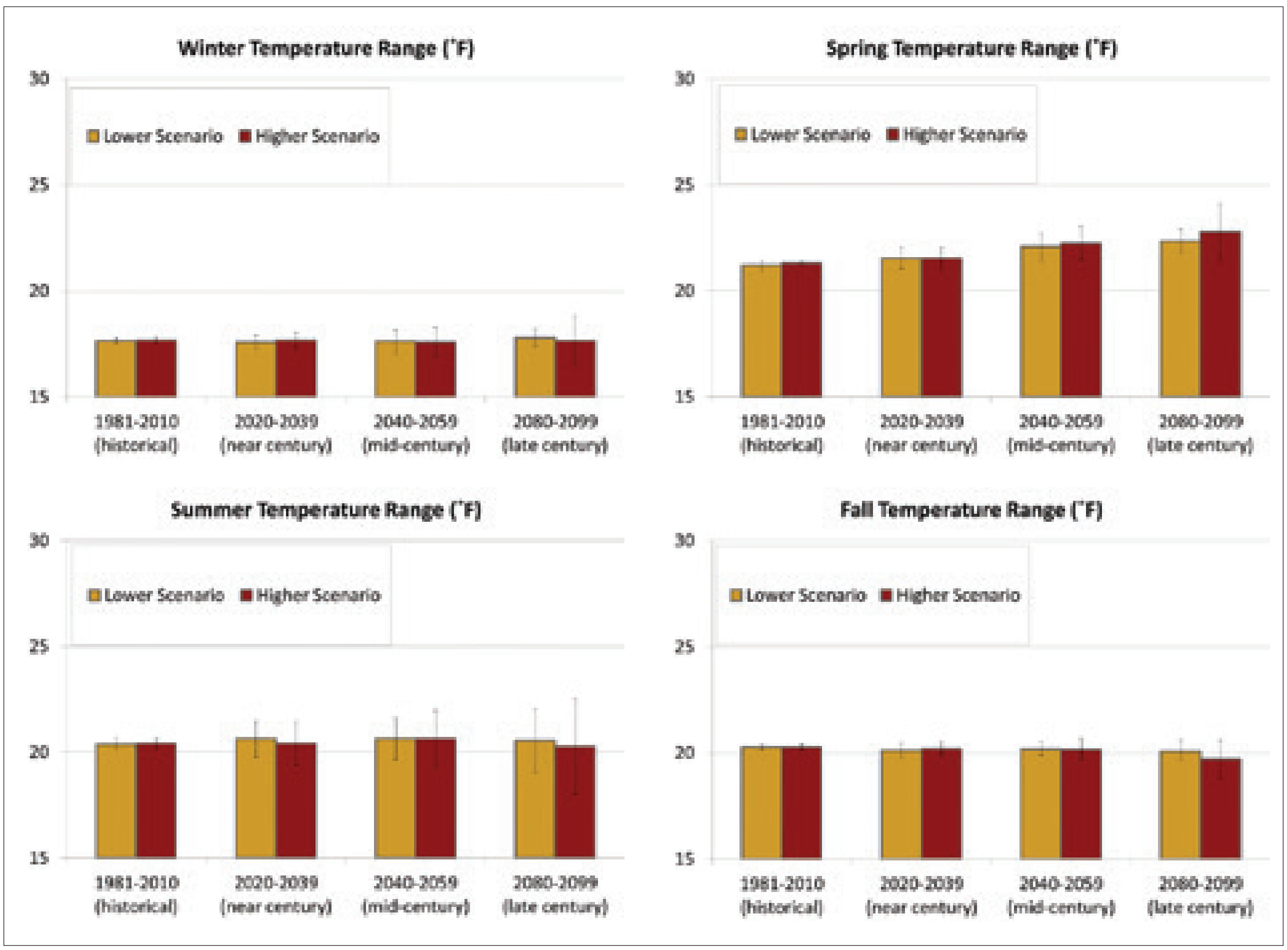


**Figure 4.4.** Historical modeled and projected future **temperature range (maximum - minimum temperature)** for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sept-Oct-Nov). Increases in the range are projected in spring, and decreases in fall. No change is projected in winter and summer, nor annually. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the range of scientific uncertainty from multiple climate models.

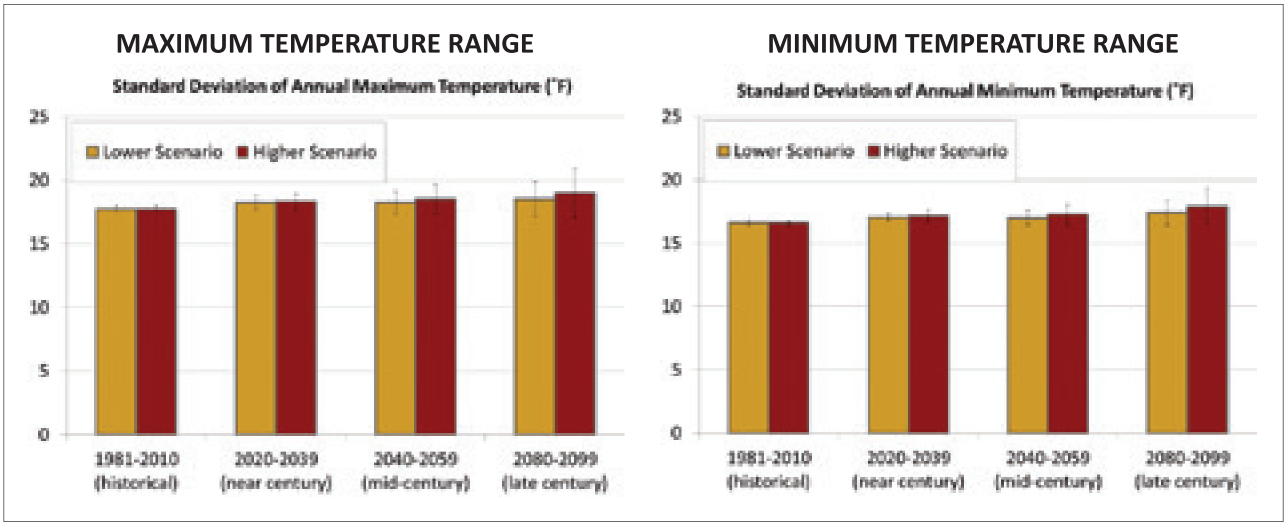


**Figure 4.5.** Historical and projected future **variability in day-to-day** annual maximum (daytime) and minimum (nighttime) temperature, **measured as the standard deviation** of daily values for each time period, in degrees F. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black "whiskers" indicate the scientific uncertainty that results from using multiple climate models.

of around 0.5°F under the lower scenario and 1°F under the higher scenario and for minimum temperature an increase of around 0.5°F under the lower scenario and 1.5°F under the higher scenario for the multi-model mean (**Figure 4.5**). Individual models do not necessarily agree: although the mean shows an increase, some models project no change or even a slight decrease. On average, this means that future climate change may increase the range in day-to-day temperatures as compared to the historical average, but this increase is not certain.

## 4.3.2. Temperature Extremes

As average maximum and minimum temperatures increase, extreme heat is also expected to become more frequent and more severe. Extreme cold is expected to become less frequent. What is viewed as "extreme" is often location-specific: while a 32°F or 90°F day may be extreme for one place, it may be normal for another. For that reason, a broad range of temperature extremes and thresholds were calculated: some using fixed thresholds (e.g., days per year over 100°F or below 32°F) and others using percentiles (e.g., future days per year colder than the coldest 1 percent of days, or warmer than the warmest 5 percent of days).

Beginning with percentiles, the temperature of the historical 1-in-100 (1 percent) and 1-in-20 (5 percent) coldest nights of the year currently averages around 18 to 19°F and 27 to 28°F, respectively. As average temperatures increase, the frequency of 1-in-20 coldest nights is projected to decrease from the historical average of 5 percent to 4 percent by 2020-2039, 3 percent by mid-century, and ultimately 2 percent by late-century, with slightly greater changes by late-century under the higher as compared to lower scenario (**Figure 4.6**, left). Little significant change is expected in 1-in-100 coldest nights, however. There is some indication of a small decrease in frequency, but it is not significant.

In terms of high temperatures, the temperature of the historical 1-in-20 (95 percent) and 1-in-100 (99 percent) hottest days averages around 80°F and 84-85°F, respectively. The frequency of 1-in-20 hottest days, currently 5 percent, is projected to increase to 7 to 11 percent by 2020-2039, 10 to 15 percent by mid-century, and around 15 percent under the lower scenario and more than 25 percent under the higher scenario by late-century (**Figure 4.6**, right). The frequency of the 1-in-100 hottest day, currently 1 percent, is projected to increase proportionally more to around 3 percent near-term, 6 percent by mid-century, and 5 to 10 percent under the lower scenario and almost 20 percent under the higher scenario by late-century. In other words, the very coldest nights will still occur, but very hot days will become much more frequent, particularly the 1-in-100 hottest day, which could become as much as 20 times more frequent under the higher scenario by 2080-2099. This is consistent with an increase in the standard deviation of both maximum and minimum temperature discussed previously.

The two **cold temperature** thresholds examined here are the number of times per year when minimum (nighttime) temperatures fall below 20°F and below freezing, or 32°F. Historically, there are typically around 20 nights per year below 20°F and 85 nights per year below freezing (**Figure 4.7**). In the future the number of times minimum temperature falls below 20°F is projected to drop by 5 days to an average of 15 by 2020-2039, by almost 5 more to an average of just over 10 times per year by 2040-2059, and to a minimum of 10 times per year under the lower scenario and only 3 to 4 times per year under the higher scenario by 2080-2099. In general, much larger changes in nights below 20°F are projected under the CMIP5 lower scenario (RCP 4.5) as compared to the CMIP3 lower scenario (B1), while projected changes under the two higher scenarios (RCP 8.5 and SRES A1fi) are similar.

The number of times minimum temperature drops below freezing is also expected to decrease: by

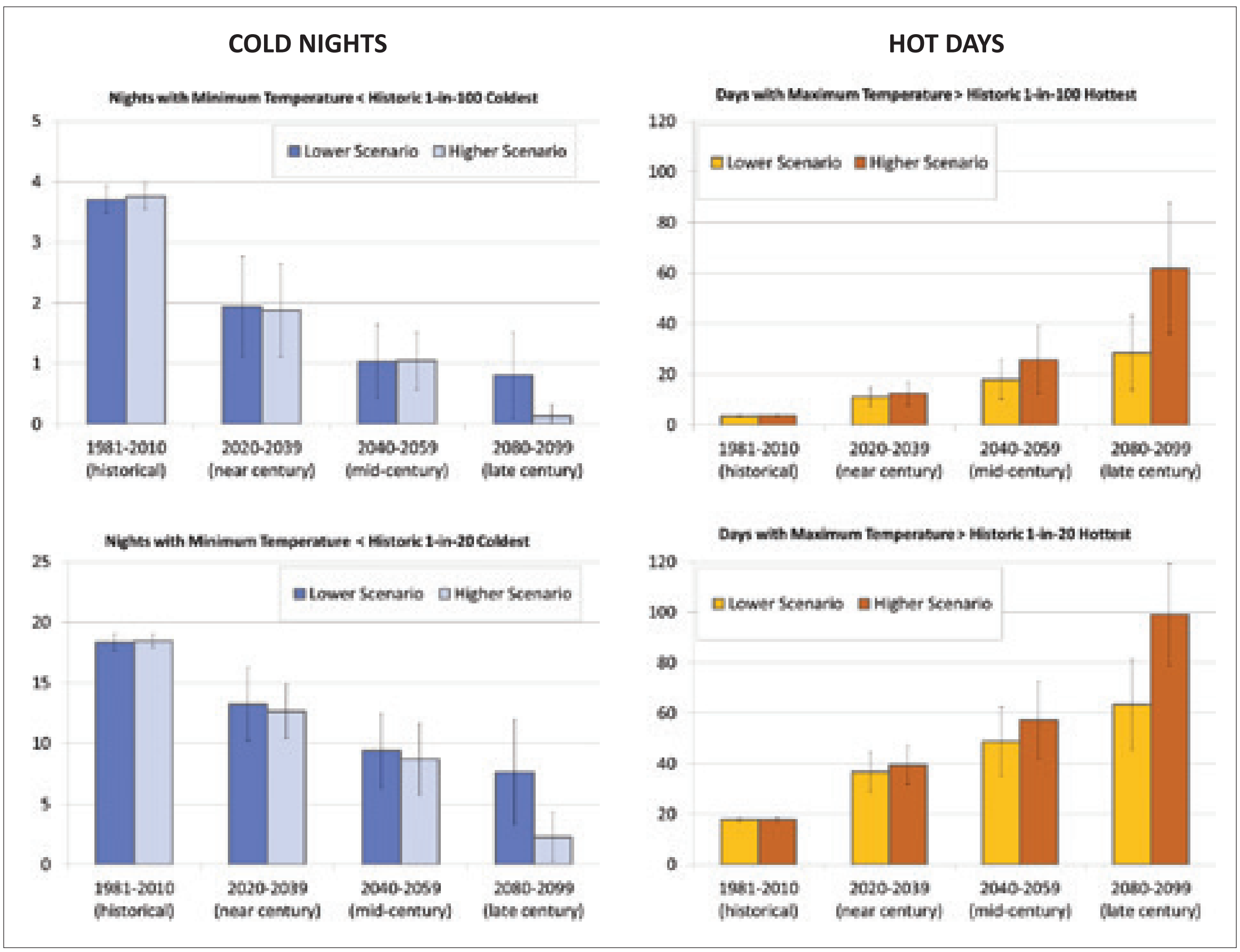


**Figure 4.6.** Projected number of **cold nights** (left) and **hot days** (right) that exceed the historical 1% (1-in-100 coldest), 5% (1-in-20 coldest), 95% (1-in-20 hottest), and 99% (1-in-100 hottest) days of the year. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the range of scientific uncertainty from multiple climate models.

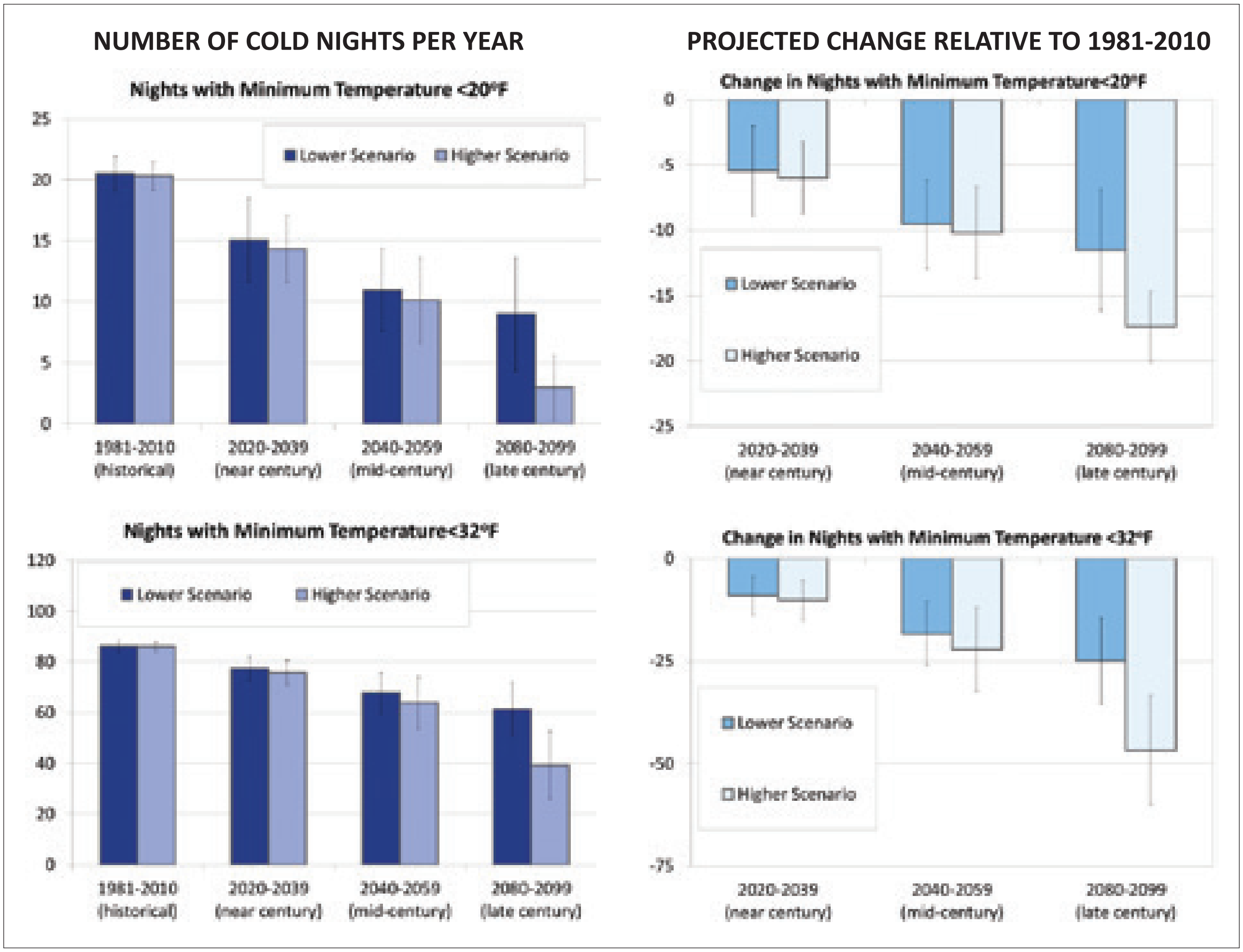


**Figure 4.7.** Historical and projected future number of **cold nights per year** (left) and projected change relative to 1981-2010 average (right) with minimum temperature below 20ºF (top) and 32ºF (bottom). Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the scientific uncertainty that results from using multiple climate models.

around 10 nights near-term, and by 20 nights by mid-century (**Figure 4.7**). By late-century there are projected to be around 60 to 70 nights per year with below-freezing temperatures under the lower scenario and 40 to 50 nights per year under the higher scenario. For this threshold, greater changes tend to be projected under CMIP5 scenarios as compared to CMIP3.

The first and last dates of freeze each year are closely related to the length of the **growing season**. Although the growing season can be defined in different ways for different crops and various regions, it is defined here simply as the "frost-free" season, counting the number of days between the last frost in spring and the first frost in fall or winter. Across Delaware, the growing season currently averages around 210 days per year. In the future, it is projected to lengthen: by about 10 days over the near-term, around 20 days by mid-century, and from 30 days under the lower scenario up to 50 days longer under the higher scenarios for late century (**Figures 4.8**).

For **high temperatures**, the days per year above four high temperature thresholds (95, 100, 105, and 110ºF) are all projected to increase, with proportionally greater increases in the absolute number of days per year for the more extreme indicators (e.g., days over 105 or 110ºF) as compared to the less extreme thresholds (e.g., 95ºF; **Figure 4.9**). For example, Delaware currently experiences an average of less than 5 days per year with maximum temperature exceeding 95ºF. By 2020-2039, that number of days is projected to increase to 10 to 15 per year. By mid-century, the

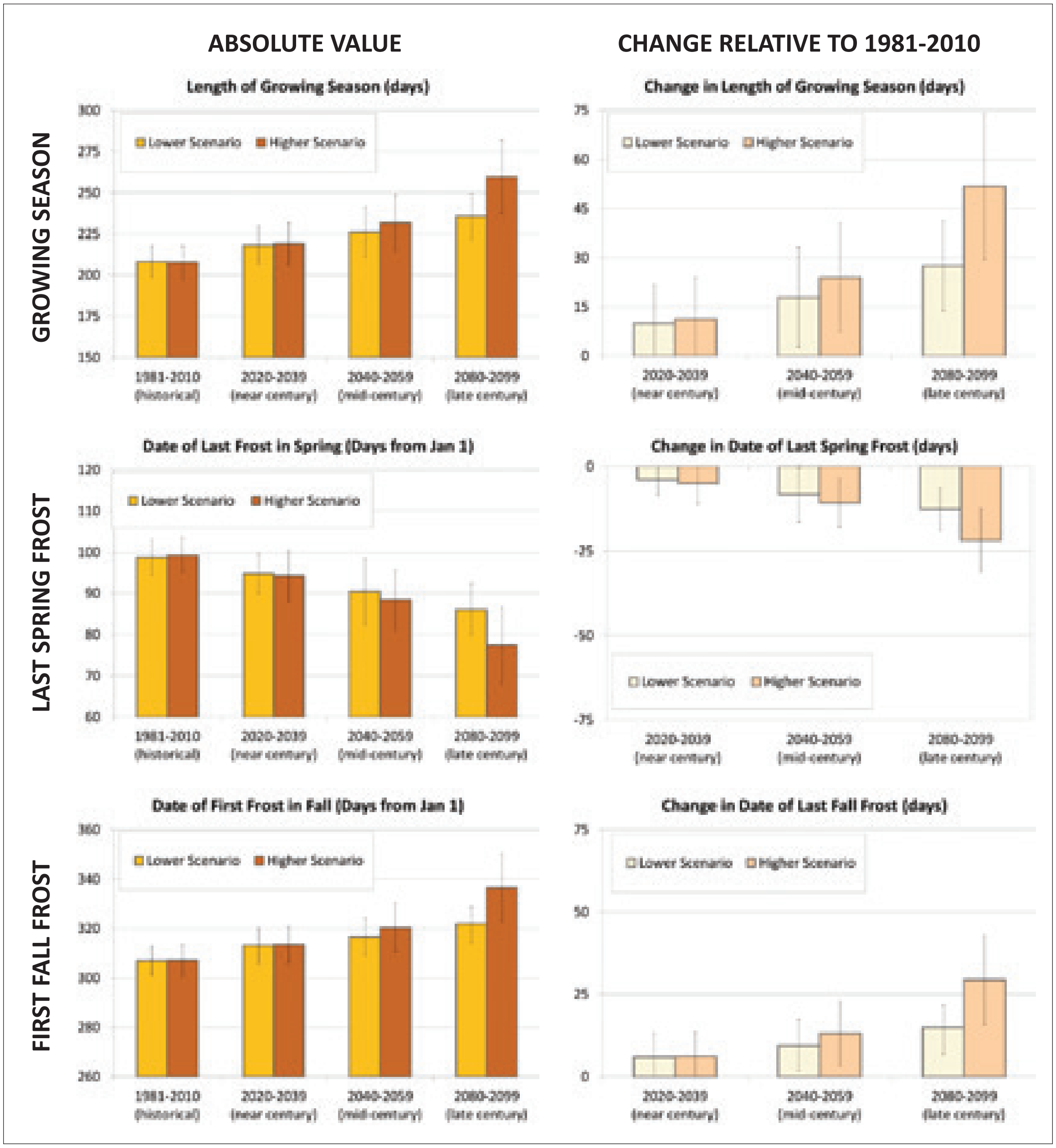


**Figure 4.8.** Projected absolute value (left) and change compared to 1981-2010 (right) in **growing season** (top), **date of last spring frost** (middle) and **first fall frost** (bottom). Greater changes are projected for spring and summer as compared to winter and fall. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the range of uncertainty from multiple climate models.

range increases to 15 to 30 days per year. By late-century, there could be an average of 20 to 30 days per year under the lower scenario and 50 to 65 days per year over 95°F under the higher scenario, an increase on the order of 4 to 6 times higher than historical values under the lower and more than 10 times historical values under the higher scenario. In contrast, a day over 100°F occurs only once every few years in the historical record. By 2020-2039 there are projected to be between 1 and 3 such days per year, and by 2040-2059, between 1.5 to 8 days per year. By late-century under the lower scenario there could be between 3 and 10 days per year over 100°F, an increase on the order of 10 to 30 times historical values; under the higher scenario, between 15 and 30 days per year. For maximum temperature extremes, CMIP5 projections are generally greater than CMIP3 under both higher and lower scenarios. For minimum temperature extremes, however,

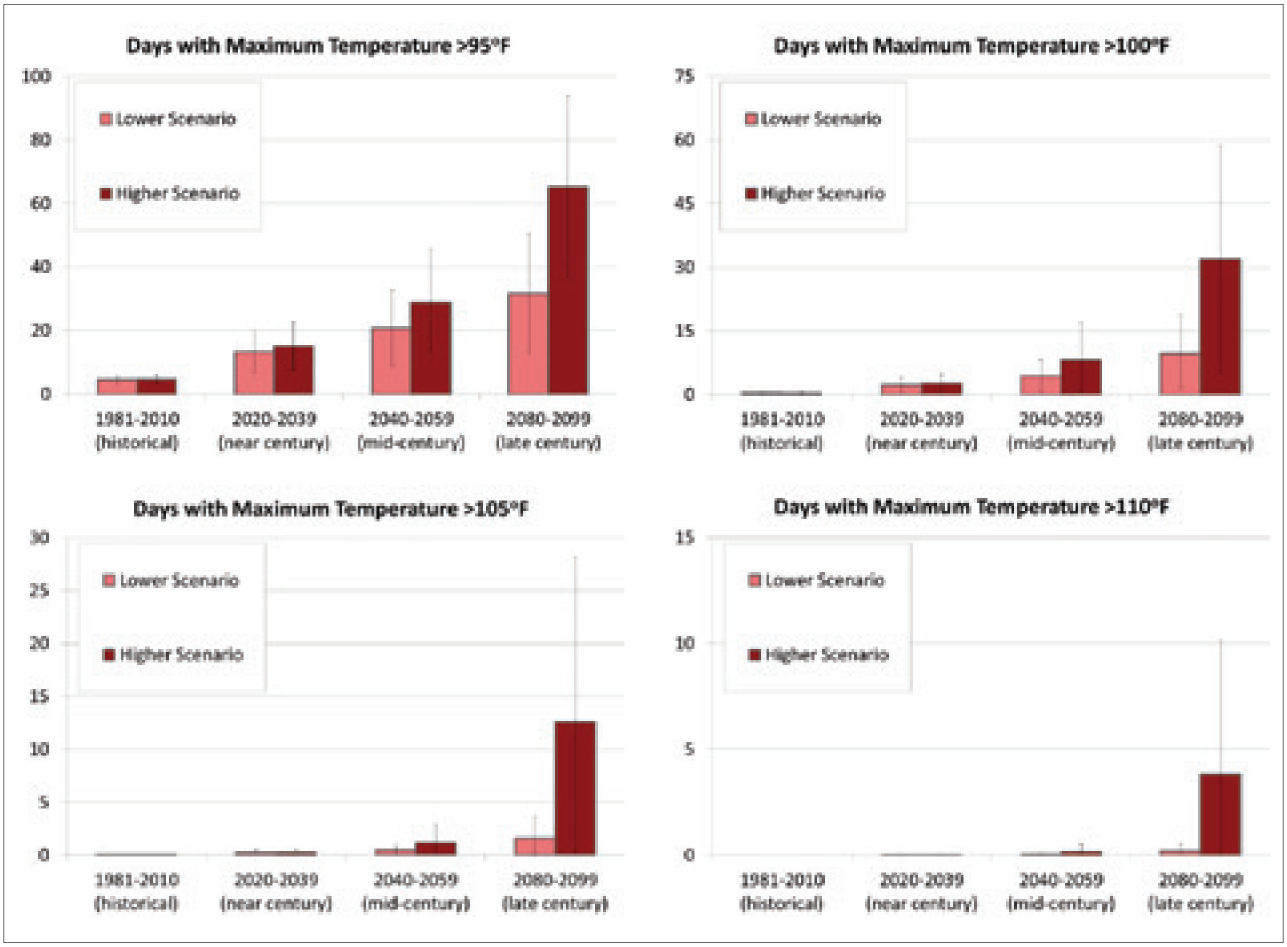


**Figure 4.9.** Historical and projected future number of **days per year with maximum temperature** above 95, 100, 105, and 110ºF. Note different range on y-axis in each figure: from 0 to 100 days per year for 95oF to 0 to 15 days for 110ºF. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black "whiskers" indicate the scientific uncertainty that results from using multiple climate models.

both CMIP3 and CMIP5 higher scenarios are noticeably and significantly higher than both CMIP3 and CMIP5 lower scenarios.

This analysis also calculated projected changes in three **minimum temperature** or **warm night** thresholds: the number of nights per year above 80, 85, and 90°F. Higher temperatures at night are often associated with health impacts, as warm nights offer no respite from high daytime temperatures. As with daytime maximum temperatures, the frequency of these nights is also projected to increase (**Figure 4.10**). Historically, nights over 80°F or higher are quite rare: averaged across the 14 weather stations used for this analysis, less than one per decade. In the future, an average of 3 nights per year above 80°F is projected for mid-century under the lower scenario, and 5 nights under the higher. By the end of the century, projected changes range from 1 to 17 nights per year (with an average of 8) over 80°F in the lower scenario and between 10 and more than 50 nights per year (with an average of 32) under the higher scenario. Projected changes in the number of nights per year above 85°F and 90°F are around one-third and one-eighth as large, respectively, as the projected changes in nights per year over 80°F by late-century. The number of nights per year with minimum temperatures below the 1st and 5th percentiles of the distribution, and the number of days with maximum temperature above the 95th and 99th percentiles of the distribution were also calculated as part of this analysis (not shown). These projections are available in the Appendix.

**Heat waves** are another measure of extreme temperatures. Heat waves are generally defined as a period of prolonged, unusual heat. Here we use four different definitions of heat waves to examine the difference in relatively mild versus more severe events. The first definition is the number of consecutive days with maximum daytime temperature exceeding 90°F (**Figure 4.11**). Historically, the longest stretch of back-to-back days exceeding 90°F averages around a week. This is projected to increase to 2 weeks by the near-term period of 2020-2039, 2½ to 3 weeks by mid-century, and almost 4 weeks under the lower scenario and more than 6 weeks under the higher scenario by late-century. The second and third definitions are similar: the longest stretch of days with maximum daytime temperature exceeding 95°F and 100°F. Historically, there are typically around 2 consecutive days over 95°F per year on average, but no more than one day over 100°F at a time. These numbers are also projected to increase. By late-century, the longest period of time over 95°F could average around 12 days under the lower and 25 days under the higher scenario by late-century. The longest period over 100°F could average around 4 days under the lower and 13 days under the higher scenario.

The definition of an extreme heat wave based on Kunkel et al. (1999; see key terms) is calculated based on the historical record of the strongest heat wave per decade. Historically, such events are rare, by definition. Near-term, heat waves (by this definition) are projected to occur on average every 3 out of 5 years. By mid-century, there could be an average of one event per year under the lower scenario and two per year under higher. By the end of the century, there are projected to be an average of 3 events per year under the lower scenario (with an uncertainty range from 1 to 5 per year) and 10 per year under the higher scenario (with an uncertainty range from 3 to 17). In other words, a heat wave that historically occurs only once per decade could be occurring 10 times per year by late-century.

## 4.3.3. Energy-Related Temperature Indicators

One of the many ways in which temperature increases can affect society and human systems is through changing the overall demand for energy, including for heating energy in the winter and cooling energy in the summer. Across the United

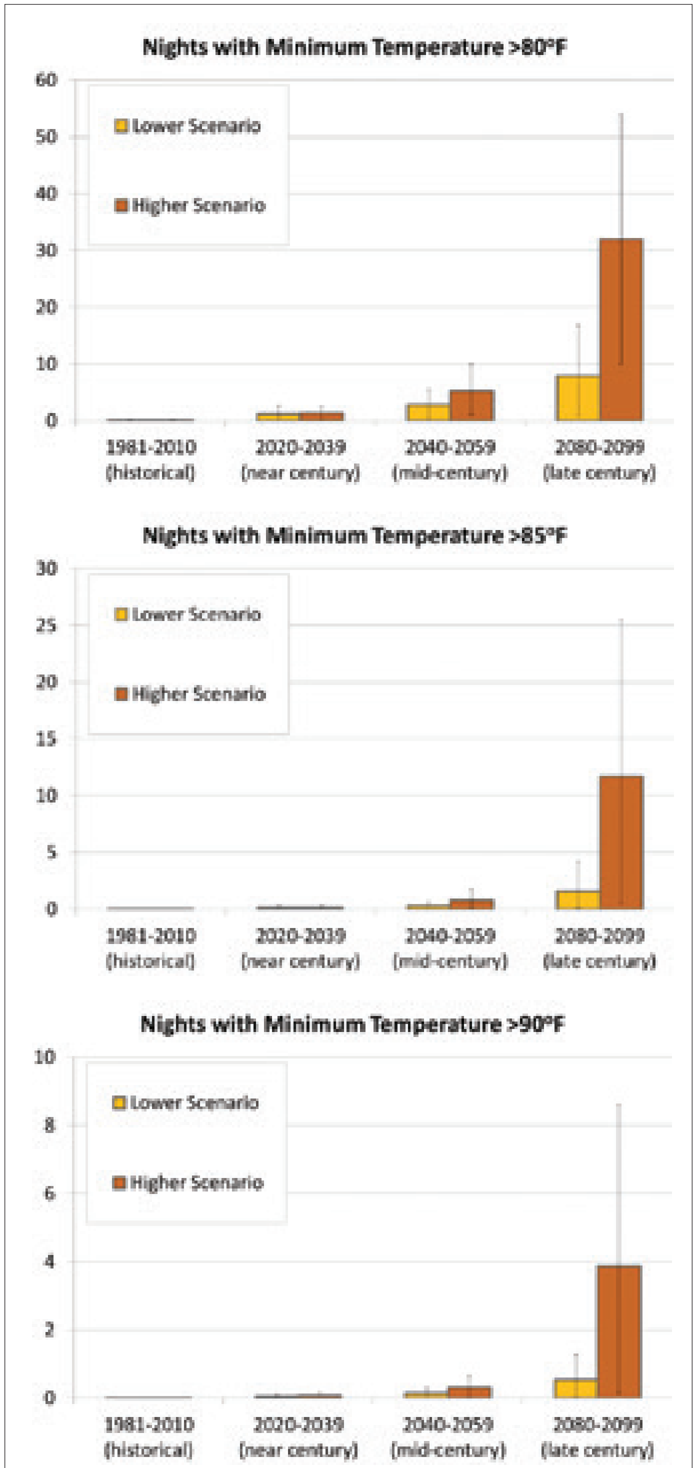


**Figure 4.10.** Historical and projected future number of **nights per year with minimum temperature** above 80, 85, and 90ºF. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the scientific uncertainty that results from using multiple climate models.

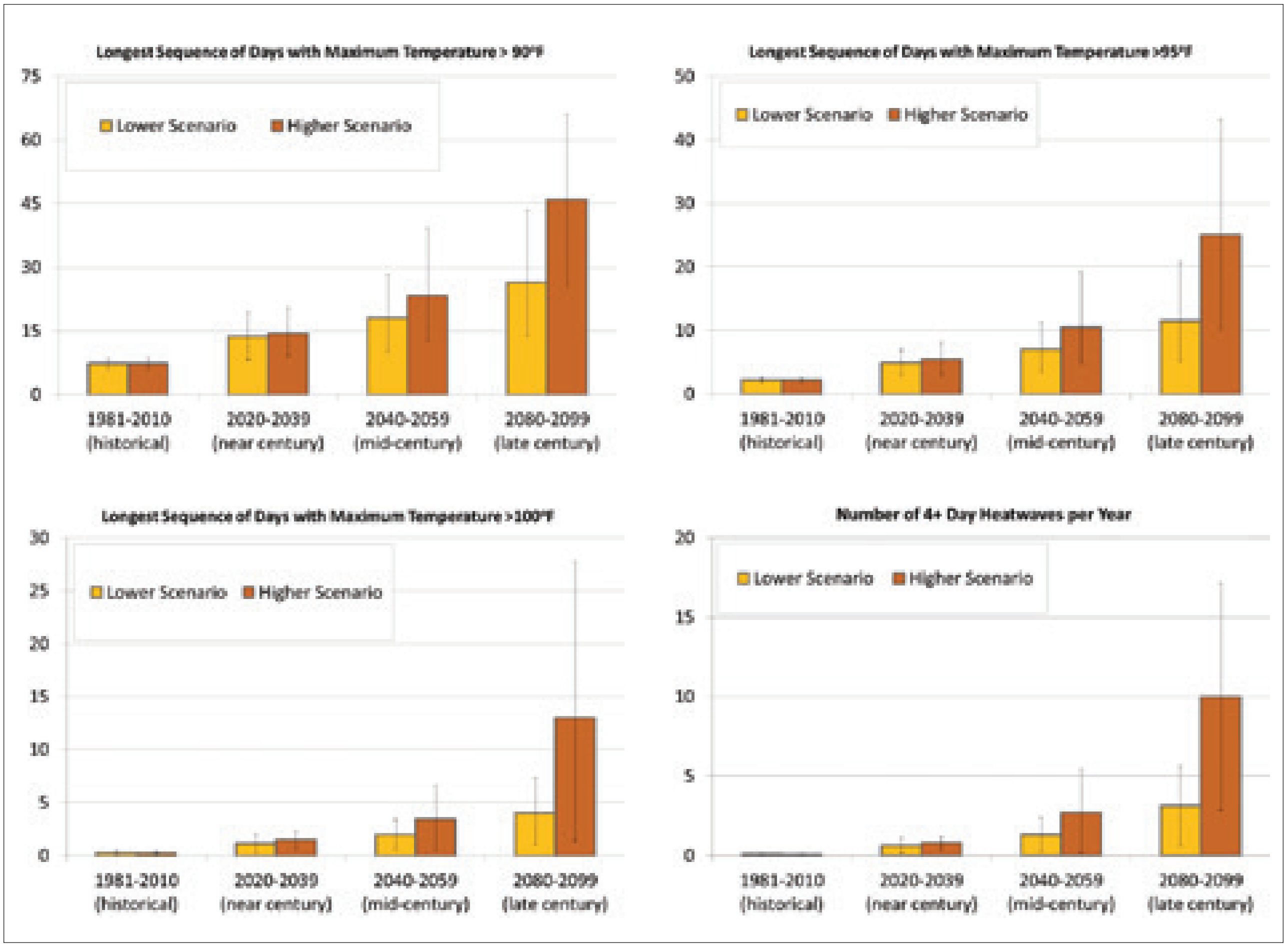


**Figure 4.11.** Historical and future **longest consecutive stretches of days with maximum daily temperature** exceeding 90, 95, and 100ºF, and average number of extreme 1-in-10 year heat waves per year. Extreme heat waves are defined after Kunkel et al. (1999) as occurring on average once per decade during the historical period. Note different scales on y-axes of figures. Events are the average for the state of Delaware, based on individual projections for 14 weather stations. The black "whiskers" indicate the scientific uncertainty that results from using multiple climate models.

States, buildings account for approximately 40 percent of overall energy use, and most of that energy use consists of heating or cooling the interior space. Cooling and heating degree-days provide a useful indicator of demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). They are typically calculated as the cumulative number of hours per year above (for cooling) or below (for heating) a given temperature threshold, here taken to be 65°F.

As temperatures increase, cooling degree-days and hence the demand for air conditioning in the summer are projected to increase; heating degree-days and demand for space heating will decrease. Currently, the annual average demand for cooling across Delaware is relatively small (about 1,200 degree-days per year) compared to demand for heating (about 4,500 degree-days per year). As average and seasonal temperatures warm, demand for cooling will increase while demand for heating decreases. Under the higher scenario, by the end of the century, the demand for heating and cooling is projected to be approximately equal, around 3,000 degree-days per year (each, for heating and cooling). Under the lower scenario, demand for cooling is projected to be around two-thirds that of heating: 2,100 cooling degree-days per year as compared to around 3,500 heating degree-days per year.

This analysis makes no attempt to assess the ultimate impact on the consumer. It simply estimates projected changes in the demand for cooling: a 30 percent increase by 2020-2039, a 35 to 70 percent increase by 2040-2059, and an average increase of 50 percent under the lower scenario and 130 percent under the higher scenario by late-century (**Figure 4.12**). Heating demand is projected to decrease: by about 10 percent near-term, nearly 20 percent by mid-century, and around 20 percent under the lower scenario and almost 40 percent by late-century. It is important to note, however, that the sources of energy for heating versus cooling are generally different (electricity versus gas or oil). For that reason, increases in cooling degree-days are not likely to be offset by decreases in heating degree-days but rather will have different impacts on energy supply and costs.

## 4.4. Precipitation-Related Indicators

As the earth warms, precipitation patterns are also expected to shift in both space and time. Some seasons may get wetter, while others get drier. The intensity and frequency of heavy rainfall, as well as the duration of dry periods, may be altered. Mid-latitudes are generally projected to become wetter, with increases in heavy precipitation events. Across the Northeast and Mid-Atlantic region, heavy precipitation has already increased – by more than 70 percent over the last 60 years, in many locations, according to the Third U.S. National Climate Assessment.[16]

This section summarizes the changes in precipitation and related secondary indicators that are projected to occur in response to global climate change.

### 4.4.1. Annual and Seasonal Precipitation

Annual precipitation across Delaware averages around 45 inches per year. It is evenly distributed throughout the year, with more than 10 inches on average falling in each season. Slightly less precipitation (around 1 to 2 inches less) tends to fall in fall and winter as compared to spring and summer.

In the future, annual average precipitation is projected to increase (**Figure 4.13**), consistent with a general increase in precipitation projected for mid-latitudes, including the northern half of the United States. Increases are greater and more consistent by late-century compared to earlier time periods. For both the near-term and mid-century periods, for example, the multi-model average shows an increase in precipitation under all scenarios, but some individual model simulations show decreases. By late-century, in contrast, all but one model

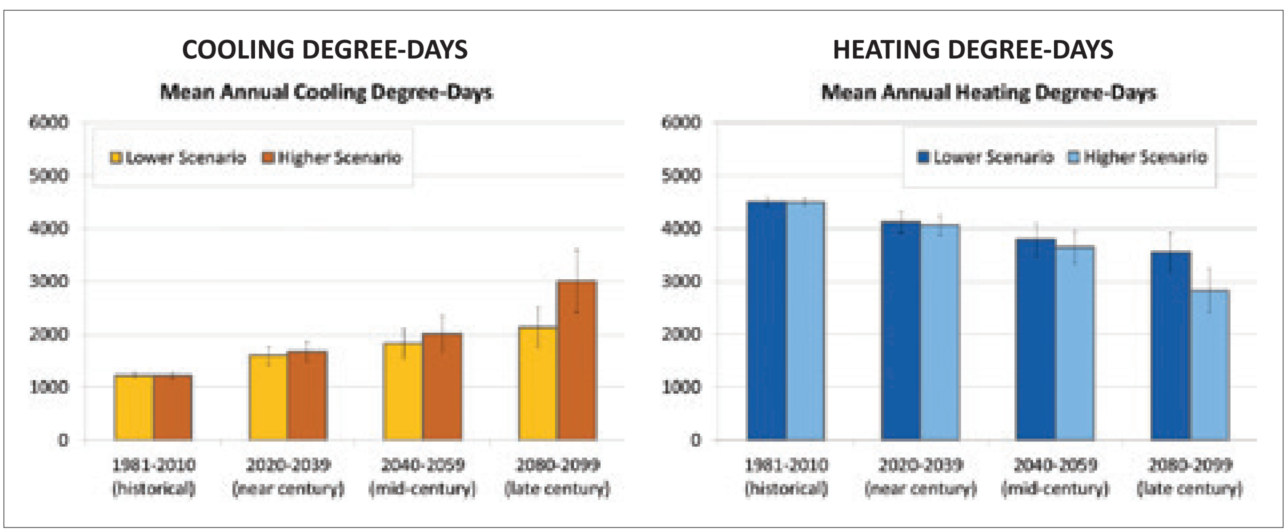


**Figure 4.12.** Historical and projected future annual cumulative **cooling and heating degree-days** using a temperature threshold of 65ºF. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Projected changes under the lower scenario are shown in yellow for cooling degree-days (which are warm) and dark blue for heating degree-days (which are cold). The black "whiskers" indicate the uncertainty that results from using multiple climate models.

shows an increase, as indicated by the black bars in **Figure 4.13**. There is a small and, given the range of uncertainty, likely insignificant difference between the amount of increase projected to occur under the higher versus lower scenario. Projected increases under CMIP3 simulations tend to be slightly higher than under CMIP5 simulations (10 to 20 percent versus 7 to 10 percent, respectively, by late-century; not shown here).

Seasonal changes show stronger differences between scenarios for projected precipitation increases in winter (**Figure 4.14**). In winter, when the largest precipitation increases are projected to occur, increases projected under a higher scenario are higher by late-century than under a lower scenario. Projected changes in spring, summer, and fall precipitation do not show significant scenario differences (or much change at all, as the ranges of uncertainty for each multi-model average all encompass both positive and negative changes, even out to the end of the century; **Figure 4.14**, right side).

The seasonality of changes in precipitation is a key area where older CMIP3 simulations (based on four global climate models) differ from newer CMIP5 simulations (based on nine global climate models). CMIP3 projections show increases in precipitation to be distributed evenly throughout the year. In contrast, CMIP5 shows precipitation increases only in winter and fall. In addition to seasonal changes in precipitation, changes in 3-month, 6-month, and 12-month cumulative precipitation were calculated for periods beginning with each month from January to December. These results are available in the Appendix.

## 4.4.2. Dry and Wet Periods

As climate changes, precipitation is projected to increase, particularly in winter. However, little to no change is projected in annual dry days. This can be explained by the increase in precipitation intensity. Although there is more precipitation, the average amount of precipitation falling on wet days is also increasing: by around 2 percent over the near term, 3 to 4 percent by mid-century, and 5 percent under a lower scenario and 11 percent under a higher scenario by the end of the century. This increase in the average amount of precipitation falling on a given wet day keeps pace with the projected increase in winter precipitation. Thus, little to no change in dry days is projected (**Figure 4.15**). The total number of dry days per year is another variable on which CMIP3 and CMIP5 projections for the future disagree slightly. Under CMIP3, the number of dry days is projected to decrease by a few days a year. This small difference is likely the result of projected increases in annual precipitation under CMIP3 being slightly larger than projected increases under CMIP5; simply put, with that

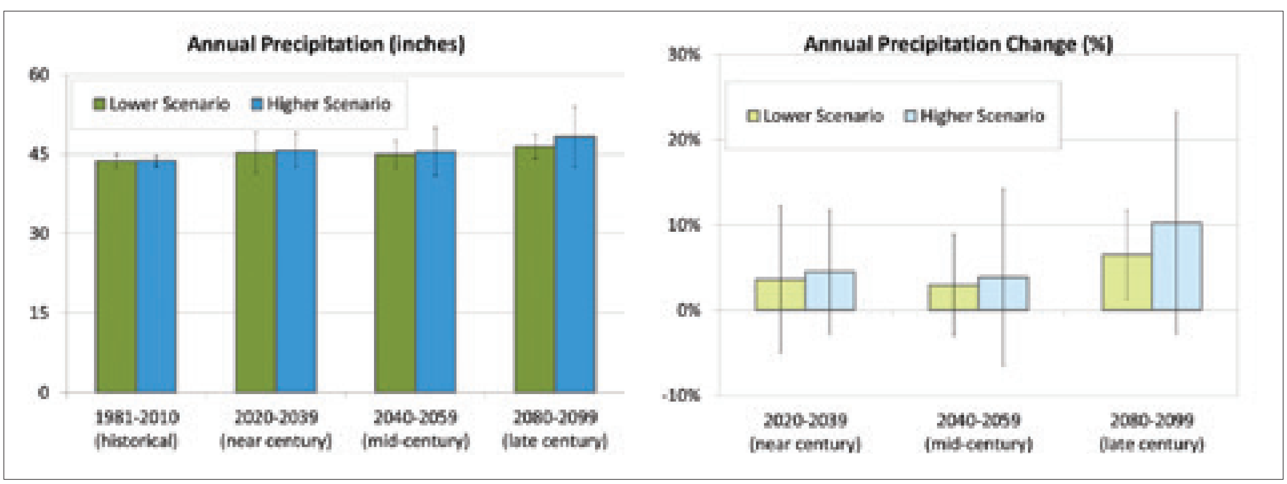


**Figure 4.13.** Historical and future simulated annual average precipitation (left) and change in **annual average precipitation** (right) as simulated under a lower (green) and higher (blue) future scenario. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. The black "whiskers" indicate the uncertainty that results from using multiple climate models.

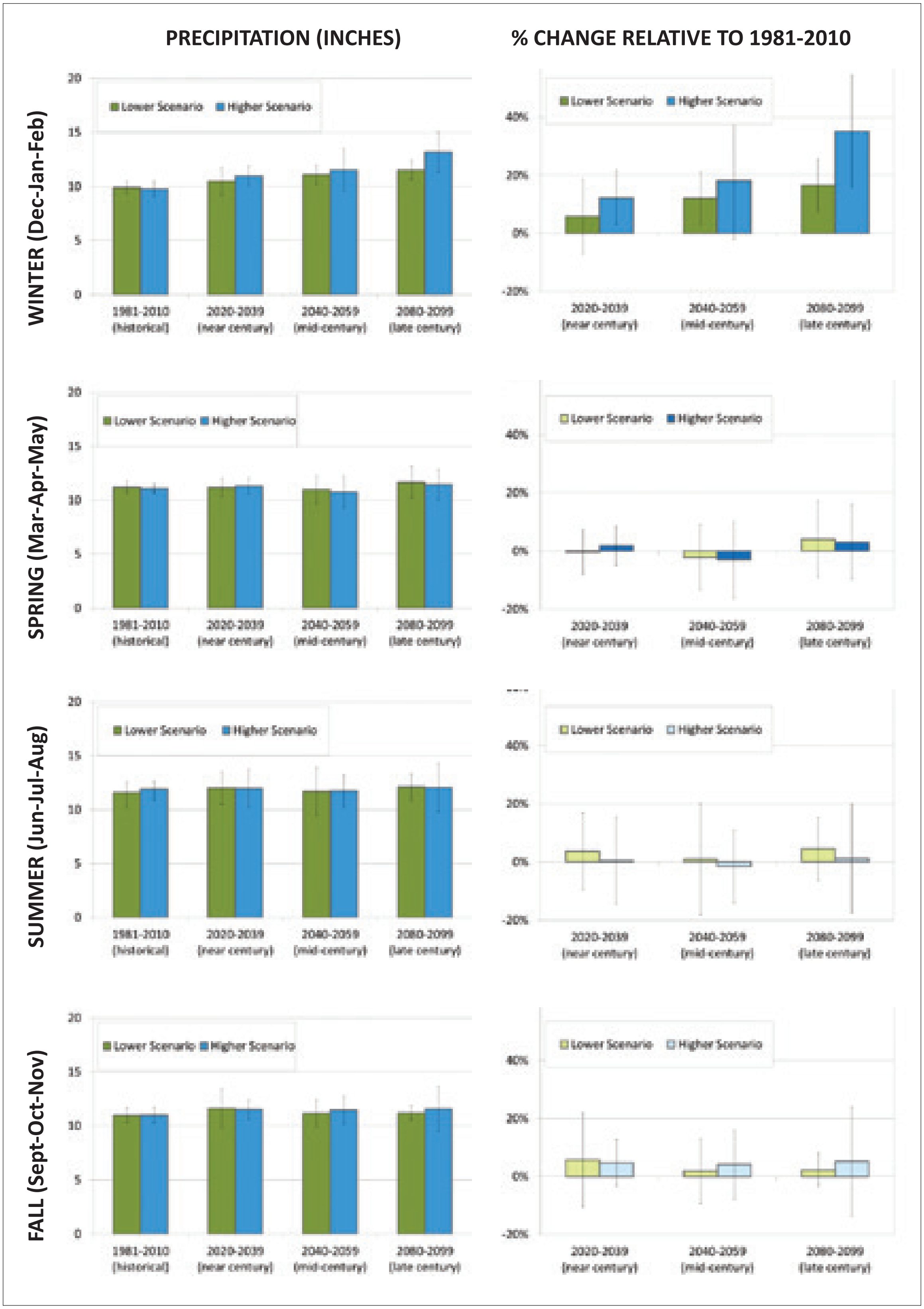


**Figure 4.14.** Historical and future cumulative **seasonal precipitation** (left) and percentage change in cumulative precipitation compared to 1981-2010 (right) for winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sept-Oct-Nov). Greater changes are projected for winter and fall, little change in spring and summer. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the range of scientific uncertainty from multiple climate models.

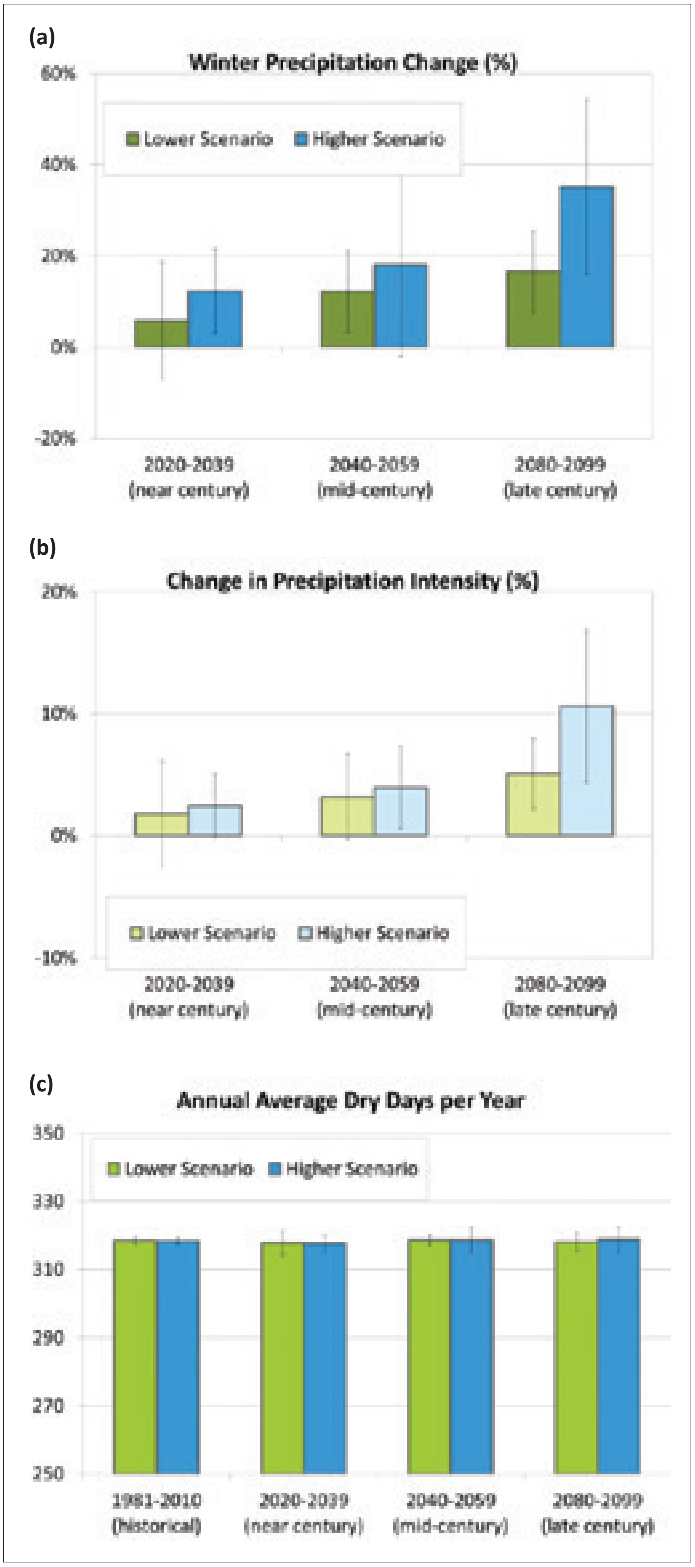


**Figure 4.15.** Historical and future percentage changes in (a) winter **precipitation** and (b) **precipitation intensity** balance out to suggest little change in (c) the overall number of **dry days** per year. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Black "whiskers" indicate the range of scientific uncertainty from multiple climate models.

much more rain, there are a few more wet days each year.

The Standardized Precipitation Index (SPI) offers a different way to look at dry and wet conditions. This index is commonly used by the National Drought Mitigation Center and the National Climatic Data Center to indicate dry and wet areas within the continental United States on an ongoing basis. It is standardized, such that zero represents normal conditions for that location; negative values indicate conditions drier than average, from 0 to -7, while positive values indicate wetter conditions, from 0 to +7. Projections suggest a trend towards slightly wetter conditions, with average SPI increasing by 0.1 over the course of this century, consistent with increases in average precipitation (not shown; figure available in the Appendix). However, given an index from 0 to 7, this increase is very small and the uncertainty range due to multiple models encompasses zero, suggesting that some models project a slight decrease in SPI and others, an increase and overall, results are not very significant.

## 4.4.3. Heavy Precipitation Events

Heavy precipitation events are already increasing globally, across the United States, and across the northeast region of the United States in particular. The increased frequency of these events has been formally attributed to human-induced climate change. In many regions, the observed trend in heavy rainfall is expected to continue in the future as warming temperatures accelerate the hydrologic cycle at both the local and global scale.[17]

National and global studies typically look at heavy precipitation over a single range; however, depending on the region, different levels of heavy snow and rain can have very different impacts. Here, a broad range of precipitation indicators were analyzed. They consist of:

- Number of days per year with more than 0.5, 1, 2, 3, 4, 5, 6, 7 and 8 inches of precipitation in 24 hours;
- The wettest day, 5 days, and 2 weeks in 1, 2, and 10 years; and

- Number of days per year exceeding the historical 2-, 4-, and 7-day maximum rainfall

For the state of Delaware, nearly every indicator of extreme precipitation is projected to increase in the future (**Table 4.1**). This is consistent with observed trends as well as with future projected trends across the eastern United States. For "less extreme" indicators (e.g., days per year over 0.5 or 1 inches in 24 hours), there was little difference in projected changes under the higher versus lower scenario, although overall larger changes are projected by late-century as compared to near-term. For "more extreme" indicators (e.g., days per year with 2 inches or more of precipitation in 24 hours), projected changes under the higher scenario were generally greater than projected changes under the lower scenario, although in all cases the range of uncertainty due to using multiple model projections continues to overlap, suggesting that the differences between scenarios may not be statistically significant. For "very extreme"

**Table 4.1.** Other projected changes in **indicators of extreme precipitation** calculated in this analysis include: (1) the average number of days per year where cumulative precipitation exceeds thresholds between 0.5 and 8 inches; the total amount of precipitation falling in the wettest 1, 5, and 14 consecutive days of (2) the year, (3) 2 years, and (4) 10 years; and (5) the number of times per year the historical 2-, 4- and 7-day maximum precipitation amounts are exceeded in the future.

| | 1981-2010 | 2020-2039 | 2040-2059 | | 2080-2099 | |
|---|---|---|---|---|---|---|
| | | | Lower | Higher | Lower | Higher |
| **(1) Days per year exceeding a given threshold of 24-hour cumulative precipitation** | | | | | | |
| 0.5 | 28.1 | 29 | 28.6 | 28.6 | 29.3 | 29.6 |
| 1 | 12.0 | 12.9 | 12.9 | 13.1 | 13.6 | 14.7 |
| 2 | 2.1 | 2.5 | 2.5 | 2.7 | 2.7 | 3.4 |
| 3 | 0.7 | 0.8 | 0.8 | 0.8 | 0.9 | 1.2 |
| 4 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.55 |
| 5 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.29 |
| 6 | 0.1 | 0.10 | 0.10 | 0.10 | 0.14 | 0.18 |
| 7 | 0.04 | 0.06 | 0.07 | 0.07 | 0.09 | 0.13 |
| 8 | 0.03 | 0.04 | 0.04 | 0.05 | 0.07 | 0.10 |
| **(2) In one year, wettest …** | | | | | | |
| 1 day | 3.3 | 3.5 | 3.5 | 3.6 | 3.8 | 4.2 |
| 5 days | 6.4 | 6.6 | 6.7 | 6.8 | 7.1 | 7.4 |
| 2 weeks | 14.2 | 14.3 | 14.3 | 14.4 | 14.5 | 14.5 |
| **(3) In 2 years, wettest …** | | | | | | |
| 1 day | 4.1 | 4.3 | 4.3 | 4.6 | 4.9 | 5.4 |
| 5 days | 7.4 | 7.7 | 7.8 | 8.3 | 8.8 | 9.0 |
| 2 weeks | 14.4 | 14.5 | 14.6 | 14.7 | 15.2 | 15.1 |
| **(4) In 10 years, wettest …** | | | | | | |
| 1 day | 6.2 | 6.7 | 6.7 | 7.1 | 8.1 | 8.6 |
| 5 days | 10.7 | 11.1 | 11.4 | 12.7 | 14.3 | 13.3 |
| 2 weeks | 15.7 | 15.9 | 16.4 | 17.3 | 18.7 | 17.9 |
| **Number of times historical threshold is exceeded** | | | | | | |
| 2-day maximum | 0.001 | 0.013 | 0.011 | 0.019 | 0.019 | 0.046 |
| 4-day maximum | 0.000 | 0.005 | 0.005 | 0.013 | 0.008 | 0.024 |
| 7-day maximum | 0.000 | 0.003 | 0.001 | 0.009 | 0.004 | 0.015 |

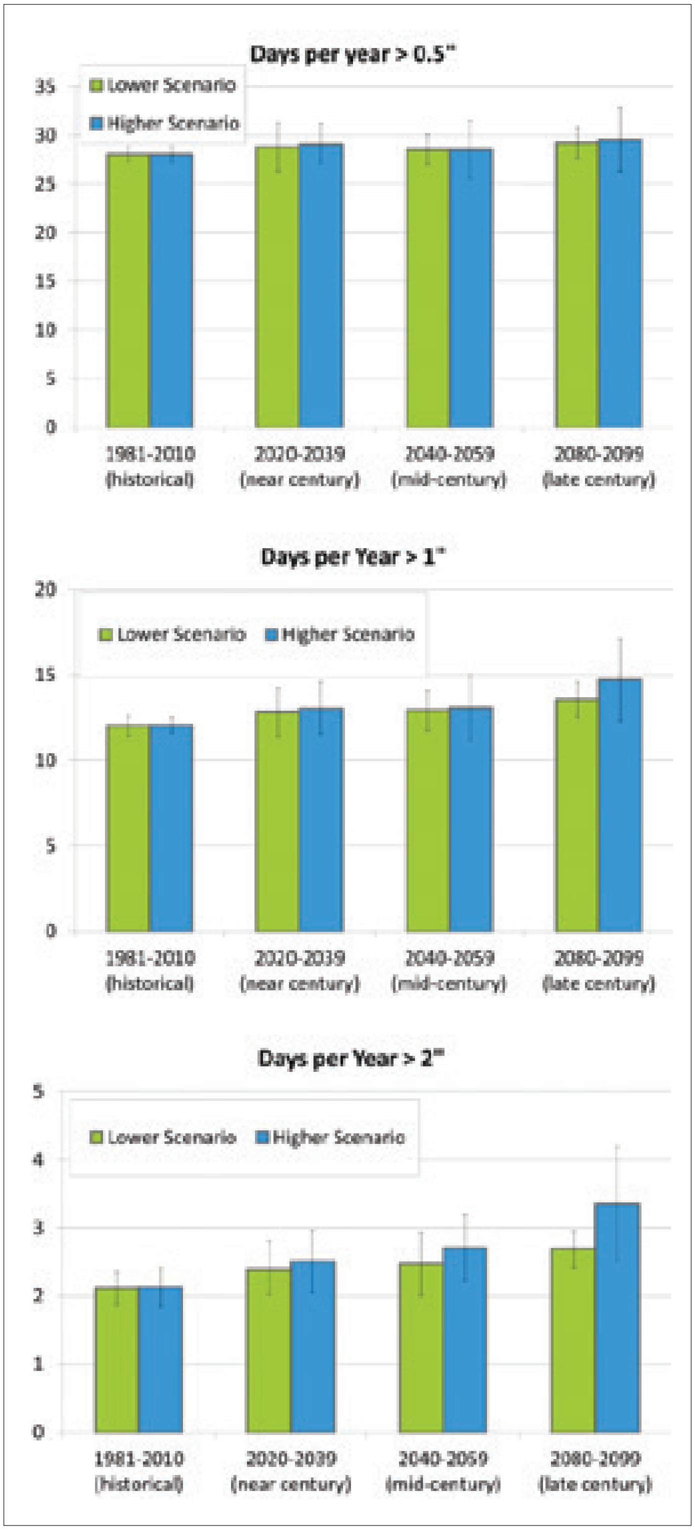


**Table 4.16.** Projected future changes in the number of days per year with **cumulative precipitation** exceeding a range of thresholds from 0.5 to 2 inches in 24 hours. Changes are the average for the state of Delaware, based on individual projections for 14 weather stations. Projections using the lower future scenario are green; the higher scenario, blue. Black "whiskers" indicate the scientific uncertaintly that results from using multiple climate models.

indicators (e.g., wettest 1 or 5 days of the year or beyond), there was less of a difference between higher versus lower scenarios. Finally, the amount of precipitation falling in the wettest 2 weeks of the year (or 2 years, or 10 years) showed little to no change over any time frame. This suggests that the largest impact of climate change will be on short-duration precipitation events, which can be both convective and large-scale in nature, rather than on the frequency and duration of large weather systems that bring extended rain over multiple weeks.

In terms of thresholds, precipitation records across 14 Delaware stations shows that, on average, the state currently experiences around 28 days per year with more than 0.5 inches of rain in 24 hours; 12 days with more than 1 inch; and 2 days with more than 2 inches. By late-century, these numbers are projected to increase by 1 to 2 days for 0.5 inches, 2 to 3 days for 1 inch, and an average of 0.5 to 1 day per year for 2 inches (Figure 4.16). Additional changes projected for other indicators are listed in **Table 4.1**.

For lower amounts of heavy precipitation (0.5 to 2 inches in 24 hours), projected changes under CMIP3 are generally greater than under CMIP5, likely because CMIP3 models project larger increases in average precipitation as compared to CMIP5. For higher levels of precipitation (3 to 8 inches), however, CMIP3 and CMIP5 projections are similar.

## 4.5. Hybrid Variables

Temperature and precipitation alone do not capture the full extent of relevant change in Delaware's climate. For that reason, this report also presents projected changes in humidity and in "hybrid" or multivariable indicators such as heat index (a combination of temperature and humidity that measures how hot it "feels" to the human body), potential evapotranspiration (which depends on solar radiation, humidity, temperature, winds, and other factors), and cool and wet or hot and dry days.

### 4.5.1. Relative Humidity and Dewpoint Temperature

**Figure 4.17** compares projected changes in dew point temperature (defined as the temperature to which the air must be cooled to condense the water vapor it contains into water) with projected changes in average temperature by season, compared to the 1981-2010 average. In general, projected changes for dew point temperature are similar to and slightly less than those projected for average temperature. This could be the result of small decreases in relative humidity projected for most seasons except spring (not shown; available in the Appendix). However, it could also be related to the fact that dew point temperature projections could be calculated only for three airport locations with long-term humidity records.

## 4.5.2. Summer Heat Index and Potential Evapotranspiration

Heat index is often used in the summer to express how hot it "feels" to the human body, based on a combination of both temperature and humidity, which affects evaporation and cooling. A related metric is potential evapotranspiration, or PET. This measures the amount of evaporation that would occur, given certain levels of temperature, wind, humidity, and solar radiation, and an unlimited water supply.

The relationships among heat index, temperature, and humidity are not linear. Despite little change to a slight decrease being projected for relative humidity in summer (**Figure 4.18**), projected increases in summer heat index by the end of the century are approximately double the projected changes for maximum daytime summer temperature alone. In other words, the projected increase in temperature may *feel* twice as large

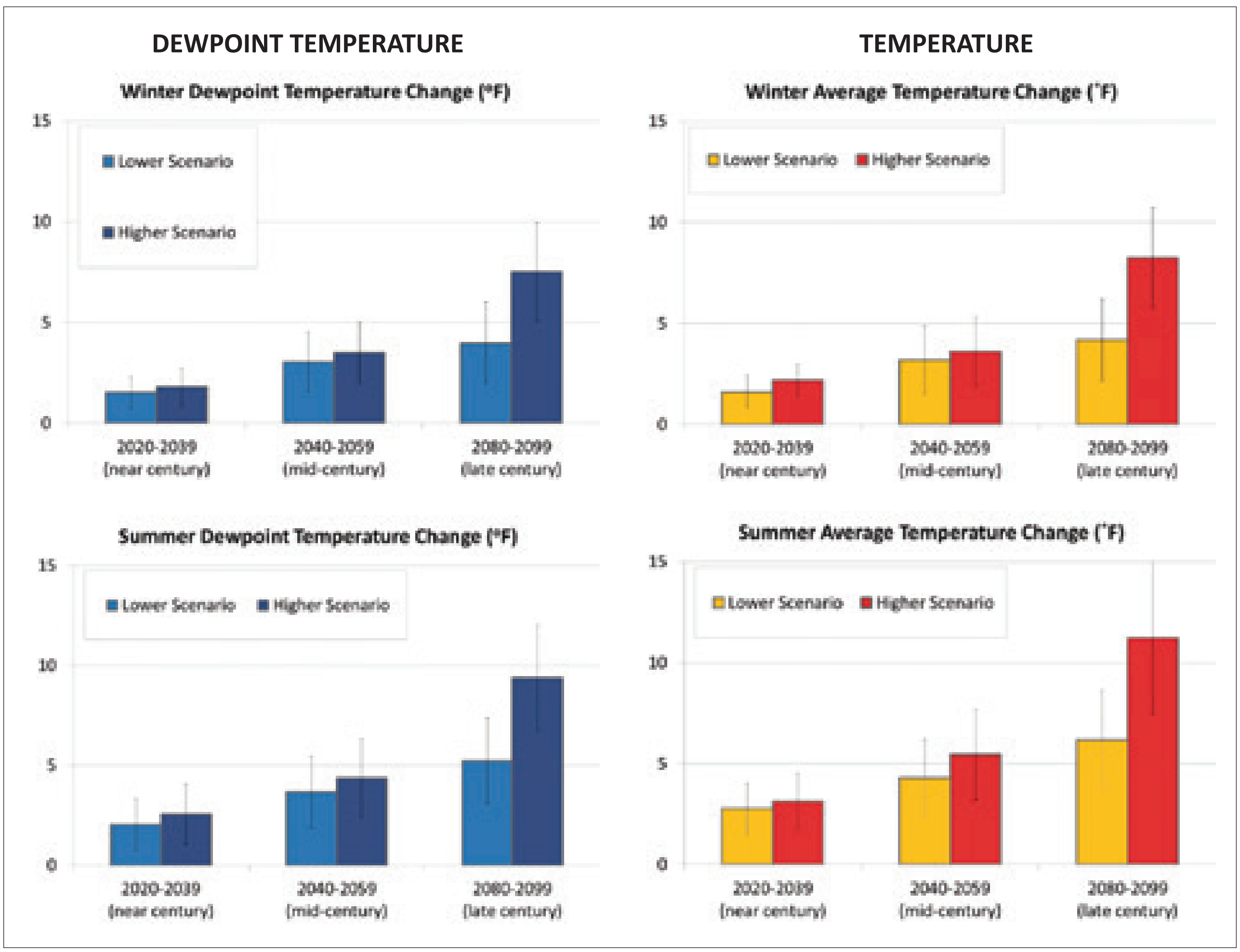


**Figure 4.17.** Historical simulated and future projected precipitation amounts in **dew point temperature** (left) and average temperature (right) for winter and summer. (Spring and fall graphs provided in the Appendix.) Dew point temperatures are based on projections for three airport locations only; average temperatures are based on projections for all 14 weather stations. The black "whiskers" indicate the uncertainty that results from using multiple climate models.

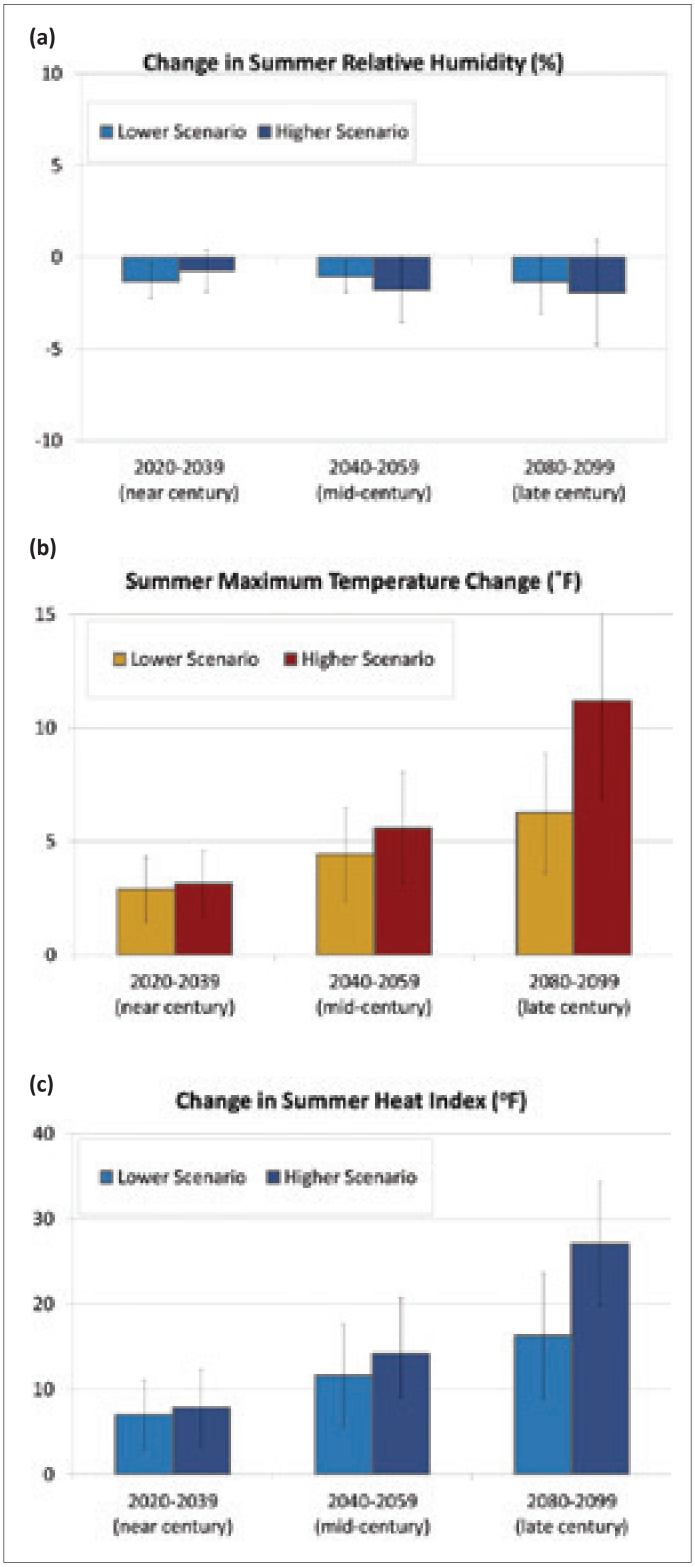


**Figure 4.18.** Historical simulated and future projected changes in summer (June, July and August) **(a) relative humidity, (b) maximum temperature, and (c) heat index**. Projections in (a) and (c) are based on 3 airport locations only; average temperatures in (b) are based on projections for all 14 weather stations. The black "whiskers" indicate the scientific uncertainty that results from using multiple climate models.

as it actually is, due to the interactions between humidity and temperature.

Evaporation is projected to increase, primarily driven by increases in temperature. The largest increases are projected for summer, followed by spring and fall (**Figure 4.19**).

### 4.5.3. Hybrid Temperature and Precipitation Indicators

The final set of hybrid indicators focuses on the combination of temperature and precipitation. The number of "hot dry" days with maximum temperatures over 90°F without measurable rain is projected to increase 50 to 100 percent over the near term. By late-century there could be between two and more than four times more hot/dry days (**Figure 4.20**) compared to the 1981-2010 average, depending on which scenario is more likely. In contrast, the number of "cool wet" days with maximum temperatures below 65°F and measurable precipitation is projected to decrease, but not by much. Slightly greater changes are projected under the higher (4 to 6 days) as compared to the lower (1 to 2 days) scenario by the end of the century. The amount of precipitation that falls as rain rather than snow is already quite high for Delaware, around 98 to 99 percent. In the future, slightly more precipitation is projected to fall as rain than snow as temperatures warm; however, this is not likely to have a significant impact, because it amounts to a change of only 1 to 2 percent (not shown – see Appendix).

## 4.6. Conclusions

Climate change is expected to affect Delaware and the surrounding region by increasing average, seasonal, and extreme temperatures, as well as increasing average precipitation, increasing the frequency of heavy precipitation events, and increasing 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 the higher as compared to lower

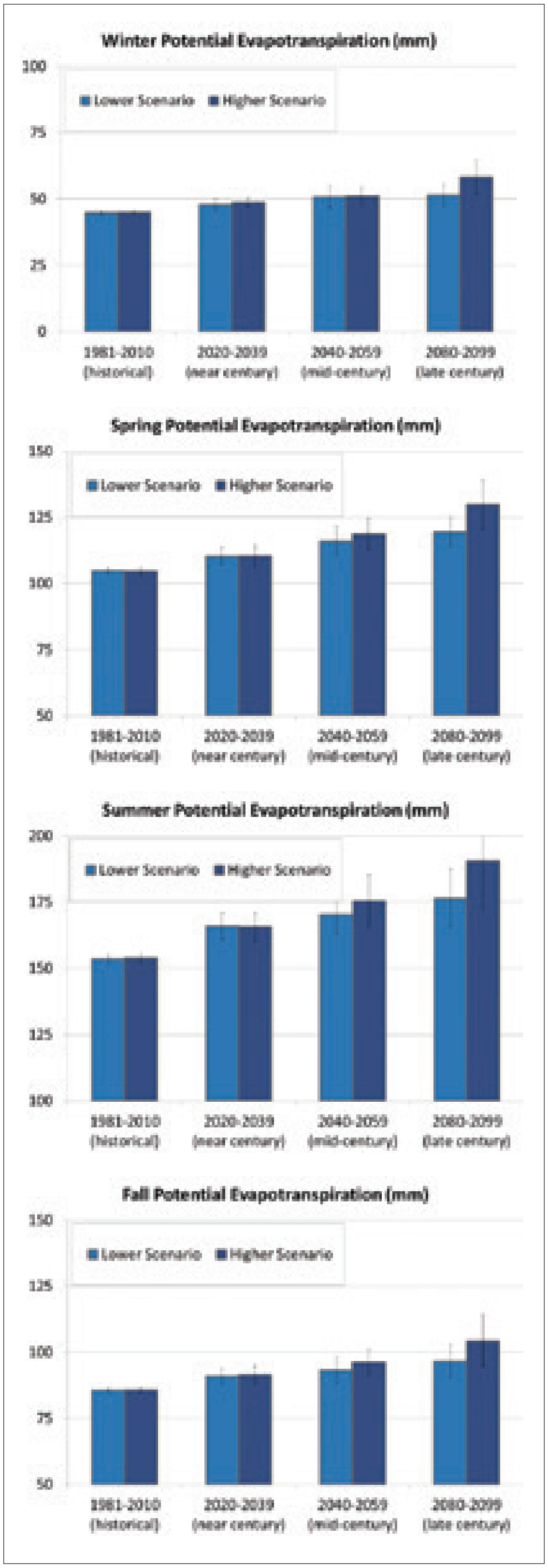


**Figure 4.19.** Historical simulated and future projected changes in **seasonal potential evapotranspiration** (PET). Although the y-axis of the plots covers a different range, the total range covered is identical (100 mm), so relative changes can be seen from one season to the next.

scenario by late-century. For many of them, this difference begins to emerge by mid-century.

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 B1 or RCP 4.5 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 A1FI or RCP 8.5 scenarios can be avoided by concerted mitigation efforts. The greater the reduction in climate forcing from human activities, the more possible it will be to successfully adapt to a changing climate.

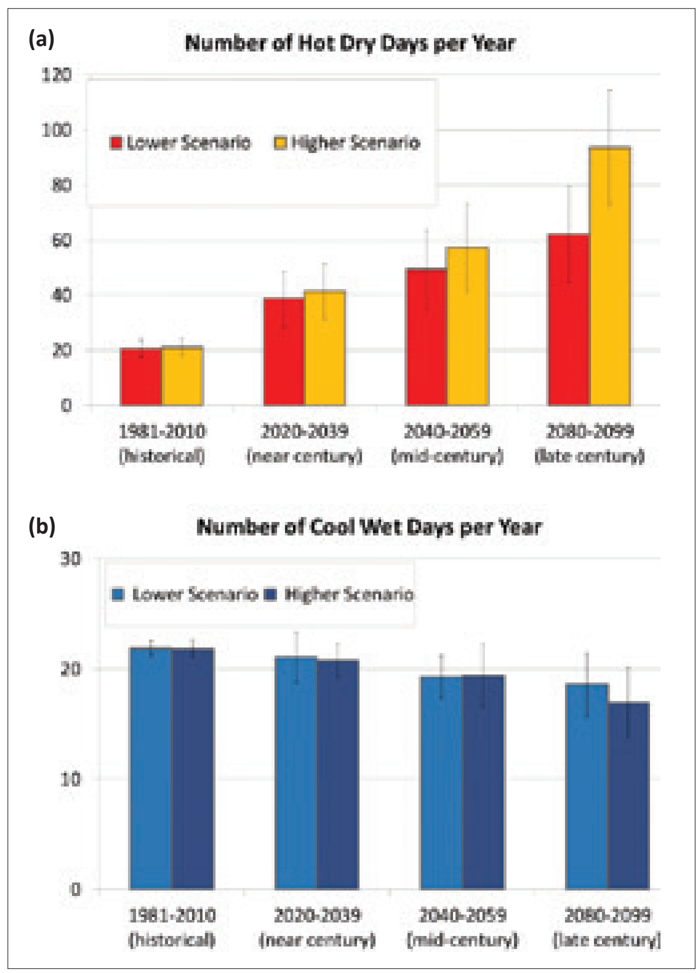


**Figure 4.20.** Historical simulated and future projected changes in (a) the number of **hot dry days** with no precipitation and (b) **cool wet days** with precipitation.

# Sources
## (Endnotes)


1 Kunkel, K. E., Pielke, Jr., R. A., & Changnon, S. A. (1999). Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of American Meteorological Society,* 80, 1077-1098.

2 Andres, R. J., Fielding, D. J., Marland, G., Boden, T. A., & Kumar, N. (1999). Carbon dioxide emissions from fossil-fuel use, 1751-1950. *Tellus* 51B, 759-765.

3 Stern, D.I., & Kaufmann, R.K. (1998). Annual estimates of global anthropogenic methane emissions: 1860-1994. *Trends Online: A Compendium of Data on Global Change.* Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, doi: 10.3334/CDIAC/tge.001

4 Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., … R. Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (Eds.)]. Cambridge University Press, Cambridge, U.K.

5 Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., … Zhai, P. (2007). Observations: Surface and atmospheric climate change. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, U.K.

6 Abraham, J., Baringer, M., Bindoff, N., Boyer, T., Cheng, L., Church, J. … Willis, J. (2013) A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics,* 51, 450-483.

7 Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014). Chapter 2: Our Changing Climate. In: *The Third U.S. National Climate Assessment.* In press.

8 Hegerl, G.C., Zwiers, F. W., Braconnot, P., Gillett, N. P., Luo, Y., Marengo Orsini, J. A., … Stott, P.A. (2007). Understanding and attributing climate change. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, U.K.

9 Huber, M., & Knutti, R. (2011). Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nature Geoscience,* doi:101.1038/NGEO1327

10 Foster, G., & Rahmstorf, S. (2011). Global temperature evolution 1979-2010. *Environmental Research Letters,* 6, 044022.

11 Gillett, N., Arora, V., Flato, G., Scinocca, J., & von Salzen, K. (2012). Improved constraints on 21st-century warming derived using 160 years of temperature observations. *Geophysical Research Letters,* 39, L017074.

12 IPCC. (2007). Summary for policymakers. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (Eds.)]. Cambridge University Press, Cambridge, U.K.

13 U.S. Global Change Research Program (USGCRP). (2009). *Global climate change impacts in the United States.* Cambridge University Press. http://www.globalchange.gov/usimpacts/

14 Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014). Chapter 2: Our Changing Climate. In: T*he Third U.S. National Climate Assessment.* In press.

15 Hawkins & Sutton. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of American Meteorological Society,* 90, 1095.

16 Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014). Chapter 2: Our Changing Climate. In: *The Third U.S. National Climate Assessment.* In press.

17 Tebaldi, C., Hayhoe, K., Arblaster, J., & Meehl, G. (2006). Going to the extremes: An intercomparison of model simulated historical and future changes in extreme events. *Climatic Change,* 79, 185-211.

# DELAWARE
# Climate Change Impact Assessment

PREPARED BY

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

## Section 3: Delaware's Resources

# Chapter 5 – Public Health Summary

## Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

## Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

## Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century (**Figure 5.1**).

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

- Heat waves, or consecutive days with sustained high temperatures, are expected to increase. Heat wave events in which temperatures are

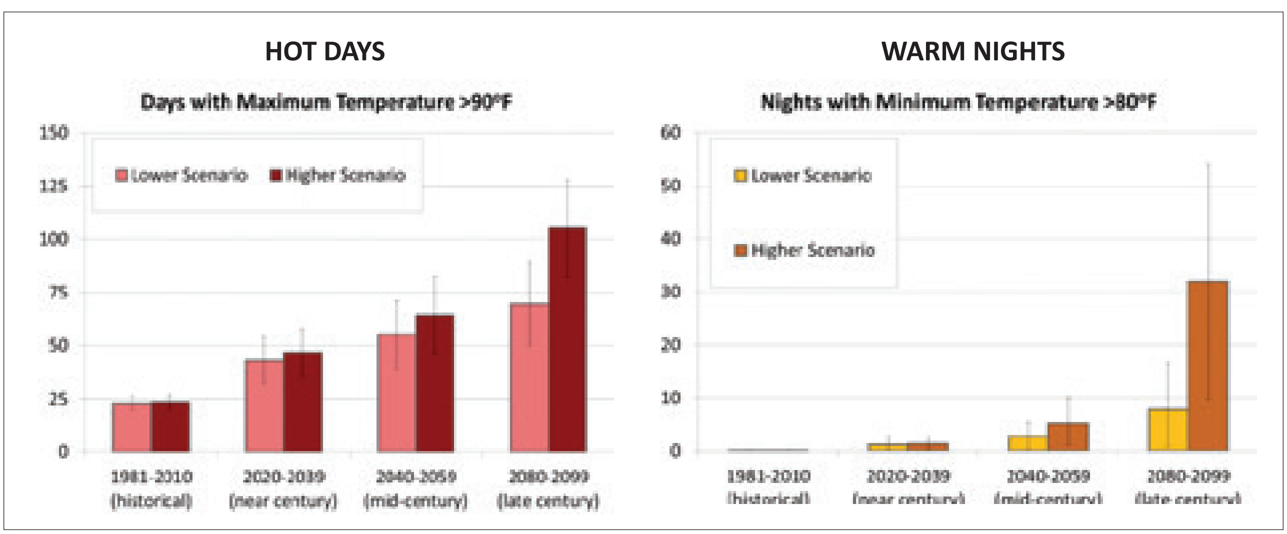


**Figure 5.1** Increasing daytime and nighttime temperatures. Source: Hayhoe et al. (2013).

over 95°F are projected to average 12 days (lower emission scenario) to 25 days (higher emission scenario). Hundred-degree (100°F) heat wave events over the next century could average around 4 days under a lower scenario and 13 days under a higher scenario.

## Precipitation Changes

- 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.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

## Potential Impacts to Public Health

- Delawareans' exposure to increased temperatures is projected to increase over the next century, especially in the summer months. Human health is directly affected by high heat. Delaware is likely to confront an increase in heat-related mortality and morbidity.

- Delawareans at risk to heat: Communities and individuals who are economically disadvantaged and/or have underlying illnesses may have increased impacts related to heat stress. Urban communities – specifically those without access to cooling – may suffer from increased impacts due to heat island effects.

- Delaware's air quality may continue to degrade as conditions for ground-level ozone increase (increased temperatures and heat waves). It is likely that without additional regulations or policies to control the pollutants that cause ground-level ozone, concentrations will increase and affect the health of people living in Delaware.

- Increasing precipitation and temperatures may lead to conditions that are ideal for increased exposure to allergens as well as pathogenic diseases. Relationships among the environment, organisms, and diseases are complex; however, increases in ideal breeding conditions (temperature and precipitation) or habitats for harmful organisms may increase human exposure.

- Risk factors play a strong role in community health as well as in individual health.

# Chapter 5 – Public Health

## Chapter Contents

- Overview of Climate Change and Public Health (based on review of scientific reports and studies – national scope)
- Direct Impacts
  - Temperature
- Indirect Impacts
  - Air Quality
  - Diseases
  - Risk Factors

## 5.1. Overview of Climate Change and Public Health

Human health is inextricably linked to the surrounding environment. The interactions between humans and their environment drive the spread of diseases and contribute to illness and even death. This section examines the role that climate plays with human health; how changing climatic conditions affect human health; those factors that contribute to increases in illness and mortality; and the public health vulnerabilities that the state of Delaware may face with a changing climate. The public health impacts of climate change transcend geographic borders—many of the issues discussed in this section are not unique to Delaware and continue to be of regional and national significance.

This chapter examines a variety of climatic impacts on human health, including temperatures, air quality, and disease. Direct impacts on human health are those impacts that are directly attributed to the change in the surrounding environment, primarily the human response to temperature. Indirect impacts are more nuanced and/or have an intermediate factor that influences human health. The indirect impacts on human health are those changes in the environment that shift how diseases spread, how organisms grow and proliferate, and how environmental factors can aggravate underlying health conditions. Extreme weather events such as hurricanes, nor'easters, coastal flooding, and other natural hazards directly affect public health, safety, and security. Public safety is considered in the infrastructure chapter (9).

A critical component of understanding human health is a population's or community's risk factors. Risk factors include but are not limited to age, socioeconomic status, access to medical care/facilities, and the surrounding built environment. These risk factors cannot be ignored when understanding a community's vulnerabilities to climate change and preparing for public health interventions.

## 5.2. Direct Impacts on Public Health Related to Climate Change

### 5.2.1. Temperature

Temperature, especially temperature extremes have direct and measurable impacts on the human body, and all people, regardless of age, socioeconomic status, and race are susceptible. Some of the visible impacts related to temperature include heat rash and frostbite; other impacts include exacerbation of underlying health problems such as cardiopulmonary conditions. It is critical to note that although temperature has direct effects on human health, some effects may be delayed and difficult to attribute to one temperature event. This section will discuss both high- and low-temperature impacts on human health and the changes associated with climate change.

Every year, attention is given to extreme heat and cold events, including in the state of Delaware. In general, Delaware's climate is considered temperate, characterized by warm to hot summers and cold winters. Delaware has two temperature zones: the north and the south. The northern climate zone includes New Castle County, where the average temperature is 54.0°F. Kent and Sussex Counties make up the southern climate zone, where the average yearly temperature is 58.1°F. Though Delaware is considered a temperate climate, extremes in temperature can affect human health throughout the state. It is well documented that illness and death increase as temperatures deviate from the region's average temperature range, even if the deviation is not considered extreme.

As temperatures deviate from typical ranges, illness and mortality become more prevalent. The mechanisms that account for the body's reaction to heat and cold are the same: the body must work harder to maintain a steady core temperature.[2] Once the body cannot regulate the core temperature, illness and mortality begin to occur. Not all responses to temperature are straightforward. As mentioned above, some of the direct impacts of temperature are easily understood and attributed to exposure to extreme temperatures, while other impacts may be more nuanced. These indirect impacts include the exacerbation of underlying health conditions, which may delay onset of illness and/or even death. Studies have found that the onset of temperature-related mortality varies between hot and cold events. Mortality almost immediately peaks (2 to 5 days) following a high heat event, while mortality following a cold temperature event can be delayed up to 30 days.[3] Recognizing this deviation in mortality is important for responding to and preparing for extreme temperature events in those populations most at risk.

## Extreme Heat

Heat is the leading cause of weather-related death in the United States.[4] The Centers for Disease Control and Prevention (CDC) defines a heat wave as, "A period of abnormally and uncomfortably hot and unusually humid weather. Typically a heat wave lasts two or more days."[5] There are plenty of examples of the impacts of heat waves across the nation, including the 2006 California heat wave that claimed the lives of 400 people[6] and one of the most notable U.S. heat waves, which occurred in Chicago in 1995 and resulted in at least 700 deaths.[7] These events, along with others around the globe, continue to gain the attention of the public and government officials.

Prolonged exposure to heat, especially high heat days combined with high humidity, can cause death by overwhelming the body's cooling systems, leading to cardiovascular stress and failure. Direct impacts of heat include heat rash, heat cramps, heat exhaustion, and heat stroke. Heat stroke is considered the most serious heat-related illness; it occurs when the body can no longer maintain its core temperature. At that point body temperature may rise to 106°F or more in less than 15 minutes, causing death or permanent disability.[8] Another bodily response to heat is heavy perspiration. Loss of fluids further stresses the body's responses to heat and can limit the ability of the body's circulatory system. Heat rash, cramps, exhaustion, stroke, and dehydration account for a portion of heat-related mortality. Aggravation of chronic or underlying illnesses can also cause the failure of the heart, kidneys, lungs, and other internal organs as the body works harder to cool the core.[9]

Urban heat island impacts also play a role in public health. Urban areas typically have large amounts of asphalt, concrete, and other surfaces that absorb and retain heat, leading to higher temperatures compared to rural areas. In Delaware, the northern, more urbanized portion of the state can have temperatures higher than the southern region of the state. The U.S. Environmental Protection Agency (US EPA) states that in cities with one million or more people, annual average temperatures can be 1.8˚F to 5.4˚F higher than surrounding rural areas. Exposed urban surfaces (e.g., roofs, asphalt, etc.) can be heated 50 to 90˚F warmer than the surrounding air temperature. Even after the sun sets, the urban areas can be warmer than surrounding areas. As buildings, asphalt, and concrete cool in the evening, they slowly release the heat that was absorbed during the day, warming the night air. The urban heat island effect can exacerbate heat-related illness and mortality in urban areas.[10] Research has found that urban populations can be at a higher risk for heat-related illness due to the heat island effect,[11] especially people who do not have access to air conditioning or who have limited social interactions (isolation).

The CDC estimates that annual temperature-related mortality in the United States could increase from approximately 700 deaths today to as many as 3,000 to 3,500 by the end of the century.[12] Projections indicate that annual average and summertime temperatures in the Mid-Atlantic region, including Delaware, will be warmer. Average temperature projections for Delaware in the near term (2020-2039) are for increases of 1.5 to 2.5°F. By mid-century (2040-2059), the lower emission scenario projects changes ranging from 2.5 to 4°F and the higher emission scenario projects that changes could be as high as 4.5°F. Extreme high temperatures are also expected to increase. Projections show that very warm days (temperatures over 95°F) are likely to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

Heat waves[a] are also expected to increase (**Figure 5.2**). Historically, there are on average around 2 consecutive days with temperatures over 95°F per year, and rarely days over 100°F (no more than one day per year). By late-century, the longest period of time over 95°F could average around 12 days per year under the lower emission scenario and up to 25 days per year under the higher emission scenario. Hundred-degree (100°F) heat wave events over the next century could average around 4 days (lower scenario) to 13 days (higher scenario).

[a] Dr. Katharine Hayhoe defines heat waves thus: "An extreme heat wave, based on Kunkel et al. (1998), is at least 4 consecutive days where average (day plus nighttime temperature) exceeds the historical 1-in-10-year event. In other words, such heat waves are calculated based on the historical record of the strongest heat wave per decade."

## Extreme Cold

Exposure to cold can cause not only direct impacts such as hypothermia and frostbite, but also illness or mortality from respiratory infections such as influenza and pneumonia. Research continues to better explain how the spread of influenza and other respiratory diseases is affected by temperature changes.[13] There is a general correlation between annual average warming related to climate change and decreased mortality related to cold weather extremes. Delaware temperature projections estimate that the number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039 to only 3 to 4 days per year by 2080-2099.

# 5.3. Indirect Impacts on Public Health Related to Climate Change

## 5.3.1. Air Quality

Air quality is a serious health concern for Delaware's citizens. Historical levels of ozone and particulate matter have continually exceeded national standards under the Federal Clean Air Act, which is commonly referred to as nonattainment. In recent years, however, ozone and particulate matter levels are improving throughout the state.[14] Poor air quality is known to be harmful to human health through impacts on respiratory and cardiovascular systems. Air pollution in the

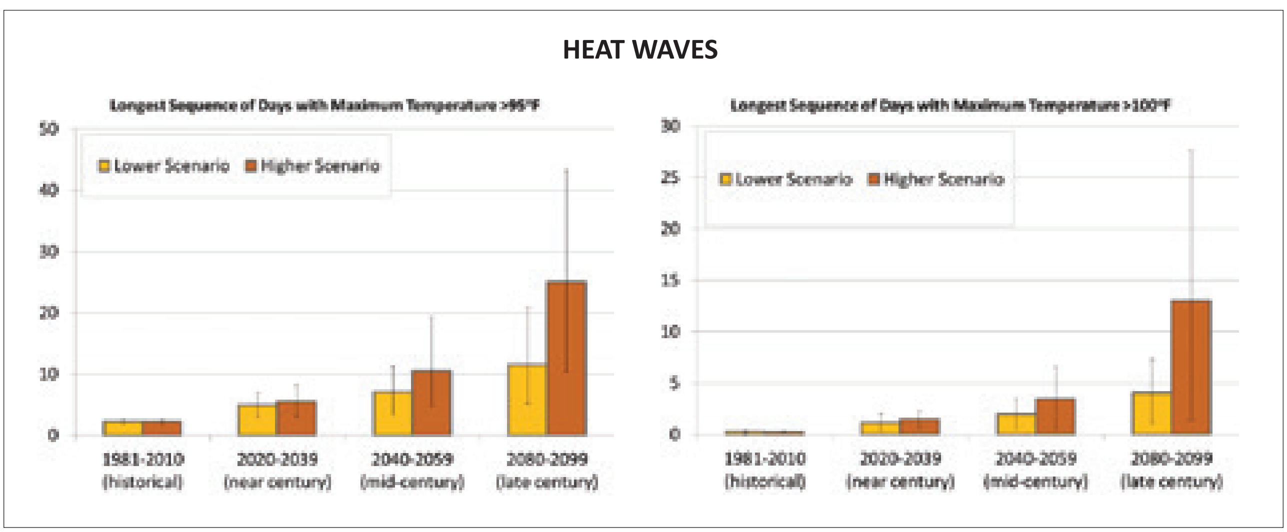


**Figure 5.2** Consecutive days of extreme high temperatures. Differences between the high scenario and low scenario are greater by mid-century and end-of-century. Source: Hayhoe et al. (2013).

form of ozone and particulate matter is well known to irritate the lungs and airways as well as the cardiovascular system.[15] In addition, pollen and mold can cause allergic reactions in populations that have increased sensitivity.

Asthma is an issue in Delaware. A 2005 study found that almost 72,000 adults and 23,000 children in Delaware reported suffering from asthma at some point in their life. The yearly costs associated with asthma in Delaware were estimated to be $25 to 30 million. Although asthma can be triggered by a variety of factors, air pollution, poor air quality, and mold and pollen are well known to exacerbate breathing issues in asthmatic individuals.[16]

## Ozone and Particulate Matter

Delaware is one of the most affected regions for ozone and particulate matter pollution in the United States. Trends indicate that although levels of both pollutants are improving in Delaware, there are still days every year when acceptable levels are exceeded. Specifically, the US EPA considers New Castle County as a nonattainment county for both ozone and particulate matter, and Sussex County is in nonattainment for ozone.

Delaware has made significant strides to improve air quality in the state. Since 1990, aggressive policies and regulations have targeted the precursor chemicals needed for ozone production as well as the sources of particulate matter.[17] This subsection examines ozone and particulate matter pollution and possible changes related to climate change.

## Ozone

Ozone is a respiratory irritant that even at low concentrations can cause coughing, shortness of breath, and chest discomfort, and can be a trigger for asthma attacks. Humans and human processes do not directly emit ozone; instead, human activities emit the chemicals that are necessary for the creation of ozone. Ozone is a reactive gas formed in the presence of pollutants emitted from industrial processes and combustion engines (nitrogen oxides and volatile organic compounds).[18] Local weather conditions are closely linked with the formation of ozone. Heat waves and high temperatures can create the optimum conditions for ozone generation, which is considered a summertime issue. Delaware's ozone season begins in April and ends in October, with the peak ozone season being June to August.[19]

The relationships between temperature and ozone creation are well understood. Climate change is expected to increase the intensity of summer temperatures. Increased summer temperatures and longer duration of heat waves may create optimum conditions for increased ozone formation.[20] Seasonal shifts in temperature may also influence ozone concerns in the state of Delaware. The current peak ozone season could be extended if warm temperatures increase in the "shoulder" months, now considered May and September. In addition to high temperatures, future increased emissions could also drive ozone formation during the peak ozone season.[21]

## Particulate Matter

Particulate matter is a type of air pollution composed of small solid and liquid particles that are suspended in the air, many of which are invisible to the naked eye. The particles vary in chemical makeup and composition. Particulate matter is characterized based on the size of the particle. Two categories are important when considering human health impacts: particulate matter 10 or ($PM_{10}$) and particulate matter 2.5

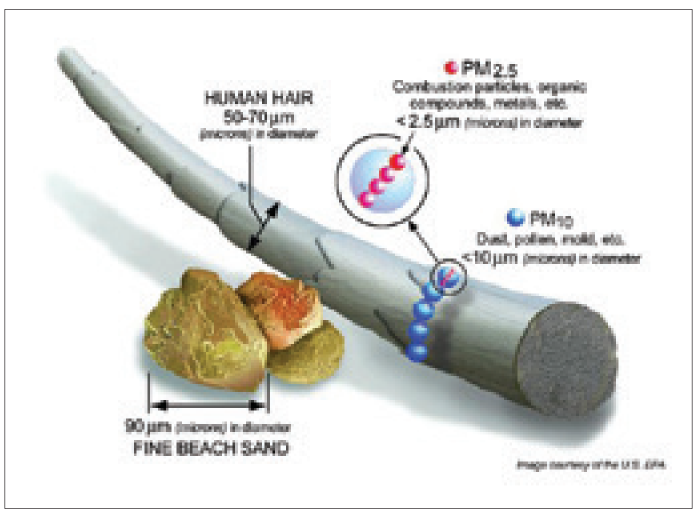


**Figure 5.3** Size comparison of particulate matter. Source: U.S. Environmental Protection Agency.

($PM_{2.5}$) – also referred to as coarse or fine particles (**Figure 5.3**). "Inhalable coarse particles"( $PM_{10}$) are generated from suspension of dust, soil, other soil-like materials (e.g., dust or materials from roads, windstorms, mining, and volcanoes), pollen, mold spores, and sea salts.[24] "Fine particles" ($PM_{2.5}$) can form in the atmosphere through chemical reactions or be released in various chemical and industrial processes such as emissions from vehicles, power plants, and industrial facilities.[25] ($PM_{10}$ is defined as particles that are larger than 2.5 micrometers (μm) but smaller than 10 μm. $PM_{2.5}$ is defined as particles that are smaller than 2.5 μm.)

Particle pollution is also known to be harmful to human health. Particles can enter the lungs and cause respiratory irritation and, depending on their size, can enter into the bloodstream, leading to impacts on cardiovascular health.[26] Coarse particles ($PM_{10}$) have been shown to increase asthma attacks and decrease lung function. Fine particles ($PM_{2.5}$) are small enough to work their way deep inside lung tissue. Research has shown that prolonged exposure to fine particles can cause respiratory problems, such as decreased lung function, and cardiovascular problems, such as irregular heartbeat and heart attacks.[27]

The linkages between climate change and particulate matter are not as well understood as the linkages with ozone. Particulate pollution is linked to human activities and environmental conditions. Extreme temperature may drive increases in both coarse and fine particle concentrations through increases in combustion processes that burn fossil fuels, increases in wildfire events, and changes in weather patterns that transport particles in the air.[28]

## Mold and Pollen

Allergies caused by molds and pollen are a common complaint throughout the United States. Mold is a living organism and therefore is sensitive to changes in environmental conditions, including temperature and precipitation. Pollen is a fine powdery substance produced by plants that can be released in the wind or transmitted to humans. Both mold and pollen can trigger allergic reactions in humans. Understanding the linkages between climate change and allergic illnesses is a focus of ongoing research. The US EPA found in their 2008 study on allergens and climate change that pollen production is expected to increase in many parts of the United States, because the timing of spring bloom will be earlier for many species that trigger allergic reactions. The study also found that pollen and mold content may be more potent in some species as environmental conditions become more favorable for plant growth and reproduction.[29]

The U.S. Global Change Research Program found that in certain areas, if climate projections are correct (increased temperatures, carbon dioxide, and precipitation) many plants will likely have increased growth and productivity.[30] Delaware's projections show that the growing season could lengthen from the current average of around 210 days per year to around 240 days (lower scenario) to 260 days (higher scenario) by the end of the century. This extension of the growing season will affect pollen production and increase the exposure to those populations sensitive to pollen.

Increasing amounts of carbon dioxide ($CO_2$) in the environment have been shown to increase plant productivity. This includes plant species that are well known to cause allergic reactions. Studies conducted on common ragweed found that higher levels of $CO_2$ and rising temperatures increased pollen production.[31] One experimental study found that the levels of $CO_2$ projected in the latter part of the 21st century increased ragweed pollen production by 131 to 320 percent.[32] Climate change could have multiple impacts for sensitive populations by lengthening pollen seasons, increasing pollen production and intensity, and introducing airborne allergens from new plant species.[33] These impacts may increase chronic allergy illness, health care costs, and absences from school and work related to respiratory illnesses.

Changes in temperature and precipitation may lead to more favorable environmental conditions for mold growth and reproduction. Indoor air quality may be degraded as temperature and humidity increases, especially those spaces without air conditioning or dehumidification

## Air Quality Index

The Air Quality Index (AQI) was created to inform the public of their surrounding air quality. A daily air quality reporting system was required in the 1977 amendments to the Clean Air Act and, after a name change in 1999, the AQI became the nationally recognized measure of air quality in the United States. Today, the US EPA and the Delaware Division of Air Quality, along with agencies in more than 300 major U.S. cities, work together to provide the daily air quality announcements as well as air quality forecasts. The AQI tracks the following air pollutants, all of which can be harmful to human health: ozone, particulate matter, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Daily monitors from across the country gather data on pollutants and send the information to the US EPA, where scientists run formulas to turn that data into the AQI value for that day. Cities and local air boards can also provide air quality forecasts to allow residents to plan for the coming day(s).

| Air Quality Index (AQI) Values | Levels of Health Concern | Colors | Implications for Public Health |
|---|---|---|---|
| When the AQI is in this range: | ... air quality conditions are: | ... as symbolized by this color: | |
| 0 to 50 | Good | Green | Air quality is satisfactory and poses little or no health risk. |
| 51 to 100 | Moderate | Yellow | Air quality is acceptable, but may pose a health concern for people who are especially sensitive. |
| 101 to 150 | Unhealthy for Sensitive Groups | Orange | Air quality may pose concerns for those who have sensitivities to air pollution. |
| 151 to 200 | Unhealthy | Red | Air quality is compromised and everyone may begin to experience health effects. |
| 201 to 300 | Very Unhealthy | Purple | Air quality is very unhealthy and everyone may experience more serious health effects. |
| 301 to 500 | Hazardous | Maroon | Air quality is hazardous to human health. The entire population is more likely to be affected by serious health effects. |

Source: This table was adapted from the US EPA's Air Quality Index and levels of health concern.

The AQI is an index that runs from 0 to 500, with 0 being the lowest level of pollution and 500 the highest. The higher the AQI number, the higher concern for human health. Generally, the level 100 corresponds to the national air quality standards that the US EPA has determined to be an acceptable level to protect human health. An index over 100 for a pollutant is considered to be unhealthy. Often there may be more than one pollutant at levels that are harmful to human health. If this is the case, the pollutant with the highest AQI value is reported for that day with a note about other pollutants that have harmful levels. Colors assist in communicating the AQI for the given day. The graphic below shows the AQI levels along with the implications for public health.[22]

The Delaware Division of Air Quality is taking active measures to monitor and alert Delawareans on the impacts of air quality by providing daily air quality alerts and forecasts for the state. The Delaware Air Quality Monitoring Network[23] allows residents to receive real-time air quality data throughout the state. The Division of Air Quality also works with surrounding states, planning organizations, and the US EPA on large-scale programs to control and prevent air pollution, including tougher emission controls on emitters of the heaviest pollution loads, cleaner-running cars, and vehicle emission testing programs. These measures are assisting in reducing air pollution throughout the state and making the air easier to breathe.

capabilities. These spaces could experience increasing incidences of mold growth and decreases in human respiratory health. Studies have suggested that extreme events that cause flooding could increase conditions for mold growth, especially in the presence of high humidity. Studies conducted after Hurricane Katrina found that mold growth increased in flooded buildings and spaces. For sensitive individuals, these changes can cause increased or prolonged allergic reactions.[34]

## 5.3.2. Diseases

The spread and transmission of diseases are shaped by the environment, climate, and human interactions. Seasonal patterns influence the diseases (viruses, bacteria, parasites, etc.), the mechanisms by which they spread (mosquitoes, ticks, etc.), and the exposure (spending time outdoors, swimming, etc.). Though all of these interactions are complex, changes in climate may influence the incidence of disease, the geographic distribution, and periods of exposure to diseases that harm human health.

### Vector-Borne Diseases

Vector-borne diseases (VBD) are transmitted from the infected bite of one organism (mosquitoes, ticks, fleas, mites, etc.) to humans and/or other animals.[35 36] Vector-borne diseases are some of the world's most problematic, including malaria, plague, West Nile virus, dengue fever, and the most common VBD in the United States, Lyme

**Table 5.1 Mosquitoes and vector-borne diseases in Delaware**

| *Disease* | *Mosquito Vector (scientific name)* | *Vector Characteristics* |
|---|---|---|
| Dengue fever | yellow fever *(Aedes aegypti)* | primary vector for dengue in far southern U.S. |
| | Asian tiger *(Aedes albopictus)* | a primary vector for dengue in southeast Asia; only a minor vector to date for dengue in far southern US |
| Malaria | common malaria *(Anopheles quadrimaculatus)* | common in Delaware, capable of causing locally transmitted malaria if malaria-infected humans are present |
| West Nile virus (WNV) | Asian tiger *(Aedes albopictus)* | a minor vector to date for WNV |
| | common house *(Culex pipiens)* (northern subspecies) *(Culex quinquefasciatus)* (southern subspecies) | primary WNV vector for humans |
| | unbanded saltmarsh or little sal *(Culex salinarius)* | brackish marsh relative of common house mosquito, secondary vector for WNV |
| | white-dotted *(Culex restuans)* | primary vector for WNV among birds |
| | cedar swamp or black-tailed *(Culiseta melanura)* | primary vector for WNV among birds |
| | encephalitis *(Culex tarsalis)* | primary vector for WNV among birds |
| Eastern equine encephalitis (EEE) | cedar swamp or black-tailed *(Culiseta melanura)* | primary vector for EEE among birds |
| | cattail or irritating *(Coquilletidia perturbans)* | freshwater vector for EEE in humans |
| | floodwater *(Aedes vexans)* | freshwater vector for EEE in humans |
| | brown saltmarsh *(Aedes cantator)* | secondary vector for EEE in humans |
| | common saltmarsh *(Aedes sollicitans)* | primary vector in Delaware for EEE for humans |
| St. Louis encephalitis (STE) | common house<br>*(Culex pipiens )*(northern subspecies)<br>*(Culex quinquefasciatus)* (southern subspecies)<br>Other species, including some *Culex, Aedes, and Coquillettidia,* can be vectors | primary vector *(Culex pipiens)* in Delaware for STE for humans |
| La Crosse encephalitis (LCE) | eastern tree hole *(Aedes triseriatus)* | Primary vector for LCE |

disease.[37] The vectors, the diseases, the hosts, and the environment all have complex interactions that make predicting and modeling vector-borne disease spread difficult.[38]

Mosquitoes transmit a variety of diseases known in the United States (**Table 5.1**), such as West Nile virus and encephalitis, as well as diseases more commonly found in the tropics, such as malaria and dengue fever. Historically, the Mid-Atlantic was prone to outbreaks of malaria; however, advances in detection, public health, water purification, and medical treatment have decreased occurrences of malaria in the region.[39] Other tropical diseases are not endemic to Delaware, although they can occur as the result of travel outside of the region or country.[40]

Delaware is considered a hot spot for mosquito activity.[41] This is primarily because the large amount of wetlands (coastal and freshwater) throughout the state and high population densities along the coast lead to higher rates of exposure. Of the 57 species of mosquitoes found in Delaware, 19 are identified as problematic. Problematic mosquitoes are those that act as the vector for disease or are considered to be an aggressive nuisance to humans as well as other mammals and birds. Mosquito season in Delaware ranges from mid-March to late October or early November. During this time, mosquitoes are most prevalent and environmental conditions are optimal for breeding.[42]

Ticks are another common vector throughout the United States and in Delaware. Ticks are known to spread a variety of diseases, including Lyme disease, spotted fever rickettsiosis, and Ehrlichia, as well as rarer diseases such as tularemia and babesiosis.[43] Lyme disease is the most common tick-borne disease in the United States and in Delaware. In 2011, the CDC reported just over 24,000 cases of Lyme disease in the United States[44]; this includes 874 reported cases in the Delaware.[45] It is important to note that Lyme disease can go undetected and is underreported in the United States. The CDC also estimates that in 2011 there were another 8,700 probable, but not confirmed, cases of Lyme disease in the United States, including 106 probable cases in Delaware. Delaware's rate of incidence is 84.6 confirmed cases per 100,000 population, the highest in the nation.[46] **Table 5.2** lists common tick-borne diseases that have been reported in Delaware and the species of ticks that carry the disease.

The interactions among the vectors, diseases, and hosts are complex, as are the impacts of climate change, including increasing temperatures and changes in precipitation patterns. Warmer average temperatures may hasten pathogen and vector development and increase survivability. Geographic ranges may shift for both the vector and the pathogen, leading to emergence of diseases in new areas. Changes in temperature and precipitation increase duration of infectiousness, allowing for increased periods of transmission and outbreaks of disease. However, increased awareness of the diseases, improved public health infrastructure, and monitoring and control of the vectors are likely to prevent large-scale outbreaks in the United States.[47]

**Table 5.2 Ticks and vector-borne diseases in Delaware**

| Disease | Vector |
|---|---|
| Lyme disease | blacklegged tick (also known as deer tick) *(Ixodes scapularis)* |
| Rocky Mountain spotted fever | wood tick (also known as American dog tick *(Dermacentor variabilis)*<br>brown dog tick *(Rhipicephalus sanguineus)* |
| Babesiosis | blacklegged tick *(Ixodes scapularis)* |
| Ehrlichiosis/ anaplasmosis | lone star tick *(Amblyomma americanum)*<br>blacklegged tick *(Ixodes scapularis)* |
| Tularemia | wood tick *(Dermacentor variabilis)*<br>lone star tick *(Amblyomma americanum)* |
| Powassan encephalitis | blacklegged tick *(Ixodes scapularis)* |

## Water- and Food-Borne Diseases

Water and food-borne pathogens are a current issue of concern, and climate change has the potential to increase the spread of and exposure to these pathogens. Waterborne pathogens affect human health via drinking water contamination and skin contact with contaminated waters. Waterborne diseases can contaminate food through application to fresh produce and in waters that affect seafood. The CDC estimates that each year 1 in 6 people in the United States, roughly 48 million people, will be sickened by consuming contaminated food.[48] The majority of waterborne and food-borne pathogens are bacteria (*Salmonella*, *Campylobacter*, *Vibrio*, and *Leptospira*), viruses (Noroviruses and Rotaviruses), and parasites such as *Crytospridium* and *Giardia*. Incidences of water- and food-borne illnesses are underreported because symptoms are generally short-lived, making quantification difficult.

Water and food safety are complex issues, and climate change may influence many of the variables that lead to increases in water- and food-borne illness.[49] Climate change could increase human exposure to waterborne and food-borne diseases. Increases in precipitation, warmer temperatures, and increasing frequency of extreme events could make water- and food-borne illnesses and outbreaks a more common occurrence.[50 51 52]

The CDC describes several direct and indirect impacts of climate change on waterborne disease. Direct impacts include changes in temperature and precipitation frequency that may change local flood and run-off conditions and affect wastewater treatment facilities. In addition, changes in ocean health could lead to human exposure to neurotoxins from seafood and shellfish.[53] Indirect impacts include changes in ecosystems that may foster increases in pathogens, and extreme events that would result in decreased water quality and allow pathogens to proliferate.[54]

Research has found a strong correlation between outbreaks of waterborne illness and extreme rainfall event. Increases in pathogens in untreated, surface, and groundwater have been documented across the nation.[55] Increased precipitation creates pathways for pathogens to spread, increasing contamination risks in drinking and recreational waters as well as water used to process fresh foods and shellfish. Increased temperatures could increase pathogen survivability and geographic range of the microorganisms. Temperatures may also influence the developmental cycles of vectors that may spread the pathogens. The CDC's Climate Change Science Program has noted a strong association between sea surface temperatures and the proliferation of many *Vibrio* bacteria species, including the species that causes cholera. The CDC has suggested that rising temperatures would lead to increased occurrences of *Vibrio*-related illnesses.[56]

Wastewater treatment infrastructure is often where extreme events can increase exposure to waterborne pathogens. Combined sewer system (systems that treat both storm water and wastewater) treatment facilities are currently affected by extreme precipitation events, which can overwhelm these systems, causing backups and/or overflows, leading to contamination of surrounding surface waters. Combined sewer systems are found throughout Delaware, and several have been known to back up and overflow during precipitation events. Onsite sewage treatment facilities (septic systems) may fail due to high water tables and/or repeated flooding. Septic system failure or malfunction may release bacteria and pathogens, leading to contaminated surface and/or ground water. Coastal areas may also have the compounded risk of septic systems and sea level rise. (Note that water infrastructure is also discussed in the water resources chapter [6].) Urban and rural runoff serves as an additional pathway for surface water contamination. Pathogens can enter water systems through runoff from agricultural operations and livestock operations as well as urban sites contaminated with chemicals or other waste.

## 5.3.3. Risk Factors

Certain populations and communities have higher risks of climate-related incidents. The risks related to temperature, air quality, and disease vary depending on certain risk factors that include age, socioeconomic factors, underlying health conditions, and degree of exposure. Special attention must be given to these risk groups, changes in these populations, and development patterns when considering adaptation or intervention measures related to future climate change and climate impacts.

### Age

Infants, children, and the elderly are of particular concern. Children's small body size can limit their ability to deal with high heat or cold. In addition, young children's nervous system is not fully developed, furthering hampering their ability to cope with extreme temperature.[57] Children often do not recognize the symptoms of exposure and may have increased sensitivities to air pollution because of time spent outside. Elderly people also have difficulty regulating their core body temperature due to a reduced ability to sense extremes. In addition, the elderly are more likely to have chronic diseases or underlying health problems.[58]

In Delaware, population projections show that overall the population is graying. It's estimated that by 2040 almost a quarter (24 percent) of the population will be over the age of 65. In 2012, around 15 percent of the population was over age 65. Population projections show that the number of children under the age of 10 is expected to decrease slightly on a percentage basis from 12 percent to 11 percent.[59] These shifts in population, along with increasing temperatures, may have public health impacts on populations identified to be sensitive to extreme temperatures.

## Socioeconomic Factors

People living in poverty are especially vulnerable to health risks related to climate. Low-income individuals who lack access to heating and/or cooling, medical assistance and care, and/or live alone are all considered to be at risk to temperature extremes. Socioeconomic factors also play a role in displacement after extreme events. People of lower socioeconomic standing can often not afford to or do not have the resources to rebuild in the existing community. In addition, they often have difficulties regaining the livelihoods that they had prior to the event. Migration can also be an issue with low-income communities post-event. Many people and households will choose to permanently relocate instead of returning to their home community. This can lead to mental health distress and/or stress-related disorders.[60] According to the 2010 U.S. Census, there are currently 102,700 people (11.2 percent) in Delaware living below poverty level.[b] These populations may struggle to cope with changes in temperature, precipitation, and extreme events.

## Underlying Health Conditions

Underlying health conditions, such as heart and lung diseases, diabetes, and autoimmune disorders, can impair the body's response to extreme temperature, as well as vector-, water- and food-borne illness. These impacts may aggravate the underlying conditions, leading to illness or death. Individuals who are obese and those with limited physical fitness can be at high risk for temperature-related problems. In addition, certain medications that may be used to treat the underlying condition may reduce the body's ability to maintain a steady core temperature by obstructing blood flow or inhibiting mineral and fluid balance. [61]

## Exposure

People who work or spend time outdoors may be at risk to extreme temperatures and to diseases. Workers who spend a great deal of time outside during the summer months are more likely to experience a temperature-related illness (heat stroke or frostbite) or dehydration. In urban areas, individuals who live in the upper floors of buildings but do not have access to temperature controls can also be at risk for extreme temperatures. This is most notable with the urban heat island effect and lack of air conditioning.

Children and adults who spend time outdoors have a greater exposure to air pollution, which can affect their respiratory system and increase sensitivity. Outdoor recreationalists who spend time in wooded areas or parks have greater exposure to vector-borne diseases such as Lyme disease and West Nile virus. In addition, those people who recreate in untreated water bodies (nonchlorinated or underchlorinated) can have increased exposure to waterborne diseases.

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**b** Poverty level is defined by the U.S. Department of Health and Human Services and is based on income and household size guidelines. For Delaware, 2013 poverty guidelines are, for a family/household of four people, a household income of $23,550. See http://aspe.hhs.gov/poverty/13poverty.cfm#guidelines for additional information on poverty guidelines.

# 5.4. Potential Impacts of Climate Change to Delaware's Public Health

## 5.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The **lower scenario** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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.

### Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5ºF are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4ºF and around 4.5ºF for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

### Extreme Temperatures

- The number of very cold days (minimum temperature below 20ºF) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95ºF) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century (**Figure 5.1**).

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

- Heat waves, or consecutive days with sustained high temperatures, are expected to increase. Heat wave events in which temperatures are over 95°F are projected to average 12 days (lower emission scenario) to 25 days (higher emission scenario). Hundred-degree (100°F) heat wave events over the next century could average around 4 days under a lower scenario and 13 days under a higher scenario (**Figure 5.4**).

### Precipitation Changes

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

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

## 5.4.2. Potential Impacts to Public Health

- Delawareans' exposure to increased temperatures is projected to increase over the next century- especially in the summer months. Human health is directly affected by high heat. Delaware is likely to confront an increase in heat-related mortality and morbidity.

- Delawareans at risk to heat: Communities and individuals who are economically disadvantaged and/or have underlying illnesses may have increased impacts related to heat stress. Urban communities – specifically those without access to cooling – may suffer from increased impacts due to heat island effects.

- Delaware's air quality may continue to degrade as conditions for ground level ozone increase (increased temperatures and heat waves). It is likely that without additional regulations or policies to control the pollutants that cause ground level ozone, concentrations will increase and affect the health of people living in Delaware.

- Increasing precipitation and temperatures may lead to conditions that are ideal for increased exposure to allergens and mold as well as pathogenic diseases. Relationships among the environment, organisms, and diseases are complex; however, increases in ideal breeding conditions (temperature and precipitation) or habitats for harmful organisms may increase human exposure.

- Risk factors play a strong role in community health as well as in individual health.

# Sources

## (Endnotes)


1 Hayhoe, K., Stoner, A., & Gelca, R. (2013). Climate Change Projections and Indicators for Delaware. Report dated December 2013.

2 Shortle, J., Abler, D., Blumsack, S. Crane, R., Kaufman, Z., McDill, M., Najjar, R., Ready, R., Wagener, T., & Wardrop, D. (2009). *Pennsylvania climate impact assessment report to the Department of Environmental Protection.* The Environment and Natural Resources Institute. The Pennsylvania State University report, June 2009. Retrieved from http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-75375/7000-BK-DEP4252.pdf

3 McGeehin, M., & Mirabelli, M. (2001). The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environmental Health Perspectives, 109(2), 185-189.* http://ehpnet1.niehs.nih.gov/docs/2001/suppl-2/185-189mcgeehin/abstract.html

4 Karl, T., Melillo, J., & Peterson, T. (Eds.). (2009). *Global climate change impacts in the United States* (pp. 89-98). Cambridge University Press report. Retrieved from http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf

5 Centers for Disease Control and Prevention. (2012). *Emergency response and response information for specific groups.* Atlanta, GA: National Center for Environmental Health (NCEH)/ Agency for Toxic Substances and Disease Registry (ATSDR), Coordinating Center for Environmental Health and Injury Prevention (CCEHIP). Retrieved January 12, 2013 from http://emergency.cdc.gov/disasters/extremeheat/specificgroups.asp

6 Deschenes, O., & Moretti, M. (2009). Extreme weather events, mortality and migration. *The Review of Economics and Statistics,* MIT Press, 91(4), 659-681, 02.

7 McGeehin, M., & Mirabelli, M. (2001). The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environmental Health Perspectives,* 109(2), 185-189. http://ehpnet1.niehs.nih.gov/docs/2001/suppl-2/185-189mcgeehin/abstract.html

8 Centers for Disease Control and Prevention. (2012). *Frequently asked questions (FAQ) about extreme heat.* Atlanta, GA: National Center for Environmental Health (NCEH)/ Agency for Toxic Substances and Disease Registry (ATSDR), Coordinating Center for Environmental Health and Injury Prevention (CCEHIP). Retrieved January 12, 2013 from http://www.bt.cdc.gov/disasters/extremeheat/faq.asp

9 Shortle, J., Abler, D., Blumsack, S. Crane, R., Kaufman, Z., McDill, M., Najjar, R., Ready, R., Wagener, T., & Wardrop, D. (2009). *Pennsylvania climate impact assessment report to the Department of Environmental Protection.* The Environment and Natural Resources Institute. The Pennsylvania State University report, June 2009. Retrieved from http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-75375/7000-BK-DEP4252.pdf

10 U.S. Environmental Protection Agency. (2008). *Reducing urban heat islands: Compendium of strategies.* Retrieved January 12, 2013 from http://www.epa.gov/hiri/resources/compendium.htm

11 McGeehin, M., & Mirabelli, M. (2001). The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environmental Health Perspectives,* 109(2), 185-189. http://ehpnet1.niehs.nih.gov/docs/2001/suppl-2/185-189mcgeehin/abstract.html

12 Centers for Disease Control and Prevention. (2009). *Climate and Health Program, Heat waves.* Atlanta, GA National Center for Environmental Health. Retrieved January 12, 2013 from http://www.cdc.gov/climateandhealth/effects/heat.htm

13 Ebi, K., Balbus, J., Kinney, P., Lipp, E., Mills, D., O'Neill, M., & Wilson, M. (2008). Effects of global change on human health. In: *Analyses of the effects of global change on human health and welfare and human systems.* The U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 39–87. Retrieved January 12, 2013 http://downloads.climatescience.gov/sap/sap4-6/sap4-6-final-report-all.pdf

14 Delaware Department of Natural Resources and Environmental Control, Division of Air Quality. (2011). *Delaware annual air quality report.* Delaware Division of Air Quality Report. Retrieved January 13, 2012 http://www.dnrec.delaware.gov/whs/awm/AQM/Documents/Ann%20Rpt%2011%20final.pdf

15 U.S. Environmental Protection Agency. (2003). *Ozone: Good up high, bad nearby.* (EPA publication EPA-451/K-03-001) Washington, DC: Office of Air and Radiation. Retrieved January 12, 2013 http://www.epa.gov/glo/pdfs/ozonegb.pdf

16 Delaware Department of Health and Social Services & Delaware Department of Natural Resources and Environmental Control. (2005). *The burden of asthma in Delaware.* Delaware Division of Public Health. Retrieved January 13. 2013 http://dhss.delaware.gov/dph/dpc/files/asthmaburden_rpt.pdf

17 Delaware Department of Natural Resources and Environmental Control, Division of Air Quality. (2011). Delaware annual air quality report. *Delaware Division of Air Quality Report.* Retrieved January 13, 2012 http://www.dnrec.delaware.gov/whs/awm/AQM/Documents/Ann%20Rpt%2011%20final.pdf

18 U.S. Environmental Protection Agency. (2003). *Ozone: Good up high, bad nearby.* (EPA publication EPA-451/K-03-001) Washington, DC: Office of Air and Radiation. Retrieved January 12, 2013 http://www.epa.gov/glo/pdfs/ozonegb.pdf

19 Majeed, M. A., Delaware Department of Natural Resources and Environmental Control, Division of Air Quality. (personal communication, August 4, 2011).

20 Ebi, K., Balbus, J., Kinney, P., Lipp, E., Mills, D., O'Neill, M., & Wilson, M. (2008). Effects of global change on human health. In: *Analyses of the effects of global change on human health and welfare and human systems.* The U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 39–87. Retrieved January 12, 2013 http://downloads.climatescience.gov/sap/sap4-6/sap4-6-final-report-all.pdf

21 Majeed, M. A., Delaware Department of Natural Resources and Environmental Control, Division of Air Quality. (personal communication, August 4, 2011).

22 U.S. Environmental Protection Agency. (2012). *Particulate matter.* Retrieved January 13, 2013 http://www.epa.gov/pm/

23 U.S. Environmental Protection Agency. (2012). *Particulate matter.* Retrieved January 13, 2013 http://www.epa.gov/pm/

24 Portier, C., Thigpen Tart, K., Carter, S., Dilworth, C., Grambsch, A., Gohlke, J., … Whung, P-Y. (2010). *A human health perspective on climate change: A report outlining the research needs on the human health effects of climate change.* Research Triangle Park, NC. Environmental Health Perspectives/National Institute of Environmental Health Sciences. doi:10.1289/ehp.1002272. Retrieved January 13, 2013 http://www.niehs.nih.gov/climatereport

25 Portier, C., Thigpen Tart, K., Carter, S., Dilworth, C., Grambsch, A., Gohlke, J., … Whung, P-Y. (2010). *A human health perspective on climate change: A report outlining the research needs on the human health effects of climate change.* Research Triangle Park, NC. Environmental Health Perspectives/National Institute of Environmental Health Sciences. doi:10.1289/ehp.1002272. Retrieved January 13, 2013 http://www.niehs.nih.gov/climatereport

26 Ebi, K., Balbus, J., Kinney, P., Lipp, E., Mills, D., O'Neill, M., & Wilson, M. (2008). Effects of global change on human health. In: *Analyses of the effects of global change on human health and welfare and human systems.* The U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 39–87. Retrieved January 12, 2013 http://downloads.climatescience.gov/sap/sap4-6/sap4-6-final-report-all.pdf

27 U.S. Environmental Protection Agency. (2009). *Air Quality Index: A guide to air quality and your health* (EPA publication EPA-456/F-09/002). Research Triangle Park, NC. Office of Air Quality Planning and Standards Outreach and Information Division. Published August 2009. Retrieved January 15, 2013 http://www.epa.gov/airnow/aqi_brochure_08-09.pdf

28 Delaware Department of Natural Resources and Environmental Control. (undated). *Delaware air quality monitoring network.* Delaware Division of Air Quality. Retrieved January 15, 2013 http://apps.dnrec.delaware.gov/AirMonitoring/

29 U.S. Environmental Protection Agency. (2008). *Review of the impacts of climate variability and change on aeroallergens and their associated effects.* (EPA publication EPA-600/R-06/164F). Washington, DC. National Center for Environmental Assessment, Office of Research and Development. Published August 2008. Retrieved January 12, 2013 http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=190306#Download

30 Melillo, J., Janetos, A., Schimel, D., & Kittel, T. (2001). Vegetation and biochemical scenarios. In *Climate change impacts on the United States.* The potential consequences of climate variability and change, foundation report. United States Global Change Research Program. Cambridge University Press, Cambridge. Retrieved January 13, 2013 http://www.gcrio.org/NationalAssessment/2EC.pdf

31 Rogers, C., Wayne, P., Macklin, M., Muilenberg, C., Wagner C., Epstein, P., & Bazzaz, F. (2006). Interaction of the onset of spring and elevated atmospheric CO2 on ragweed *(Ambrosia artemisiifolia L.)* pollen production. *Environmental Health Perspectives,* 114(6), 865-869. doi:10.1289/ehp.8549.

32 Ziska, L., & Caulfield, F. (2000). Rising $CO_2$ and pollen production of common ragweed. *Australian Journal of Plant Physiology,* 27(10), 893-898.

33 U.S. Environmental Protection Agency. (2008). *Review of the impacts of climate variability and change on aeroallergens and their associated effects.* (EPA publication EPA-600/R-06/164F). Washington, DC. National Center for Environmental Assessment, Office of Research and Development. Published August 2008. Retrieved January 12, 2013 http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=190306#Download

34 U.S. Environmental Protection Agency. (2008). *Review of the impacts of climate variability and change on aeroallergens and their associated effects.* (EPA publication EPA-600/R-06/164F). Washington, DC. National Center for Environmental Assessment, Office of Research and Development. Published August 2008. Retrieved January 12, 2013 http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=190306#Download

35 Portier, C., Thigpen Tart, K., Carter, S., Dilworth, C., Grambsch, A., Gohlke, J., … Whung, P-Y. (2010). *A human health perspective on climate change: A report outlining the research needs on the human health effects of climate change.* Research Triangle Park, NC. Environmental Health Perspectives/National Institute of Environmental Health Sciences. doi:10.1289/ehp.1002272. Retrieved January 13, 2013 http://ww.niehs.nih.gov/climatereport

36 Ebi, K., Balbus, J., Kinney, P., Lipp, E., Mills, D., O'Neill, M., & Wilson, M. (2008). Effects of global change on human health. In: *Analyses of the effects of global change on human health and welfare and human systems.* The U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 39–87. Retrieved January 12, 2013 http://downloads.climatescience.gov/sap/sap4-6/sap4-6-final-report-all.pdf

37 Delaware Department of Health and Social Services, Division of Public Health. (undated). *Lyme disease.* Retrieved January 13, 2013 http://dhss.delaware.gov/dph/epi/lyme.html

38 Portier, C., Thigpen Tart, K., Carter, S., Dilworth, C., Grambsch, A., Gohlke, … Whung, P-Y. (2010). *A human health perspective on climate change: A report outlining the research needs on the human health effects of climate change.* Research Triangle Park, NC. Environmental Health Perspectives/National Institute of Environmental Health Sciences. doi:10.1289/ehp.1002272. Retrieved January 13, 2013 http://www.niehs.nih.gov/climatereport

39 Meredith, W., Delaware Department of Natural Resources and Environmental Control, Mosquito Control Section. (personal communication, August 10, 2011).

40 Rogers, J. & Shannon, M., Delaware Department of Health and Social Services, Division of Public Health. (personal communication, November 17, 2011).

41 Meredith, W., Delaware Department of Natural Resources and Environmental Control, Mosquito Control Section. (personal communication, August 10, 2011).

42 Meredith, W., Delaware Department of Natural Resources and Environmental Control. (undated). *Delaware's "bad actor" mosquitoes.* Delaware Mosquito Control Section. Retrieved January 13, 2013 http://www.dnrec.delaware.gov/fw/Services/Documents/DELAWARE%27s%20BAD-ACTOR%20MOSQUITOES%20_2_.pdf

43 Centers for Disease Control and Prevention, Division of Vector-Borne Diseases (DVBD). (2012). *Ticks.* Retrieved January 13, 2013 http://www.cdc.gov/ticks/

44 Centers for Disease Control and Prevention. (2012). *Lyme disease: Reported cases of Lyme disease by state or locality 2002-2011.* National Center for Emerging and Zoonotic Infectious Diseases (NCEZID) & Division of Vector-Borne Diseases (DVBD). Retrieved January 13, 2013 http://www.cdc.gov/lyme/stats/chartstables/reportedcases_statelocality.html

45 Delaware Department of Health and Social Services, Division of Public Health. (2011). *Communicable disease yearly statistics.* Retrieved January 13, 2013 http://dhss.delaware.gov/dhss/dph/healthdatastats.html

46 Centers for Disease Control and Prevention. (2012). *Lyme disease: Reported cases of Lyme disease by state or locality 2002-2011.* National Center for Emerging and Zoonotic Infectious Diseases (NCEZID) & Division of Vector-Borne Diseases (DVBD). Retrieved January 13, 2013 http://www.cdc.gov/lyme/stats/chartstables/reportedcases_statelocality.html

47 Ebi, K., Balbus, J., Kinney, P., Lipp, E., Mills, D., O'Neill, M., & Wilson, M. (2008). Effects of global change on human health. In: *Analyses of the effects of global change on human health and welfare and human systems.* The U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 39–87. Retrieved January 12, 2013 http://downloads.climatescience.gov/sap/sap4-6/sap4-6-final-report-all.pdf

48 Centers for Disease Control and Prevention. (2012). *CDC Estimates of Foodborne Illness in the United States.* National Center for Emerging and Zoonotic Infectious Diseases (NCEZID) & Division of Foodborne, Waterborne, and Environmental Diseases (DFWED). Retrieved January 13, 2013 http://www.cdc.gov/foodborneburden/2011-foodborne-estimates.html

49 Kniel, K., University of Delaware, Department of Animal and Food Sciences. (personal communication, November 29, 2012).

50 Rose, J., Epstein, P., Lipp, E., Sherman, B., Bernard, S., & Patz, J. (2001). Climate variability and change in the United States: Potential impacts on water and foodborne diseases caused by microbiologic agents. *Environmental Health Perspectives* 109 (supp2), 211-221. Retrieved January 13, 2013 http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1240668/pdf/ehp109s-000211.pdf

51 Greer, A., Ng V., & Fisman, D. (2008). Climate change and infectious disease in North America: The road ahead. *The Canadian Medical Association* 178(6), 715-722. Retrieved January 13, 2013 http://www.cmaj.ca/content/178/6/715.full.pdf+html

52 Curriero, F., Patz, J., Rose, J. & Lele, S. (2001). The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *American Journal of Public Health,* 91, 1194–1199. Retrieved January 13, 2013 http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1446745/

53 Centers for Disease Control and Prevention. (2010). *Climate and Health Program: Neurological diseases and disorders.* Climate and Health Program & National Center for Environmental Health. Retrieved July 2, 2013 http://www.cdc.gov/climateandhealth/effects/neurological.htm

54 Centers for Disease Control and Prevention. (2010). *Climate and Health Program: Waterborne diseases.* Climate and Health Program & National Center for Environmental Health. Retrieved January 13, 2013 http://www.cdc.gov/climateandhealth/effects/waterborne.htm

55 Portier, C., Thigpen Tart, K., Carter, S., Dilworth, C., Grambsch, A., Gohlke, J., … Whung, P-Y. (2010). *A human health perspective on climate change: A report outlining the research needs on the human health effects of climate change.* Research Triangle Park, NC. Environmental Health Perspectives/National Institute of Environmental Health Sciences. doi:10.1289/ehp.1002272. Retrieved January 13, 2013 http://www.niehs.nih.gov/climatereport

56 Centers for Disease Control and Prevention. (2010). *Climate and Health Program: Foodborne diseases and nutrition.* Climate and Health Program & National Center for Environmental Health. Retrieved July 2, 2013 http://www.cdc.gov/climateandhealth/effects/foodborne.htm

57 Mayo Clinic. (2011). *Heat stroke, risk factors.* Retrieved January 13, 2013 http://www.mayoclinic.com/health/heat-stroke/DS01025/DSECTION=risk-factors

58 Ebi, K., Balbus, J., Kinney, P., Lipp, E., Mills, D., O'Neill, M., & Wilson, M. (2008). Effects of global change on human health. In: *Analyses of the effects of global change on human health and welfare and human systems.* The U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Washington, DC, 39–87. Retrieved January 12, 2013 http://downloads.climatescience.gov/sap/sap4-6/sap4-6-final-report-all.pdf

59 The Delaware Population Consortium. (2012). *Annual population projections.* The Delaware Population Consortium. October 25, 2012. Retrieved September 13, 2013 http://stateplanning.delaware.gov/information/dpc/DPC2012v1.0.pdf

60 Centers for Disease Control and Prevention. (2010). *Climate and Health Program: Mental health and stress-related disorders.* Climate and Health Program & National Center for Environmental Health. Retrieved July 2, 2013 http://www.cdc.gov/climateandhealth/effects/mental_health.htm

61 Mayo Clinic. (2011). *Heat stroke, risk factors.* Retrieved January 13, 2013 http://www.mayoclinic.com/health/heat-stroke/DS01025/DSECTION=risk-factors

# Chapter 6 – Water Resources Summary

## Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower emissions scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

## Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

## Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

## Precipitation Changes

- Precipitation is projected to increase, particularly in winter.

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events (**Figure 6.1**), indicating an increase in precipitation intensity.

## Potential Impacts to Water Resources

- ***Water supply and demand*** will be affected by rising temperatures and potentially more frequent droughts, especially in summer months. Water demands for both domestic and public water supply as well as irrigation water peak in summer months. As average temperatures increase, the period of peak demand may lengthen as the warm summer temperatures

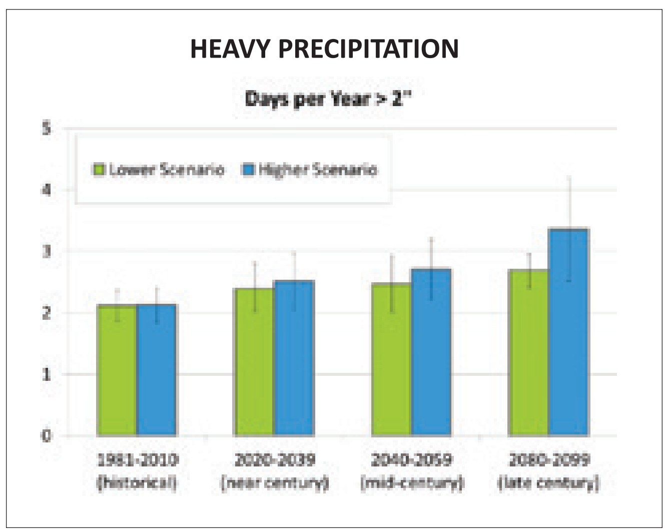


**Figure 6.1.** Records across 14 Delaware weather stations show that on average the state currently experiences approximately 2 days per year with more than 2 inches of precipitation. By end of century, these numbers are projected to increase by +0.5 to 1 days per year with more than 2 inches of precipitation. Source: Hayhoe et al. (2013).

develop earlier in the year and extend later into the autumn.

- ***Water quality*** may be affected by sea level rise and changes in precipitation, including droughts and extreme rain events. Salinity in tidal reaches of rivers and streams may be affected by climate change impacts. Extreme weather events and flooding can increase runoff and pollutant transport, resulting in contaminated surface water and groundwater.

- Climate change impacts are likely to magnify risks for Delaware's ***water infrastructure***, including public water supply, wastewater treatment, individual wells and septic systems, stormwater systems, and water storage and flood control structures. With the projected increase of more intense rain and storm events, water infrastructure will be increasingly strained to manage peak flows that may exceed their design specifications. Sea level rise and increased flooding associated with extreme rain events may result in structural or operational damage to dams, levees, impoundments, and drainage ditches.

- ***Public health and safety*** are challenged by Delaware's flooding and drainage problems, both in coastal areas and inland floodplains. Climate change impacts associated with sea level rise and extreme rain events are likely to result in more frequent and extensive flood problems that compound or magnify other stressors.

# Chapter 6

# Water Resources

## Chapter Contents

- Overview of Delaware's freshwater resources, both surface water and groundwater
- Summary of climate change impacts that pose challenges to water resources throughout the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to water resources (nonclimatic impacts to resources)
- Potential vulnerabilities to water resources in Delaware (based on current research and expert interviews – statewide scope)

This chapter focuses on the current and potential impacts of climate change on Delaware's freshwater resources. These include developed water sources and infrastructure used for public supply, agriculture, and industry, as well as aquatic resources and natural habitat. Both water supply and water quality issues are addressed. Note that climate change impacts to aquatic ecosystems are discussed further in Chapter 8, Ecosystem and Wildlife, of this Assessment.

## 6.1 Overview of Delaware's Freshwater Resources

### 6.1.1. Freshwater Resources and Uses

Delaware has relatively high annual precipitation (average 45 inches per year), distributed fairly evenly throughout the year. In addition, geologic conditions in Delaware are good for storage and recharge of significant groundwater supplies. As a result, the state enjoys plentiful freshwater resources from both surface and groundwater sources.

North of the Chesapeake and Delaware Canal, 70 percent of public water supplies is obtained from surface water resources and 30 percent is obtained from groundwater resources. South of the canal, all water used for public and domestic supply and more than 98 percent of water used for irrigation is obtained from groundwater resources.[2] Freshwater withdrawals in Delaware (from both surface water and groundwater sources) totaled over 600 million gallons per day (mgd) in 2005 (**Figures 6.2** and **6.3**).[3] According to water use data from the U.S. Geological Survey, nearly two-thirds of freshwater withdrawals were used for thermoelectric energy production (nonconsumptive use of water for cooling).[4] (Note that both surface freshwater and saline water are used in thermoelectric power production; no groundwater is used for thermoelectric.) One-third of freshwater withdrawals – approximately 200 million gallons per day (mgd) – is used primarily for public supply (96 mgd), irrigation (65 mgd), and industry (42 mgd).

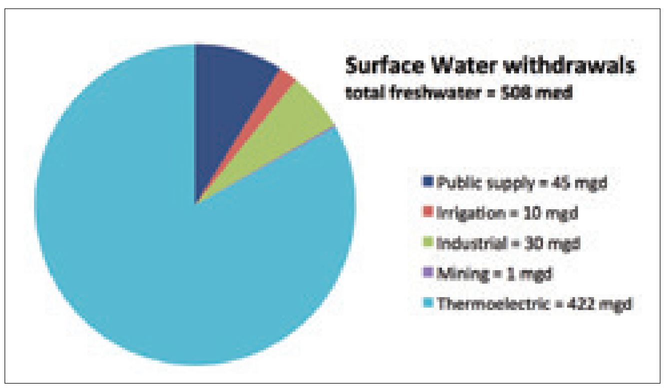


**Figure 6.2.** Surface freshwater withdrawals in Delaware. Source: USGS 2005.

### Surface Fresh Water

Delaware has four major drainage basins: the Chesapeake Bay, Delaware River and Bay, Delaware Inland Bays, and Piedmont watersheds. The Christina River and Brandywine Creek are important tributaries in the Piedmont watershed that provide surface water supply for drinking water and industrial use in the northern part of the state (**Figure 6.2**).

Surface water supplies can be vulnerable to severe shortages under drought conditions. In 2002, the worst drought on record hit Delaware, with significant impacts in northern New Castle County. Streamflows reached a record low for the county with brackish, waters encroaching into freshwater areas such as the tidal portions of White Clay Creek and Christina River. In response, the Delaware Water Supply Self-Sufficiency Act (House Bill 118) was passed into law in July 2003.

Under the act, water utilities had to ensure there were sufficient sources of water supply to withstand another 100-year drought like that of 2002. In addition, the state and private water suppliers invested in increasing water storage capacity through several large infrastructure projects.

## Groundwater

Groundwater is the primary water source (**Figure 6.3**) for southern New Castle County and most of Kent and Sussex Counties. Ten major aquifers are found in Delaware, both confined and unconfined. The Columbia Aquifer is the most heavily used for public and domestic water supply and irrigation. As an unconfined surficial aquifer, it is highly susceptible to contamination. Maintaining base flow of groundwater is important, because it is also a major supplier of water to streams. In times of drought, almost all surface water flow comes from groundwater discharge. Therefore, preventing overdraft[a] of aquifers is essential to maintaining surface water supplies that provide much of the state's water.

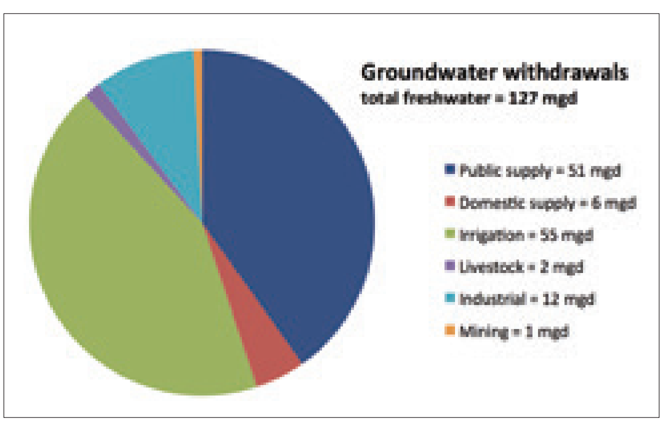


Figure 6.3. Groundwater withdrawals in Delaware. Source: USGS 2005.

The seasonality of water demands is significant in Kent and Sussex Counties. Water demand increases in the summer because of irrigation needs for farming and landscaping and the increased population of vacationers and summer residents. This stress on water resources is compounded because the increased demand coincides with lower groundwater levels, a result of increased evapotranspiration rates and reduced rainfall.

## Freshwater Aquatic Resources

Delaware has more than 2,500 miles of rivers and streams and 3,000 acres of ponds and lakes.[5] Additionally, wetlands cover as much as a quarter of Delaware's land area. The recently published wetlands inventory and assessment report, "Delaware Wetlands: Status and Changes from 1992 to 2007,"[6] revealed that total wetland acreage continues to be lost in Delaware. Continued losses of wetlands will have important consequences for the state's water quality.

Wetlands provide critical ecosystem services, including flood control by mitigating the effects of severe storms by absorbing precipitation; protecting coastal property and ecosystems from storms; providing groundwater flow; filtering contaminants from surface and groundwater; and providing habitat for a range of flora and fauna.

The Delaware River is a significant water resource that provides a wide range of economic and environmental benefits to the citizens and businesses in the state and region. The river's watershed encompasses 13,539 square miles, including portions of New York, Pennsylvania,

[a] Groundwater overdraft refers to withdrawals of groundwater from an aquifer at rates considered to be excessive and that may lead to declining groundwater levels, increased pumping costs, deterioration of water quality, and reduction of water in streams and lakes.

New Jersey, and Delaware. The river provides drinking water for a population of 16 million people, including 8 million who live in the basin and 8 million who live in northern New Jersey and New York City. The Delaware River provides critical water supply for industry and thermal energy production and serves as a major transportation corridor for shipping, linking the Atlantic Ocean to the Port of Wilmington, the Port of Philadelphia, and the Chesapeake Bay via the Chesapeake and Delaware Canal. (Aquatic habitats, wetlands, and rivers are discussed further in Chapter 8, Ecosystems and Wildlife.)

### 6.1.2. Water Infrastructure

Water infrastructure in Delaware includes a wide range of systems and structures built and operated for many purposes:

- Public water supply systems provide drinking water through pumping, storage, treatment, and distribution infrastructure.
- Individual domestic wells provide water supply to rural households; wells also provide nonpotable water supplies for farm, nursery, and golf course irrigation.
- Wastewater systems provide collection, transport, and treatment of wastewater from municipal, residential, and industrial sources.
- Septic systems and community on-site wastewater treatment systems are widely used in subdivisions and rural areas not connected to public wastewater systems.
- Stormwater systems, including sewers and drainage structures, manage surface water runoff from rain and snowmelt.
- Dams, dikes, and ditches include structures built to control or channel surface water and provide flood protection.

Public drinking water supply in Delaware is provided by a network of 486 public water systems managed by municipal- and investor-owned utilities.[7] More than 80 percent of Delaware residents obtain their water from community sources, which include municipal supplies, private water companies, or shared groundwater wells. Over half of the state's drinking water is supplied through four major providers: the City of Wilmington Department of Public Works, Artesian Water Company, Tidewater Delaware, and United Water Delaware. Some water utilities in Delaware provide both drinking water and wastewater services. Wastewater treatment systems are managed by both public and private entities. There are 30 public wastewater treatment facilities, with more than 600 pumping stations in Delaware.

Water and wastewater systems have extensive underground pipe networks that can be subject to leakages and breakage, resulting in sewage spills and contamination of water supplies. Aboveground infrastructure can also be vulnerable to flooding and extreme weather events that affect the function of storage tanks, pumping stations, sedimentation and aeration tanks, filters, and other structures. Water and wastewater infrastructure requires continual monitoring; system managers must be able to respond quickly to system damage or failures to ensure water service that is reliable and safe.

In rural areas of the state, many households are not connected to public or community water or wastewater systems; these homes rely on individual domestic wells for drinking water supply and on septic systems for wastewater disposal. Individual wells are typically less than 100 feet in depth and tap into shallow groundwater, making them more vulnerable to groundwater contamination than deep water wells. There are approximately 78,000 septic systems statewide, with approximately half of these in Sussex County.[8]

Stormwater infrastructure provides a critical function in diverting surface runoff from rain and snowmelt from paved surfaces and structures and reducing flooding impacts during storm events. Stormwater drainage systems are built to manage the quantity and distribution of runoff; some systems also provide additional benefits such as erosion control or groundwater recharge.

Stormwater can cause physical damage, from scouring or erosion, and is also a significant water quality challenge, as water picks up pollutants as it travels across paved surfaces, farm fields, and suburban lawns. Stormwater infrastructure includes inlets, storm sewers, and outfalls. Inlets are openings in road pavements to divert stormwater into underground sewer pipes. Stormwater exits the system through an outfall, which is typically a pipe outlet made of concrete, metal, or plastic. Outfalls may deposit stormwater directly into a water body, such as a stream or bay, or may convey stormwater into a ditch, swale, or constructed wetland. Stormwater wetlands may be integrated into the system as "green infrastructure," removing pollutants through settling and biological processes.[9]

Water infrastructure in Delaware also includes many structures built to control or channel surface water and provide flood protection. These include dams, dikes, levees, and impoundments. In Delaware, dams are primarily associated with mill ponds that are located inland; dikes are primarily located in coastal regions. Delaware's Dam Safety Program has conducted a statewide inventory of dams and identified 48 dams that are classified as "high hazard" or "significant hazard." (The classification is based on the potential consequences of dam failure, not on the condition of the dam.) Approximately 42 of these regulated dams are managed by the State of Delaware, and many of them are located adjacent to or integrated into state-managed roads and bridges.

Tax ditch channels are another type of infrastructure used for drainage. Tax ditch channels range in size from 6 to 80 feet wide, and 2 to 14 feet deep. A "tax ditch" refers not to the drainage channel itself, but to the legal entity responsible for maintenance of the tax ditch channel. Formation of a tax ditch can be initiated only by landowners who petition Superior Court to resolve drainage or flooding concerns. Delaware has 228 individual tax ditch organizations, ranging in size from 56,000 acres in Marshyhope Creek Tax Ditch in southern Delaware to a two-acre system in Wilmington. These organizations manage more than 2,000 miles of channels, primarily in eastern Sussex and Kent Counties.[10]

Coastal impoundments are areas of upland or wetland habitat where low-level dikes or levees have been constructed to restrict, retain, or exclude water over a selected area.[11] Impoundments provide important breeding and wintering habitat for migratory birds and nursery habitat for fish. In addition, many impoundments also provide flood protection for roads and coastal communities. There are 350 impoundments in the state, encompassing more than 12,000 acres; most are publically owned and managed. (Note that coastal impoundments are discussed in Chapter 8, Ecosystems and Wildlife.)

## 6.1.3. Water Quality

In almost all of Delaware's watersheds, at least half of the monitored stream segments are classified as impaired (**Figure 6.4**). This means that they do not achieve the regulated water quality standards for certain constituents. The majority of the impairments are for low levels of dissolved oxygen and elevated levels of nutrients (nitrogen and phosphorus) and bacteria. In most cases, the nutrients and bacteria come from nonpoint sources. These pollutants enter surface water through groundwater discharges and as runoff from agricultural and suburban lands, urban stormwater, and wastewater discharges from treatment plants and septic systems. Nutrients, bacteria, and chemical pollutants can pose a serious threat to aquatic wildlife, degrade ecosystem health, and pose health risks to humans.

As required by the federal Clean Water Act, the State of Delaware has established a total maximum daily load (TMDL) for each impaired waterway for nutrient, toxics, and bacteria impairments. More work is underway for toxics as detailed in the Watershed Approach to Toxics Assessment and Restoration Plan.[12] A TMDL is the maximum amount of a pollutant that can enter a waterway without violating water quality standards. Approximately 96 percent of the state is covered by a TMDL regulation. Nonpoint reductions required by TMDLs range from 0 (capping of load) to 85 percent for nitrogen, 0 to

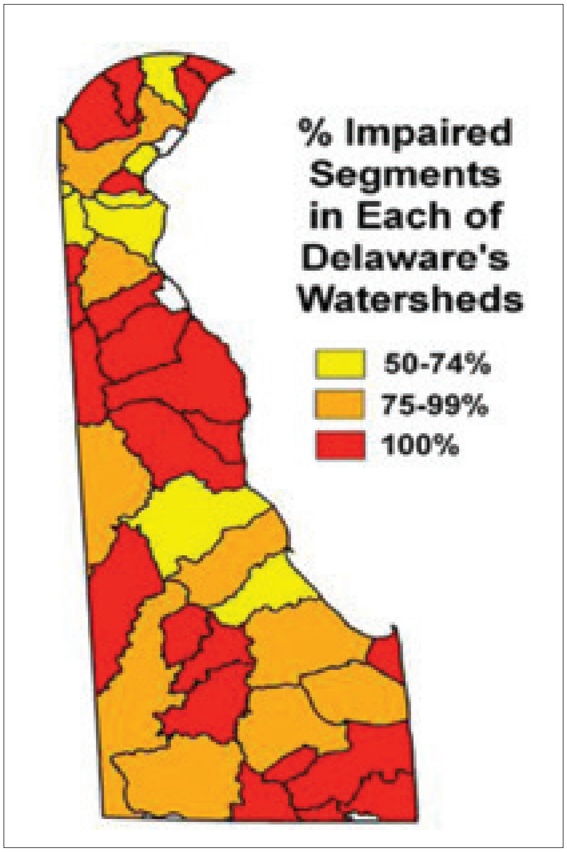


**Figure 6.4.** Delaware's impaired streams. Source: DNREC Watershed Assessment Section.

65 percent for phosphorus, and 8 to 90 percent for bacteria. In addition, more than 60 organic compounds represent contaminant risks to surface and groundwater supplies, including pesticides, gasoline compounds, solvents, and disinfectant by-products. Trace elements – such as fluoride, lead, and arsenic – also can be found in surface and groundwater. Many prominent streams, including Brandywine Creek, Christina River, Red Clay Creek, and St. Jones River, currently have fish consumption advisories in place due to the presence of toxic compounds such as mercury, dioxin, and PCBs (polychlorinated biphenyls).

## 6.2. Climate Change Impacts to Water Resources in the United States

### 6.2.1. National Overview

In recent years, a number of technical reports and policy guidance documents have been developed at the national level to summarize current climate science information and to provide an analytical framework for incorporating climate change considerations into planning processes and policy development. The U.S. Climate Change Science Program has produced a series of synthesis and assessment (SAP) reports (2006-2009) to provide a review of scientific literature on the historical and potential impacts of climate change. In the assessment of water resources (SAP 4.3), the report notes that water managers use various methods to plan for variability in water supplies and changing flows. However, these methods assume that historic observations of streamflow are statistically "stationary." Thus, water systems have been designed for a range of climate variability defined by past streamflow and weather variations. However, research reviewed in the assessment suggests that "in the era of changing climate this assumption is no longer tenable."[13]

In the 2009 interagency report "Climate Change and Water Resources Management: A Federal Perspective," the authors note that climate change is one of many dynamic processes affecting water resources management. Changes in population size and distribution, land use patterns, emerging technologies, and aging infrastructure also must be considered in a "holistic approach to water management." This report also states that "given a changing climate, it may be appropriate to evaluate the system response for a range of hydro-climatic variability wider than in the historic record."[14] In October 2011, the Interagency Climate Change Task Force released the "National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate." One of the recommendations of the plan is to strengthen the assessment of vulnerability of water resources to climate change, stating that "to adapt to climate change, water resources managers must first determine the degrees of risk and vulnerability in their systems."[15]

Climate change impacts are likely to affect water resources in a variety of ways, posing potential vulnerabilities across many sectors, including public health, agriculture, industry, tourism, and infrastructure. **Table 6.1** summarizes the linkages between various types of climate change impacts, affected sectors, and impacts to water supply and water quality.

In January 2013, the U.S. Global Change Research Program released a draft of the Third U.S. National Climate Assessment; the final report is due to be released in 2014. The draft national climate assessment describes a number of climate impacts that affect water resources nationally, as well as in the Northeast region of the United States (including Delaware). The draft

**Table 6.1 Climate change impacts to water resources across sectors in the United States**

| *Climate change impacts* | *Affected sectors* | *Water resource impacts* |
|---|---|---|
| ***Increased temperatures*** | | |
| Increased demand for electricity in summer | Energy | Water supply |
| Increased demand for irrigation water in summer | Agriculture | Water supply |
| Increased demand for domestic and municipal water use (landscaping, home use) | Public health<br>Tourism and recreation | Water supply |
| Increased algal blooms and eutrophication ➔ decreased oxygen in bays, rivers, lakes | Wildlife and ecosystems<br>Tourism and recreation (fishing, swimming, boating) | Water quality |
| Increased water temperatures ➔ heat stress impacts to aquatic species | Wildlife and ecosystems | Water quality |
| Increased water temperatures ➔ reduced efficiency for industrial cooling water | Energy<br>Industry/energy | Water quality/supply |
| ***Increased variability of precipitation ➔ heavy precipitation events*** | | |
| Overflow from combined sewer systems | Infrastructure<br>Wildlife and ecosystems<br>Public health | Water quality |
| Contaminated surface water from runoff and pollutant transport | Public health<br>Wildlife and ecosystems | Water quality |
| Contamination of groundwater recharge areas and wells | Infrastructure<br>Public health | Water quality |
| Damage to water supply and wastewater treatment systems, including on-site wastewater treatment systems | Infrastructure<br>Public health<br>Wildlife and ecosystems | Water quality |
| ***Increased variability of precipitation ➔ droughts*** | | |
| Reduced surface water supplies | Public health<br>Infrastructure<br>Agriculture<br>Wildlife and ecosystems | Water supply |
| Increased groundwater withdrawals ➔ groundwater overdraft | Public health<br>Agriculture<br>Industry | Water quality/supply |
| ***Sea level rise ➔ coastal inundation, shoreline erosion*** | | |
| Contamination of surface water and groundwater recharge areas and wells | Infrastructure<br>Public health | Water quality |
| Damage to water supply and wastewater treatment systems | Infrastructure<br>Public health<br>Wildlife and ecosystems | Water quality |
| Upstream shift of salt line in the Delaware River | Infrastructure<br>Industry<br>Wildlife and ecosystems | Water quality/supply |

assessment reports that, across the Northeast region, annual precipitation has increased by 5 inches (10 percent) between 1895 and 2011. The region has also experienced a greater increase in heavy precipitation events than any other region in the United States, with a 74 percent increase in the amount of precipitation falling in extreme rain events. At the same time, seasonal drought in summer and fall is expected to increase in the Northeast region, as higher temperatures result in greater evaporation and earlier snowmelt in winter and spring.[16] Changes in precipitation patterns also affect streamflow, which can lead to impacts in water supply, water quality, and risk of flooding. In the Northeast and Midwest regions of the country, annual peak flows have increased in the past 85 years. These peak flows, along with soil moisture and other factors, influence the volume of runoff that may contribute to an increase in flooding. Surface runoff, especially when combined with intense precipitation, is increasing loading of sediment, nutrients, and other contaminants in surface waters, resulting in negative impacts to water quality.[17]

### 6.2.2. Impacts to Water Supply and Water Quality

It is important to note that water quality and water supply are strongly linked. For example, contamination of surface water may render that source unusable for drinking water, reducing supply. In addition, climate change–related impacts to water supply and water quality can have significant economic costs, such as repair, replacement, or relocation of water infrastructure; additional treatment to bring degraded water to safe drinking water standards (increasing cost and energy use); and declines in tourism due to beach closures or flood-damaged recreational facilities. Climate change impacts that may affect *water supply* include:

- Increased air temperatures, leading to increased water use for public and domestic water supply and irrigation (peak demand in summer);
- Increased water temperatures, potentially reducing efficiency of cooling water for industry and energy production;
- Extreme weather events and flooding, stressing the capacity of and potentially damaging water supply infrastructure;
- Increased variability of rainfall, potentially leading to droughts and surface water shortages;
- Sea level rise, leading to upstream shift in salinity in rivers and streams, potentially affecting water supply for industry and energy production.

Climate change impacts that may affect *water quality* include:

- Increased air and water temperatures, leading to increased algal blooms in surface water and decreased oxygen levels in bays, rivers, and lakes;
- Extreme weather events and flooding, leading to increased runoff and pollutant transport that can contaminate surface water and groundwater recharge areas and cause physical damage to water infrastructure;
- Sea level rise and coastal inundation, posing risk of saltwater intrusion in wells and contamination of groundwater recharge areas;
- Extreme weather events, flooding, and coastal inundation, leading to degradation or loss of wetlands and reduction in the ecosystem benefits they provide as nutrient sinks;
- Extreme weather events and flooding, stressing 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, resulting in failure of septic drain fields as groundwater levels rise.

### 6.2.3. Impacts to Water Infrastructure

Climate change impacts to water supply and water quality also affect the function and operation of *water infrastructure*. For example, extreme weather events and flooding can stress the capacity of stormwater systems, leading to sewage spills that pose public health risks and damage ecosystems. In particular, increases in heavy rainfall events pose a growing threat to aging infrastructure and systems not designed for higher levels of flow.

Water infrastructure encompasses a wide range of systems that integrates natural resources and human-built structures to produce, transport, or contain water and wastewater. Providing clean and reliable water supplies for domestic and industrial use requires wells, water treatment facilities (for drinking water and wastewater), pumps, pipelines, and distribution systems. The function of these structures depends on the availability of freshwater of sufficient quantity and quality to meet the demand for drinking water, power generation, irrigation, and other uses. In addition, significant effort, engineering, and expense have been invested in infrastructure designed to contain or store water. This includes large water storage structures, such as dams, reservoirs, and impoundments, as well as smaller millponds. Dikes and levees are widely used for flood protection, and canals and ditches across the landscape function to drain wetlands or shunt water from one location to another.

Water storage and flood control structures, such as dams and impoundments, are also vulnerable to climate change impacts. Changes in precipitation, extreme weather events, and sea level rise are expected to affect water infrastructure. Impacts can occur through gradual changes, such as higher average rainfall, that accelerate the deterioration of structures. High-impact events can damage or destroy the structural integrity of dams, levees, and impoundments, leading to breaching events and catastrophic flooding. Dams are classified in terms of their hazard potential relative to the consequences of failure. A "high hazard potential" dam is one that may result in loss of life in the case of failure. The number of high hazard potential dams is growing as a result of increasing development below dams, putting more people at risk. In addition, the average age of dams in the United States is just over 50 years; thus, many dams are considered deficient as a result of aging, deterioration, and lack of maintenance.

Septic systems are highly vulnerable to the impacts of climate change. The increased risk of flooding and higher water table could result in greater risks and impacts to water quality due to malfunction or failure of septic systems. Pathogens present in septic waste are usually attenuated in the soil system. A rising water table might increase the risk of contamination of surface waters, where inadequately treated sewage poses a significant threat to drinking water and human health. These potential impacts are elevated by the risk of flooding from sea level rise and increases in heavy precipitation events due to climate change. The flushing of nutrients and pathogens will deteriorate the coastal ecosystem as well as the functioning of on-site wastewater treatment systems.

## 6.3. External Stressors

*Population growth* (**Figure 6.5**) is expected to increase demand for freshwater withdrawals from both surface and groundwater sources. Population growth will also lead to an increasing volume of wastewater that must be treated and discharged.

*Increasing demand* for irrigation water is driven by economic forces as well as changes in climate and drought patterns. Irrigated acreage has expanded greatly in Delaware over the past 20 to 30 years, and continues to increase. This trend will result in greater demand for freshwater in peak summer

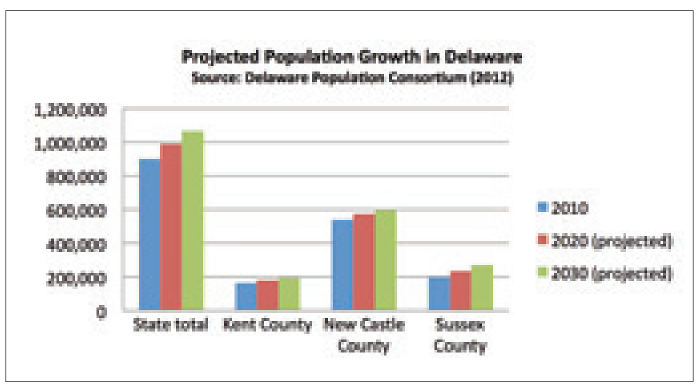


**Figure 6.5.** Projected population growth in Delaware. Source: Delaware Population Consortium (2012).

months. Increased withdrawals could lead to localized water shortages, overdraft of surficial aquifers, or impacts to local streams and wetlands.

*Land use changes* that accompany population growth have direct and indirect effects on water resources. Impacts associated with an increase in impervious surface have been widely studied. Impervious surfaces – buildings, concrete, and pavement – alter natural hydrology, resulting in higher volumes of stormwater runoff, increased erosion, and more frequent flooding. In addition, impervious surfaces can affect groundwater levels by impeding recharge.

Impervious surfaces change the natural flow of water (hydrology), because water moves faster over the hard surfaces, resulting in less time and opportunity for vegetation to trap and take up pollutants and water. Loss of vegetation along streams and waterways as a result of development can also increase water temperatures in streams and rivers, which can harm fish and invertebrate species and trigger algal blooms. Water quality in Delaware is already challenged by excess nutrients from a wide range of sources, including wastewater treatment plants, septic systems, agricultural runoff, pet waste, and fertilizers used in urban and suburban landscaping.

*Energy costs* of water treatment and distribution are a significant economic stressor for water utilities. Water pumping and transport accounts for a large portion of energy use, both in water systems that rely on groundwater and surface water sources. The U.S. Environmental Protection Agency estimates that 4 percent of national electricity consumption annually is used in water processing and transport, and accounts for as much as 75 percent of the cost of providing water service.[18] Energy consumption and costs for water treatment are likely to increase when the water quality of source water becomes degraded. For example, flooding events can transport sediment and other pollutants into streams or reservoirs, resulting in higher levels of treatment needed to meet drinking water standards. Saltwater intrusion into surface or groundwater supplies can also lead to higher energy costs for treatment or blending.

*Aging infrastructure* is an ongoing concern for water utilities and municipalities. National attention has focused on the costs of repair, replacement, and disruption of service caused by failure of water mains and valves. Many water systems have pipes installed during the construction booms of the post-World War II era or earlier. In the eastern United States, many large cities have water infrastructure systems more than a century old. One common problem with aging infrastructure is leakage; this results in water losses that have an economic cost (including the energy cost of treatment and distribution of lost water). In addition, water leakage in wastewater and sewer systems can exacerbate water quality problems and lead to increased soil erosion, which further undermines the structural integrity of the water system.[19]

## 6.4. Potential Impacts of Climate Change to Delaware's Water Resources

### 6.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under the higher as compared to the lower emission scenario and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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.

#### Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

## Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3-4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

## Precipitation Changes

- Precipitation is projected to increase, particularly in winter.

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 6.1**).

## 6.4.2. Water Supply – Increasing Demand

Changes in precipitation patterns – especially droughts – and increasing temperatures will likely have effects on water supply and demand. The Delaware Water Supply Coordinating Council has developed water supply and demand plans for New Castle County and is currently developing plans for Kent and Sussex Counties to project water supply needs through 2030. The University of Delaware Water Resources Agency estimates that potable water demands in Kent and Sussex Counties may increase from 2010 levels of 61 million gallons per day (mgd) to 83 mgd by 2030, based on population growth. This represents the combined total of public water and individual wells.[20]

Water storage capacity for northern New Castle County has increased significantly in response to severe drought in 2002. As a result of a state-level initiative, water utilities in northern New Castle County developed more than 1.8 billion gallons in new water reserve supplies, including the construction of Newark Reservoir, increased capacity in Hoopes Reservoir, and development of aquifer storage and recovery projects. In addition, water conservation efforts have been implemented that have reduced water demands in northern Delaware from a historic peak of 93 million gallons per day (mgd) to 80 mgd. Conservation water rates have helped reduce water demand; many utilities have also improved water efficiency through leak detection and infrastructure repairs. These additional water supplies are expected to meet projected water demands through 2020 even under conditions experienced during the 2002 drought of record.[21]

The University of Delaware Water Resources Agency conducted an analysis of air temperature data for Wilmington Airport and water demand data in New Castle, Kent, and Sussex Counties. Results indicated that water demand increases by 3 percent for every 1 percent increase in air temperature.

At 90°F, peak drinking water demand during 2010 in Kent and Sussex Counties was 58 million gallons per day (mgd). If air temperature is projected to increase by 2°F by 2030 (or 2/90 = 2 percent), then peak water demand may increase by 6 percent to 61 mgd by 2030 due to atmospheric warming. Resources for the Future published a report that concluded a 1 percent rise in air temperature would increase water demand by as much as 3.8 percent.[22] A study in northeastern Illinois concludes that by 2050, future water demand would increase by 9.1 percent with an air temperature increase of 6°F, or 1.5 percent for every degree Fahrenheit.[23] Based on these findings, by 2030 water demands in Kent and Sussex Counties may increase by 35 percent due to population growth as well as by 8 percent due to a projected 2°F or 2 percent rise in air temperature.

### 6.4.3. Water Quality – Changes in Salinity and Temperature

Water quality may be affected by sea level rise and changes in precipitation that can result in salinity fluctuations in water resources. Freshwater resources may be affected by intrusion or encroachment of salt water in several ways. Sea level rise and storm surge can cause saltwater intrusion into coastal aquifers, affecting local wells. Some Delaware coastal communities have already had to abandon municipal wells due to high chloride levels and develop new wells further inland. The Sea Level Rise Vulnerability Assessment for Delaware assessed domestic, industrial, irrigation, and public wells that could be affected by sea level rise within the projected ranges of 1.6 feet, 3.3 feet, or 4.9 feet of inundation. For example, the Sea Level Rise Vulnerability Assessment estimates that more than 2,000 domestic wells and 25 public wells could be inundated by a 1.6-foot (0.5-meter) sea level rise.[24] Higher sea level rise scenarios would affect more water infrastructure; an estimated 75 public wells could be inundated under 4.9 feet (1.5 meter) of sea level rise.

Salinity in tidal reaches of rivers and streams may also be affected by climate change impacts. The "salt line" in the Delaware Estuary – defined as the 250 milligrams per liter chloride concentration – fluctuates along the tidal portion of the Delaware River as flows increase or decrease. During low-flow conditions, the salt line moves upriver, which can cause corrosive damage to water infrastructure. Movement of the salt line upriver may affect the freshwater tidal portion of the estuary, threatening many species adapted to this habitat. Sea level rise could increase the tidal influence and salinity levels upriver, although increased precipitation could offset the increasing salinity with additional freshwater inflow.[25] The salt line of the tidal saltwater wedge also migrates 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 further exacerbated with sea level rise.

In addition to salinity changes that affect water quality, increasing water temperature can also lead to changes in water quality and water chemistry. For example, peak water temperatures now exceed 86˚F (30˚C) along the Brandywine Creek and Christina River during the summer, which decreases levels of dissolved oxygen necessary for fish and aquatic health.[26] (The potential impacts of

#### Salinity in Drinking Water – White Clay Creek

Changing patterns of precipitation and sea level rise may affect salinity in White Clay Creek and pose problems for the Stanton Water Treatment Plant (WTP). The WTP has a freshwater intake situated on White Clay Creek near the confluence with Red Clay Creek. Operated by United Water Delaware, the Stanton WTP withdraws up to 30 million gallons per day (mgd).

Streamflow in White Clay Creek is influenced by freshwater inflow from upstream watersheds and the incoming tide from the Delaware Estuary. Reduced snowpack in upper Delaware Basin affects the timing and quantity of flows; periods of summer drought also reduce flows. A minimum streamflow of 17.2 mgd is needed to protect fisheries and creek habitat and to maintain water quality. Data collected during previous droughts indicate that when streamflow falls below the minimum 17.2 mgd for more than 5 to 7 consecutive days, chloride levels in the stream can exceed the 250 parts per million (ppm) drinking water threshold for chloride.[a] Chloride levels are also tidally influenced by the upstream encroachment of the salt line, a trend that may be enhanced with sea level rise. When chloride levels exceed the drinking water standard, the water must be blended with another source of freshwater to dilute the chloride concentration to an acceptable level.

To manage and monitor chloride levels in White Clay Creek, the water utility has installed a tidal capture structure and implemented a chloride monitoring plan. The tidal capture structure is an expandable bladder that inflates at high tide to temporarily impound freshwater, allowing continued water withdrawals. The structure is deflated at low tide to allow downstream flow. The system must be carefully managed to ensure that minimum flows are maintained for fish passage, and to monitor changes in chloride levels.

changes in water temperature and salinity are also discussed in Chapter 8, Ecosystems and Wildlife.)

### 6.4.4. Water Infrastructure – Flooding and Sea Level Rise

Climate change impacts are likely to magnify risks for water infrastructure that is already in need of repair or replacement. With the projected increase of more intense rain and storm events, water infrastructure will be increasingly strained to manage peak flows that may exceed their design specifications. The U.S. Environmental Protection Agency has developed an assessment tool for water utilities to identify vulnerabilities and potential adaptation actions to reduce the impacts of climate change to the utilities' infrastructure and operations. The decision framework for the tool provides a guide to potential consequences of climate impacts, including revenue or operating income loss; costs of equipment repair or replacement; degradation of source water or receiving water; and community public health impacts.[27]

Sea level rise may also affect the condition and function of many types of water infrastructure. The Sea Level Rise Vulnerability Assessment for Delaware evaluated wastewater infrastructure and identified pumping stations and treatment facilities that could be inundated as a result of sea level rise through the 21st century. The Sea Level Rise Vulnerability Assessment identified 44 pumping stations (7 percent of the statewide total) that could be affected by a 1.6-foot (0.5-meter) sea level rise; an estimated 136 pumping stations (21 percent of the statewide total) could be inundated under the highest scenario of 4.9-foot (1.5-meter) sea level rise.[28]

### 6.4.5. Public Safety – Flooding

Water infrastructure in Delaware includes dams and reservoirs, levees, impoundments, and drainage ditches. Some of these structures were built more than a century ago and pose challenges for maintenance and repair. Sea level rise and increased flooding associated with extreme rain events may result in structural or operational damage to flood control structures. Over time, exposure to wind, waves, and tides can cause erosion or seepage that weakens the structure, if not properly maintained. In addition, overtopping of dams and dikes during storm events can lead

### Aging Infrastructure – City of Wilmington

Like many older urban developed areas in the United States, the sewer infrastructure used today in the City of Wilmington includes an extensive network of combined sewer overflows (CSOs) that carry both sewage and stormwater. CSOs can lead to water quality issues when the combined sewer system cannot handle the volume of flow from stormwater runoff in addition to the baseline sewage flow during a precipitation event. High tides can also prevent CSOs from functioning properly. When Wilmington's combined sewer system is overwhelmed during a precipitation event, untreated sewage and stormwater runoff can be directly discharged into the tributaries of the Delaware River, including Brandywine Creek, Christina River, Silverbrook Run, and Shellpot Creek.

Due to preventive measures taken over the past two decades since regulations were developed for CSOs through the Federal CSO Control Plan, CSO events have decreased significantly in the City of Wilmington. A major expansion of the Wilmington wastewater treatment plant completed in 1997 at a cost of $30 million improved the capacity of the city's combined sewer system. The improvements expanded capture of the CSOs from 49 percent to 70 percent. As a result, water quality has improved in the waterways that receive CSO discharges and CSO incidents are considered a relatively small contributor to overall water pollution.

Increased precipitation, flood events, and storms are likely to exacerbate the challenge and cost of decreasing and/or controlling CSO events, leading to increased water quality impacts from CSOs. Water quality impacts from CSOs may increase under a climate change scenario with increased precipitation, storm events, and flooding. Discharges of untreated sewage and stormwater runoff into Delaware's water resources may occur more frequently and at a great cost to water quality.

to damage or collapse, increasing the risks of severe flooding in communities protected by these structures. Breaching or failure of dikes and levees can also pose water quality risks if the water impounded by the structure contains contaminated sediments, sewage, or other pollutants that could be released or transported in the event of flooding.

Delaware already faces challenges from flooding and drainage problems, both in coastal areas and inland floodplains. Climate change impacts associated with sea level rise and extreme rain events are likely to result in more frequent and extensive flood problems that compound or magnify other stressors. As described above, changes in watershed characteristics such as increased impervious surface area and loss of wetlands and forests are key factors that influence flood risk. The combination of extreme rain events and changes in watershed hydrology may lead to flooding in areas that have not been previously subject to flooding.

Monitoring data show that Delaware is already experiencing changes in streamflows. For example, floods that exceed the 10-year recurrence interval have become more frequent along the Brandywine Creek since the 1970s. During the same period, drought low flows along Brandywine Creek have declined, with a slight rise following the multiyear drought of 1995-2002.[29] **Figure 6.6** shows annual peak discharge on the Brandywine River at Wilmington, Delaware. Changes in the timing, amount, and velocity of peak flows can affect the river or stream corridor, such as by increased erosion and flooding, and can also affect water withdrawals for drinking water, thermoelectric power generation, and industrial uses.

Water and transportation infrastructure is often physically integrated. In Delaware, approximately 42 regulated dams are owned by the State of Delaware, and many have state roads or highways built on top of the dams. In heavy rain events, rising water levels behind the dam can pose a threat of overtopping, which can flood roads on top or adjacent to the dam. In extreme conditions, overtopping of the dam can cause significant

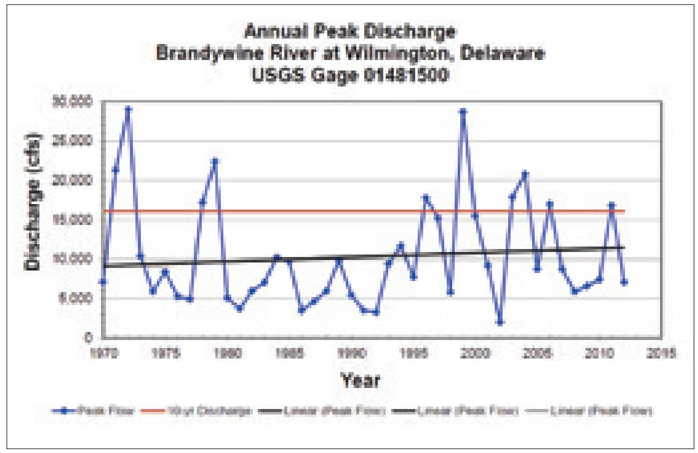


**Figure 6.6.** Peak streamflows in Delaware (1970-2012). Source: Kauffman (2013).

erosion that weakens the dam structure; in worst cases, erosion or washouts can result in dam failure, releasing huge volumes of stored water downstream at high velocity and causing catastrophic damage.

To prevent overtopping and protect dams from damage, both structural and operational actions can be taken. Erosion protection can involve adding concrete or rock (armoring) to all or a portion of the embankment. Adding a hard surface to a dam structure can also help reduce other impacts to the structural integrity of the dam from seepage, encroachment of roots from woody vegetation, and holes from burrowing animals. Operational measures include opening spillways to lower water levels behind the dam and increasing the spillway capacity. In Delaware, most dams have a single spillway that can be opened by removing boards or opening gates.

In anticipation of Hurricane Sandy, in October 2012, state staff from the Department of Transportation and Department of Natural Resources and Environmental Control coordinated efforts to open gates and remove boards from 30 dams around the state. Monitoring weather forecasts, rain gauges, and water levels provided critical information to determine which dams needed immediate action. As a result, no dams overtopped during the storm.[30] Precipitation and flooding impacts to transportation are also discussed in Chapter 9, Infrastructure.

Flooding poses both economic and safety risks for homes and communities. Costs resulting from flood damages affect homeowners, insurers, and government. More than 200 flood-damaged homes in Delaware have been purchased through government buyout programs since 2000, using local, state, and federal funding. In addition, an estimated $65 million has been spent by state and local governments to address drainage problems resulting from ineffective or inconsistent standards and codes. Flood insurance for property owners in designated floodplains will likely become more expensive.

In an effort to improve floodplain standards across Delaware, a Floodplain and Drainage Advisory Committee was convened in 2011 to recommend proposed standards that would provide more effective flood management and protection than the minimum standards required under the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program (NFIP). The NFIP minimum floodplain standards were set at minimal levels when the program was created, with the expectation that many communities would enact higher standards when needed to better protect public safety and property. The Advisory Committee recommended floodplain and drainage standards that address improved planning, mapping, and land development and building construction. Development standards consider restrictions on development in floodplains to reduce encroachment. Building standards consider freeboard requirements (floor elevations above flood elevations) and guidelines for basements, crawl spaces, and ventilation systems.[31]

## Sources
### (Endnotes)


**a** Kauffman, G. J., University of Delaware, Water Resources Agency. (personal communication on September 10, 2013).

**b** Delaware Department of Natural Resources and Environmental Control. (2012). *Floodplain and Drainage Advisory Committee final summary report with standards and recommendations.* Water Stewardship Division. Retrieved from http://www.dnrec.delaware.gov/swc/Pages/FloodplainandDrainageCodeWorkGroupCommittee.aspx

**1** Hayhoe, K., Stoner, A., & Gelca, R. (2013). Climate Change Projections and Analysis for Delaware. Report dated December 2013.

**2** Delaware Geological Survey. http://www.dgs.udel.edu/water-resources

**3** Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., & Maupin, M. A. (2009). *Estimated use of water in the United States in 2005.* U.S. Geological Survey Circular 1344. Retrieved from http://water.usgs.


### Flood Control Structures – City of New Castle

The construction of earthen dikes along the Delaware River dates back to the late 1600s. The City of New Castle, located directly adjacent to the Delaware River, has four dikes – Buttonwood, Broad Marsh, Gambacorta Marsh, and Army Creek – that protect areas of the city from flooding. These dikes were the focus of a 2011 assessment by the Department of Natural Resources and Environmental Control – Delaware Coastal Programs to evaluate the dikes' condition and develop plans to ensure that the structural integrity of the dikes is sufficient to protect the city against the impacts of coastal storms and rising sea levels.

Overtopping or failure of dikes poses a significant vulnerability for homes and structures in the potential inundation area. Dike failure can result in flooding that is often rapid and forceful, and can occur with little or no warning. The risk of overtopping is increased with the anticipated impacts of sea level rise. Risks of flooding are further exacerbated during extreme rain events, when water enters the protected areas from two sources – river floodwaters and stormwater runoff.

The elevation of dikes can vary over time due to settlement of the structure, impacts of erosion, compaction from vehicle use, and animal burrowing activity. The assessment of the New Castle dikes included measurements of the dikes' lowest elevations compared to flood elevations for 100-year floods, 500-year floods, and projected flood elevations under three sea level rise scenarios for 2100 (0.5-, 1.0-, and 1.5-meter rise). The lowest dike elevations range from 5.5 to 6.0 feet, while flood elevations range from 9 feet for a 100-year storm to nearly 14 feet under the highest sea level rise projection for 2100.[b]

gov/watuse/data/2005/index.html

4 US Geological Survey. Fact Sheet FS 111-03 http://pubs.usgs.gov/fs/fs11103/

5 Delaware Department of Natural Resources and Environmental Control. (1998). 1*998 watershed assessment report (305b).*

6 Tiner, R.W., Biddle, M.A. , Jacobs, A.D., Rogerson, A.B., & McGuckin, K.G. (2011). *Delaware wetlands: Status and changes from 1992 to 2007.* U.S. Fish and Wildlife Service, Cooperative National Wetlands Inventory Publication. Northeast Region, Hadley, MA, and the Delaware Department of Natural Resources and Environmental Control, Dover, DE. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/DelawareWetlandsStatusandTrends.aspx

7 Delaware Water Supply Coordinating Council. (2011). *Eleventh report to the Governor and General Assembly: Estimates of water supply and demand for Kent County and Sussex County through 2030.* Report by University of Delaware, Water Resources Agency, dated June 14. Retrieved from http://www.wra.udel.edu/files/wscc_11th_report_Kent%20County%20and%20Sussex%20County%20Water%20Supply%20and%20Demand%20final_0.pdf

8 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report dated July. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

9 Delaware Department of Transportation. Retrieved November 2, 2012 from http://www.deldot.gov/stormwater/description.shtml

10 Delaware Department of Natural Resources and Environmental Control. (2008). *Tax ditch right-of-way task force report.* May 27. Retrieved from http://www.dnrec.delaware.gov/swc/Drainage/Documents/Tax%20Ditch%20Task%20Force%202008%20Final_EXECUTIVE%20SUMMARY_rev2a.pdf

11 Kane, A., Bennett, K., Chytalo, K., Glick, P., Hossler, R., Jasinski, P., … Torgan, J. (2011). *Practical guidance for coastal climate-smart conservation projects in the Northeast.* Report prepared by panel on coastal systems and climate change convened by the National Wildlife Federation. http://www.georgetownclimate.org/resources/practical-guidance-for-coastal-climate-smart-conservation-projects-in-the-northeast

12 Delaware Department of Natural Resources and Environmental Control. (2013). *Watershed Approach to Toxics Assessment and Restoration.* Report dated April 23. Division of Watershed Stewardship and Division of Waste and Hazardous Substances. Retrieved from http://www.dnrec.delaware.gov/swc/wa/Documents/WAS/WATAR%20Work%20Plan_March27_2013_Final.pdf

13 Lettenmaier, D., Major, D., Poff, L., & Running, S. (2008). Water Resources. *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* Washington, DC: U.S. Climate Change Science Program and Subcommittee on Global Change Research. 362 pp.

14 Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., … White, K.D. (2009). *Climate change and water resources management—A federal perspective.* US Geological Survey Circular 1331, 65 pp. Retrieved from http://pubs.usgs.gov/circ/1331/

15 Interagency Climate Change Task Force. (2011). *national action plan: Priorities for managing freshwater resources in a changing climate.* Retrieved from http://www.whitehouse.gov/administration/eop/ceq/initiatives/adaptation

16 Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014). Chapter 2: Our Changing Climate. In: *The Third U.S. National Climate Assessment.* In press.

17 Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014). Chapter 2: Our Changing Climate. In: *The Third U.S. National Climate Assessment.* In press.

18 U.S. Environmental Protection Agency. (2012). *Adaptation strategies guide for water utilities.* EPA Water Program report dated January, EPA 817-K-11-003. Retrieved from http://water.epa.gov/infrastructure/watersecurity/climate/index.cfm

19 U.S. Environmental Protection Agency. (2007). *Innovation and research for water infrastructure for the 21st century research plan.* Office of Research and Development report dated April. EPA/600/X-09/003. Retrieved from http://www.epa.gov/awi/

20 Delaware Water Supply Coordinating Council. (2011). *Eleventh report to the Governor and the General Assembly regarding the progress of the Delaware Water Supply Coordinating Council.* Report by University of Delaware, Water Resources Agency, dated June 14. Retrieved from http://www.wra.udel.edu/wp-content/uploads/2013/02/wscc_11th_report_Kent-County-and-Sussex-County-Water-Supply-and-Demand-final.pdf

21 Delaware Water Supply Coordinating Council. (2008). *Tenth report to the Governor and the General Assembly regarding the progress of the Delaware Water Supply Coordinating Council.* Report by University of Delaware, Water Resources Agency, dated April 28. Retrieved from http://www.wr.udel.edu/publicservice/govwscc.html

22 Frederick, K., 1997. *Water resources and climate change,* Climate Issues Brief No. 3. Resources for the Future. 16 pp.

23 Dziegielewski, B., & Chowdhury, F. J. (2008). *Regional water scenarios for northeastern Illinois: 2005-2050 Project completion report.* Southern Illinois University. 217 pp.

24 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report dated July. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

25 Kreeger, D., Adkins, J., Cole, P., Najjar, R., Velinsky, D., Conolly, P. & Kraeuter, J. (2010). *Climate change and the Delaware Estuary: Three case studies in vulnerability assessment and adaptation planning.* Partnership for the Delaware Estuary Report. Report No. 10-01. June. Retrieved from http://delawareestuary.org/science_projects_climate_ready_products.asp

26 Kauffman, Gerald J., University of Delaware, Water Resources Agency. (personal communication, September 10, 2013).

27 U.S. Environmental Protection Agency. (undated). *Climate resilience evaluation and awareness tool.* Retrieved from http://water.epa.gov/infrastructure/watersecurity/climate/

28 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report dated July. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

29 Kauffman, G. J., University of Delaware, Water Resources Agency. (personal communication on September 10, 2013).

30 Twing, D. Delaware Department of Natural Resources and Environmental Control. (personal communication on November 13, 2012).

31 Delaware Department of Natural Resources and Environmental Control. (2012). *Floodplain and Drainage Advisory Committee final summary report with standards and recommendations.* Water Stewardship Division. Retrieved from http://www.dnrec.delaware.gov/swc/Pages/FloodplainandDrainageCodeWorkGroupCommittee.aspx

# Chapter 7 – Agriculture Summary

## Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

## Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.
- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.
- 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 (**Figure 7.1**).

## Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.
- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.
- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

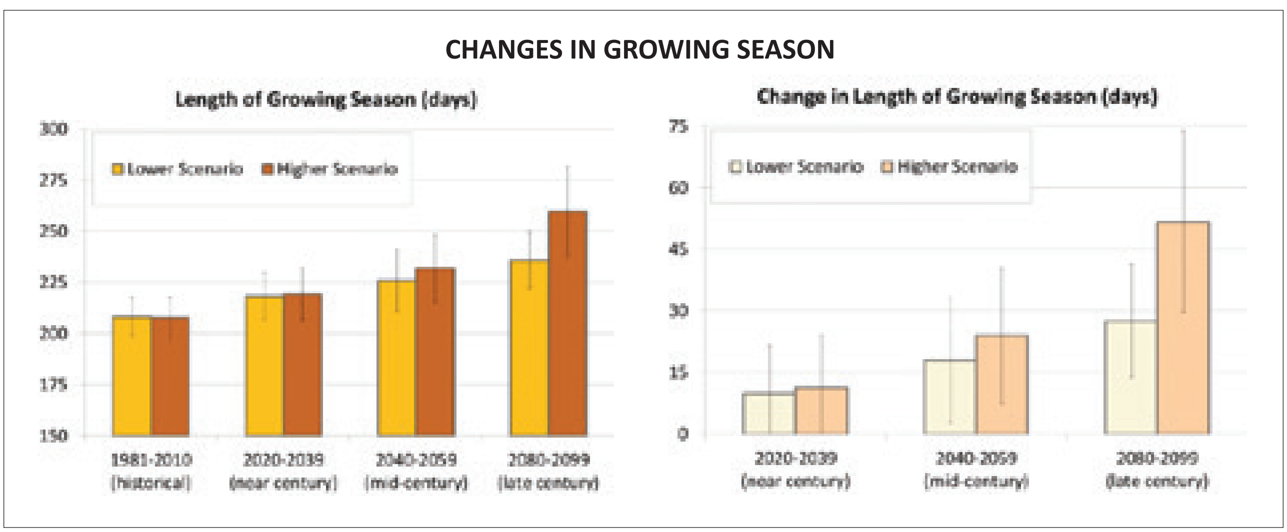


**Figure 7.1.** The growing season (frost-free days) is projected to continue to lengthen. Differences between the high scenario and low scenario are greater by mid-century and end of century. Source: Hayhoe et al. (2013).

## Precipitation Changes

- 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.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

## Potential Impacts to Agriculture

### Animal Agriculture

- Heat-related stresses resulting from extreme heat days or sustained heat waves can have significant impacts for poultry and other livestock.

- The potential impacts of higher temperatures, changes in precipitation patterns, and extreme weather events may make manure management more difficult for Delaware poultry and livestock farmers. For example, additional technology solutions to mitigate ammonia emissions, which increase with temperature, from animal housing may be needed. Designs for manure storage structures may need to be modified to counteract effects of extreme weather events, should such events increase in frequency and severity.

### Crop Production

- Rain events of increasing frequency and intensity could have significant impacts at critical periods in crop production, such as delayed planting or post-planting washouts and increases in disease pressure.

- Rising temperatures and increased frequency of dry days may lead to crop losses, reduced yields, impaired pollination and seed development, and higher infrastructure and energy costs to meet irrigation needs.

- A longer growing season and warmer winter temperatures may result in increased competition from weed species and insect pests, and an expanding range for pests that are currently limited by winter temperatures.

- Nutrient management strategies for crop production will need to evolve to meet climate-based changes because the soil nitrogen and phosphorus cycles are very dependent upon temperature and moisture. Monitoring programs, in combination with on-farm research and extensions projects, should help identify how climate change affects nitrogen (N) and phosphorus (P) cycles and guide any necessary changes in agricultural nutrient management practices.

# Chapter 7
# Agriculture

## Chapter Contents

- Overview of Delaware's agricultural resources
- Summary of climate change impacts that pose challenges to agriculture throughout the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to agriculture (nonclimatic impacts to resources)
- Potential impacts to agriculture in Delaware (based on current research and expert interviews – statewide scope)

## 7.1. Overview of Delaware's Agricultural Resources

Agriculture plays a strong role in the local and regional economies and culture throughout the state, generating close to $1.1 billion in market sales (in 2007). According to 2011 agricultural statistics, Delaware had approximately 2,500 farms and 490,000 acres in farmland (about 40 percent of the state's total acreage). The average farm size for the state is nearly 200 acres; however, more than half of Delaware's farms are less than 50 acres in size.[2]

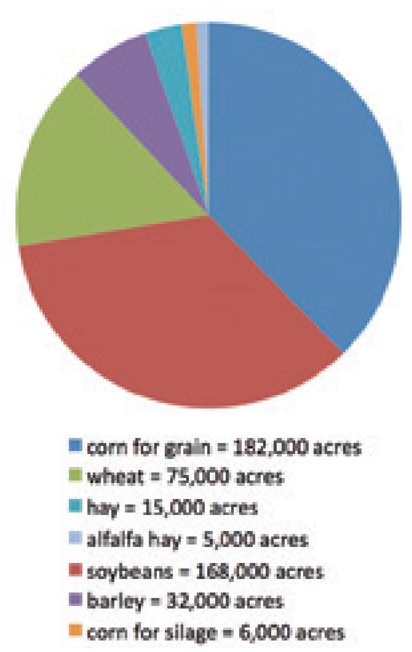


**Figure 7.2.** Delaware agricultural land use by crop - acres harvested (2011).
Source: Delaware Agriculture Statistics Service.

### 7.1.1. Agricultural Land Use

Delaware's agricultural landscape is dominated by grain crops (**Figure 7.2**) – corn, soybeans, and wheat – grown primarily as feed for the state's poultry industry, which is concentrated in the southern part of the state. Roughly half of all farm acreage is in Sussex County, while Kent County supports about one-third of all farmland. According to agricultural census data from the U.S. Department of Agriculture (USDA), in 2007:[a]

- Cropland represented 85 percent of all farmland acreage
- Irrigated land represented 24 percent of all cropland
- Acreage in corn (for grain) represented 43 percent of all cropland
- Acreage in soybeans represented 36 percent of all cropland (can include acres rotated in corn)
- Approximately 84 percent of all poultry (broiler) farms were in Sussex County
- Vegetables represented 9 percent of all cropland (for fresh market and for processing)

[a] These are the census data statistics published by the U.S. Department of Agriculture for the State of Delaware. Note that percentages and acreages may have changed. For example, irrigated acreage has increased steadily since 2007.

## 7.1.2. Agricultural Economy

Agriculture in Delaware makes an important contribution to the state's economy. Measured by the value in market sales, reported by the Delaware Department of Agriculture, Delaware produced nearly $1.1 billion in cash receipts in 2010. In market sales, the poultry industry and grain production dominate Delaware's agricultural market value (**Figures 7.3** and **7.4**). Sussex County ranks first in the United States for broiler production with more than 200 million birds produced each year. The state's poultry sales represent 74 percent of total agricultural sales, totaling more than $785 million in market sales in 2010. Corn and soybeans represent nearly 12 percent of total sales, amounting to more than $130 million.[3] A study conducted by the University of Delaware in 2010 estimated that Delaware's total economic contribution from all categories of agriculture is close to $8 billion, representing the added value of employment and direct and indirect expenditures. The report estimates that agriculture supports a total of 30,000 jobs, including full-time, part-time, and seasonal employment (estimate for 2008).[4]

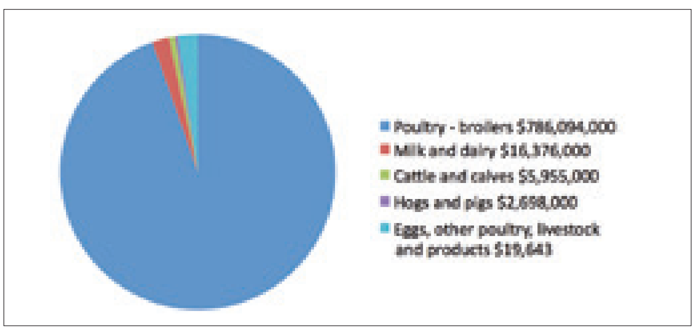


**Figure 7.3.** Value of poultry and livestock in Delaware (2010), measured by cash receipts.
Source: Delaware Department of Agriculture, Delaware Agricultural Statistics and Resource Directory 2010-2011.

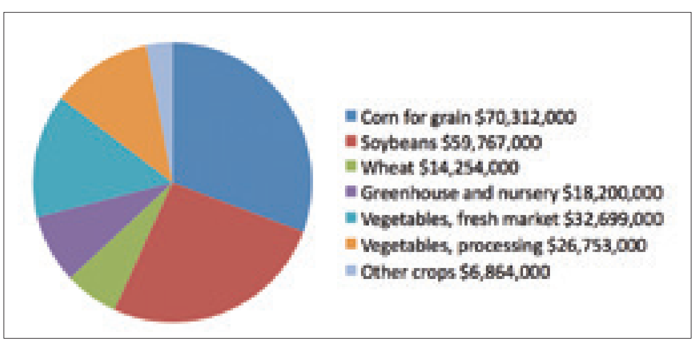


**Figure 7.4.** Value of crops in Delaware (2010), measured by cash receipts.
Source: Delaware Department of Agriculture, Delaware Agricultural Statistics and Resource Directory 2010-2011

Although poultry and grain crops are major contributors to Delaware's economy, there are a variety of other industries that add to the diversity and economic value of the state's agricultural sector, including:

- *Dairy*: Delaware supported 83 dairy farms with approximately 6,500 milk cows in 2007. The number of milk cows and milk production has declined in recent years, although cash receipts for milk products increased in 2010 to $16.4 million. More than half of Delaware's dairy farms are in Kent County.[5]

- *Equine*: Delaware's equine industry includes both racing and nonracing horses in three categories: private (pleasure, work, etc.), commercial (racing, breeding, boarding, etc.), and participant and spectator events (racing, shows, and competitions, etc.). A survey conducted in 2004 reported 2,000 equine operations statewide, with 13,000 equine (including racing and nonracing horses, ponies, donkeys, burros, and mules). Kent County supports the largest number of equines and operations, as well as two of the three horse racing tracks in the state. An estimated 27,000 acres of land are in equine-related use (based on the 2004 survey). The survey also estimates the equine industry output (direct and indirect) totaled more than $360 million in 2003.[6]

- *Vegetables*: Approximately 42,000 acres in Delaware were planted in vegetable crops in 2010. Vegetables for processing accounted for more than three-quarters of the total acreage, and totaled more than $19 million in value. Top crops included green lima beans, sweet corn, and green peas. Vegetables grown for fresh market accounted for one-fourth the acreage (11,400 acres) but represented a higher total value of more than $33 million (based on 2010 statistics). Fruits and vegetables grown for fresh market include sweet corn, watermelons, potatoes, snap peas, and pumpkins.[7]

- *Forestry*: Approximately 30 percent of the state supports forest land cover (371,000 acres), most of which is privately owned. The Delaware Forest Service estimates that roughly 4,800 acres are harvested annually, generating approximately $4 million of income for landowners.[8] (Note that forests and forest ecosystems are discussed further in Chapter 8, Ecosystems and Wildlife.)

- *Green Industry* (nursery, greenhouse, landscaping, sod): Delaware supports a growing industry of greenhouse and nursery crops, which produced more than $18 million in sales in 2010.[9] This includes garden bedding plants, potted plants, and cut flowers, as well as greenhouse production of vegetables, including greenhouse tomatoes. Delaware's green industry also includes a number of turf and sod farms that supply horticulture and landscape businesses in the state.

## 7.1.3. Agricultural Infrastructure

Agricultural operations rely on many kinds of infrastructure to produce, process, store, and transport farm products. In animal production, barns and poultry houses are critical structures for maintaining optimum conditions for animal health. In crop production, in addition to the buildings and equipment housed at the farmstead, irrigation equipment is a major investment for grain and vegetable farmers, and the operation of irrigation and pumping equipment adds maintenance requirements and energy costs. Processing facilities in Delaware include poultry, dairy, and vegetable processing plants. There are currently six poultry processing facilities in Delaware; five are located in Sussex County and one is in Kent County. Delaware is also an important producer of vegetables for processing; growers rely on canning and freezing facilities located in Delaware and neighboring states. Storage facilities for grain and other farm products are essential links for distribution and transport. These networks of infrastructure are critical for bringing Delaware agriculture products to markets throughout the country.

## 7.1.4. Trends in Agricultural Land Use and Production

Over the past several decades, agricultural production and the value of agricultural market sales in Delaware have increased by more than 200 percent. At the same time, the number of farms and total acreage in farmland has decreased as a result of changes in land use, population growth, and other economic factors. Statewide, the total number of farms and the total farm acreage declined by roughly 25 percent between 1978 and 2007 (**Table 7.1**). These trends in the state reflect larger patterns across U.S. agriculture: agricultural productivity has grown dramatically even as farmland acreage has declined. It should be noted, however, that development pressure and loss of agricultural land has declined in recent years due to the economic downturn, leading to less conversion of farmland to housing and other nonagricultural uses.

The decline in number of farms is also a result of consolidation of farming; as some producers leave farming, other farmers purchase their land and increase their acreage. Thus, the average farm size in Delaware has generally increased since the 1940s. Although less than 10 percent of farms are 500 acres or more in size, a small number of very large farm operations accounts for much of the agricultural production in the state.[10]

Gains in agricultural output are largely due to increased production efficiencies through technology innovations, such as traditional plant breeding and genetic engineering; new, large-scale equipment for tillage, planting, and harvesting; adoption of irrigation for grain and vegetable crops; new cropping systems (e.g., no-tillage); integrated pest management; and improvements in the efficiency of use of plant nutrients (e.g., fertilizers and manures).[11] Increasing efficiencies in livestock operations and improved animal genetics have also led to large gains in poultry production. In Delaware, the number of broilers produced increased by 69 percent between 1978 and 2007, even as the number of farms producing broilers decreased by 16 percent.

Delaware's total forest acreage has remained relatively stable in the past three decades; however,

**Table 7.1 Trends in agricultural land use and production (2007).**
Source: U.S. Department of Agriculture, National Agricultural Statistics Service, 2007 Census of Agriculture[12]

| | 1978 | 2007 | Approx. percent change (%) |
|---|---|---|---|
| Number of farms | 3,398 | 2,546 | -25 |
| Acreage in farmland | 669,646 | 510,253 | -24 |
| Number of farms growing corn for grain | 1,600 | 843 | -48 |
| Acreage in corn for grain | 156,517 | 185,407 | +18 |
| Number of farms growing soybeans | 2,124 | 817 | -62 |
| Acreage in soybeans | 262,363 | 155,548 | -41 |
| Number of farms producing broilers | 1,005 | 845 | -16 |
| Number of broilers sold | 145,796,536 | 246,098,878 | +69 |
| Market value of livestock and poultry products | $218,310,000 | $872,400,000 | +300 |
| Market value of agricultural products sold | $321,248,000 | $1,083,035,000 | +237 |

changes in forest tract size, tree age, and species composition have occurred. Forest assessments indicate that average forest tract size is declining and forest habitat is becoming more fragmented, largely as a result of development. The average size of forest ownership has declined from 30 acres in 1975 to less than 10 acres today. The Delaware Forest Service estimates that only 20 percent of all forest parcels are 500 acres or larger.[13] In addition, seedling and sapling forests represent less than 25 percent of forested land. These younger forests are needed to replace older forests as they are harvested or lost to storm damage or natural mortality. In recent decades, the species composition of Delaware's forests has been shifting from high value upland hardwoods and loblolly pine to lower quality hardwoods, such as red maple, which now comprise roughly half of the state's growing stock volume.[14]

## 7.2. Climate Change Impacts to Agriculture in the United States

Crop and livestock production and viability are affected by temperatures and changes in precipitation. Climate change impacts that may affect agriculture production include reduced animal and crop health and productivity related to heat stress; exposure to increased or new parasites and diseases, leading to increased mortality; and higher production costs.

### 7.2.1. Animal Agriculture

- Increasing temperatures may negatively affect livestock operations by increasing the intensity and frequency of summer heat stress. Heat stress can depress animal growth and reproduction for weeks or even months and result in decreased production and increased animal mortality. Agricultural operators can compensate by introduction of heat-tolerant genetics through selective breeding programs.

- Extreme weather events can damage agricultural infrastructure (barns, storage buildings, and processing facilities). Interruptions to transportation and energy can affect operations, often with costly impacts.

- Changes in temperature and precipitation may increase the impact of pathogens and parasites that affect the health of livestock. Earlier arrival of spring and warmer winters may create conditions that allow the spread of diseases and increased survival and number of reproduction cycles of insect pest parasites.[15]

Animal responses to heat are well documented in various aspects of animal production. Optimal livestock production requires temperatures that do not negatively alter the animal's functions or behaviors. When an animal's body temperature moves out of normal ranges, the animal must expend energy to conserve or reduce heat. An animal's response to heat stress is often observed as a decline in physical activity and eating or grazing activity. For example, voluntary feed intake can drop to less than half of normal amounts during hot spells.[16] As a result, the animal has less energy available for meat or milk production and/or reproduction. Continued exposure to high heat can cause death of the flock or herd.[17]

Broilers (chickens raised for meat), like many other types of livestock, are sensitive to high heat. Temperatures in the mid-90s (Fahrenheit) combined with high humidity can lead to elevated body temperatures, which result in higher feed conversion ratios, lower feed intake and weight gain, and increased mortality.[18] The timing of high heat days can also be critical; birds close to their maximum weight are more sensitive to heat stress. The majority of poultry operations exist in large indoor facilities where the birds are kept safe from adverse weather and predators, and where their health and welfare can be closely monitored. Under these conditions, heat stress can become an issue during the summer months.[19] Heat-related stresses in poultry houses are offset by ventilation systems that include fans and various types of evaporative cooling.

Dairy cows are sensitive to both heat and humidity. The optimum temperature range for milk production is between 39 and 75°F. Heat stress and decreased milk production can occur at 75°F when relative humidity is greater than 65 percent or at higher temperatures (81°F) when relative humidity is greater than 30 percent.[20] Warming temperatures could lead to increased impacts to livestock from pathogens and parasites. Earlier arrival of spring and warmer winter seasons could create conditions that allow these pests to proliferate, expanding their range both geographically and temporally.[21]

Direct damage from extreme weather, such as heavy rain or snow events, can result in huge economic costs, including repair and replacement costs of buildings and equipment, loss of income, and removal of snow, silt, or debris left behind. Severe weather events can also affect infrastructure and systems that are critical to agriculture. For example, flooding and heavy snow can slow or block transportation of crops or livestock to markets or processing facilities, or prevent deliveries of feed. Barns, grain silos, manure storage facilities, and other farm infrastructure may be affected by high winds or heavy snows, as described above in the example of poultry houses. Extreme weather can also damage or impair processing facilities for poultry and other livestock. Electricity outages caused by extreme weather events present vulnerabilities for livestock producers. There is increasing need to maintain and upgrade backup generation to cope with power disruptions.

Controlling and preventing animal diseases is a critical part of livestock operations, and is supported by extensive research, monitoring, and technical outreach programs. In Delaware, the state veterinarian is empowered with the authority to control, suppress, and eradicate infectious diseases in livestock and poultry. To assist in that effort, the University of Delaware's Poultry Health System provides surveillance and early detection of infectious diseases that can cause significant health threats to poultry. The program routinely tests for infectious diseases such as Newcastle disease, bronchitis, and avian influenza. Many vaccines developed through the nationwide university research community continue to improve poultry health and save the poultry industry millions of dollars annually.[22] There is insufficient research to determine which, if any, animal pathogens and diseases may expand in range or increase in frequency or severity as a result of climate changes. However, it is fairly well documented that if animal health suffers from other stressors (such as heat or cold stress), there is increased susceptibility to diseases that are already present in the environment.[23]

### 7.2.2. Crop Production

Plant production is affected by several impacts related to climate change: increased temperatures, changes in precipitation patterns and amount of rainfall, increased carbon dioxide concentrations, increased ozone levels, and changes in growing season.[24]

## Temperature Impacts

- Higher temperatures, earlier arrival of spring, and increasing length of the frost-free growing season could be beneficial for some crops.
- Warmer temperatures can facilitate increased growth in crops; however, the fruit of the plant may not reach full maturity, resulting in lower yields. High temperatures during the critical reproductive stages of plant development can affect pollen viability, fertilization, and seed or fruit formation in many crops.
- Higher winter temperatures can negatively affect crops that require a chilling period for optimum flowering, fruit set, and seed development. Midwinter warming can also pose a risk for plants that emerge or bloom during an early warm period followed by a late spring cold snap or nighttime frost or freeze.
- Warmer temperatures, especially in winter, are expected to increase the northward spread of weed species that can cause significant reductions in yields through competition with crops for water and nutrients. Increasing frequency and intensity of pest outbreaks will likely boost pesticide use, resulting in economic and environmental impacts.[25]

Crops have optimum temperatures for each phase of their growth and development cycle; significant changes in seasonal temperatures due to climate change could disrupt plant growth and yields. Increases in frost-free periods may be beneficial for crops that require longer growing periods and may allow for more double and triple cropping. On the other hand, increased plant stress due to high temperatures, periods of drought, increasing weed competition, and insect and disease pressure may outweigh the benefits of an increased growing season.

Increased summer temperatures generally tend to lead to lower yields for some grain crops. For example, higher temperatures will affect pollen development and viability in corn. Pollination in corn is a critical period for development and sufficient yield. If the corn silks are exposed to temperatures greater than 95°F with low relative humidity and low soil moisture, desiccation of the exposed silks can occur, and at sustained high temperatures pollen, is no longer viable. Shorter life cycles result in smaller plants, shorter reproductive phase duration, and lower yield potential.[26] Many fruiting vegetable crops will have reduced fruit set as temperatures increase and others vegetables may flower prematurely or have reduced quality due to higher temperatures.

Increasing temperatures will likely allow the northward spread of weeds, insect pests, and diseases that already cause significant crop damage in southern states. Some aggressive weeds, such as kudzu (*Pueraria montana* var. *lobata),* which are sensitive to freezing temperatures, are limited by minimum winter temperatures.[27] Temperature is also an important limiting factor affecting the distribution of insect pests. Warmer winters are likely to increase populations of some insect pests that are currently limited in their overwintering range. Climate projections indicate the potential for expansion of the overwintering range for numerous insect species; some may be crop pests, while others may be beneficial.[28]

Changes in annual and seasonal temperatures also affect the growing season, defined as the period between the last frost date in spring and the first frost date in fall. The average length of the growing season has already been increasing: in the eastern United States, the length of the growing season has increased by approximately eight days since 1895.[29] Longer growing seasons can trigger earlier emergence of insects and promote more reproductive cycles, affecting populations of both insect pests and beneficial insect species. Milder winter temperatures and longer growing seasons may alter the life cycles of beneficial pollinator species that are critical for many flowering plant crops. A study published in 2011 reported that over the past 130 years several species of North American bees are emerging earlier in spring – by about 10 days – with most of the shift in timing occurring since 1970. The potential for "mismatch" between the timing of flowering plants and insects could occur if flowering crop species are not in sync with the earlier emergence of pollinators.[30]

## Precipitation and Extreme Weather Impacts

- Increasing variability of precipitation will require farmers to cope with flood and drought conditions. 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.

- Increased temperatures increase transpiration in plants and cause higher water demands, resulting in the need to irrigate to mitigate water stress. This can lead to higher energy costs for pumping water and increased investments in irrigation equipment and labor. Increased water stress in plants will limit yields in crops by reducing photosynthesis.

- Extreme weather events, such as heavy rain, snow, and/or wind, can have severe impacts on crop production such as wind or rain knocking down grain crops late in the growing season and delays in planting or harvesting due to flooding of fields.

It is projected that droughts will occur during the peak growing season when crop demand for water is high. Water stress, like heat stress, can reduce plant vigor and productivity. Although irrigation infrastructure already is common throughout Delaware, increased water demand may expand the need for irrigation equipment, resulting in higher costs for capital investment and energy costs.

Plant production can be jeopardized depending on the timing and intensity of precipitation events throughout the growth cycle. For example, heavy spring rains can delay planting or force producers to operate heavy equipment on wet soils, leading to soil compaction.[31] Large rain events in the spring post-planting can cause seed washout and soil crusting, which reduce seed emergence. Field flooding during the growing season can cause crop loss due to increases in susceptibility to root diseases, anoxia (lack of oxygen in the soils), loss in topsoil, and leaching of nutrients.[32] For example, the 1993 floods of the Mississippi River in the U.S. Midwest resulted in agricultural damages estimated at $6 to $8 billion. Approximately 70 percent of total crop losses were due to saturated soils in upland areas.[33]

## Carbon Dioxide and Ozone Impacts

- Increasing concentrations of carbon dioxide ($CO_2$) can stimulate plant growth; however, the combined effects of increased $CO_2$, higher temperatures, and increased ozone may collectively result in a negligible benefit to yields.

- Many weed species respond more positively than crop species to higher concentrations of $CO_2$. In addition, widely used herbicides such as glyphosate (trade names Roundup™, Roundup Pro™, and Accord™) lose efficacy under higher $CO_2$ conditions.[34]

Increasing concentration of atmospheric $CO_2$ has the direct effect of stimulating plant growth, although the response varies considerably among plant species and varieties. Higher $CO_2$ levels also trigger the partial closure of leaf pores (stomata) and thus can produce a water-conserving effect. However, when the combined effects of increased $CO_2$ and increased temperature are considered together, the results are mixed. Some crops, such as leafy greens, may benefit in the vegetative phase of growth, where increasing leaf area increases crop yield.[35] However, for many grain crops, the benefits of $CO_2$ alone are unlikely to compensate for the negative impacts of heat stress in the reproductive phase of plant development.[36]

Many weed species may benefit more than agricultural crops from combined increases in temperature and $CO_2$.[37] For example, research conducted on soybeans under current and increased levels of $CO_2$ found that while soybean growth was stimulated by higher $CO_2$ level, weed growth was stimulated to a greater extent, assuming normal precipitation levels.[38]

Another climate change impact related to increasing temperatures is the associated increase in ozone pollution, which is known to be damaging for many plants. Some widely grown crop species, such as soybeans and wheat, are particularly sensitive to ozone.[39]

### 7.2.3. Forest Management

Climate change impacts affect managed forests in ways that are complex and different than climate effects on annual crops. Forest species are long-lived, and therefore exposed to a wide range of variability in seasonal and annual weather patterns. Projected increases in temperature and atmospheric $CO_2$ and changes in precipitation are likely to affect forests across the United States, both directly and indirectly.

Increasing temperatures and longer growing seasons will contribute to increased forest growth. However, temperature changes will affect different tree species to varying degrees and are likely to alter species composition in forests. Some tree species may benefit by expanding their range and/or increasing population, while other species may decline or shift to higher elevations or higher latitudes. In the northeastern United States, for example, some forest types, such as oak-hickory, are expected to expand, while maple-beech-birch forests are expected to contract.[40] Increasing temperatures may also lead to greater mineralization of soil nutrients, which can enhance forest growth but may also lead to increased nutrient losses to streams and rivers.[41]

Rising levels of atmospheric $CO_2$ are likely to increase forest productivity and may also increase carbon uptake and storage. Research conducted through Free Air $CO_2$ Enrichment (FACE) experiments suggests that North American forests will absorb and retain more $CO_2$ – increasing the rate of carbon sequestration – where there are nutrient-rich soils with no water limitations.[42]

Changes in precipitation will affect different tree species in different ways. Overall increases in precipitation may benefit some species. However, projected changes in precipitation patterns for the eastern United States suggest an increase in heavy rain events that may lead to increased flooding, erosion, and loss of sediment into streams – all of which may have negative consequences for forest management.[43] Climate change impacts may also affect forests indirectly, through increases in outbreaks of forest insects and pathogens. Increasing temperatures can affect insect populations by increasing overwintering survival and life cycle development rates as a result of warmer winter temperatures and a longer growing season. Insect pests may also shift or expand their ranges as temperatures rise.

## 7.3. External Stressors

Climate change is one of many stressors that can affect agricultural productivity and profitability. Other external stressors include land use changes, environmental regulations, energy and input costs, and fluctuations in market demands and prices. Some of these factors are local or statewide – such as land use changes and population growth. Others are national or global – such as global market prices for commodities.

*Land use changes* in Delaware's rural landscape have followed a pattern similar to much of the United States. As described above, the number of farms and total acreage in farmland in Delaware has declined by approximately 25 percent over the past 30 years. Loss of farm acreage is driven in part by population growth and increasing demand for new urban, suburban, and commercial development. This growth spurred rising land values that have added pressure to convert farmland to other uses.

Farmland that lies in close proximity to existing towns and cities may be subject to annexation and subsequent changes in zoning that allow for subdivision in lot sizes that support residential development. Between 2004 and 2008, incorporated towns and cities in Delaware expanded their boundaries by 9,735 acres; more than half of this newly incorporated land (5,396 acres) was in Sussex County, which is dominated by agricultural land use. Another trend in housing growth that affects the agricultural landscape is a growing demand for homes in unincorporated areas outside towns and urban centers. In addition, between 1995 and 2000, approximately 23 percent of new construction was on lots of one acre or more in size.[44] It should be noted, however, that the pace of development – and subsequent pressure on agricultural land – varies over time in response to economic cycles. The recent downturn in the economy, both nationally and statewide, has slowed the pace of building and land conversion over the past five years.

*Environmental regulations and government programs* can present constraints and additional costs to farmers, but can also provide some financial support and incentives for adopting agricultural practices that reduce environmental impacts and improve agricultural productivity. Federal and state water quality and air quality regulations affect most growers and producers. Delaware's Nutrient Management Law requires a nutrient management plan to be developed for the majority of operations with the goal of reducing the loss of nitrogen and phosphorus from agricultural lands by better management of all nutrient sources (fertilizers, manures), including their methods, rates, and timing of application. Additionally, the law requires certification of anyone who generates or handles nutrients as well as those individuals who write the plans. The federal Clean Water Act through the National Pollution Discharge Elimination System Permitting Program also requires concentrated animal feeding operations (CAFOs) to obtain a permit limiting the pollution that can be discharged from these sites.

Although compliance with environmental regulations can be costly, voluntary programs offer some opportunities to help farmers implement management practices designed to reduce losses of nutrients and sediments to water and/or air. Federal programs through the USDA and local conservation districts provide financial assistance through cost-share grants to install water quality improvements such as buffer strips and drainage structures. In addition, federal Farm Bill programs cover a wide range of economic incentives for farmers in the form of loans, price supports, and crop insurance.

*Energy costs* represent a significant expense in agricultural production, and include both the direct costs of fuel and electricity and energy-intensive inputs, such as fertilizer. Energy expenses averaged 13 percent of total production costs in the United States in the period 2005 to 2008 (roughly half of this amount for direct energy use and half for fertilizer). However, some major field crops such as corn require much higher energy inputs. For irrigated crops, energy demands are greater, but may be offset by the value of increased yield. Energy-related costs affect livestock producers also, particularly when feed costs increase as a result of higher energy prices relative to total production costs. Poultry production is somewhat less affected than other types of meat production (poultry requires less feed per pound of meat produced); however, poultry growers also must cope with increased energy costs in heating and cooling of poultry houses, and poultry processing can also be affected by higher energy costs.[45]

Projecting future impacts of energy costs on agriculture is difficult, given the complexities of fluctuating energy prices and the uncertain effects of future governmental policies on carbon-based fuels. However, numerous government programs and incentives have developed in recent decades to assist farmers in improving energy efficiency and adopting renewable energy sources. In addition, there may be a future potential for agricultural producers to participate in emerging carbon markets by using practices that reduce greenhouse gas emissions, creating marketable offset credits.

*Fluctuating market prices* are a significant external stressor in Delaware agriculture. For some agricultural products, such as fruit and vegetables, prices may be determined largely by local and regional markets. For commodity crops, such as corn and soybeans, national and global market demand and supply are key drivers in crop prices.[46]

Livestock production also follows trends in market supply and demand. Delaware's poultry industry produced a record 282 million broilers in 2005; the number has declined in recent years to a total of 217 million in 2011, due in part to oversupply and low prices. Higher prices for feed corn have also had an impact in Delaware; two poultry companies filed for bankruptcy in 2010 and 2011, both citing the impact of increasing cost of feed.

Delaware's three largest agricultural products – poultry, corn, and soybeans – are highly interdependent. The feed grain crops grown in the Delmarva region supply roughly two-thirds of the feed grain needed for the broiler industry; the remaining third must be imported, generally from the Midwest grain belt. The proportion of locally grown feed grain varies from year to year, and may be increasing as a result of the expansion of irrigation, which can greatly increase crop yields. Any significant changes to the availability and prices of grain crops – locally, nationally, and globally – have direct impacts on poultry growers' costs and profitability.

## 7.4. Potential Impacts of Climate Change to Delaware's Agriculture

### 7.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under the higher as compared to the lower scenario and by end of century as compared to more near-term projections. 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.

#### Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

- 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 (**Figure 7.1**).

#### Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

#### Precipitation Changes

- 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.

- By end of century, nearly every model simulation shows projected increases in the frequency and amount of heavy precipitation events.

### 7.4.2. Vulnerability to impacts

Agriculture is a highly dynamic industry. Like all businesses, agricultural producers cope with a range of variables and risks, including market demand, economic conditions, regulatory requirements, and labor and input costs. In addition, agriculture is especially vulnerable to weather-related risks. Seasonal and annual weather fluctuations and climate-related events have a strong influence on yields in both crop and livestock production. As a result, there is considerable variability in year-to-year agricultural output. Farmers have managed to cope with these dynamic conditions since the beginnings of agriculture, and therefore have considerable skill and experience in adapting to change.

Climate change represents a potentially increasing exposure to variability, a "risk magnifier" that may affect the limits within which certain types of agriculture activities are economically viable. This section discusses potential vulnerabilities in Delaware's agricultural sector by examining several types of agricultural production that could face increasing challenges from rising temperatures, changes in precipitation, sea level rise, and exposure to extreme weather events. Also noted are some practices already being developed that may provide adaptive strategies for climate change, and current and ongoing research underway to better understand the potential impacts of climate change on agriculture.

In a changing climate, warming temperatures may offer benefits or opportunities as well as challenges. As previously described, the United States has seen overall increases in agricultural production in recent decades, through the development of new varieties of crops and increasing efficiency in agricultural operations. Some crops have benefitted from changes in climate and weather patterns. However, in regard to extreme weather, there is very little potential for benefits to agriculture or to any other sector. In recent decades, the frequency, intensity, and duration of extreme weather events have had significant, largely negative, economic impacts on crop and

## Increasing Irrigation Use and Efficiency

In Delaware, irrigation is used for the main grain crops – corn, soybeans, and wheat – as well as for most vegetable crops. Irrigated crop acreage has more than tripled in Delaware in the past several decades. Irrigated acreage now accounts for roughly one-fourth of all crop acres, and continues to expand. Increasing efficiency in irrigation benefits farmers by ensuring that crops get sufficient water when they need it, based on weather and soil moisture conditions. Improving irrigation efficiency also reduces water waste, which helps lower costs. A number of programs and research projects in Delaware currently focus on increasing irrigation use and efficiency:

The Delaware Rural Irrigation Program (DRIP) is a joint effort of the Delaware Department of Agriculture and Delaware Economic Development Office. The program, created in 2011, offers no-interest loans to finance up to 25 percent of the total cost of installing irrigation systems. In the first year, the program has helped bring more than 850 acres of farmland under irrigation.

The Delaware Irrigation Management System (DIMS), launched in 2012 by the University of Delaware, is an irrigation scheduling application developed specifically for Delaware that uses automatically updated weather data. The online system is designed for a number of grain and vegetable crops, including corn, soybeans, sweet corn, cucumbers, watermelons, cantaloupes, lima beans, and peas.

University of Delaware Cooperative Extension is also conducting field research on subsurface drip irrigation (SDI), a system of plastic irrigation tapes or drip lines placed 10 to 16 inches below ground to provide water at the plant's root zone. SDI is well suited to small or irregularly-shaped fields that are impractical for center-pivot irrigation. SDI is currently being tested with corn, soybeans, lima beans, and small grains in a variety of irrigation scenarios to determine which scenario results in the best yields and improves nutrient uptake and water efficiency.

Improvements in technology can help increase irrigation efficiency, but optimizing that efficiency depends on having the best available data on conditions in the field. For example, when data from soil moisture sensors located throughout a crop field are used in conjunction with irrigation scheduling software, there is greater accuracy in determining the timing and amount of irrigation needed. Proper calibration of irrigation equipment is also important for ensuring that crops are receiving the intended amount of water. To date, much of the irrigation research has been done on heavy soils in low humidity regions. There is a need to refine and regionalize irrigation research to determine the ideal irrigation management strategies for Delaware's sandy soils and humid climate.

livestock production. Agriculture in the United States and globally has seen dramatic losses and economic impacts due to extreme temperatures (high heat or cold periods), changes in rainfall (drought or flooding), and seasonal changes (early spring or late frost).

### 7.4.3. Animal Agriculture – Heat Impacts

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-related stresses on animal health and reduced feed and growth efficiency. Heat, drought, and extreme weather may affect the dairy industry by reducing forage supply and quality. (Forage generally refers to the plants eaten by grazing animals in pasture, and may include hay or silage harvested and later used as feed.) Forage accounts for more than half of the feed requirements for dairy cows, and cannot be readily purchased to make up short supplies. Extreme heat also causes poor reproduction in dairy cows. Under higher emission scenarios, by mid-century dairy cattle in Delaware would be under moderate heat stress levels that could result in a 10 to 25 percent decrease in milk production.[47]

The broiler industry has an advantage in coping with heat events because the animals are raised indoors in poultry houses that are environmentally controlled. Since the 1990s, the construction of poultry houses in Delaware has changed; the open, curtain-style houses have largely been replaced by enclosed poultry houses with insulation and ventilation systems to help maintain the necessary range in temperature, humidity, and air quality within the houses year-round.

Higher summer temperatures will require greater ventilation and thus increase energy usage. Improvements in tunnel ventilation poultry houses have also increased capital investment costs for growers. Many farms have upgraded electrical equipment and well capacity to meet the increasing demand for water from evaporative cooling. One of the most cost-effective measures used to cope with temperature extremes (both heat and cold) is weatherization of barns, poultry houses, and other livestock structures. Just as with any house or commercial building, effective insulation and ventilation of livestock structures can improve animal health by reducing cold or heat stress, and improve energy efficiency, reducing costs of heating and cooling.

Genetic improvements in poultry breeds are a long-term strategy for coping with increasing temperatures. Research is currently underway at the University of Delaware to study the effects of heat stress in poultry by comparing modern breeds to poultry breeds of the 1950s. As part of a 5-year study funded by USDA, UD professor Carl Schmidt is looking for genetic variations that have been bred out of modern chickens, affecting their resistance to heat stress.

## Managing Heat Stress in Poultry

“Tunnel ventilation” houses include fans with evaporative cooling units to provide air cooling. Ventilation systems are designed to improve indoor air quality in winter as well as summer. Keeping poultry at a comfortable temperature supports overall health, growth, and weight gain in broilers, and helps improve their resistance to disease. Providing a climate-controlled environment also allows growers to produce more pounds of broilers at commercial densities.

The advantage of technology comes with two costs: system maintenance and energy costs. Achieving the optimum advantage of technology requires that the systems be carefully maintained and monitored; ineffective or failing equipment can result in rapid change in heat and humidity, leading to severe heat stress. Energy to operate fans and other equipment is generally provided from grid sources, but back-up generators are essential equipment that must be properly maintained. Improvements in building insulation and ventilation can improve energy efficiency and thus reduce energy costs. Energy audits are available to poultry growers and may be required for certain federal cost-share programs that support energy efficiency improvements in poultry operations.

## 7.4.4. Crop Production – Heat and Changing Rainfall

Changes in temperature and/or precipitations patterns may alter the viability of some crops in the state and promote the need for alternative farming and agricultural practices. Delaware may see positive and negative impacts on crop productivity. Continued increases in average temperatures and temperature extremes may produce a negative impact for some crops when temperatures reach a critical threshold. Crops are also sensitive to extreme fluctuations in precipitation, both in amount and timing of rainfall at critical points of plant development.

Grain farmers in Delaware, as in other parts of the country, have coped with heat waves and drought cycles for decades. The large acreages of sandy soils with low moisture-holding capacities are a major contributing factor to Delaware's drought-related crop production problems. Two important strategies have enabled farmers to adapt to changing conditions. First, genetic researchers continue to develop new varieties and hybrids of crop species that are adapted to common environmental stressors, including drought tolerance. Second, investment in irrigation equipment and improvements in irrigation efficiency have dramatically increased yields of many crops and buffered the uncertainties of seasonal rainfall patterns. The benefits of irrigation for crop farmers in Delaware are significant. Although crop yields per acre vary within the state, water is the single most important factor in determining yield. Irrigation increases overall productivity and provides an important buffer during prolonged or recurring drought periods. Irrigation also provides improvement in nutrient efficiency in dry conditions: during drought periods, irrigated crops are potentially twice as efficient at nitrogen recovery as nonirrigated crops.[48]

High heat also damages vegetable and fruit crops. At temperatures above 94˚F, photosynthesis decreases and can lead to reduced plant growth and lower yields. High nighttime temperatures are especially damaging, as plant respiration increases and limits fruit and seed development. Inadequate water and dry soil add to heat stress; hot dry wind is a significant factor in heat buildup in plants and accelerates damage to crops. Plant tissues die at temperatures of around 115˚F, indicated by scorched leaves and stems and sunburned fruits.[49] High temperatures can also aggravate blossom end rot, a condition that affects tomatoes and peppers, by interfering with calcium movement through the plant. In hot weather, transpiration increases through the leaves, reducing the amount of calcium received by the fruits.[50] In summary, the major vegetable crops grown in Delaware (lima beans, sweet corn, peas, cucumbers, and snap beans) will be at risk for having limited yields due to heat and water stress. Some of this can be mitigated with plant breeding efforts and cultural practices, such as better irrigation.[51]

Increased levels of ozone are another factor associated with high temperatures that can cause serious damage to vegetable crops. Ozone is a strong oxidant formed by the combination of sunlight and volatile organic compounds, generally from emissions from fuel combustion; crop damage is often most visible in fields closest to major roadways. Crops in Delaware susceptible to ozone damage include watermelons, cantaloupes, snap beans, pumpkins, squash, and potatoes. Ozone damage in sensitive vegetable crops develops when ozone levels are 70 to 80 parts per billion (ppb), which is roughly equivalent to the 8-hour ozone standard under air quality regulations.[51]

## 7.4.5 Weeds, Diseases, and Insect Pests

There is very little research in Delaware to confirm that climate change impacts will cause or accelerate the spread or incidence of weed species, insect pests, or plant pathogens. Weeds and pests may be increasing in response to climate changes as well as to other variables. For example, weeds that are drought-tolerant may expand rapidly in dry years, while fungal diseases may spread in wet years. Crop species that are already stressed by extreme temperature or precipitation conditions (e.g., high heat, wet soils) may be more affected by these pests and pathogens.

Some weed species and insect pests are likely to expand their range northward as climate warms. Species that now flourish in the south may move into areas in the Delmarva Peninsula that were previously too cold to support their populations. In addition, ecological disturbance caused by extreme weather events could facilitate the spread of invasive species, as nonnative species encroach into disturbed ecosystems more quickly than native species can re-establish. The following discussion provides a few examples of weeds, diseases, and insect pests that represent known and potential threats to Delaware agriculture and forests. (Note these are described here only to provide a sample of potential impacts, not as a comprehensive summary.)

**Palmer amaranth** (*Amaranthus palmeri*) is a plant species native to the southwestern United States and is a problem weed in crop fields throughout the South. Related to pigweed, Palmer amaranth has been described as "pigweed on steroids" because of its rapid and aggressive growth. Without effective control, the plant can reach 5 to 6 feet in height and overwhelm a crop field within a few years. Because of its ability to grow quickly, effective control requires herbicide treatment within just a few days after the plant emerges, before the plant reaches 4 inches in height.

As a further challenge to controlling this aggressive weed, a variety of Palmer amaranth that is resistant to the herbicide glyphosate (Roundup™) is known to occur in Georgia and North and South Carolina. In addition, some Palmer amaranth biotypes are resistant to multiple herbicide modes of action. Delaware observations of Palmer amaranth were first noted in the September 2010 posting of the Weekly Crop Update by the University of Delaware Cooperative Extension, but early indications were that this was not the herbicide-resistant variety of the plant, and therefore it could be controlled with glyphosate. However, in June 2012, the presence of glyphosate-resistant Palmer amaranth was confirmed on the Delmarva Peninsula. The Weekly Crop Update notes that in southern states where glyphosate-resistant Palmer amaranth has appeared in cotton fields, some farmers have had to resort to hand weeding to control this weed species.[52]

**Soybean rust** (*Phakopsora pachyrhizi)* is a fungal disease that causes significant damage to soybean crops and can result in losses of up to 90 percent. The fungus is spread by windblown spores, and thus has the potential for long-distance dispersal. It is thought that soybean rust became established in the continental United States as a result of wind-borne spores carried by Hurricane Ivan in 2004.[53] Soybean rust fungus is an obligate pathogen that cannot spread without a living plant host. Soybeans are one of many plant species that are known hosts, including other bean species, clover species, and kudzu (*Pueraria montana* var. *lobata).* Because it requires a living host to survive, soybean rust fungus overwinters only in frost-free regions.

Epidemics of the disease can occur where the fungus survives the winter and environmental conditions are warm and wet. Infection begins when viable spores land on the leaves of a host plant species. Leaves must be wet, and temperatures must be in the range of 54°F to 84°F. The USDA and state agricultural programs have been carefully monitoring soybean rust and tracking changes in its distribution each year. In 2013, soybean rust fungus was found in eight states (Alabama, Mississippi, Florida, Georgia, Louisiana, South Carolina, Arkansas, and North Carolina). Soybean rust has not yet been found in Delaware, and has not been detected in neighboring states. The University of Delaware Cooperative Extension forecasts that the disease does not pose an immediate threat to soybean growers in the state.[54]

**Southern pine beetle** (*Dendroctonus frontalis)* is a native insect pest found throughout the southern and southeastern United States that can infect and kill many species of pine within its distribution. In Delaware, and in much of the southeastern United States, the primary host is the native loblolly pine (*Pinus taeda*). In New Jersey, more than 20,000 acres of pitch pine (*Pinus rigida*) forest have been infected in recent years. Since the mid-1990s, Delaware scientists have participated in a regional study to monitor the southern pine beetle by surveying four sites in loblolly pine and one pitch

## Salt-Tolerant Crops

The Delaware Sea Grant program has been conducting field research on seashore mallow *(Kosteletzkya virginica)*, a salt-tolerant marsh plant, to evaluate its potential as an oil and feed crop. The plant produces seeds with an oil content of 18 to 20 percent – similar to soybeans – and has a fatty acid profile similar to cottonseed oil. In addition, seashore mallow can be planted and harvested with conventional farm machinery.

As a native plant adapted to brackish and saline conditions, seashore mallow can survive and even thrive in coastal areas where soils have been affected by high spring tides or storm tides that flood low-lying farmlands. The plant is also suitable for crop fields where groundwater sources for irrigation have become too brackish or saline for other crops. As a marsh plant, seashore mallow is flood-tolerant; as a perennial plant with a deep root system, it is also drought-tolerant.

The development of seashore mallow as a commercially viable crop may offer farmers a transition option for agricultural fields that are exposed to saltwater from storms and from sea level rise. Coastal fields planted in seashore mallow could supply ecosystem benefits by providing a buffer to reduce erosion and nutrient runoff on land that would otherwise be left fallow.

pine stand in Sussex County. The southern pine beetle uses a "mass attack" strategy in which large aggregations of beetles respond to pheromones emitted by female beetles. The mass infestation of beetles overwhelms the trees' natural defense system of resin production. In southern states, the emergence of overwintering beetles coincides with the blooming of flowering dogwood (*Cornus florida* L.). The initial phase of dispersal is followed by rapid and widespread infestations. Increasing temperatures are likely to affect the range of this insect species; a future northward range expansion is projected for several southern insect pests, including the southern pine beetle.[55] In addition, a longer growing season may allow for a greater number of reproductive cycles. In Delaware, the southern pine beetle typically has two to three generations per year;[56] however, the species can produce as many as seven generations per year as its reproductive cycle accelerates in the spring and summer.[57] Current management of this insect pest includes active monitoring and fast response to outbreaks to prevent widespread mortality from the southern pine beetle.

### 7.4.6. Agricultural Land Use – Sea Level Rise

A relatively small percentage of agricultural land in Delaware is located in coastal regions that may be affected by sea level rise. The Sea Level Rise Vulnerability Assessment for Delaware assessed agricultural lands identified as Prime Farmland and Farmland of Statewide Importance and found that only 2 to 4 percent of these highly productive soils are potentially exposed to sea level rise under the three scenarios (1.6-, 3.3-, and 4.9-foot rise by 2100). Although the percentage of the total statewide acreage is small, the number of acres of potentially inundated farmland does have an impact on local agricultural communities. The Sea Level Rise Vulnerability Assessment estimates a range of 12,564 to 32,361 acres (1.6-foot and 4.9-foot rise, respectively) could be inundated. In addition to the farmland directly affected by inundation, another potential impact to coastal agriculture is the risk of salt water intrusion into groundwater used for irrigation or into shallow aquifers. Increasing salinity in water applied or available to crops will affect crop yields and the productivity of soils even before inundation occurs.

### 7.4.7. Nutrient Management – Climate Impacts

Climate change impacts may have direct and indirect effects on nutrient (nitrogen and phosphorus) and sediment losses from agricultural systems. Nutrient management is a critical component of farm management, for both animal agriculture and crop production. Nutrient losses have negative consequences for farmers because they represent economic losses (applied nutrients are an input cost), and because of the environmental impacts of nutrient leaching and runoff into waterways and emissions from

**Table 7.2 Climate change impacts and nutrient management**

| *Climate Change Stressor* | *Potential Vulnerability* |
|---|---|
| Increasing temperatures | • Increased volatilization losses of ammonia-N, a nutrient associated with animal production, are known to occur as temperature increases; animal facilities may require new technology solutions to prevent air quality impacts from ammonia release.<br>• Increased volatilization of surface-applied ammonia-based fertilizers or poultry manures, both commonly used for crops in Delaware, occurs as temperatures increase. This can reduce N use efficiency (economic cost) and may be a potential air quality impact; wider use of practices such as soil incorporation of manures and fertilizers to mitigate ammonia volatilization losses may be required.<br>• Manure organic N will be converted to nitrate-N more quickly and completely in warmer soils, assuming adequate soil moisture. Thus, practices to prevent nitrate leaching from Delaware's sandy soils will likely need to be more efficient. |
| Changing precipitation patterns - drought | • Drought conditions reduce the efficiency of plants in using applied nitrogen fertilizers and manures, leading to lower yields and increased concentrations of nitrate-N in soils at the end of the growing season that can be susceptible to leaching losses during late fall and winter.<br>• Lower yields also lead to a slower drawdown of phosphorus in "high P" soils via crop harvest; these conditions may lead to a need to further expand or increase the efficiency of irrigation use in Delaware cropping systems to counteract any increases that may occur during drought. |
| Changing precipitation patterns – extreme rain events | • Prolonged and intense periods of precipitation will increase runoff of sediment and nutrients to surface waters.<br>• Extreme rain events increase the risk of nutrient losses from overflow of manure storage facilities.<br>• Application of organic nutrient sources may be delayed or made more difficult in wet conditions following extreme rain events, and may lead to increased nutrient losses. |
| Extreme weather events | • Structures related to best management practices may fail or be damaged, resulting in losses of nutrients and sediment; this can include buffer strips, drainage structures, constructed wetlands, and manure storage facilities. |

croplands of greenhouse gases. Nutrient losses can also deplete soil fertility and thus reduce crop productivity. The potential impacts of higher temperatures, changes in precipitation patterns, and extreme weather events will present a different set of nutrient management challenges for many Delaware farmers. However, changing climate conditions may offer some beneficial trade-offs. For example, longer growing seasons will lead to greater growth of winter cover crops, making them more effective in using nutrients remaining in soils after crop harvest. **Table 7.2** summarizes some potential vulnerabilities that climate change impacts may present for nutrient management.

## Sources


**1** Hayhoe, K., Stoner, A., & Gelca, R. (2013). Climate Change Projections and Analysis for Delaware. Report dated December 2013.

**2** U.S. Department of Agriculture. (2007). State level data, Chapter 1: Table 9 – Land in farms, harvested cropland, and irrigated land, by size of farm. *2007 Census of agriculture.* National Agricultural Statistics Service. Retrieved from http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Delaware/

**3** Delaware Department of Agriculture. (undated). *Delaware agricultural statistics and resource directory 2010-2011.*

**4** Awokuse, T. O., Ilvento, T. W., & Johnston, Z. (2010). *The impacts of agriculture on Delaware's economy.* University of Delaware College of Agriculture and Natural Science report dated December. Retrieved from http://ag.udel.edu/deagimpact/index.html

**5** Delaware Department of Agriculture. (undated). *Delaware agricultural statistics and resource directory 2010-2011.*

**6** Delaware Department of Agriculture. (2004). *Delaware equine industry 2004.* Retrieved from http://extension.udel.edu/equine/2011/11/03/an-assessment-of-the-educational-needs-of-delaware-horse-owners/

**7** Delaware Department of Agriculture. (undated). *Delaware agricultural statistics and resource directory 2010-2011.*

8 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

9 Delaware Department of Agriculture. (undated). *Delaware agricultural statistics and resource directory 2010-2011.*

10 Awokuse, T.O., Ilvento, T.W., & Johnston, Z. (2010). *The impacts of agriculture on Delaware's economy.* University of Delaware College of Agriculture and Natural Science report dated December 2010. Retrieved from http://ag.udel.edu/deagimpact/index.html

11 Shortle, J., Abler, D., Blumsack, S., Crane, R., Kaufman, Z., McDill, M., … Wardrop, D. (2009). *Pennsylvania climate impact assessment: Report to the Department of Environmental Protection.* Environment and Natural Resources Institute report 7000-BK-DEP4252 dated June. Retrieved from http://www.green.psu.edu/resources/pdfs/climateImpactAssessment.pdf

12 U. S. Department of Agriculture. (2007). State level data, Chapter 1: Table 1 – Historical highlights: 2007 and earlier census years. 2007 Census of agriculture. National Agricultural Statistics Service. Retrieved from http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Delaware/

13 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

14 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

15 Baylis, M., & Githeko, A.K. (2006). The effects of climate change on infectious diseases of animals. *Foresight.* T7.3. 2006. Retrieved from http://www.bis.gov.uk/assets/foresight/docs/infectious-diseases/t7_3.pdf

16 Hatfield, J. L. (2008). Chapter 2: Agriculture. *The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.gcrio.org/library/sap-final-reports.htm

17 Shortle, J., Abler, D., Blumsack, S., Crane, R., Kaufman, Z., McDill, M., … Wardrop, D. (2009). *Pennsylvania climate impact assessment: Report to the Department of Environmental Protection.* Environment and Natural Resources Institute report 7000-BK-DEP4252 dated June. Retrieved from http://www.green.psu.edu/resources/pdfs/climateImpactAssessment.pdf

18 Brown, B., University of Delaware Cooperative Extension. (Personal communication, July 24, 2012).

19 Boesch, D. F. (Ed.). (2008). *Global warming and the Free State: Comprehensive assessment of climate change impacts in Maryland.* Report of the Scientific and Technical Working Group of the Maryland Commission on Climate Change. Cambridge, MD: University of Maryland Center for Environmental Science. http://www.umces.edu/climateimpacts/FINAL-Global percent20Warming_view.pdf.

20 Wolfe, D. W., Ziska, L., Petzoldt, C., Seaman, A., Chase, L., & Hayhoe, K. (2008). Projected change in climate thresholds in the Northeastern U.S.: Implications for crops, pests, livestock, and farmers. *Mitigation Adaptation Strategies Global Change,* 13, 555-575.

21 Hatfield, J. L. (2008). Chapter 2: Agriculture. *The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.gcrio.org/library/sap-final-reports.htm

22 University of Delaware. (2012). *Poultry health system.* Retrieved from http://ag.udel.edu/abc/poultry/pagetwo.html

23 Collier, S., University of Delaware Cooperative Extension. (Personal communication, July 23, 2012).

24 Hatfield, J. L. (2008). Chapter 2: Agriculture. *The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.gcrio.org/library/sap-final-reports.htm

25 Frumhoff, P. C., J. J. McCarthy, J. M. Melillo, S. C. Moser, & D. J. Weubbles. (2007). *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions.* Synthesis report for the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS).

26 Hayhoe, K., Wake, C., Huntington, T., Luo, L., Schwartz, M., Sheffield, J., … Wolf, D. (2006). Past and future changes in climate and hydrological indicators in the US Northeast. *2006 Climate Dynamics.* doi: 10.1007/s00382-006-0187-8. Retrieved from http://www.glerl.noaa.gov/seagrant/ClimateChangeWhiteboard/Resources/Uncertainty/Mac1/hayhow06.pdf

27 Wolfe, D. W., Ziska, L., Petzoldt, C., Seaman, A., Chase, L., & Hayhoe, K. (2008). Projected change in climate thresholds in the Northeastern U.S.: Implications for crops, pests, livestock, and farmers. *Mitigation Adaptation Strategies Global Change,* 13, 555-575.

28 Wolfe, D. W., Ziska, L., Petzoldt, C., Seaman, A., Chase, L., & Hayhoe, K. (2008). Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. *Mitigation Adaptation Strategies Global Change.* 2008 13:555-575.

29 Kunkel, K. E. (2013). Update to data originally published in: Kunkel, K. E., D. R. Easterling, K. Hubbard, and K. Redmond. 2004. Temporal variations in frost-free season in the United States: 1895–2000. *Geophysical Research Letters* 31, L03201. Retrieved from http://www.epa.gov/climatechange/pdfs/print_growing-season-2013.pdf

30 Bartomeus, I., Ascher, J. S., Wagner, D., Danforth, B.N., Colla, S., Kornbluth, S., and Winfree, R. (2011). Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proceedings of the National Academy of Sciences,* 108, (51), 20645-20649; published ahead of print December 5, 2011, doi:10.1073/pnas.1115559108. Retrieved from http://www.pnas.org/content/108/51/20645.full?sid=a51364fd-db59-40f1-b4e3-1db1df9a48dc

31 Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States.* Report of the U.S. Global Change Research Program. Cambridge, MA: Cambridge University Press. Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts.

32 Wolfe, D. W., Ziska, L., Petzoldt, C., Seaman, A., Chase, L., & Hayhoe, K. (2008). Projected change in climate thresholds in the Northeastern U.S.: Implications for crops, pests, livestock, and farmers. *Mitigation Adaptation Strategies Global Change,* 13, 555-575.

33 Rosensweig, C., Tubiello, F.N., Goldberg, R., Mills, E., & Bloomfield, J. (2002). Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change*, 12, 197-202. Retrieved from http://pubs.giss.nasa.gov/abs/ro02200i.html

34 Wolfe, D. W., Ziska, L., Petzoldt, C., Seaman, A., Chase, L., & Hayhoe, K. (2008). Projected change in climate thresholds in the Northeastern U.S.: Implications for crops, pests, livestock, and farmers. *Mitigation Adaptation Strategies Global Change,* 13, 555-575.

35 Hatfield, J. L. (2008). Chapter 2: Agriculture. *The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.gcrio.org/library/sap-final-reports.htm

36 Hatfield, J. L. (2008). Chapter 2: Agriculture. *The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.gcrio.org/library/sap-final-reports.htm

37 Frumhoff, P. C., J. J. McCarthy, J. M. Melillo, S. C. Moser, and D. J. Weubbles. (2007). *Confronting climate change in the U.S. Northeast: Science, impacts, and solutions.* Synthesis report for the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS).

38 Ziska, L. H., & Goins, E. W. (2006). Elevated atmospheric carbon dioxide and weed populations in glyphosate treated soybean. *Crop Science,* 46, (3), 1354-1359. Retrieved from http://naldc.nal.usda.gov/download/3496/PDF

39 Hatfield, J. L. (2008). Chapter 2: Agriculture. *The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.gcrio.org/library/sap-final-reports.htm

40 Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States.* Report of the U.S. Global Change Research Program. Cambridge, MA: Cambridge University Press. Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts.

41 Vose, J. M., Peterson, D. L., & Patel-Weynand, T., (Eds.). 2012. *Effects of climatic variability and change on forest ecosystems: A comprehensive science synthesis for the U.S. forest sector.* Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 pp. http://www.fs.fed.us/pnw/pubs/pnw_gtr870/pnw_gtr870.pdf

42 Ryan, M. G., Archer, S. R., Birdsey, R., Dahm, C., Heath, L., Hicke, J. … Schlesinger, W. (2008). Chapter 3: Land Resources. *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.climatescience.gov/Library/sap/sap4-3/final-report/sap4-3-final-land.pdf

43 Vose, J. M., Peterson, D. L., & Patel-Weynand, T., (Eds.). 2012. *Effects of climatic variability and change on forest ecosystems: A comprehensive science synthesis for the U.S. forest sector.* Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 p. http://www.fs.fed.us/pnw/pubs/pnw_gtr870/pnw_gtr870.pdf

44 Cabinet Committee on State Planning Issues (Delaware). (2008). Report to the Governor and the 144th General Assembly, dated January. Retrieved from http://stateplanning.delaware.gov/information/documents/ccspi_rep_01_03_08.pdf

45 Sands, R., & Westcott, P. (Eds.). (2011). *Impacts of higher energy prices on agriculture and rural economies.* U.S. Department of Agriculture, Economic Research Service Report ERR-123, dated August. Retrieved from http://www.ers.usda.gov/media/118156/err123_reportsummary.pdf

46 Shortle, J., Abler, D., Blumsack, S., Crane, R., Kaufman, Z., McDill, M., … Wardrop, D. (2009). *Pennsylvania climate impact assessment: Report to the Department of Environmental Protection.* Environment and Natural Resources Institute report 7000-BK-DEP4252, dated June. Retrieved from http://www.green.psu.edu/resources/pdfs/climateImpactAssessment.pdf

47 Hayhoe, K., Wake, C., Huntington, T., Luo, L., Schwartz, M., Sheffield, J., … Wolf, D. (2006). Past and future changes in climate and hydrological indicators in the US Northeast. *2006 Climate Dynamics.* doi:10.1007/s00382-006-0187-8. Retrieved from http://www.glerl.noaa.gov/seagrant/ClimateChangeWhiteboard/Resources/Uncertainty/Mac1/hayhow06.pdf

48 Sims, T., Waterhouse, H., Leathers, D., & Brinson, K. (2012). *Advancing irrigation management to reduce nutrient loads to the Delaware headwaters of the Chesapeake Bay.* Report to Delaware Department of Natural Resources and Environmental Control, dated May 24.

49 Johnson, G. (2012). *Weekly crop update.* University of Delaware Cooperative Extension publication WCU 20, (19), July 27, http://agdev.anr.udel.edu/weeklycropupdate/?p=4558

50 Johnson, G. (2012). *Weekly Crop Update.* University of Delaware Cooperative Extension publication WCU 20, (18), July 20, http://agdev.anr.udel.edu/weeklycropupdate/?p=4513

51 Johnson, G. (2011). *Weekly Crop Update.* University of Delaware Cooperative Extension publication WCU 19, (14), June 24, http://agdev.anr.udel.edu/weeklycropupdate/?p=3244

52 Van Gessel, M. University of Delaware Cooperative Extension. (Personal communication, July 10, 2012).

53 Iowa State University. (undated). Fact sheet. Retrieved from http://www.plantpath.iastate.edu/soybeanrust/generalfacts

54 Kleczewski, N. (2013). *Weekly crop update.* University of Delaware Cooperative Extension publication WCU 21, (22), August 23. Retrieved from http://extension.udel.edu/weeklycropupdate/?p=6241

55 Ryan, M. G., S. R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, … W. Schlesinger. (2008). Chapter 3: Land Resources. *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.3. Retrieved from http://www.climatescience.gov/Library/sap/sap4-3/final-report/sap4-3-final-land.pdf

56 Valenti, M. Delaware Forest Service, Department of Agriculture. (Personal communication, September 6, 2013).

57 U.S. Forest Service. (undated). Stressors of pine forests, web page. Retrieved from http://www.fs.fed.us/r8/foresthealth/hosf/spb.htm

# Chapter 8 – Ecosystems & Wildlife – Summary

## Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

## Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.
- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.
- 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.

## Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3-4 days per year under higher scenarios by 2080-2099 (**Figure 8.1**).
- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.
- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

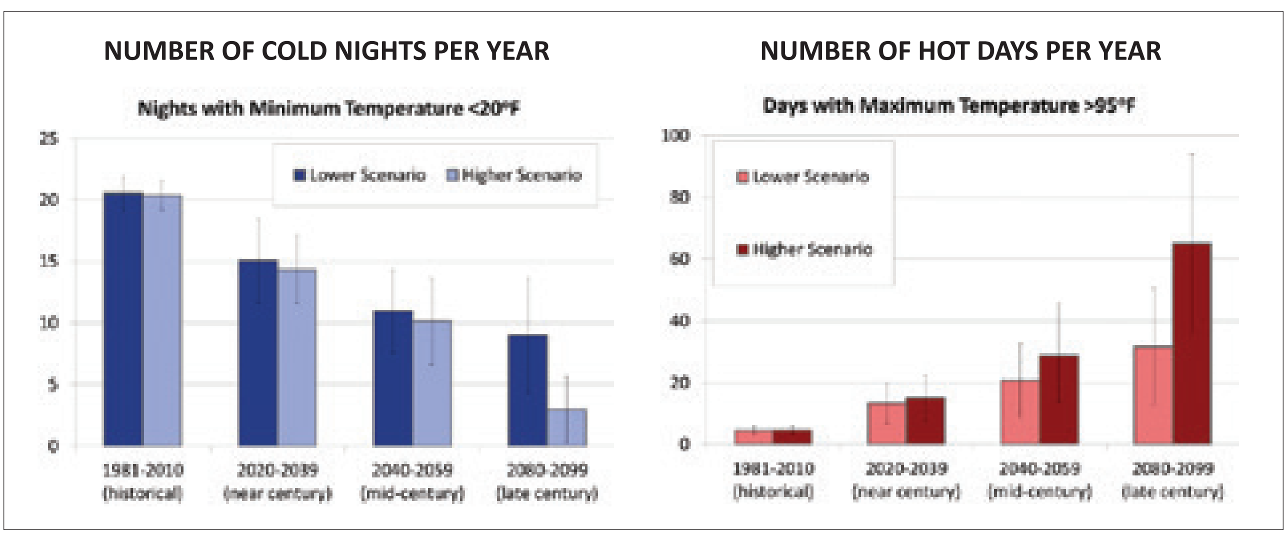


**Figure 8.1.** Projections for temperature extremes indicate an increasing number of very hot days and decreasing number of very cold days and nights. Differences between the high scenario and low scenario are greater by mid-century and end of century. Source: Hayhoe et al. (2013).

## Precipitation Changes

- Precipitation is projected to increase, particularly in winter (**Figure 8.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 8.2**).

# Potential Impacts to Ecosystems and Wildlife

- 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. Species with very restricted ranges and isolated populations are likely to be most vulnerable to climate change impacts, compounded by other stressors. Changes in temperature and precipitation will affect species that depend on wetland and aquatic habitats.

- Delaware's ***beach and dune ecosystems***, including beaches, dunes, dune swale wetlands, and tidal flats, are already vulnerable to coastal storms. If sediment input into the system is unbalanced, the combined effects of sea level rise and severe storms may lead to increased erosion and loss of beaches and dunes. Barrier beaches and dunes may be subject to more frequent overwash from storm surge, and may be increasingly vulnerable to breaching and formation of new inlets.

- Delaware's diverse range of ***wetland and aquatic ecosystems***, including tidal, nontidal, freshwater, brackish, and saltwater wetland habitats, as well as stream and riverine habitats, will be vulnerable to sea level rise and increased storm surge from extreme weather events. Climate change impacts will likely accelerate erosion in tidal marshes, leading to further wetland losses, landward migration of marsh habitat, or conversion to open water. 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.

- Delaware's ***forest ecosystems*** may experience shifts in the range of forest species and composition of forest communities, triggered by changes in temperature. Increased frequency and/or duration of drought combined with increased air temperatures will 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.

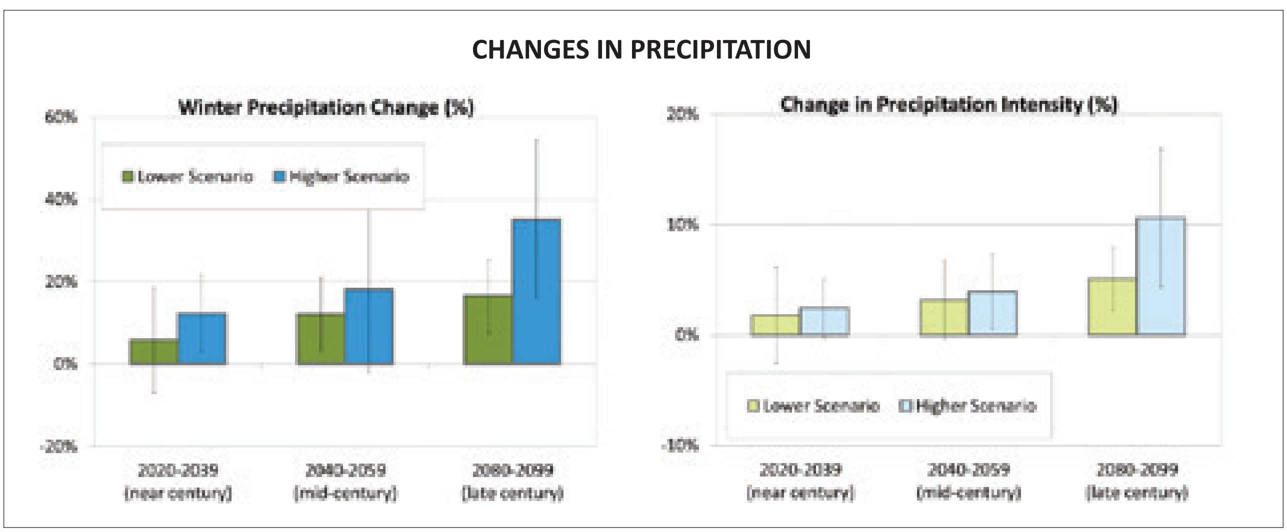


**Figure 8.2.** Precipitation increases are projected, primarily for winter and fall. Increasing precipitation intensity reflects projected increases in the frequency of heavy rainfall. Source: Hayhoe et al. (2013).

# Chapter 8
# Ecosystems and Wildlife

## Chapter Contents

- Overview of Delaware's ecosystem and wildlife resources
- Summary of climate change impacts that pose challenges to ecosystems and wildlife in the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to ecosystems and wildlife (nonclimatic impacts to resources)
- Potential vulnerabilities to ecosystems and wildlife in Delaware (based on current research and expert interviews – statewide scope)

This chapter includes an overview of the state's wildlife species and ecosystems. The overview section (8.1) provides a very brief summary of wildlife species; a detailed description of all of Delaware's fish, wildlife and plant species, including species in the marine environment, is beyond the scope of this Assessment. The overview section also summarizes Delaware's rich diversity of habitats into three general ecosystem types: beach and dune, wetland and aquatic, and forest. Climate change impacts are not limited to habitats found in these ecosystems, but not all ecosystems and habitat types could be fully described in the overview section. The Delaware Division of Fish and Wildlife is the primary source for more information on the statewide distribution and status of fish, wildlife, plants, and habitats.

This chapter also includes a brief discussion of the functions that ecosystems serve, not only for the species and habitats they support, but for physical and biological functions on which human societies depend. Ecosystem goods and services are generally described as the "benefits people obtain from ecosystems." This definition is reflected in the Millennium Ecosystem Assessment[2] and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[3] Ecosystem services include:

- *Provisioning services* that provide ecosystem goods such as food, freshwater, timber, fiber, and fuel;
- *Regulating services* that moderate climate, floods, disease, wastes, and water quality;
- *Supporting services* that provide essential functions that maintain and support life on earth, such as soil formation, photosynthesis, and nutrient cycling; and
- *Cultural services* that support human well-being through recreational, aesthetic, and spiritual benefits.

Ecosystem services are also discussed in other chapters of the Climate Change Impact Assessment. For example, the Agriculture chapter (7) reflects the provisioning services in agricultural systems. Ecological services are also discussed in Chapter 9, Infrastructure, to underscore the importance of natural systems in providing benefits that support human needs.

## 8.1 Overview of Delaware's Ecosystems and Wildlife

Delaware's diversity of wildlife and habitats reflects its unique geography. Bordering both the Delaware Bay and the Atlantic Ocean, the state supports extensive coastal and estuarine habitats. The state's terrestrial habitats fall within the Coastal Plain and Piedmont physiographic regions (**Figure 8.3**). These are areas defined by distinct geology, topography, and communities of native plants and animals. The major drainage basins and watersheds

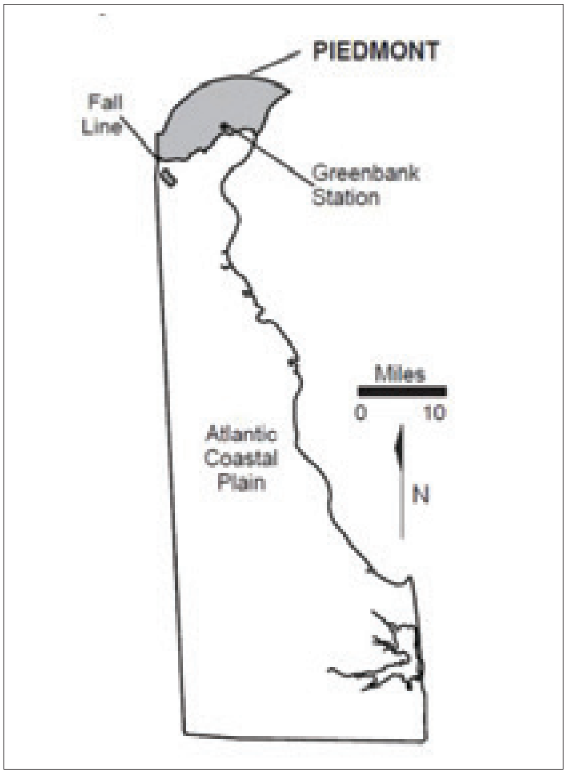


**Figure 8.3.** Delaware physiographic regions. Source: Delaware Geologic Survey.

also help guide discussions about the distribution of habitats and species throughout the state. Delaware has four major basins and 45 watersheds.

Ecosystem types can be described or categorized in different ways. Some classification systems describe geophysical characteristics, while others describe the dominant vegetation types or vegetation communities (assemblages of plant species that occur together). The following summary draws from the descriptions of key wildlife habitats in the Delaware Wildlife Action Plan, 2007-2017.[4] The plan identifies more than 125 types of habitat, more than 50 of which are considered habitats of conservation concern.[a]

For this Assessment, Delaware's habitat types are described briefly within three general ecosystem types:

- **Beach and dune ecosystems** include habitats found in the zone extending from the landward limit of the dunes to the sand or mud intertidal flats exposed at low tide. Low wetland swale habitats found among the dunes are also included in this ecosystem. Beach and dune habitats are found along the Delaware Bay and Atlantic Ocean shoreline.

- **Wetland and aquatic ecosystems** include wetland and aquatic habitats that are tidal, nontidal, freshwater, brackish, and saltwater. Examples of wetland habitats found in Delaware include coastal wetland impoundments, vernal pools, Coastal Plain seasonal pond wetlands, peat wetlands, and Piedmont stream valley wetlands. Examples of aquatic habitats include ponds, reservoirs, streams, rivers, bays, and oceans, including the open waters of these habitats and submerged bottom substrates, submerged aquatic vegetation, and exposed riverine sand and gravel bars and shorelines. Wetland and aquatic habitats are found extensively throughout the state in all major watershed basins in Delaware: Delaware Bay and Estuary, Chesapeake Basin, Delaware Inland Bays, and Piedmont Basin.

- **Forest ecosystems** include Piedmont upland forest, Coastal Plain upland forest, forested floodplain and riparian swamps, isolated forested wetlands, and freshwater tidal forested wetlands. Young forest habitat consisting largely of seedlings and saplings is also addressed; however, other early successional habitats such as shrub or grass and other herb-dominated field habitats and edge habitats (transition zones between forests and fields or marsh) are not addressed in this Assessment. Forest habitats can be found throughout the state.

## 8.1.1. Wildlife Species

More than 3,200 species and varieties of plants and animals have been documented in Delaware, including more than 1,000 species of animals[b] and more than 2,200 species and varieties of plants.[c] More than 450 animal species are identified

[a] Habitats of conservation concern are habitats that are rare, have special significance in Delaware, are particularly sensitive to disturbance, and/or have a high diversity of rare plants.

[b] This total includes invertebrates and native and nonnative species.

[c] This total includes native and nonnative species.

as "species of greatest conservation need" in the Delaware Wildlife Action Plan,[5] which was developed to address the need to manage for a diversity of habitat types, with the goal of "keeping common species common" while continuing to protect rare animal species. Plants are not addressed in the Delaware Wildlife Action Plan; however, the Delaware Division of Fish and Wildlife maintains the official list of plants occurring in the state, including distribution and status information for each species. Of 1,586 species and varieties of native plants documented in Delaware, 573 (36 percent) are rare or uncommon.

Historically, rare or endangered nongame species have been monitored and managed separately from game species. This focus has shifted to a more integrated approach to wildlife management that emphasizes the importance of the habitats on which both game and nongame species depend. Nonetheless, because there will be a specific interest from hunters and anglers on the impacts of climate change to species harvested for recreational and commercial purposes, some of these species are specifically noted here.

The Delaware Division of Fish and Wildlife manages 58 species classified as game animals, including 44 bird species, 11 mammal species, two reptile species, and one amphibian species.[6]

The list of migratory game birds includes species of ducks, geese (including brant), doves, rails, woodcock, and snipe. Mammal species that are legally hunted include white-tailed deer, rabbit, squirrel, muskrat, and red fox. Other game species that are monitored or managed to expand their numbers include wild turkey (*Meleagris gallopavo*) and northern bobwhite quail (*Colinus virginianus).*

Delaware's diverse freshwater and marine aquatic habitats support a number of fish and shellfish species that are economically valuable for commercial and recreational harvest. The Delaware Bay has more than 200 resident and migrant fish species. A few of these important resources include: striped bass (*Morone saxatilis*), American shad (*Alosa sapidissima*), American eel (*Anguilla rostrata*), eastern oyster (*Crassostrea virginica),* blue crab (*Callinectes sapidus),* and horseshoe crab (*Limulus polyphemus*).[7]

The Delaware Wildlife Action Plan 2007-2017 addresses conservation strategies for all wildlife, including fish, invertebrates, and marine species, but does not address conservation strategies for individual plant species. The plan focuses on conservation issues and actions that affect habitats and notes which animal species of greatest conservation need are associated with each habitat type. The plan identifies more than 450 animal "species of greatest conservation need." This designation is partially based on assessments by the Delaware Division of Fish and Wildlife, which tracks species distribution and abundance using internationally recognized natural heritage methodologies.[d] Species of greatest conservation need are indicative of the overall diversity and health of the state's wildlife resources. Some may be rare or declining, others may be vital components of certain habitats, and still others may have a significant portion of their population in Delaware. Eighty-six animal species are listed as State Endangered, including 21 birds, eight reptiles, three amphibians, nine mammals, seven fish, seven freshwater mussels, and 31 insects.

## 8.1.2. Beach and Dune Ecosystems

Delaware's beach and dune ecosystems include estuarine and ocean beach, dune and dune-swale wetland habitats found along the tidal shoreline of Delaware Bay and the Atlantic Ocean. These habitats are subjected to variations in salinity, wave energy, and substrate. All of these areas are composed of sediments that were either deposited during or reworked from previous higher and lower sea levels. The following summary describes three areas where the beach and dune habitats are found.

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[d] Natural Heritage Methodology is described further in the Nature Serve web page: http://www.natureserve.org/prodServices/heritagemethodology.jsp

- The *Delaware Bay* estuary hosts beach and dune habitats that are interconnected with extensive tidal marshes interspersed with tidal creeks and rivers. Wave energy increases along the central and southern section of Delaware Bay. In the central section of the bay, beaches are generally narrow with broad, intertidal flats; dunes are sparse and low-lying. Toward the mouth of the bay, beaches are generally wider and often flanked by high, vegetated dunes. Erosion rates along the shoreline are highly variable, with rates of shoreline retreat ranging from less than 2 feet per year to more than 17 feet per year.[8]

- *Cape Henlopen* is a narrow spit of land located at the mouth of Delaware Bay that includes beach and dune habitats of both the bay and Atlantic Ocean. Sand transported by ocean currents is expanding the spit northward. The beaches and dunes at Cape Henlopen are naturally accreting (building up land by deposition of sand or sediment). The Great Dune, a major feature at Cape Henlopen situated perpendicular to the Atlantic shoreline, is migrating southward at a rate of up to six feet per year, altering maritime forest habitat as it progresses.[9]

- The *Atlantic Ocean* beach and dune habitats south of Cape Henlopen are either backed by headlands (at Rehoboth Beach and Bethany Beach) or are found on the bay mouth barriers that separate the ocean from the Inland Bays. These beaches and dunes serve as a line of defense against storms for the adjacent marsh habitats that rim the eastern portion of Rehoboth, Indian River, and Assawoman Bays. Dunes form a vegetated ridge that runs parallel to the shoreline. The Atlantic Ocean beaches and dunes are exposed to higher wave energy than their Delaware Bay counterparts, and in both areas (Delaware Bay and Atlantic Ocean), the beaches and dunes can be overtopped or breached during storms.

Beach and dune habitats are strongly influenced by the dynamic conditions that continually shape and reshape their physical and biological features. Winds, waves, and tides are three forces creating constant change. Coastal storms amplify the effects of winds, waves, and tides by increasing height and strength of waves as they reach higher on the shore and remove sand from the dune face to be transported offshore onto sandbars. In extreme storms, the dunes may be breached or overtopped, moving sand landward. The forces of water and wind create a highly dynamic system in which beach and dune habitats can be eroded, inundated, or relocated as sand and sediment are moved alongshore.[10]

Beach and dune habitats support a rich diversity of plants and animals adapted to a highly dynamic environment. Plant material and debris that wash up on the sandy beach provide organic matter for scavenging amphipods such as sand fleas, which, in turn, are an important food source for shorebirds and crustaceans. Dune habitats offer food and shelter for numerous insects and other arthropods, including beetles, butterflies, and spiders, as well as important nesting habitat for diamondback terrapins.[11] Delaware Bay and Atlantic Ocean beaches and coastal habitats provide important habitat for many species of gulls and shorebirds. Along Delaware Bay, beach and dune habitats offer an abundant food source for many migratory species, such as the red knot (*Calidris canutus)* and other shorebirds that feed on the eggs of horseshoe crabs in the spring. The Delaware Bay is the largest spring staging area for migratory shorebirds in eastern North America; during their spring migration, an estimated one million shorebirds use these beach, marsh, and mudflat habitats. Ninety-five percent of these birds are represented by four species: red knots, ruddy turnstones, semipalmated sandpipers, and dunlins.[12] Beaches also provide important nesting habitat for several species, such as least tern (*Sternula antillarum*) and piping plover *(Charadrius melodus*).

Dune systems are highly diverse habitats, supporting plants and animals adapted to harsh conditions, including high temperatures, inundation by salt water and salt spray, and continual movement of sand. Beach and foredune habitats are generally vegetated with small annuals. Foredune and backdune areas may be dominated by American beachgrass (*Ammophila breviligulata)* and other salt- and drought-tolerant plants. Interdunal swales form where water collects behind dunes, and are characterized by a variety of shrubs, sedges, and rushes. More than 20 species of rare plants are found in these wetland habitats.[13] Secondary dunes support maritime forests of loblolly pine (*Pinus taeda*) and thickets of native shrubs.[14]

Beach and dune habitats act as a protective buffer from the direct impacts of storm waves and surges. During storm events, wave energy is diffused by moving sand and reconfiguring the beach and dunes. Although bay beaches are subject to less wave energy than ocean beaches, adjacent tidal marsh habitats also help absorb the impacts of wave action and high tides. In addition to these natural forces, human activities add to the complexity of these highly active ecosystems.

## 8.1.3. Wetland and Aquatic Ecosystems

Wetlands are perhaps Delaware's most significant natural feature, covering one-fourth of the state, with a total of approximately 320,000 acres.[15] An estimated 47 percent of wetlands are located in Sussex County, 38 percent in Kent County, and 15 percent in New Castle County. Wetland habitats include a wide range of types – tidal, nontidal, freshwater, brackish, and saltwater, and include coastal wetland impoundments, vernal pools, Coastal Plain seasonal pond wetlands, peat wetlands, and Piedmont stream valley wetlands. Wetlands are found along the shores of the Delaware Bay and Inland Bays, along rivers, streams, and ponds, and in forests and fields throughout the state.

According to the U.S. Fish and Wildlife Service's wetland classification system, wetlands occur in five ecological systems. The majority of Delaware wetlands fall into two systems:[16] *Freshwater wetlands* include freshwater floodplains, headwaters, and isolated wetlands and ponds. These represent the predominant wetland types in Delaware, comprising roughly 76 percent of the state's wetlands; more than 85 percent of these freshwater wetlands are forested. *Estuarine wetlands*, where freshwater mixes with seawater, make up more than 23 percent of the state's wetlands; salt marshes are the dominant type of estuarine wetlands.

Wetlands can receive water from many sources: precipitation, surface runoff, groundwater discharge, and tides. Some wetlands are inundated daily, whereas others are wet seasonally. Some forested wetlands rarely have surface water, but have high water tables near the surface that keep the soils wet for extended periods. Wetlands are generally defined by hydric (waterlogged) soils that result from repeated or prolonged saturation. This saturation creates anaerobic (oxygen-deficient) conditions; plants must by adapted to hydric soils (hydrophytes) to survive and reproduce in these habitats.

Wetlands perform critical functions such as buffering inland areas from storm surge, providing water storage to reduce flooding, filtering contaminated runoff from upland areas, limiting sediment inputs into aquatic systems, and sequestering carbon.[17] Wetlands also provide organic matter, which serves as food for aquatic invertebrates. Estuarine ecosystems, including marsh and aquatic habitats, are among the most productive in the world, and provide spawning and nursery habitat for numerous fish and shellfish species. (Wetland ecosystem services are also discussed in Chapter 9, Infrastructure.)

Delaware's aquatic habitats include streams, rivers, ponds, reservoirs, bays (Delaware Bay and Inland Bays), and the Atlantic Ocean, including the open waters of these habitats and submerged bottom substrates, submerged aquatic vegetation, and exposed riverine and estuarine mud, sand, and gravel bars. In the Piedmont region of the state, aquatic habitats are freshwater. In the Coastal Plain region, there are dozens of freshwater millponds that were formed by damming streams in the 18th and 19th centuries. Upstream from millpond dams, the headwater wetlands and steam segments are also freshwater. Downstream from millpond dams, streams and rivers are generally tidal and range from freshwater to brackish or saltwater. Salinity varies, depending on the distance from the coast and distance up the estuary. Historically, stream channelization and ditching were practiced extensively on the Coastal Plain to support agriculture; the vast network of ditches is still evident today, particularly in Sussex County.

Freshwater streams, rivers, and ponds support a variety of warm-water species that are both ecologically and economically important. Freshwater mussels provide an important ecological function by filtering the water, and game fish such as largemouth bass (*Micropterus salmoides*) provide excellent recreational angling opportunities.

The species found in Delaware's streams and rivers are highly influenced by both topography and water chemistry. The Piedmont physiographic region has faster flowing water than streams found on the Coastal Plain, resulting in fish communities that are strikingly different between these two regions of the state (**Figure 8.3**). On the Coastal Plain, the slow-moving waters accumulate higher amounts of tannin from adjacent vegetation communities, making the water more acidic and ideal for certain species such as the blackbanded sunfish (*Enneacanthus chaetodon*).

Delaware also has managed wetland and aquatic habitats that provide wildlife habitat value even though they were not naturally formed. Many streams on the Coastal Plain were dammed for milling purposes in centuries past. Although their original function was for powering mill operations, today millponds also function as habitat for waterfowl, fish, mussels, and other aquatic species. Millpond dam structures also prevent brackish water from entering the freshwater aquatic system farther upstream, protecting Atlantic white cedar and bald cypress wetland habitats. Other ponds have been created or enlarged with dams to provide recreational fishing opportunities. In addition, ponds have been built to provide stormwater management for new development; these are technically considered wetlands, but provide very limited ecological function compared to natural wetlands.[18]

Coastal impoundments are managed wetland habitats where low-level dikes and water-control structures have been constructed to restrict, retain, or exclude water over a selected area.[19] Delaware has an extensive complex of coastal impoundments along the Delaware Bay, Atlantic Ocean (Gordons Pond), and Little Assawoman Bay. Impoundment wetland habitats vary from fresh to brackish, depending on how the water depths and flows are controlled. Water-level management often varies seasonally to benefit particular species or meet specific conservation goals. For example, water levels may be kept high in winter and drawn down slowly to support invertebrate populations, an important food source for migratory waterfowl and shorebirds in spring. In summer, water levels are often kept low to allow vegetation to grow; the impoundments are then flooded to provide food and habitat for waterfowl on their return migration in fall.

Delaware's wetland and aquatic habitats are often described by watershed basins (**Figure 8.4**). A watershed basin is the area of land that drains into a stream, river, or bay.

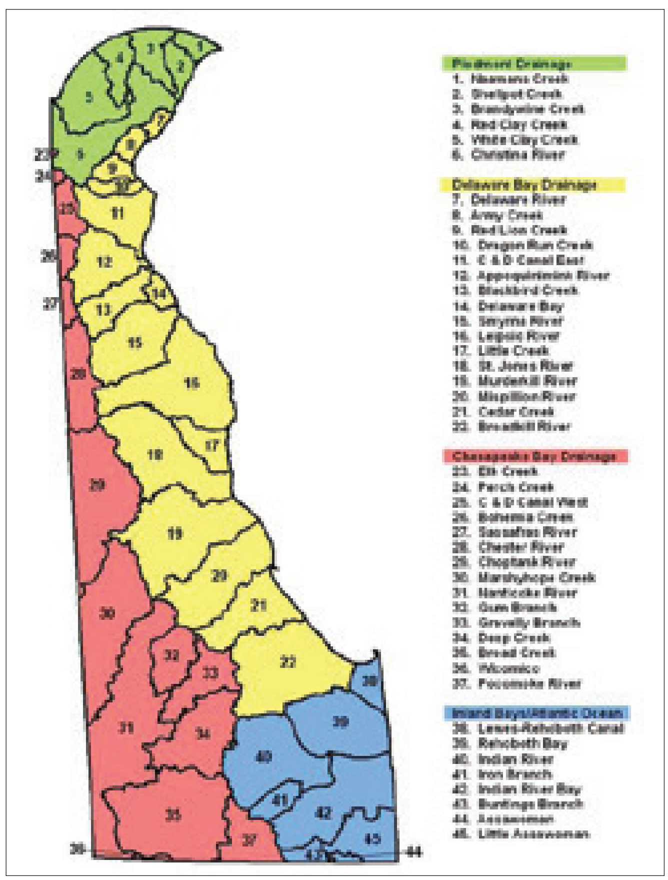

**Figure 8.4.** Delaware basins and watersheds.
Source: Delaware Department of Natural Resources and Environmental Control, Water Quality Monitoring Network portal.

## Delaware Bay and Estuary

The Delaware River watershed covers 814 square miles of Delaware's land area, and includes the watersheds of numerous tributary streams and rivers, such as Blackbird Creek, Murderkill River, Leipsic River, and Appoquinimink River.[20] Most of the freshwater wetlands in Delaware's portion of the Delaware Basin consist of bottomland forest, swamps, riparian wetlands, and freshwater marshes. The Delaware Bay coast is dominated by tidal estuarine wetland habitats, characterized by salt or brackish waters. These habitats are found along the coast and in coastal rivers upstream to the point where salinity levels fall below 0.5 parts per thousand. The largest portion of tidal wetlands is salt marsh habitat dominated by salt-tolerant grasses such as *Spartina* spp. Coastal Plain seasonal pond wetlands are found farther inland, primarily in the Delaware Bay drainage, but are also in the Chesapeake and Inland Bay drainages. These are shallow, seasonally flooded freshwater wetlands, usually less than an acre in size. These unique wetland communities support 45 rare and uncommon plant species and a high diversity of amphibians, including five salamander species and 13 frog species, including the barking tree frog (*Hyla gratiosa)*.[21]

## Chesapeake Basin

In Delaware, the Chesapeake Basin drains approximately 769 square miles, and includes portions of the Choptank River, Nanticoke River, Marshyhope Creek, and Broad Creek watersheds. Almost all (99 percent) of the wetlands in Delaware's portion of the Chesapeake Basin consist of bottomland forest, swamps, riparian wetlands, and tidal and nontidal freshwater marshes. Several unique and threatened wetland types are found in Delaware's portion of the Basin, including bald cypress *(Taxodium distichum)* and Atlantic white cedar *(Chamaecyparis thyoides)* forested wetland habitats. The Chesapeake Basin also supports riverine aquatic and submerged vegetation habitats, which are found in stream channels and backwaters throughout the Coastal Plain, and most extensively in the Nanticoke watershed.[22]

## Delaware Inland Bays

This 292-square-mile watershed consists of three coastal bays and their tributary rivers, including Rehoboth, Indian River, and Assawoman Bays. The Inland Bays basin is a matrix of salt marshes, tidal flats, and winding creeks where freshwater mixes with seawater that flows into the bays through Indian River Inlet. Wetlands cover 39 percent of the Inland Bays watershed and include both tidal and nontidal wetlands as well as rare wetland communities such as Atlantic white cedar swamps.[23] Nearly 10,000 acres of salt or brackish tidal wetlands provide habitat for waterfowl and migratory birds and nursery habitat for fish, and also serve important ecosystem functions, including regulating water quality by filtering nutrients and sediments.[24] Nontidal wetlands include flat wetlands, generally found at the headwaters and between streams, and riverine wetlands, located adjacent to streams. These poorly drained wetlands retain heavy precipitation and are thus helpful in reducing downstream flooding. Peat wetlands are another rare habitat found in only two locations in the Inland Bays area.[25]

## Piedmont Basin

The Piedmont Basin covers 605 square miles in Delaware and Pennsylvania, and includes the Christina River, Brandywine Creek, Red Clay Creek, and White Clay Creek watersheds. Wetlands in the basin are generally associated with the headwaters of streams or with tidal estuaries, and with seasonally flooded depressions. Forested wetlands are the most common wetland habitat in the Piedmont Basin. Floodplain forests dominated by red maple (*Acer rubrum*) are found throughout the Coastal Plain portion of the basin. Floodplain forests dominated by American sycamore (*Platanus occidentalis)* and box elder *(Acer negundo)* are found along Piedmont streams such as White Clay Creek and Red Clay Creek. Headwater riparian wetlands are ecologically important for helping to maintain water quality through sediment trapping and uptake of nitrogen and phosphorus.

## 8.1.4. Forest Ecosystems

Forests cover approximately 30 percent of Delaware's land area, an estimated 371,000 acres, with a diverse variety of forest and woodland community types. Delaware represents the northern extent of some forest species, such as loblolly pine (*Pinus taeda*) and bald cypress (*Taxodium distichum)*, and supports populations of northern species such as sugar maple (*Acer saccharum*) that are generally not found south of Delaware except at higher elevations.

Historically, Delaware's forests covered an estimated 90 percent of the state. European settlers cleared forests for timber, agriculture, and settlements, so that by the 20th century, forest cover ranged between 370,000 and 450,000 acres. Although the state's total forest acreage has remained relatively stable in the past three decades, forest assessments indicate that average forest tract size is declining and forest habitat is becoming more fragmented, largely as a result of development. The average size of forest ownership has declined from 30 acres in 1975 to less than 10 acres today. The Delaware Forest Service estimates that only 20 percent of all forest parcels are 500 acres or larger.[26] In addition, seedling and sapling forests represent less than 25 percent of forested land. These younger forests are needed to replace older forests as they are harvested or lost to storm damage or natural mortality. Seedling and sapling forests are also important habitat for certain species, such as American woodcock *(Scolopax minor)*.[27]

Forests provide a wide range of ecosystem functions that help maintain water quality for both surface water and groundwater. Riparian buffers and forested wetlands help filter surface water, by slowing runoff and trapping sediments and pollutants before they reach waterways. Forests are important for protecting water quality in groundwater recharge areas. Forests also serve to moderate local climate conditions; for example, riparian buffers that shade streams help to maintain cooler water temperatures, benefitting fish and invertebrate aquatic species. Forest ecosystems can also function as carbon sinks; the Delaware Forest Service estimates that Delaware's forests store more than 20 million tons of carbon.[28]

Delaware forest habitats support a number of rare and sensitive species, including a diversity of bird species. In Delaware, 113 bird species are known to depend on forest habitat for breeding, migrating, or overwintering; four of these are state-listed as endangered. A number of bird species are considered "forest interior dwelling species," meaning they require large blocks of forest habitat to successfully reproduce. Smaller fragments of forest, with more edge habitat, increase competition for suitable nest sites and food resources with edge-tolerant species. Greater edge-to-interior ratios increase the risk of predation, especially for ground or near-ground nesting birds. Smaller patches also expose many forest interior birds to higher rates of nest parasitism by opportunistic brown-headed cowbirds.

Forest habitats, as with other ecosystem types, can be described or categorized in different ways. The Delaware Forest Service recognizes forest types based on inventories by the U.S. Forest Service through its Forest Inventory and Analysis (FIA) program. The FIA is organized by species associations and identifies six forest type groups in Delaware: loblolly-shortleaf; oak-pine; oak-hickory; oak-gum-cypress; elm-ash-red maple; and northern hardwoods.[29] Based on these categories, the FIA estimates that the oak-hickory group makes up more than half of the forested area in Delaware, and pine and oak-pine types comprise approximately one-fourth of the total forest area. Minor hardwood components (gum, maple, etc.) occupy the remaining 15 percent of the forested acreage.[30]

The Delaware Wildlife Action Plan 2007-2017 uses *The Natural Communities of Delaware,* which is based on the National Vegetation Classification System, as a wildlife habitat classification framework. This system provides a more detailed classification than FIA, and is also based on dominant species associations. These forest habitats are summarized below with highlights of some of the rare and unique forest types found in the state.

### Upland Forests

Piedmont upland forests are found in the northern part of Delaware on steep slopes in stream valleys and on adjacent rolling hills. The canopy is a mix of deciduous species, such as tulip poplar, American beech, oaks, and hickory. Piedmont upland forests often support a rich flora of spring wildflowers, which include a number of state rare species. Coastal Plain upland forests are found in central and southern Delaware on dry or moist, but not wet, soils. These forest types vary from deciduous oak-hickory communities to coniferous stands dominated by loblolly pine (*Pinus taeda*). Ancient Sand Ridge forest is found in the Nanticoke River area on relic sand dunes that originated before the last glacial period, and is generally dominated by Virginia pine (*Pinus virginiana*) and southern red oak (*Quercus falcata*). This rare forest type provides vital habitat for caterpillars of the frosted elfin (*Callophrys irus),* a globally rare butterfly whose caterpillar feeds exclusively on the wild lupine (*Lupinus perennis*), which grows only in this forest community.

### Forested Wetlands

This group of forest types occurs in seasonally flooded areas and in floodplain depressions with saturated soils. Red maple (*Acer rubrum*) is found in several species associations with green ash, sweet gum, and bald cypress. Atlantic white cedar (*Chamaecyparis thyoides*) nontidal wetlands are found only from southern Delaware along slow-flowing streams with poorly drained soils. These forested wetlands provide habitat for several rare plant species, such as the swamp pink (*Helonias bullata*), which is federally listed as threatened. Bottomland forest types such as baldcypress-red maple-swamp black gum swamp habitat have also experienced declines due to logging and extensive drainage as a result of ditching and stream channelization. Isolated forest wetlands can provide important refuge for wildlife, particularly when strategically located to serve as a habitat corridor to link larger forest blocks. Freshwater tidal forested wetlands are found in central and southern Delaware on systems such as the Murderkill River in Kent County and the Nanticoke River in Sussex County. Freshwater tidal forests are either a mix of red maple and pumpkin ash (*Fraxinus profunda*), or Atlantic white cedar.

## 8.2. Climate Change Impacts to Ecosystems and Wildlife in the United States

Climate change will have direct and indirect impacts on the natural world at all levels: species, habitats, and ecosystems. Responses to changes in temperature, precipitation, extreme weather events, and sea level rise will affect the distribution of species and functions of ecosystems in many different ways. Some of these changes, such as poleward shifts in species ranges, have already been observed. In addition, the impacts of climate change will be compounded by impacts from other external stressors, such as habitat fragmentation, invasive species, and pollution.

### 8.2.1. Biodiversity and Ecosystem Function

The diversity of living organisms (biodiversity) is fundamental to ecosystem structure and function. Impacts to individual animal or plant species can have far-reaching effects on the role that species plays in an ecosystem. For example, a top predator species may fill a key function in the food chain, keeping prey populations in check, and a migratory insect species that acts as a critical pollinator may be vital to the propagation of the plants it pollinates. Thus, the decline or loss of biodiversity as a result of climate change can trigger larger changes at the habitat and ecosystem level.

Many scientific studies indicate that the rate of climate change and its magnitude may exceed the ability of many species to adjust quickly enough to survive, resulting in localized extinctions and loss of overall biodiversity.[31] The response to climate change of an individual species reflects its life cycle, sensitivity to change, and ability to migrate or move in pace with the changing environmental conditions. In addition, the availability of migratory pathways or corridors is critical for many species. Entire communities do not shift at the same time or in the same ways; therefore, significant changes in species composition and ecosystem function can result from varied responses to climate change.[32]

## 8.2.2. Responses to Change

The ways in which species and populations respond to climate changes can vary widely. Differences in how organisms respond to climate change — their adaptive capacity — will lead to some species benefitting, by expanding their range and/or increasing population, and other species declining. In the northeastern United States, for example, some forest types such as oak-hickory are expected to expand, while maple-beech-birch forests are expected to contract.[33]

Responses to climate change that have already been observed include changes in geographic range and the timing of life cycle events such as migration and reproduction. Numerous studies show shifts in the geographic range of species in response to increasing temperatures. As the climate warms, species may shift poleward (north in the northern hemisphere) or to higher elevations. For example, winter bird counts taken in the United States over the past 40 years showed a significant shift northward for more than half of the species tracked (177 of 305); nearly 20 percent of the species recorded had shifted more than 100 miles to the north.[34] These northward shifts are also being observed in ocean habitats. In U.S. waters, marine species are shifting northward, and changing distributions of both cold- and warm-water fish species have been recorded.[35]

Changes in bloom time, migration, and nesting are also well documented. Some changes in life cycle activities are triggered by the increasing length of the growing season. Global satellite data show that the onset of spring across temperate latitudes has advanced by 10 to 14 days over the past two decades.[36] However, a species' ability to adjust geographically or temporally does not guarantee survival. The timing of these shifts can be critical for ecologically linked species, potentially resulting in a mismatch between species and the resources they need to survive. Migratory birds, for example, depend on food supply in breeding territories, wintering grounds, and throughout their migratory path. The earlier onset of spring may alter the optimum timing for arrival of birds that rely on peak food availability to support their breeding cycle.

In addition to being an existing external stressor, new invasive species and diseases may emerge as they benefit from changing climate conditions, readily establishing in new areas and outcompeting native species for resources. The spread of new diseases and pathogens may also be enhanced by changing climate conditions, potentially affecting native species and humans. **Table 8.1** summarizes the potential ecological impacts in response to climate change.

## 8.2.3. Ecosystem Thresholds

There has been considerable research on how species and natural communities respond and adapt to climate change impacts. In addition, some scientific analyses are examining the complexities of how the structure and function of ecosystems are affected by large-scale change. Two key concepts that describe these consequences of climate change are *ecosystem resilience* and *ecological thresholds*.

Ecosystem resilience describes the "ability to adapt naturally" to environmental changes; in other words, the species within an ecosystem and the ecosystem as a whole have the capacity to adapt in pace with changing conditions. Resilience is also described in terms of how much disturbance an ecosystem can tolerate before changing to a different state. Global assessments of climate change widely recognize that climate change acts in combination with other human-induced pressures, such as resource extraction, habitat fragmentation, and pollution.[37]

An ecological threshold can be defined as the point at which there is an abrupt change in an ecosystem's condition or function that is potentially irreversible. This concept recognizes that an ecosystem's ability to adapt to gradual change (resilience) can be disrupted when a threshold,

**Table 8.1 Potential ecological impacts in response to climate change**

| Observed or projected physical change | Examples of potential impacts on biodiversity |
|---|---|
| Increased temperature | • Species and population range shifts<br>• Changes in phenology leading to alteration or loss of biotic interactions |
| Changes in annual and seasonal precipitation | • Changes in species composition of communities and habitats |
| Increased frequency of extreme events | • Mortality resulting from flooding after storms<br>• Damage or mortality resulting from drought or heat waves |
| Changes to hydrologic regimes | • Reduced streamflow affecting species population persistence and community composition |
| Changes to fire regimes | • Changes in species composition of communities |
| Ocean acidification | • Change in water chemistry affecting calcification rates of marine organisms |
| Sea level rise | • Habitat loss and fragmentation from coastal erosion or inundation |
| Increases in ocean stratification | • Reduced productivity of pelagic ecosystems |
| Changes in coastal upwelling and/or ocean temperatures | • Changes in productivity of coastal ecosystems and fisheries<br>• Species and population range shifts and/or changes in phenology leading to alteration or loss of biotic interactions |

Adapted from: National Climate Assessment (2012).[38]

or tipping point, is crossed. Small changes in climate can trigger large responses through positive feedbacks, which amplify or increase the initial change in the same direction (see Chapter 1, Section 1.5, Climate 101). Threshold crossings or transitions create a domino-like effect, so that the failure of one component in an ecosystem triggers instability throughout the rest of the system.

The combined effects of climate change and other human-induced stressors can push an ecosystem toward ecological thresholds. For example, the Chattahoochee-Apalachicola River basin in Alabama, Florida, and Georgia is an important ecosystem for fisheries that depend on access to tributaries for feeding and spawning. Increasing water withdrawals for human use, in combination with climate change trends, are creating conditions of water stress for many aquatic species. It is estimated that minimum river flows may fall below threshold levels in the summer by mid-century, potentially eliminating vital habitat for fish populations and significantly changing the ecosystem and its function.[39]

Although the conceptual understanding of ecological thresholds is still developing, the complexity of ecosystem dynamics makes it very difficult to predict the tipping point for a given ecosystem. Ecosystem resilience is likely to vary widely among different types of ecosystems and under different combinations of climate change drivers and other stressors. In its Fourth Assessment Report (2007), the Intergovernmental Panel on Climate Change stated that the resilience of many ecosystems is likely to be exceeded by "an unprecedented combination of change in climate, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification) and in other global change drivers (especially land-use change, pollution and over-exploitation of resources), if greenhouse gas emissions and other changes continue at or above current rates.[40]

## 8.3. External Stressors

Species and ecosystems are already challenged by a number of human-caused stressors, including habitat loss and fragmentation, altered hydrology, water quality impacts, invasive and nuisance species, and other resource and recreational uses. The impacts of climate change are likely to add to or exacerbate other stressors, increasing the vulnerability of those ecosystems facing multiple pressures.

*Habitat loss and habitat fragmentation* are leading factors in loss of biodiversity. Habitat loss eliminates feeding, nesting, and shelter areas for resident and migrant wildlife species. Habitat fragmentation degrades the quality of habitat and increases exposure of wildlife to predators and invasive, nonnative species. The primary cause of habitat loss is residential and commercial development. Land use changes that accompany population growth have direct and indirect effects on wildlife and ecosystem resources. These impacts result from changes in land use (conversion or development of natural habitat) or from management or operations of agriculture, transportation, or industrial activities (degrading habitat quality).

*Altered hydrology* that accompanies development and other land use changes can have long-term impacts on both aquatic and terrestrial habitats. Residential and commercial development practices increase impervious surface, which leads to degraded streams and wetlands as a result of polluted surface runoff, and reduces groundwater recharge. Impervious surfaces and other hydrologic changes, such as filling, ditching, and draining of wetlands, increase streamflow rates, raise water temperatures, and degrade water quality. Surface water withdrawals can reduce streamflow, especially during summer periods of peak demand. Loss of vegetation along streams and waterways as a result of development can also increase water temperatures in streams and rivers, which can harm fish and invertebrate species and trigger algal blooms. Dredging of waterways also has significant impacts on marine and estuarine habitats.

*Water quality impacts* are associated with agriculture, industry, new construction, and land use practices related to commercial and residential development. In many states, including Delaware, water quality is already impaired by excess nutrients from wastewater treatment plants, septic systems, agricultural runoff, pet waste, and fertilizers. Sedimentation from land-clearing activities (for development, agriculture, or forestry) affects water quality by decreasing dissolved oxygen levels and by reducing the penetration of sunlight, which affects aquatic vegetation. Nutrients from fertilizer use in suburban, urban, and agricultural landscapes leads to nutrient enrichment, algal blooms, and lower oxygen levels.

*Invasive and nuisance species* can have direct and indirect effects on wildlife and ecosystems. Invasive plant species displace native plants and reduce plant diversity. Nonnative insect species can have devastating effects on forests and other habitats. More than 450 nonnative forest insects are known to occur in the United States. Nonnative aquatic species compete with native species, leading to a decline in species diversity in freshwater systems. Native species can also become nuisance species when populations expand due to lack of predators or increasing food opportunities. For example, white-tailed deer *(Odocoileus virginianus)* thrive in rural and agricultural landscapes; their increasing numbers lead to intensive browsing, reducing vegetation and impairing the regeneration of forest trees and understory shrubs. The snow goose *(Chen caerulescens)* has also become a nuisance species in areas where excessive numbers degrade tidal wetlands, streams, and ponds due to their feeding habits.[41]

Other human activities that represent external stressors on species and habitats include resource use and recreation. *Resource uses* include surface and groundwater withdrawals; reducing freshwater flows can impair recharge and deplete streamflows, leading to degradation or loss of aquatic habitat. Recreational and commercial harvest of fish and game species can put direct pressure on population size and also have indirect impacts, such as fishery bycatch or ingestion of lead shot. *Recreational activities* can cause disturbance to wildlife or degrade habitats. For example, wakes from pleasure boats and personal watercraft can disturb shorebirds and waterfowl, and can cause increased shoreline erosion.

## 8.4. Potential Impacts of Climate Change to Delaware's Ecosystems and Wildlife

### 8.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. Species and habitats will be responding to the interaction of these factors, which complicates an assessment of the impacts Delaware's ecosystems and wildlife may experience. 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 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.

### Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar. 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.

### Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099 (**Figure 8.1**).

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- All simulations show large increases in average summer heat index, potential evapotranspiration, and the number of hot and dry days per year.

### Precipitation changes

- Precipitation is projected to increase, particularly in winter (**Figure 8.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 8.2**).

## 8.4.2. Climate Impacts to Species and Ecosystems

The Intergovernmental Panel on Climate Change defines ***vulnerability*** as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity."[42] ***Sensitivity*** includes intrinsic characteristics of a species, such as habitat specialization, physiological tolerances, and dispersal ability. ***Adaptive capacity*** describes the ability of a system (or species or population) to adjust to adjust to climate variability and extremes.[43]

*Plant species* are affected by increasing temperatures, leading to altered bloom times, changes in reproductive cycle, and potential mismatch of timing with pollinator species. Plant communities are likely to be affected by increased temperature combined with drought, leading to stress that increases their vulnerability to insect pests and pathogens. Invasive species may be an increasing problem in many plant communities. Higher levels of atmospheric $CO_2$ stimulate plant growth, and some studies have shown that invasive plants respond with greater growth rates than native plants. In addition, invasive plant species are often able to tolerate a wide range of environmental conditions and are better able to move into new locations.[44]

*Wildlife species* will face alterations in habitat type, quality, timing and availability of food sources, abundance of pests and diseases, and other stressors related to changes in temperature and precipitation. Some species will adapt to changing conditions, and some will even thrive. Other species will have to change behaviors or migrate to new areas to adapt. Climate change will compound other environmental stressors, such as pollution or competition from invasive species, making it difficult to predict the impacts of climate change on particular wildlife species. Changes in species distribution and abundance have already been observed; many northeastern U.S. birds are expanding their range northward, a shift that correlates with regional climate change. Research on forest bird species indicates that many resident forest birds have increased in abundance, a trend that is projected to continue. In contrast, short-distance migrant birds are projected to decline, and neotropical migrant species will likely see both increases and decreases, depending on their geographic range and conditions in their migratory habitats.[45]

*Ecosystems* represent unique assemblages of species living within a physical environment. When the environment changes – physically, biologically, or chemically – the composition and abundance of species and the overall suitability of the habitat is likely to change as well. Climate change is one of many drivers affecting environmental conditions that can have subtle or dramatic effects on ecosystems.

This summary focuses on three broad categories of ecosystem types in Delaware: beaches and dunes, wetland and aquatic systems, and forests. The potential vulnerabilities described here are necessarily general; however, this section is intended to illustrate some examples of ecosystem issues that Delaware is already coping with, and which could present vulnerabilities for the state with increasing impacts of climate change.

### 8.4.3. Species Impacts – Changes in Habitat and Hydrology

Aquatic and wetland-dependent species will be affected by climate change impacts that result in changes in hydrology and habitat loss or fragmentation. Some species may be able to adjust to changing conditions by migrating upstream, downstream, or landward, but these adaptations may be impaired if suitable habitat is not available for migration. For example, some tidal plant and animal species have specific ranges of tolerance for water temperature and salinity; the survival of these species may depend on critical habitat shifting in pace with climate change impacts, such as increasing temperatures and sea level rise.

Species with very restricted ranges and isolated populations are facing increasing risks, with climate change compounding other stressors. For example, amphibians are already sensitive to changes in temperature and precipitation. Because most amphibians reproduce in aquatic habitats, their breeding success depends on the availability of water at specific times. Increasing temperatures

#### Delaware at the Crossroads – Loss of Genetic Diversity

Delaware's unique geographic location is a key to the state's impressive diversity of plants and animals. Situated at the "crossroads" between New England, the Mid-Atlantic, and the Southeast, Delaware supports plant species at the northern and southern extremes of their geographic ranges. These populations of plants at the edges represent part of the genetic diversity of that species to tolerate a range of environmental conditions.

For example, southern blue lobelia *(Lobelia elongata)* is found in freshwater tidal wetlands in many southern and southeastern states. Populations of the southern blue lobelia in Delaware, at the northern extent of its range, are able to tolerate colder winters than southern populations of the same species. Thus, the Delaware population of the southern blue lobelia represents a genetic variation that allows the plants to persist under local climate conditions.

Genetic diversity is critical to the long-term viability of a species. Changing climate conditions may not threaten the survival of a species throughout its range, but the loss of individual populations can mean the loss of part of that species' genetic variability.

## Assessing Vulnerability – Bird Species at Risk

Vulnerability is described as a function of the sensitivity of a particular system or species to climate changes, its exposure to those changes, and its ability to adapt to those changes (see Section 8.4.2).

Vulnerability assessments conducted at the national and state level indicate that the highest proportion of vulnerable bird species is in bird groups (taxa) that use rocky shorelines, beaches, coastal wetlands and estuaries, and nearshore waters. An assessment conducted by the U.S. Department of the Interior found that bird species in ocean and coastal environments were most vulnerable to climate change impacts.[e] In Delaware, a few examples of potentially vulnerable species are noted below.

The black rail *(Laterallus jamaicensis)* is a habitat specialist that requires wetland habitat with specific vegetation and salinity range. This species is found in coastal salt and brackish marshes dominated by Spartina patens, and nests in areas of high marsh that are flooded only during extreme high tides. These habitats are particularly vulnerable because, with sea level rise, they will be squeezed between the twice-daily inundated low salt marsh (dominated by Spartina alterniflora) and the uplands. Sea level rise and increasing exposure to storm surge will increase the vulnerability of this already-rare species.

The red knot *(Calidris canutus rufa)* arrives on Delaware Bay shores every spring on its migratory route between its wintering habitat at the tip of South America and its summer Arctic nesting grounds. The arrival of red knots in Delaware coincides with the spawning of horseshoe crabs *(Limulus polyphemus)*, whose eggs provide a critical food source for the knot on its 9,300-mile journey. As the climate warms, changing water temperatures may trigger an earlier (or later) spawning, resulting in a potential mismatch between the timing of food availability and the arrival of red knots and other migratory birds. In addition, sea level rise and accelerated coastal erosion could affect the sandy beach habitat needed by both birds and horseshoe crabs.

and more frequent drought may reduce the size and abundance of ephemeral ponds, increasing competition for breeding habitat. Additionally, changes in hydrology and water availability could affect (positively or negatively) the transmission of amphibian and reptile diseases such as chytridiomycosis and ranavirus.

Changes in precipitation and hydrology can affect both prey and predator species. Bats, for example, feed primarily on insects, and many insect prey species depend on aquatic habitats for reproduction. Reductions in summer streamflows will increase water temperatures and reduce available habitat for temperature-sensitive aquatic species, such as smallmouth bass (*Micropterus dolomieu*).The timing of snowmelt affects spring runoff in headwater streams of the Delaware River watershed; fish species that spawn in spring may be particularly vulnerable to changes in timing and amount of streamflow.[46]

Changes in precipitation will also affect water quality, temperature, and salinity, which directly affect aquatic species. For example, in very dry and warm years, movement of saline waters farther up the Delaware estuary has increased the incidence of parasites that cause disease in the eastern oyster.[47] Increased frequency of intense storms will increase surface runoff into streams and increase streamside erosion, affecting the type and quality of in-stream habitat.

### 8.4.4. Species Impacts – Extreme Weather and Temperature Changes

Extreme weather events will have direct impacts on many species, especially those facing exposure during critical periods such as nesting or migrating. Beach-nesting birds and migratory shorebirds are among the most vulnerable.[48] Severe storms cause structural damage to forest habitats, and heavy rain events trigger high flows in streams that can destroy aquatic habitats. Flooding associated with heavy rains will also affect upland species, such as ground-dwelling mammals. Increasing temperatures will also affect insect populations, including insect vectors for wildlife disease. For example, outbreaks of hemorrhagic diseases in white-tailed deer, spread by biting midges, have been observed to increase in summer seasons with high heat and drought conditions.

Availability of food is a critical factor that may be altered under changing climate conditions. Small mammals with high energy demands can be affected by even short-term fluctuations in food availability. In addition, bats are hibernating species that are vulnerable when winter temperatures are much higher or lower than their optimal range. Warmer winters could increase periods of arousal from hibernation, depleting their limited energy stores and resulting in stress or starvation.[49] A fungal disease, white-nose syndrome, affects bats during hibernation and has killed millions of cave-hibernating bats. Additional stressors from climate change could further exacerbate an already catastrophic decline.

## 8.4.5. Beach and Dune Ecosystems

As described in Section 8.1 above, this discussion of Delaware's beach and dune ecosystems includes beach, dune, interdunal wetland, and tidal flat habitats. Beach and dune habitats are already under enormous stress from pollution, habitat fragmentation, land use changes, invasive species, and erosion. Climate change impacts are very likely to compound the existing environmental stresses to coastal wetlands, dunes, and beach habitats.

Though these areas have consistently undergone a series of changes in sea level in the geologic past, today sea level rise is occurring along Mid-Atlantic coasts at higher-than-global-average rates. This higher-than-average rate of sea level rise can be partially attributed to sections of the land base in the mid-Atlantic sinking due to tectonic land subsidence[e], as well as an increasing elevation of sea level. During the 19th century, global average sea level rose approximately seven inches. In the Mid-Atlantic region (between New York and North Carolina), sea level rose about one foot during the 20th century.[50] In addition, there is evidence that the rate of rise is increasing.[51] Sea level rise can exacerbate other coastal hazards, including storm surge, shoreline erosion, wetland loss, and saltwater intrusion.

The coastal zone, which includes beach and dune habitats as well as the wetland habitats, is highly dynamic, and the impacts of sea level rise are more complex than inundation alone. Physical processes of erosion, transport, and accumulation of sand and sediment continually reshape the coastal landscape as waves and currents modify the shoreline. If a sediment balance is not maintained, inundation of coastal areas in response to sea level rise will likely occur in sheltered, low-energy areas, where sediment accretion is limited. Erosion and inundation related to sea level rise and storm surge will have damaging impacts on coastal wetlands, already diminished by habitat loss from other stressors. Beach and dune and wetland habitats will also be affected by changes in precipitation patterns; increased rainfall and more frequent extreme rain events may alter freshwater flows into coastal wetlands, affecting salinity and inputs of sediment and nutrients.[52]

Changes to beach and dune and wetland habitats in response to climate change will be influenced by many factors. Of particular importance is the relative gain or loss of sediment in the estuary. Accretion or erosion of sediments is critical to whether tidal flats, beaches, and dunes expand or shrink.

The barrier beaches and Inland Bay system in southern Delaware are particularly vulnerable to the combined effects of sea level rise and severe coastal storms. Barrier beaches and dunes are subject to overwash from storm surge, especially where there is insufficient sand or sediment available to maintain barrier width and height. With the potential for coastal storms of increasing intensity, barrier beaches and dunes may be increasingly vulnerable to breaching and formation of new inlets. Landward migration of barriers is another potential response to sea level rise and severe storms.

**e** Tectonic land subsidence refers to the sinking of the Earth's surface on a large scale. In the Mid-Atlantic region this subsidence is a response to changes in the Earth's crust following the retreat of the glaciers at the end of the last Ice Age.

## Coastal Impoundments – Planning for Climate Change

Coastal impoundments are areas of upland or wetland habitats where low level dikes have been constructed to restrict, retain, or exclude water over a selected area. Delaware has an extensive complex of coastal impoundments, managed primarily by state and federal wildlife agencies to serve a variety of purposes and habitat functions.a These managed wetlands provide migratory habitat for huge numbers of waterfowl and shorebirds, including roosting habitat for red knots. Impoundments also serve as breeding habitat for many waterfowl, shorebirds, and marsh-nesting birds, including rails and songbird species. Coastal impoundments may also be managed for mosquito control and to support fisheries.

Given their low elevation and location near shorelines, coastal impoundments are vulnerable to the climate change impacts of sea level rise and more frequent and severe coastal storms. Flooding or overtopping of impoundment dikes can dramatically alter the habitat within the impoundment ponds, rapidly changing water depth and salinity. These impacts can lead to the conversion of freshwater impoundments to saline open water habitat. Adjacent upland habitats can also be affected, as evidenced by trees in forested wetlands dying from increased salinity.a Climate change impacts can also complicate management options for impoundments; for example, higher sea levels and extreme rain events combined may limit managers' ability to draw down water levels. In addition, impoundments and their water control systems may suffer structural damage from flooding or storm surge.

As sea level rise and other climate impacts affect Delaware's tidal wetlands and marshes, the inland migration of wetland habitats is likely to be limited. Landward migration may be constrained by land uses, structures, or topography. As a result, management strategies for coastal impoundments need to adapt to changing conditions. For example, one strategy may be to divide large impoundments into smaller units and manage these for varying levels of salinity. This may lead to a transition of some impoundment ponds to salt marsh, while maintaining others as freshwater habitat. Another strategy may be a managed retreat, by creating new impoundments on the landward side of existing ones. Other options being considered for both natural and managed wetlands is the addition of sediment to marsh habitats to support the accretion of soil that helps wetlands keep pace with rising sea level. Dredge materials are one potential source of sediment, which may be coordinated with the Army Corps of Engineers for "beneficial reuse" projects.

The Delaware Division of Fish and Wildlife is coordinating with other state and federal agencies to develop a "climate smart" approach to the management of coastal impoundments under changing climate conditions. Although management practices reflect site-specific needs, long-term planning will address climate change impacts in the context of coastal wetland habitats across the state and throughout the Atlantic Flyway region.

Tidal flat habitats will respond to sea level rise in different ways, depending largely on sediment movement and availability. Where sediment inputs are low, tidal flats will become subtidal habitats and potentially convert to open water as sea level rises. Loss of tidal flats will affect numerous bird species that forage in these food-rich habitats.[53]

Estuarine beaches also play an important role in coastal food webs, particularly for horseshoe crabs that lay their eggs on beaches and intertidal habitats. Delaware Bay beaches and tidal wetlands are critical habitat for more than 40 species of migratory shorebirds. The persistence of estuarine beaches depends on the availability of sediment to replenish eroded lands. Sea level rise and coastal storms may result in increased erosion or decreased sediment availability, which may lead to loss of estuarine beach habitat.[54]

### 8.4.6. Wetlands and Aquatic Ecosystems

As described in Section 8.1 above, this discussion of Delaware's wetland and aquatic ecosystems includes a wide range of wetland types – tidal, nontidal, freshwater, brackish, and saltwater – and also includes stream and river aquatic habitats.

Climate change impacts from sea level rise, changes in precipitation, and extreme weather events will have significant effects on both freshwater and saltwater wetland habitats. In addition, increasing air temperatures will likely trigger increased water temperatures, affecting biological and chemical processes in the ecosystem. Climate change effects are highly dynamic and affect wetland ecosystems in combination with other external stressors.

Sea levels are projected to rise 1.6 to 4.9 feet (0.5 to 1.5 meters) by 2100. This will have potentially devastating effects on Delaware's coastal habitats, including tidal salt marshes. Some of the state's rarest species depend on the sliver of high marsh between the low marsh and the uplands. Much of this high marsh habitat will be lost if unable to shift inland with salt marsh migration. Some tidal plant and animal species have specific ranges of tolerance for inundation frequency, salinity, and water temperature; the survival of these species may depend on critical habitat shifting in pace with climate change impacts, such as increasing temperatures and sea level rise.

Sea level rise and increased storm surge will affect rates of erosion and accretion in tidal marshes. Climate impacts may lead to wetland losses, landward migration of marsh habitat, or conversion to open water.[55] In sheltered, low-energy coastal areas with limited sediment inputs, shoreline wetlands may be unable to keep pace with rising water levels and thus become submerged.[56]

Changes in precipitation amount and timing may affect water quality with greater swings in salinity. High temperatures combined with drought will increase evapotranspiration, altering soil moisture and increasing salt concentrations that may be intolerable to some marsh species. Temperature and moisture changes, combined with the effects of excess nutrients, will change plant productivity. High nutrient levels promote plant growth above the soil surface while not supporting rhizome growth below the soil, thus making wetland vegetation more vulnerable to loss from storm surges.[57]

Changes in water temperature and chemistry will affect both salt- and freshwater wetlands and aquatic habitats. 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. Warmer water also affects microbial processes, such as nitrogen fixation and denitrification in estuarine ecosystems.[58]

Increased temperatures, more intense storm events, and more frequent droughts will stress freshwater habitats, including streams, rivers, and ponds, and may lead to changes in species composition, especially for aquatic species dependent on specific timing and amount of available water. For example, the condition and function of vernal pools and coastal plain seasonal ponds may be affected by more intense winter storms followed by drought conditions and higher temperatures. The way species such as amphibians use these habitats may be affected. Changes in water temperature have important influences on aquatic ecosystem functions, such as reduced levels of dissolved oxygen and increased rates of biological processes. Warmer surface waters can promote algal blooms, including toxic blue-green algae, and lead to eutrophication of lakes, ponds, and streams. Increased precipitation increases the amount of organic material washing into lakes and streams, leading to higher concentrations of dissolved organic carbon (DOC), altering chemical and biological functions in the ecosystem.[59] Climate change impacts in freshwater ecosystems can also promote the establishment and expansion of invasive aquatic species.

## 8.4.7. Forest Ecosystems

As described in Section 8.1 above, this discussion of Delaware's forests includes upland forests and forested wetlands. Shifts in the range of forest species and composition of forest communities are likely to be triggered by changes in temperature. Some forest types are projected to expand their range as a result of temperature increases. Models projecting the future distribution of forest types in the northeastern United States show that oak-hickory forests are likely to increase at the expense of maple-beech-birch habitats. Loblolly pine (*Pinus taeda*) is common and widespread in Sussex County, but increased temperatures could allow it to expand its range northward. Forest composition and structure may be more critical to animal species responses than the presence or absence of any one plant.

Many factors will influence the rate and extent of changes in range and uncertainties about the ability of forest species to adapt to the relatively rapid pace of climate change.[60] Studies indicate that many tree species have a slower rate of migration that will limit their ability to keep pace with changes in temperature. For example, in a study of five eastern U.S. tree species, models suggest that these species are not likely to colonize more than 20 kilometers (approximately 12 miles) beyond their current boundary over the next 100 years. Slower migration rates are expected for species that decline in abundance toward the edge of their current boundaries.[61] In addition, the highly fragmented condition of forests in Delaware will present a barrier to migration for both plant and animal species.

Changes in air chemistry related to climate change are expected to affect forest health and productivity. Rising levels of atmospheric $CO_2$ and longer growing seasons are likely to increase productivity, but these gains may be offset by other factors, such as drought, pollution, and potential increases in pests and disease. Higher concentrations of $CO_2$ stimulate plant growth in some species more than others. For example, temperate forests have seen increases in woody vine species over the past several decades, a trend that can alter species composition and structure of forest habitats.[62] Increased $CO_2$ may also alter leaf chemistry, with potential consequences for herbivores in forest communities.[63]

Climate change is likely to cause changes to the cycling of nutrients in forest habitats. Some studies suggest that as climate warms, releases of $CO_2$ from the soil will increase as a result of increased soil respiration. This poses the possibility that forests could shift from serving as carbon sinks to being sources of carbon emissions.[64] Increased air temperatures are also associated with higher levels of ground-level ozone, which damages plant tissues and impairs photosynthesis.

Changes in precipitation will affect Delaware forests in direct and indirect ways. Increased frequency and/or duration of drought combined with increased air temperatures will 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. High rainfall events will produce changes in forest wetlands by altering hydrologic patterns, and exacerbating flooding and erosion problems.

Pests, pathogens, and invasive plants are existing threats to forest habitats; the spread and severity of pest outbreaks will be influenced by precipitation and temperature changes related to climate change. Increases in winter temperatures, in particular, are likely to allow overwintering of insect pests that are currently kept in check by cold winters. For example, southern pine beetle (*Dendroctonus frontalis*) populations fluctuate in response to winter temperatures; the Delaware Forest Service reported that a high percentage of the overwintering population of the beetle in 2011 was reduced by unusually cold temperatures in the previous winters, a trend that could reverse following mild or warm winters.

Other pest species may be “winners” or “losers” under drier or wetter climate conditions. For example, wet spring weather increases the effectiveness of the fungus *Entomophaga maimaiga* in controlling gypsy moth (*Lymantria dispar*).[65] Some harmful forest pathogens may benefit from increases in temperature and precipitation. High rainfall conditions can increase spore production of fungal pathogens and facilitate their dispersal through rain splash and surface runoff. In addition, pathogens typically infest weakened or stressed host plants, therefore presenting a greater risk to forest trees suffering from drought-stress or other climate-related impacts.

Invasive plant species also pose an existing threat to forest habitats, and some studies indicate that certain aggressive, weedy species may increase under warmer and wetter climate conditions. Many invasive plant species can tolerate a wide range of temperature and precipitation, increasing their competitive advantage over some forest species with more specific tolerances. In addition, invasive plants often have characteristics that allow for long-distance dispersal, which allows rapid expansion into new areas as climatic conditions change.[66]

## Sources (Endnotes)


1 Hayhoe, K., Stoner, A., & Gelca, R. (2013). Climate Change Projections and Analysis for Delaware. Report dated December 2013.

2 Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis.* Washington, DC: Island Press. Retrieved from http://www.maweb.org/en/index.aspx

3 Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., … Velichko, A. A. (2007). "Ecosystems, their properties, goods, and services." *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 211-272.

4 Delaware Department of Natural Resources and Environmental Control. (2006). *Delaware wildlife action plan 2007-2017.* Delaware Natural Heritage and Endangered Species Program, Delaware Division of Fish and Wildlife report dated June. Retrieved from http://www.dnrec.delaware.gov/fw/dwap/Pages/default.aspx

5 Delaware Department of Natural Resources and Environmental Control. (2006). *Delaware wildlife action plan 2007-2017.* Delaware Natural Heritage and Endangered Species Program, Delaware Division of Fish and Wildlife report dated June. Retrieved from http://www.dnrec.delaware.gov/fw/dwap/Pages/default.aspx

6 Delaware Department of Natural Resources and Environmental Control. (2001). *Assessment report of Delaware's Chesapeake Basin.* Report dated March. Retrieved from http://www.delawarewatersheds.org/publications

7 Breese, G., Bright, G., Burke, D., Clark, J., Kahn, D., Kreeger, D., … Wong, R. (2012). Chapter 6 – Living resources, in *Technical report for the Delaware Estuary and Basin.* Partnership for the Delaware Estuary, Report No. 12-01. June. pp. 166-224.

8 Delaware Department of Natural Resources and Environmental Control & Delaware Coastal Programs. (2006). *Striking a balance: A guide to coastal dynamics and beach management in Delaware.* Division of Soil and Water Conservation, Shoreline and Waterway Management Section Report. Retrieved from http://www.dnrec.delaware.gov/swc/Pages/CoastalConsBeachPres.aspx

9 Delaware Department of Natural Resources and Environmental Control & Delaware Coastal Programs. (2006). *Striking a balance: A guide to coastal dynamics and beach management in Delaware.* Division of Soil and Water Conservation, Shoreline and Waterway Management Section Report. Retrieved from http://www.dnrec.delaware.gov/swc/Pages/CoastalConsBeachPres.aspx

10 Delaware Department of Natural Resources and Environmental Control & Delaware Coastal Programs. (2006). *Striking a balance: A guide to coastal dynamics and beach management in Delaware.* Division of Soil and Water Conservation, Shoreline and Waterway Management Section Report. Retrieved from http://www.dnrec.delaware.gov/swc/Pages/CoastalConsBeachPres.aspx

11 Delaware Department of Natural Resources and Environmental Control & Delaware Coastal Programs. (2006). *Striking a Balance: A Guide to Coastal Dynamics and Beach Management in Delaware.* Division of Soil and Water Conservation, Shoreline and Waterway Management Section Report. Retrieved from http://www.dnrec.delaware.gov/swc/Pages/CoastalConsBeachPres.aspx

12 Breese, G., Bright, G., Burke, D., Clark, J., Kahn, D., Kreeger, D., … Wong, R. (2012). Chapter 6 – Living resources. *Technical report for the Delaware Estuary and Basin.* Partnership for the Delaware Estuary, Report No. 12-01. June. pp. 166-224.

13 Delaware Department of Natural Resources and Environmental Control. (2006). *Delaware wildlife action plan 2007-2017.* Delaware Natural Heritage and Endangered Species Program, Delaware Division of Fish and Wildlife report dated June, 2006. Retrieved from http://www.dnrec.delaware.gov/fw/dwap/Pages/default.aspx

14 Delaware Sea Grant Program. (2003). *Delaware's coastal dunes.* Report dated September. Retrieved from http://www.deseagrant.org/products/delawares-coastal-dunes

15 Tiner, R. W., Biddle, M. A. , Jacobs, A. D., Rogerson, A. B., & McGuckin, K. G. (2011). *Delaware wetlands: Status and changes from 1992 to 2007.* U.S. Fish and Wildlife Service, Cooperative National Wetlands Inventory Publication. Northeast Region, Hadley, MA, and the Delaware Department of Natural Resources and Environmental Control, Dover, DE. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/DelawareWetlandsStatusandTrends.aspx

16 Tiner, R. W., Biddle, M. A. , Jacobs, A. D., Rogerson, A. B., & McGuckin, K. G. (2011). *Delaware wetlands: Status and changes from 1992 to 2007.* U.S. Fish and Wildlife Service, Cooperative National Wetlands Inventory Publication. Northeast Region, Hadley, MA, and the Delaware Department of Natural Resources and Environmental Control, Dover, DE. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/DelawareWetlandsStatusandTrends.aspx

17 Kreeger, D., Adkins, J., Cole, P., Najjar, R., Velinsky, D., Conolly, P. & Kraeuter, J. (2010). *Climate change and the Delaware Estuary: Three case studies in vulnerability assessment and adaptation planning.* Partnership for the Delaware Estuary, Report No. 10-01. June. Retrieved from http://delawareestuary.org/science_projects_climate_ready_products.asp

18 Tiner, R. W., Biddle, M. A. , Jacobs, A. D., Rogerson, A. B., & McGuckin, K. G. (2011). *Delaware wetlands: Status and changes from 1992 to 2007.* U.S. Fish and Wildlife Service, Cooperative National Wetlands Inventory Publication. Northeast Region, Hadley, MA, and the Delaware Department of Natural Resources and Environmental Control, Dover, DE. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/DelawareWetlandsStatusandTrends.aspx

19 National Wildlife Federation. (2011). *Practical guidance for coastal climate-smart conservation projects in the Northeast: Case examples for coastal impoundments and living shorelines.* Report provided by an expert panel on coastal systems and climate change convened by the National Wildlife Federation. Retrieved from http://www.georgetownclimate.org/resources/practical-guidance-for-coastal-climate-smart-conservation-projects-in-the-northeast

20 Delaware Department of Natural Resources and Environmental Concern. (2005). *Delaware Bay and Estuary assessment report.* Report dated August. Retrieved from http://www.delawarewatersheds.org/publications

21 Delaware Department of Natural Resources and Environmental Concern & the Nature Conservancy. (2004). *Blackbird-Millington Corridor Conservation Area plan – Coastal Plain pond complexes.* Retrieved from http://www.dnrec.delaware.gov/fw/dwap/Pages/Blackbird-Millington.aspx

22 Delaware Department of Natural Resources and Environmental Control. (2006). *Delaware wildlife action plan 2007-2017.* Delaware Natural Heritage and Endangered Species Program, Delaware Division of Fish and Wildlife report dated June. Retrieved from http://www.dnrec.delaware.gov/fw/dwap/Pages/default.aspx

23 Bason, C. (2011). *State of the Delaware Inland bays.* Delaware Center for the Inland Bays report dated September. Retrieved from http://www.delawarewatersheds.org/sites/delawarewatersheds.org/files/publications/InlandBays2011stateofthebays.pdf

24 Rogerson, A., Howard, A., & Jacobs, A. (2009). *Wetlands condition of the Inland Bays watershed. Volume 2: Tidal wetlands.* Delaware Department of Natural Resources and Environmental Control, Watershed Assessment Section report dated June. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/InlandBays.aspx

25 Jacobs, A., Rogerson, A., Fillis, D., & Bason, C. (2009). *Wetland condition of the Inland Bays watershed. Volume 1: nontidal wetlands.* Delaware Department of Natural Resources and Environmental Control, Watershed Assessment Section report dated January. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/InlandBays.aspx

26 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

27 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

28 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

29 U.S. Forest Service, Forest Inventory and Assessment program. Retrieved September 12, 2012 from http://www.fs.fed.us/ne/fia/states/de/index.html.

30 Delaware Forest Service, Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Retrieved from http://dda.delaware.gov/forestry/index.shtml

31 Staudinger, M. D., Grimm, N. B., Staudt, A., Carter, S. L., Chapin, F. S., Kareiva, P., … Stein, B.A. (2012). *Impacts of climate change on biodiversity, ecosystems, and ecosystem services: Technical input to the 2013 National Climate Assessment.* Cooperative Report to the 2013 National Climate Assessment. Retrieved from http://assessment.globalchange.gov

32 Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States.* Cambridge, MA: Cambridge University Press. Report of the U.S. Global Change Research Program. Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts.

33 Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States.* Cambridge, MA: Cambridge University Press. Report of the U.S. Global Change Research Program. Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts.

34 Staudinger, M. D., Grimm, N. B., Staudt, A., Carter, S. L., Chapin, F. S., Kareiva, P., … Stein, B.A. (2012). *Impacts of climate change on biodiversity, ecosystems, and ecosystem services: Technical input to the 2013 National Climate Assessment.* Cooperative Report to the 2013 National Climate Assessment. Retrieved from http://assessment.globalchange.gov

35 Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States.* Cambridge, MA: Cambridge University Press. Report of the U.S. Global Change Research Program. Retrieved from http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

36 Janetos, A., Hansen, L., Inouye, D., Kelly, B. P., Meyerson, L., Peterson, B., & Shaw, R. (2008). Biodiversity, in *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* U.S. Climate Change Science Program and the Subcommittee on Global Change Research report. Washington, DC. Retrieved from http://www.climatescience.gov/Library/sap/sap4-3/final-report/

37 Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., … Velichko, A. A. (2007). "Ecosystems, their properties, goods, and services." *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 211-272.

38 Staudinger, M. D., Grimm, N. B., Staudt, A., Carter, S. L., Chapin, F. S., Kareiva, P., … Stein, B. A. (2012). *Impacts of climate change on biodiversity, ecosystems, and ecosystem services: Technical input to the 2013 National Climate Assessment.* Cooperative Report to the 2013 National Climate Assessment. Retrieved from http://assessment.globalchange.gov

39 Charles, C. W. (2009). *Thresholds of climate change in ecosystems.* U. S. Climate Change Science Program, Synthesis and Assessment Product 4.2. Retrieved from http://www.climatescience.gov/Library/sap/sap4-2/final-report/

40 Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., … Velichko, A. A. (2007). Ecosystems, their properties, goods, and services. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 211-272.

41 Delaware Department of Natural Resources and Environmental Control. (2006). *Delaware wildlife action plan 2007-2017.* Delaware Natural Heritage and Endangered Species Program, Delaware Division of Fish and Wildlife report dated June. Retrieved from http://www.dnrec.delaware.gov/fw/dwap/Pages/default.aspx

42 Intergovernmental Panel on Climate Change (IPCC). (2007). Summary for policymakers, in *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.). Cambridge, UK: Cambridge University Press, pp. 7-22. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf

43 Glick, P., Stein, B. A., and Edelson, N. A. (2011). *Scanning the conservation horizon: A guide to climate change vulnerability assessment.* Washington, DC: National Wildlife Federation. Retrieved from http://www.habitat.noaa.gov/pdf/scanning_the_conservation_horizon.pdf

44 Janetos, A., Hansen, L., Inouye, D., Kelly, B. P., Meyerson, L., Peterson, B., & Shaw, R. (2008). Biodiversity, in *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* U.S. Climate Change Science Program and the Subcommittee on Global Change Research report. Washington, DC. Retrieved from http://www.climatescience.gov/Library/sap/sap4-3/final-report/

45 Rustad, L., Campbell, J., Dukes, J. S., Huntington, T., Lambert, K.F., Mohan, J., & Rodenhouse, N. (2012). *Changing climate, changing forests: The impacts of climate change on forests of the northeastern United States and eastern Canada.* U.S. Forest Service, General Technical Report NRS-99. Retrieved from http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs99.pdf

46 Poff, N. L., Brinson, M. M., & Day, Jr., J. W. (2002). *Potential impacts on inland freshwater and coastal wetland ecosystems in the United States.* Pew Center on Global Climate Change report. Retrieved from http://www.c2es.org/docUploads/aquatic.pdf

47 Rogers, C. E., & McCarthy, J. P. (2000). Climate change and ecosystems of the Mid-Atlantic Region. *Climate Research,* 14, 235-244. Retrieved from http://www.int-res.com/abstracts/cr/v14/n3/p235-244/

48 U.S. Department of the Interior. (2010). *The state of the birds 2010 report on climate change.* Retrieved from http://www.stateofthebirds.org/2010

49 Rustad, L., Campbell, J., Dukes, J. S., Huntington, T., Lambert, K. F., Mohan, J., & Rodenhouse, N. (2012). *Changing climate, changing forests: The impacts of climate change on forests of the northeastern United States and eastern Canada.* U.S. Forest Service, General Technical Report NRS-99. Retrieved from http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs99.pdf

50 Titus, J. G. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.1. Retrieved from http://www.climatescience.gov/Library/sap/sap4-1/final-report/ 51 Sallenger, A. H. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Climate Change. Published online June 24. doi:10.1038/nclimate1597

52 Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., … Velichko, A. A. (2007). Ecosystems, their properties, goods, and services. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 211-272.

53 Galbraith, H., Jones, R., Park, R., Clough, J., Herrod-Julius, S., Harrington, B., & Page, G. (2005). *Global climate change and sea level rise: Potential losses of intertidal habitat for shorebirds.* Bird conservation implementation and integration in the Americas: Proceedings of the Third International Partners in Flight Conference, 2002. Volume 2. U.S. Department of Agriculture, Forest Service General Technical Report PSW-GTR-191.

54 Titus, J. G. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.1. Retrieved from http://www.climatescience.gov/Library/sap/sap4-1/final-report/

55 Kreeger, D., Adkins, J., Cole, P., Najjar, R., Velinsky, D., Conolly, P. & Kraeuter, J. (2010). *Climate change and the Delaware Estuary: Three case studies in vulnerability assessment and adaptation planning.* Partnership for the Delaware Estuary Report, No. 10-01. June. Retrieved from http://delawareestuary.org/science_projects_climate_ready_products.asp

56 Titus, J. G. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.1. Retrieved from http://www.climatescience.gov/Library/sap/sap4-1/final-report/

57 Kreeger, D., Adkins, J., Cole, P., Najjar, R., Velinsky, D., Conolly, P., & Kraeuter, J. (2010). *Climate change and the Delaware Estuary: Three case studies in vulnerability assessment and adaptation planning.* Partnership for the Delaware Estuary Report, No. 10-01. June. Retrieved from http://delawareestuary.org/science_projects_climate_ready_products.asp

58 Nicholls, R. J., Wong, P. P., Burkett, V. R., Codignotto, J. O., Hay, J. E., McLean, R. F., … Woodroffe, C. D. (2007). Coastal systems and low-lying areas. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 315-356.

59 Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., … Velichko, A. A. (2007). Ecosystems, their properties, goods, and services. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 211-272.

60 Rustad, L., Campbell, J., Dukes, J. S., Huntington, T., Lambert, K. F., Mohan, J., & Rodenhouse, N. (2012). *Changing climate, changing forests: The impacts of climate change on forests of the northeastern United States and eastern Canada.* U.S. Forest Service, General Technical Report NRS-99. Retrieved from http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs99.pdf

61 Iverson, L. R., Schwartz, M. W., & Prasad, A. M. (2004). How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography* 13, 209-219. Retrieved from http://www.treesearch.fs.fed.us/pubs/9410

62 Rustad, L., Campbell, J., Dukes, J. S., Huntington, T., Lambert, K. F., Mohan, J., & Rodenhouse, N. (2012). *Changing climate, changing forests: The impacts of climate change on forests of the northeastern United States and eastern Canada.* U.S. Forest Service, General Technical Report NRS-99. Retrieved from http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs99.pdf.

63 Dukes, J. S., Pontius, J., Orwig, D., Garnas, J. R., Rodgers, V. L., Brazee, N., … Ayres, M. (2009). Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict?. *Canadian Journal of Forest Research* 39 (2): 231-248. Retrieved from http://www.fs.fed.us/ccrc/bibliography/7_4_2_2_forest.shtml

64 Rustad, L., Campbell, J., Dukes, J. S., Huntington, T., Lambert, K. F., Mohan, J., & Rodenhouse, N. (2012). *Changing climate, changing forests: The impacts of climate change on forests of the northeastern United States and eastern Canada.* U.S. Forest Service, General Technical Report NRS-99. Retrieved from http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs99.pdf

65 Delaware Forest Service. (2012). FY11 annual report. Retrieved from http://dda.delaware.gov/forestry/2011/FY11_Annual%20Report.pdf

66 Dukes, J. S., Pontius, J., Orwig, D., Garnas, J. R., Rodgers, V. L., Brazee, N., … Ayres, M. (2009). Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research* 39 (2), 231-248. Retrieved from http://www.fs.fed.us/ccrc/bibliography/7_4_2_2_forest.shtml

# Chapter 9 – Infrastructure Summary

## Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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. (All climate projections and graphs are based on Hayhoe, et al, 2013.)[1]

### Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

### Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3-4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- Energy demand for cooling is projected to increase by up to 130 percent by end of century, while energy demand for heating is projected to decrease by up to 40 percent by end of century (**Figure 9.1**).

### Precipitation Changes

- Precipitation is projected to increase, particularly in winter (**Figure 9.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of

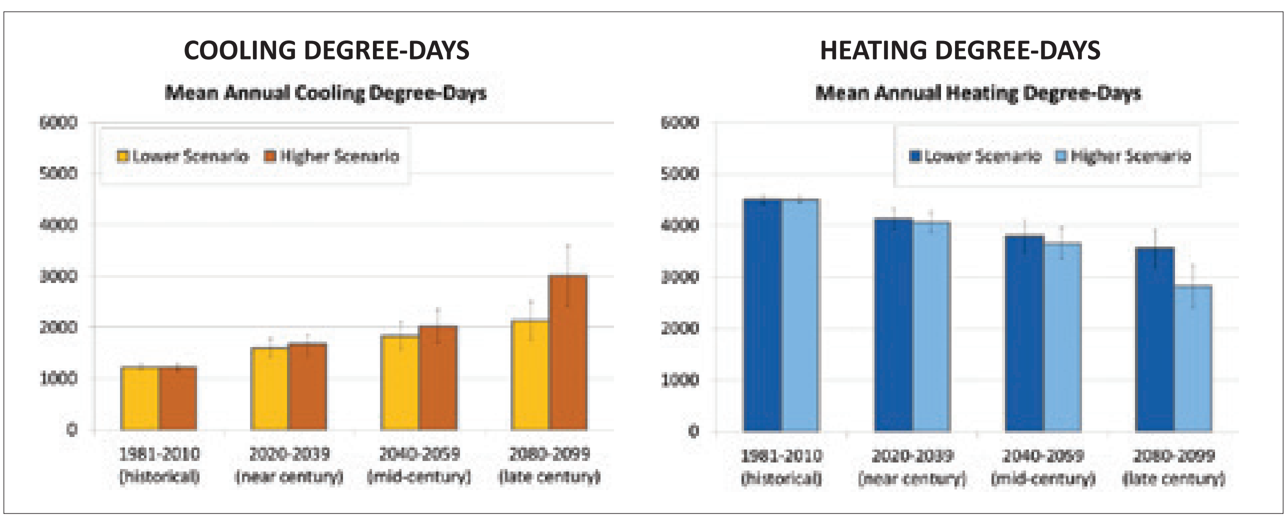


**Figure 9.1.** Cooling and heating degree-days provide a useful indicator of demand for electricity in the summer (for air conditioning) and natural gas or oil in the winter (for space heating). This is calculated as the cumulative number of hours per year above (for cooling) or below (for heating) 65˚F. Source: Hayhoe et al. (2013).

heavy precipitation events, indicating an increase in precipitation intensity.

## Potential Impacts to Infrastructure

- ***Extreme weather events*** can have direct and indirect impacts to the structural and operational use of infrastructure. Back-to-back storms or cascading events can lead to power outages and the shutdown of public transit. During 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, rail, bridges, and culverts, and other drainage structures. Many of Delaware's 48 regulated dams are located adjacent to or integrated into state-managed roads and bridges. In extreme rain events, dams may be vulnerable to damage or failure. Thus, roads or bridges located on top of, next to, or downstream from these structures are at risk of serious flooding or washout. Extreme weather events can also cause damage to natural infrastructure, such as wetlands and beaches, which may impair their ability to buffer inland areas.

- Changes in ***precipitation*** patterns may lead to a greater extent or frequency of flooding and increase the vulnerability of infrastructure in flood-prone areas. A potential shift toward more winter precipitation falling as rain instead of snow may alter the amount of snowpack in upstream portions of the Piedmont Basin. This may result in changes in the timing of spring thaw and shifts in seasonal flows and water levels that could increase flooding, particularly in urban areas of northern Delaware. Increased precipitation and associated flooding may increase the vulnerability of remediation sites and landfills associated with industrial facilities.

- ***Sea level rise*** poses potential impacts to natural and human-built infrastructure along Delaware's Atlantic and Delaware Bay coastlines. Roads and bridges throughout the state may be affected by sea level rise, particularly in the Inland Bays area. Delaware Bay beach communities may be vulnerable to more frequent tidal flooding of primary access roads and evacuation routes. The Port of Wilmington is a major facility that could be significantly affected. Public boat ramps and piers throughout coastal Delaware are also at risk for intermittent or chronic flooding as a result of sea level rise. Facilities located along the Delaware River and in the Inland Bays are vulnerable to inundation from sea level rise, and potential changes in salinity may affect industrial operations.

- ***Increasing temperatures*** and heat events are likely to affect transportation and energy infrastructure. Thermal stress or damage to energy infrastructure from heat-driven storms can impair electricity transmission. Higher air and water temperatures, or lack of available water for cooling, can affect operations and reduce electricity output. Increased heat can accelerate deterioration of the structure and surface of roads and bridges. These impacts may require increased maintenance and more frequent monitoring to prevent damage and ensure public safety.

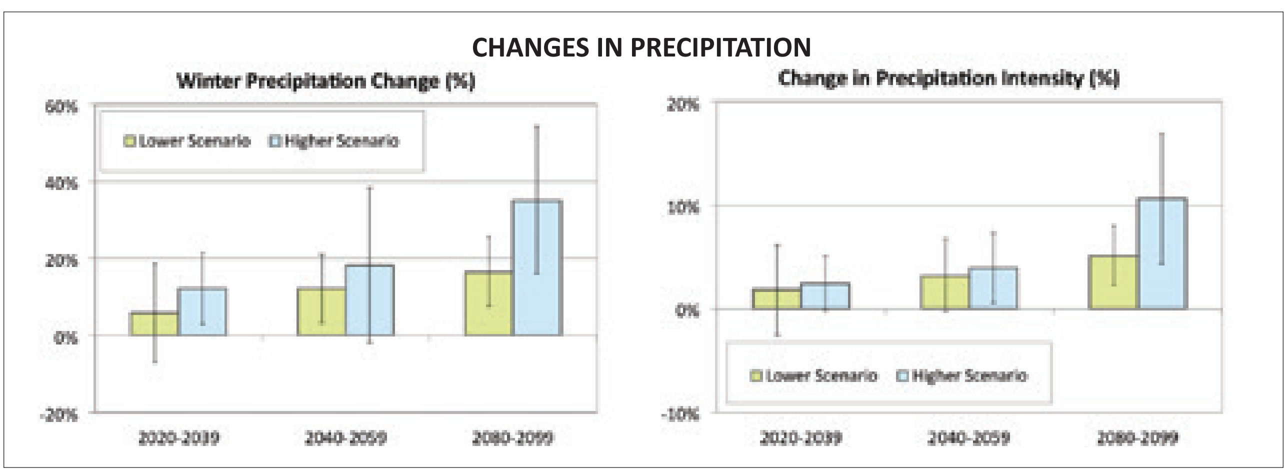


**Figure 9.2.** Precipitation increases are projected, primarily for winter and fall. Increasing precipitation intensity reflects projected increases in the frequency of heavy rainfall. Source: Hayhoe et al. (2013).

# Chapter 9 Infrastructure

## Chapter Contents

- Overview of Delaware's infrastructure, including natural and human-built infrastructure, with a focus on transportation and energy systems
- Summary of climate change impacts that pose challenges to infrastructure throughout the United States (based on review of scientific reports and studies – national scope)
- Summary of external stressors to infrastructure (nonclimatic impacts to resources)
- Potential vulnerabilities to infrastructure in Delaware (based on current research and expert interviews – statewide scope)

In this chapter "infrastructure" is used to include both the human-built environment and the natural environment. Infrastructure is not defined solely as physical structures or facilities, but also in terms of the functions it serves. These functions, including "ecosystem services," are described and integrated into many sections in the Climate Change Impact Assessment. For example, Chapter 7, Agriculture, reflects the provisioning services of agricultural systems. In Chapter 8 on Ecosystems and Wildlife, many of the ecosystem functions described reflect regulating services, such as the water filtering function of wetlands. (See definitions of ecosystem services in Section 9.1.1. below.)

It is also important to consider that natural infrastructure and human-built infrastructure operate in integrated and interdependent ways. For example, natural infrastructure such as wetlands and forests can act as critical buffers to slow surface water runoff during storm events, thus reducing the impacts to human-built stormwater conveyance structures. Similarly, natural habitats perform biological functions that help to filter, absorb, or store pollutants. As ecosystems respond to climate change impacts, human-built infrastructure will be affected by changing environmental conditions as well.[2]

The human-built infrastructure discussed in this chapter focuses primarily on transportation and energy systems. Water infrastructure (water supply, distribution, treatment, wastewater, and stormwater systems) is discussed in Chapter 6, Water Resources.

## 9.1. Overview of Delaware's Infrastructure

### 9.1.1. Natural Infrastructure

An overview of Delaware's natural infrastructure would be incomplete without a brief discussion of the services that ecosystems provide, not only for the species and habitats they support, but for physical and biological functions on which human societies depend. Ecosystem services encompass a wide range of "benefits people obtain from ecosystems."[3] These benefits are discussed in this chapter to underscore the importance of the natural systems in supporting human needs.

Ecosystem services are defined by the Millennium Ecosystem Assessment and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change to include:

- *Regulating services* that moderate climate, floods, disease, wastes, and water quality, and
- *Provisioning services* that provide goods for human use and consumption, such as water and food.[4]

Delaware supports extensive natural habitats that serve a wide variety of ecosystem functions. In the context of infrastructure, many habitats provide regulating services that can support, or perform in place of, engineered systems and structures. The function or performance of habitat in providing ecosystem services depends on the type of habitat and its condition. Loss of habitat often results in loss of the ecosystem services. Degradation or fragmentation of habitat can result in reduced function. Under current conditions, many of Delaware's natural ecosystems are fragmented or impaired by a variety of stressors. Additional impacts from climate change could reduce or eliminate these habitats, or further affect their ability to provide ecosystem services.

## Wetlands and Aquatic Ecosystems

Delaware's extensive wetland (both tidal and nontidal) and aquatic habitats provide many important functions that enhance and protect human communities and built infrastructure. In addition, these ecosystems provide cultural and aesthetic values for humans, as well as economic benefits related to tourism and recreation opportunities. Wetland types (both freshwater and saltwater) vary widely in vegetation type, hydrology, geographic location, and connectivity to other wetlands and other landforms (as described in Chapter 8, Ecosystems and Wildlife). Wetlands can serve a wide range of functions, as summarized in **Table 9.1**.

The condition of wetland habitat has a direct effect on its ecosystem function. A recent assessment of Delaware's wetlands from 1992 to 2007 concluded that between 40 and 65 percent of the state's wetlands provided high or moderate levels of ecosystem services.[6] Enhancement of wetland habitat, as well as protection from further habitat losses, is important for maintaining and improving the functional performance of wetlands.

Wetlands are also important for carbon storage; the benefit of carbon sequestration[a] in soils and vegetation can reduce or avoid carbon emissions into the atmosphere and thus helps to regulate climate. The varied ability of different types of wetlands to store carbon is being widely studied, and some research projects are attempting to develop measures for carbon storage in tidal wetlands and to evaluate factors affecting rates of carbon storage.[7]

**a** Carbon sequestration is the process by which atmospheric carbon dioxide is taken up by trees, grasses, and other plants through photosynthesis and stored as carbon in biomass (trunks, branches, foliage, and roots) and soils. The sink of carbon sequestration in forests and wood products helps to offset sources of carbon dioxide to the atmosphere, such as deforestation, forest fires, and fossil fuel emissions. (U.S. Forest Service, http://www.fs.fed.us/ecosystemservices/carbon.shtml)

**Table 9.1. Wetland ecosystem services**

| Wetland Function | Associated Ecosystem Services |
|---|---|
| Surface water detention | Flood control |
| Streamflow maintenance | Water quality<br>Water supply<br>Recreation (e.g., boating, swimming) |
| Nutrient transformation | Water quality |
| Sediment and other particulate retention | Water quality |
| Coastal storm surge detention | Storm protection |
| Shoreline stabilization | Storm protection |
| Provision of fish/shellfish habitat | Commercial fishing and shellfish harvest<br>Recreational fishing and shellfish harvest |
| Provision of habitat for waterfowl, water birds, and other wildlife | Hunting<br>Wildlife viewing |
| Carbon storage | Climate stability |

Source: Delaware Natural Resources and Environmental Control.[5]

Aquatic ecosystems, including freshwater ponds, lakes, streams, and rivers, provide many resource values for Delaware. Surface water is an important source of drinking water for the majority of the state's residents, and is essential for cooling water for electricity production and other industrial uses. In addition, waterways serve as transportation corridors, supporting the movement of goods in Delaware. The Delaware River is critical to the Port of Wilmington, and the Nanticoke River is an important waterway for transporting goods to and from the Chesapeake Bay.

## Forests

Forest habitats are widely valued for a number of ecosystem services that support water supply and water quality. Forest habitats provide riparian (streamside) buffers for water filtration of surface runoff and thus prevent or reduce nutrient and sediment pollution from reaching waterways. Forests also protect groundwater quality and support groundwater recharge. Approximately one-fourth of Delaware's groundwater recharge areas are forested.[8] In addition, by slowing and regulating the infiltration of precipitation, forests also provide flood and stormwater control. In urban settings, trees and forest buffers can function as "green infrastructure" to help reduce the volume and velocity of stormwater flow and decrease the impact of flooding during storm events.

Forests also provide ecosystem services that benefit air quality and climate regulation. Forested wetlands are estimated to provide substantial carbon storage in both soils and aboveground biomass.[9] In addition, trees filter air through their leaves and can trap particulates, such as dust and ash, and absorb gaseous pollutants. Delaware supports an estimated 7.1 million urban trees that help remove hundreds of tons of nitrous oxide, sulfur dioxide, and ground-level ozone.[10] Trees and other vegetation also lower surface and air temperatures, reducing the heat island effect in urban areas. For example, during peak temperature periods, shaded surfaces may be up to 45˚F cooler than unshaded surfaces, a difference that can help reduce air temperatures by 2 to 9˚F. Even in suburban areas, landscapes with mature trees can be 4 to 6˚F cooler than suburbs without trees.[11] These climate regulation services can improve public health and reduce energy costs. In New Castle County, urban trees provide an estimated annual savings of more than $400,000 in residential building energy costs.[12]

## Beaches and Dunes

The beaches and dunes along Delaware's bay and ocean shoreline function as the first line of defense against storm waves and tides. Wide beaches and healthy dunes serve as "shock absorbers" to distribute wave energy from coastal storms. As wave energy is expended by the movement and redistribution of sand along the shoreline, the impacts to coastal structures, such as homes, businesses, and roads, is greatly reduced. Large, vegetated dunes also serve as protection from wind and can reduce the impact of coastal flooding by buffering storm surge and storing water from heavy precipitation. Beaches and dunes provide value as buffers that protect buildings and infrastructure from storm and wave damage. On a larger scale, beaches and dunes that separate the Atlantic Ocean from the Inland Bays help protect inland tidal wetlands and aquatic ecosystems.

## Economic Benefits of Natural Infrastructure

The benefits of natural infrastructure and the ecosystem services that they provide to human communities can be measured directly and indirectly. Studies of the economic value of ecosystem services have estimated the benefits provided by various habitat types. For example, Delaware's beaches draw nearly 5 million visitors each year, and access to public beaches represents a significant economic value to the region and the state.[13] (There are several recent reports on the economic value of Delaware resources; these are referenced in Chapter 1, Introduction, Section 1.2.)

A study of the Delaware Estuary watershed estimated the economic value of goods and services provided by various types of ecosystems, such as water filtration, flood reduction, and carbon storage. This analysis estimates that the value of goods and services derived from freshwater wetlands is more than $13,000 per acre per year. Similarly, the value of goods and services derived from saltwater wetlands is estimated at more than $7,000 per acre per year.[14] A similar study of the economic value of the Chesapeake Bay watershed in Delaware described ecosystem services such as air filtration, water filtration, recycling nutrients, soil conservation, pollination of crops and plants, climate regulation, carbon sequestration, flood and stormwater control, and hydrologic-cycle regulation. This analysis concluded that forests, freshwater wetlands, and farms provide the highest ecosystem values; for example, the value of goods and services derived from forests is estimated at approximately $14,000 per acre per year.[15]

One approach to valuing ecosystem services can be estimating the anticipated costs associated with the loss of those habitats that provide the services. An economic assessment conducted in 2011 of ecosystem services provided by wetlands in Delaware highlighted the value of wetland functions for carbon storage, water purification, flood protection, and wildlife protection. This study evaluated the economic impact of a continued decline in wetlands across the state over a 15-year time frame (2007 to 2022). The study estimated that a 1.2 percent decline in wetlands during that time frame would result in the loss of ecosystem services that would have significant social costs. For example, reduced carbon storage from loss of wetlands would lead to increased carbon emissions in the atmosphere; the social cost of the additional carbon emissions is estimated to be nearly $20 million (over 15 years). The study also evaluated the loss of water purification function provided by wetlands, resulting in increased municipal water treatment costs of more than $9.5 million (over 15 years).[16]

## 9.1.2. Human-Built Infrastructure

Delaware's human-built environment encompasses a wide array of structures that serve many functions for society. A comprehensive survey of the human-built environment is beyond the scope of this Assessment, but could include: homes, businesses, schools, public buildings, industrial facilities, and communication infrastructure. Note that water infrastructure is discussed in Chapter 6, Water Resources, and agricultural infrastructure is described in Chapter 7, Agriculture . This chapter focuses on two major elements of infrastructure – transportation and energy – that are integral to Delaware's economy, public safety, and quality of life.

### Transportation Infrastructure

The Delaware Department of Transportation (DelDOT) maintains the vast majority (89 percent) of the 13,500 lane miles[b] of roads and highways in Delaware.[17] This represents nearly 9,000 miles of roadway measured by center line.[18]

The road transportation network includes interstate highways, expressways, major and minor arterials, and hundreds of miles of local roads. Major state highways include:

- State Route 1, a major north-south route from Interstate 95 near Newark to the Maryland state line in Sussex County. The coastal portion of SR 1 is a major access route to state beach parks and tourist facilities, including the 25-mile scenic coastal highway from Lewes to Fenwick Island.
- State Route 9 is a designated "Coastal Heritage and Scenic Byway" that runs 51 miles from the City of New Castle to south of Dover Air Force Base, mostly along the western shore of the Delaware River and Bay. It includes Reedy Point Bridge, which passes over the Chesapeake and Delaware (C & D) Canal and through communities such as Delaware City and Leipsic. SR 9 supports tourism-related traffic through its mostly rural corridor to many of the state's finest wildlife areas. In addition, truck traffic on SR 9 includes trucks serving the petrochemical complex near Delaware City and munitions trucks diverting around the City of Dover to reach Dover Air Force Base.

**b** Lane miles equal the length of roadway multiplied by the number of lanes; this measure reflects the increased capacity and maintenance needs of multilane roads.

- U.S. Highway 13, also known as the Du Pont Highway, is the longest stretch of highway in the state, running north-south from the Philadelphia Pike to the Maryland state line near Salisbury. The federal highway is a major linkage for towns in all three counties: from Claymont, Wilmington, and Odessa in New Castle County; through Smyrna, Dover, Camden, and Harrington in Kent County; and to Laurel, Seaford, and Delmar in Sussex County.

- Interstate 95, a federal highway, is a major east-west corridor through northern New Castle County. Annual average daily traffic on I-95 on this stretch is estimated at more than 168,000 vehicles. In addition, I-495 carries an annual average daily traffic count of nearly 76,000 vehicles.

The Delaware system of highways and roads includes designated evacuation routes that provide critical linkages during emergencies such as major tropical storms and hurricanes. There is an estimated 1,185 miles of roads serving as evacuation routes in Delaware. Some of these evacuation routes serve small coastal communities that have only one road available for ingress and egress; coastal flooding or other disruptions to the function of these roads can leave coastal residents isolated. Some urban areas are also challenged by flooding during major storm events, affecting connector roads that may cut off access to evacuation routes.

DelDOT maintains 1,576 of the 1,660 bridges in Delaware.[19] The other 84 bridges are the responsibility of the Delaware River and Bay Authority (DRBA), municipalities, railroads, and private owners. Two of the largest state-managed bridges are the Chesapeake & Delaware (C & D) Canal Bridge and the Indian River Inlet Bridge. The C & D Canal Bridge on State Route 1 (also known as the William V. Roth, Jr. Bridge) supports a daily traffic count of more than 70,000 vehicles. The Indian River Inlet Bridge in southern Delaware is a critical component of State Route 1 in Sussex County; the newly reconstructed bridge opened in January 2012. The Delaware Memorial twin suspension bridges carry more than 34 million cars annually between Delaware and New Jersey. The twin spans are managed by the Delaware River and Bay Authority (DRBA), a bistate government agency of the states of New Jersey and Delaware established by interstate compact in 1961.

The DRBA also operates the Cape May-Lewes Ferry between Cape May, New Jersey, and Lewes, Delaware, and the Three Forts Ferry Crossing (passenger ferry between Fort DuPont, Fort Delaware, and Fort Mott, NJ). The Cape May-Lewes Ferry provides passenger and car transport across Delaware Bay. Summer service averages 11 to 17 trips per day; annual ridership in 2010 totaled nearly 845,000 passengers and nearly 300,000 vehicles.[20]

Public transit in Delaware includes statewide bus and paratransit services and regional rail systems. The state's public bus system, DART First State, is managed by the Delaware Transit Corporation, a subsidiary of DelDOT. The agency operates more than 60 fixed bus routes with an annual ridership of more than 9 million (ridership represents the number of passenger trips). DART Paratransit offers door-to-door transit service for disabled riders; regular fixed-route buses are also wheelchair-accessible and equipped with bike racks.

Public transit in Delaware is also served by regional railroad systems, concentrated in northern New Castle County. Passenger rail service is provided by Amtrak, the Southeastern Pennsylvania Transportation Authority (SEPTA), and the Wilmington & Western Railroad.

- Amtrak operates intercity passenger rail service, with up an average of 80 trains daily serving the Wilmington train station and two trains daily serving the Newark Station, providing more than 700,000 passenger trips annually to and from Delaware.

- SEPTA's Wilmington-Newark line provides commuter train service to four Delaware stations, with 35 trains each weekday to Claymont and Wilmington, and 17 trains each weekday to Churchman's Crossing and Newark.

SEPTA service in Delaware is funded by the Delaware Transit Corporation and supports a ridership of more than one million each year.

- The Wilmington & Western Railroad is a historic railroad that offers tourist rail trips in the Red Clay Valley between Greenbank and Hockessin.

Freight railway in Delaware is provided by two large, long-distance railroads – CSX Transportation and Norfolk Southern Railway – and four short-line rail services. Approximately two-thirds of inbound freight consists of coal, nonmetallic minerals, and chemicals; nearly two-thirds of outbound freight consists of nonmetallic minerals, transportation equipment, and chemicals. The railway systems operated by CSX and Norfolk Southern connect regional and national transportation networks with the Port of Wilmington and other parts of the state, including shipping coal to southern Delaware for power generation. Short-line rail service is provided by Delaware Coast Line Railroad in Sussex County; East Penn Railroad with an interchange with CSX Transportation in Elsmere Junction; and Maryland & Delaware Railroad Company with rail service to Townsend, Seaford, and Frankford.

Air transportation is available through several public airports in Wilmington, Dover, and Georgetown. Delaware's public airports provide mainly private, local, and recreational service; most commercial air travelers use the Philadelphia and Baltimore international airports. The DRBA operates several aviation facilities in Delaware: New Castle Airport (Wilmington), Delaware Airpark (Dover), and the Civil Air Terminal at Dover Air Force Base. Sussex County operates the Sussex County Airport.

Dover Air Force Base, in Kent County, is the largest aerial port facility on the East Coast and serves as an important facility for overseas military operations. A joint use agreement between the base and the Department of Transportation allows private aircraft to use the adjacent DAF Civil Air Terminal.

The Port of Wilmington is a full-service deepwater port and marine terminal located at the confluence of the Delaware and Christina Rivers, 65 miles from the mouth of Delaware Bay. The port is owned and operated by the Diamond State Port Corporation, a corporate entity of the State of Delaware. It supports significant economic activity, with approximately 400 vessel calls and shipments of more than four million tons of cargo each year.[21] The port facility covers approximately 216 acres and includes seven deep-water cargo berths, a floating berth, and a petroleum berth along the Christina River. In addition, there are more than 1,000 acres surrounding the port that include transportation, storage, and processing infrastructure to support port activities.[22]

The Port of Wilmington includes the largest dockside cold-storage facility in the United States, with 800,000 square feet of cold storage in six warehouses; this cold-storage capacity makes Wilmington the top port in North America for imports of fresh fruit, bananas, and juice concentrate. An auto and roll-on-roll-off (RoRo) berth is located on the Delaware River; the port is an important auto export facility for shipping U.S. cars abroad. The port includes 33 acres of open space for RoRo containers, steel, lumber, and other bulk cargo, as well as 250,000 square feet of dry warehouse storage. Wilmington is also a major port and distribution center for liquid bulk petroleum products, with more than one million tons of liquid petroleum transported into the port by tanker vessels and barges.[23]

## Energy Infrastructure

An overview of Delaware's energy infrastructure includes a summary of production, transmission, and distribution systems that transfer electricity, natural gas, and oil to homes and businesses throughout the state. Delaware's energy production relies greatly on imported energy fuels, as the state does not produce coal, petroleum, or natural gas. These fossil fuels are transported into Delaware by ship, train, and truck to refineries, industries, and power plants. Delaware uses renewable energy sources with some biomass, solar, and wind facilities, although these represent a small portion of energy usage in the state.

Electricity in Delaware includes both generators (private, independent power producers) and distributors (utilities that manage transmission and delivery infrastructure). Larger electricity generation facilities provide base load (continual power production) and others operate during peak demand periods. (Megawatts, MW, shown below indicate total net summer capacity, according to the Energy Information Administration.) Primary energy sources used in Delaware for electricity production are natural gas and coal. As of October 2013, electricity generators in Delaware include the following:[24]

- Calpine Mid-Atlantic Generation, LLC, with five power plant facilities, including the Hay Road facility (1,130 MW) and Edge Moor facility (723 MW), both of which use natural gas. Calpine owns three peaking plants that use petroleum: Delaware City (23 MW), Christiana Energy Center (53 MW) and West Energy Center (20 MW).

- NRG Energy operates the Indian River Generating Station (795 MW), which uses coal. (This plant has ceased operation of two of its four units and another unit is scheduled to shut down in 2013.) NRG also operates the NRG Energy Center in Dover (100 MW). The power plant was converted from the last coal-fired generating unit to combined cycle natural gas in 2013.

- NAES Corporation operates natural gas–fired power plants in Dover, including the McKee Run (136 MW) and Van Sant Station (39 MW) facilities.

- Delaware Municipal Electric Corporation owns the natural gas–fired Sam Beasley Generation Station in Smyrna (98 MW).

- AMERESCO operates two biomass-fueled facilities using landfill gas in Georgetown (5 MW) and Sandtown (3 MW).

- SunPower Corporation and White Oak Solar Energy operate the Dover Sun Park (10 MW), a solar power facility that opened in 2011.

- PSEG Milford Solar Farm (15 MW), a new solar power facility, opened in 2013.

- University of Delaware operates a wind turbine (First State Marine Wind) (2 MW) at its Hugh R. Sharp Campus in Lewes; the turbine began operation in 2010.

- Delmarva Power operates the Bloom Energy Facility (30 MW), a fuel cell producer of electricity, in Newark.

Distribution of electricity to homes and businesses is provided by Delmarva Power, the Delaware Electric Cooperative, and the Delaware Municipal Electric Corporation, which represents municipal electric utilities, including Clayton, Dover, Lewes, Middletown, Milford, Newark, Seaford, Smyrna, and the City of New Castle. Transmission and distribution of electricity requires the operation and maintenance of extensive infrastructure to transfer transmission-level voltages from substations through hundreds of miles of lower-voltage electric lines, transformers, and electric wires to connect to end users. More than one-fourth of Delaware households use electricity as their primary energy source for home heating.[25]

Natural gas is used widely throughout Delaware and is distributed through two regulated utilities: Delmarva Power serves New Castle County and Chesapeake Utilities Corporation serves Kent, Sussex, and southern New Castle Counties. Two interstate pipeline systems supply natural gas through more than 300 miles of underground pipes from Pennsylvania and Maryland to Delaware. Industry and electricity generators are the largest consumers of natural gas in the state; in addition, more than one-third of Delaware households use natural gas for home heating.

Petroleum products are processed in Delaware's one refinery facility, the Delaware City Refinery, located in New Castle County. Operated by the PBF Holding Company, LLC, and the Delaware City Refining Company, the plant refines crude oil into automobile gasoline, home heating oil, and other petroleum products. Crude oil supplies are transported to Delaware through the Port of

Wilmington. Approximately one-fifth of Delaware households use heating oil as their primary energy source for home heating.

## 9.2. Climate Change Impacts to Infrastructure in the United States

Studies on the potential impacts of climate change to infrastructure often focus on the built environment, particularly with regard to transportation, energy, and water systems. The discussion of impacts to infrastructure is not limited to the structures themselves, but also to the services those structures provide. These services are essential to the health, safety, and economic productivity of human communities. For cross-reference, please note that climate change impacts to water infrastructure are described in Chapter 6, Water Resources . Also, impacts to natural systems that provide important ecosystem functions, such as water resources, wetlands, and forests, are described further in Chapter 8, Ecosystems and Wildlife.

### 9.2.1. Interdependent Systems

Infrastructure systems are highly interactive and interdependent. For example, water systems require energy for pumping, distribution, and water treatment. Transportation systems are necessary for energy production by moving raw materials to refineries and power plants, and for transporting refined energy products to end users. Infrastructure sectors, such as transportation and energy, are often planned for and managed individually. Yet in response to significant changes, such as extreme weather events, infrastructure systems are closely linked and interdependent. Disruptions that affect one infrastructure system can have a cascading effect on other systems, leading to increased vulnerability and, in some cases, unexpected impacts. For example, direct damage from Hurricane Irene in 2011 to the City of Baltimore included flooding and wind-damaged trees, but also contributed to power outages that led to sewage spills that continued for days after the storm ended. A widely cited example of the cascading effect of an extreme weather event is Hurricane Katrina in 2005. The indirect and long-lasting "ripple" effects of this disaster included a reduction in oil production, leading to a nationwide spike in gasoline prices and disruption of navigation on the Mississippi River that impeded grain shipments from reaching key ports in the Gulf vital for export.[26]

The wide-ranging, related impacts of extreme weather events reach individuals and businesses in many ways. Transportation impacts can prevent employees from getting to work, and thus cause them to lose wages. Power outages may close businesses for days, or cut off supplies and materials to keep businesses from operating at full capacity. For example, shrimp harvest in the Gulf of Mexico supplies stores and restaurants throughout the country. When severe weather disrupts the shrimp fishery or the transportation network that moves fresh shrimp to markets across the country, a "ripple effect" occurs throughout a larger region. Although many economic assessments have been made of natural disasters in the United States, it is recognized that the full scope of costs exceeds the direct damage to infrastructure.

Regional and local impacts to infrastructure vary, depending on the geographic patterns of land use and population density. For example, climate change impacts to rural areas, such as flooding of access roads, may affect relatively few people and businesses, but those who are affected may literally be cut off from emergency services or supplies for extended periods of time. Similarly, many coastal communities may be unable to access evacuation routes in extreme events. Urban areas are critical hubs for infrastructure systems and services due to their large populations and concentrations of economic and social activity. Urban infrastructure is highly integrated and provides essential functions to support people and businesses, both within the city and those who are passing through. Many U.S. cities are located in vulnerable locations on coasts or rivers. As a result, disruptions to urban infrastructure have significant impacts to the safety, mobility, and productivity of thousands of people.

## 9.2.2. Transportation Infrastructure

Transportation infrastructure includes human-built structures related to land transport (highways, roads, bridges, tunnels, and railroads), air transport (airports, runways, and related ground facilities), and marine transportation (ports, harbors, terminals, and docking infrastructure). Marine transport also relies on the natural infrastructure of rivers and waterways that provide the physical pathways for shipping and barge passage. Climate change impacts can affect transportation operations as well as infrastructure, as summarized in **Table 9.2** and discussed briefly below.

Transportation infrastructure can be affected directly and indirectly by changes in temperature, precipitation, extreme weather events, and sea level rise. All modes of transportation can be sensitive to weather events, but are most vulnerable to changes in extreme conditions.[28] Damage or disruption to transportation systems due to climate change impacts can affect public safety and economic activity across a wide area. For example, an extreme rain event in 1996 caused extensive flooding in Chicago and its surrounding suburbs, preventing commuters from reaching the city for up to 3 days. More than 300 freight trains were delayed or re-routed from Chicago, which serves as a major U.S. rail hub for freight transportation.[29]

The location of transportation infrastructure is also a factor in the degree of vulnerability to climate change impacts. Coastal areas are already subject to the effects of hurricanes and coastal storms; these impacts, along with sea level rise, are projected to increase over the next century. In addition, coastal regions are under significant development pressure. Nationwide, more than half of the population resides within a coastal watershed, and population density in coastal counties is much higher than in inland counties. Coastal areas are also important gateways for economic activity, particularly with major ports that connect freight shipping to rail and trucking networks.[30]

### Temperature Impacts

Increasing temperatures and extended periods of extreme heat have direct effects on paved surfaces, including highways and airport runways. Extended periods of heat over 90°F can soften asphalt and result in buckling of roadways and rutting from vehicle traffic. Sustained high temperatures can also cause thermal expansion of road and bridge supports, affecting bridge operations. Higher temperatures will also increase the need for refrigeration in trucking and shipping, thus raising costs and energy demand. High heat events can also delay transportation construction and maintenance projects if work stoppages are required to avoid health risks to workers.

**Table 9.2. Potential climate change impacts to transportation in the United States**

| *Climate Change Impact* | *Potential Impacts to Operations* | *Potential Impacts to Infrastructure* |
|---|---|---|
| Increased temperatures and increase in extreme heat events | • Airports: affects aircraft lift, reduced load capacity<br>• Roads: limits on construction activity due to health and safety concerns | • Roads and air runways: thermal expansion of paved surfaces causing buckling and rutting<br>• Bridges: thermal expansion of bridge joints and structure<br>• Railroads: track deformities |
| Changes in precipitation and extreme weather events | • Roads: traffic disruptions and delays<br>• Roads: increasing emergency evacuations, flooding of evacuation routes<br>• Roads/railroads: damage or clean-up from storm debris<br>• Airports: delays and cancellations | • Roads: damage to roads and culverts from flooding<br>• Bridges: damage to support structures, threat to deck stability<br>• Railroad: damage to track and support structures<br>• Ports and harbors: impacts from wave damage |
| Sea level rise | • Roads: flooding of access roads and evacuation routes<br>• Waterways: higher water levels may affect bridge clearance<br>• Ports: changes in navigation channels | • Roads/railroads: increased coastal flooding, damage to support structures<br>• Ports: decks and equipment may require retrofits to adapt to higher water levels<br>• Harbors: impairments to inland waterways |

Source: Adapted from National Research Council (2008).[27]

Railroad infrastructure is also affected by extreme heat. Air temperatures above 100˚F can cause deformities in rail tracks, such as buckling, kinks, and misalignments, that can result in train derailments. Orientation of tracks may increase vulnerability to high heat, as the sides of east-west rail tracks heat at greater rates than north-south tracks. Heat conditions may also affect rail operations, requiring lower speeds, shorter trains, or lighter loads to reduce track stress.[31]

Increasing heat can affect air transportation facilities and operations. Runway pavements may be affected as are roads and highways, with buckling and rutting of softened surfaces. Higher temperatures can alter operational capacity, because heat makes air less dense and reduces aircraft lift, particularly at high altitudes. As a result, planes need longer runways and/or reduced weight to take off.[32]

Warmer winter temperatures may result in some benefits for transportation, such as reduced snow and ice removal costs for highways and airports; reduced environmental impacts from the use of salt or chemicals on roads and bridges; fewer impacts to ports and harbors related to ice accumulation on vessels and docks; and reduced need for de-icing planes.[33]

## Precipitation and Storm Impacts

Increasing frequency and intensity of rain events is likely to result in more flooding, which will affect roads, airport runways, and other transportation facilities in low-lying areas. Land transportation infrastructure often includes large areas of impervious, paved surfaces, which magnify the effects of storm runoff. The quantity and velocity of runoff in rain events can damage or accelerate the deterioration of roads, bridges, and railroad tracks. Increased flooding can also lead to increased subsidence, erosion of embankments, and scouring of bridge supports.[34]

Extreme weather events and stronger tropical storms present several hazards to transportation infrastructure in addition to heavy rainfall. High winds can cause extensive damage and leave debris on roads and rail lines. Wind-driven storm surge also has huge impacts on coastal infrastructure. In ports and harbors, storm surge and wave action can damage or destroy cranes, docks, and storage facilities. Freight operations can be significantly affected when transportation connections are interrupted, such as barge transport on water, and freight transfers to rail and trucking systems.[35] Air transport is likely to be delayed, cancelled, or re-routed, causing interruptions to passenger and freight movement.

Storms and flooding may also lead to more frequent and extensive emergency evacuations, especially in coastal areas. This can pose a significant threat to public safety if the evacuation routes are also affected by storm damage or flooding. Evacuations associated with hurricanes can be costly, too; losses in tourism, commerce, and general productivity can exceed $1 million per mile of coastline, according to one study. Nationally, floods and hurricanes are among the most frequent incidents prompting evacuations.[36]

## Sea Level Rise Impacts

Sea level rise is likely to present significant long-term impacts to coastal transportation infrastructure. Inundation and tidal flooding of even a small portion of the coastline can lead to disruptions in transportation networks. For example, a port facility may be functional and accessible from the water, but if access roads or railways are affected, the port may be forced to reduce operations or shut down.[37] As sea level rises, dock levels may require retrofitting to function properly with dock cranes and other equipment.[38]

Sea level rise may have impacts to a range of transportation operations. Higher water levels could decrease clearance under bridges, affecting marine transport in harbor entrances and canals.[39] Changes in water levels and river flows may alter navigation channels due to changes in sedimentation rates and shifting locations of shoals. Transportation along inland waterways may also be affected by sea level rise, particularly where barrier islands are modified by increased erosion.

## 9.2.3. Energy Infrastructure

Across the United States, energy infrastructure includes a range of systems and facilities for producing and distributing energy in various forms:

- Oil and gas production involves structures for exploration and extraction (drilling equipment), processing (refinery facilities), storage (tanks), and distribution (pipelines).

- Thermal electric production includes power generation facilities that use various energy sources –coal, natural gas, nuclear energy, and petroleum – and infrastructure for electricity distribution networks (power lines, substations, and transformers).

- Renewable energy production includes hydroelectric facilities (dams, turbines, and generators), photovoltaic structures, wind turbines, geothermal energy, and distribution infrastructure to connect them to the electrical grid.

- Bioenergy sources require several stages for production: growing and harvesting feedstock (e.g., corn, woody debris); chemical processing facilities to produce ethanol or biodiesel; and infrastructure to integrate biofuels with other energy sources, such as mixing ethanol with gasoline, or using biomass for electricity generation.[40]

Climate change impacts can affect energy operations and infrastructure, as summarized in **Table 9.3** and discussed below.

Energy production and distribution can be affected directly and indirectly by changes in temperature, precipitation, extreme weather events, and sea level rise. The location of energy facilities is an important factor in the degree of vulnerability to climate change impacts. Oil and gas operations in Alaska, for example, are subject to impacts from changes in the permafrost layer supporting structures, roads, and pipelines. Coastal and off-shore oil and gas development are vulnerable to sea level rise, increasing storm intensity, and changes in ocean acidity related to increased levels of atmospheric carbon dioxide ($CO_2$).[41]

Climate change impacts on water availability will have significant effects on energy production. Power plants require large amounts of water and are sensitive to fluctuations in water supply. Regional water shortages, due to increasing temperatures and more frequent droughts, are likely to affect electricity production in many regions. In some areas, changes in seasonal water availability will alter the timing and capacity of hydroelectric power generation; in other areas,

**Table 9.3. Potential climate change impacts to energy systems in the United States**

| *Climate Change Impact* | *Potential Impacts to Operations (Production and Refining)* | *Potential Impacts to Infrastructure (Transport, Terminals, and Pipelines)* |
|---|---|---|
| Increased temperatures and increase in extreme heat events | • Reduced efficiency of thermal electricity production<br>• Regional impacts to energy production due to permafrost melt, shorter winter season (Arctic)<br>• Increased evaporation in surface reservoirs, affecting water availability for hydroelectric energy production | • Damage or disruption to energy distribution systems (e.g., pipelines, electric lines)<br>• Damage to pipelines and structures from melting permafrost (Arctic)<br>• Changes to bioenergy feedstock production |
| Changes in precipitation and extreme weather events | • Disruptions in energy production and distribution from storm events<br>• Reductions in power output from decreased water availability<br>• Impacts to hydroelectric energy production from changes in amount or timing of precipitation<br>• Coastal and offshore oil production disruption and damage to drilling infrastructure | • Damage to infrastructure (e.g., pipelines, electric lines)<br>• Flood damage to roads and rails, disrupting transport of coal to power plants |
| Sea level rise | • Disruption to distribution of energy due to sea level inundation and coastal flooding | • Damage to infrastructure from inundation or coastal flooding of power plants, refineries, and pipelines |

changes in water levels and temperatures will affect the efficiency of power plant cooling.[42]

Climate changes will also affect energy demands. Rising temperatures will increase electricity demand for cooling in most regions during peak periods (defined as a period of sustained demand for electricity at higher than average levels). For example, U.S. studies estimate that for every 1.8˚F increase in temperature, demand for cooling energy increases 5 to 20 percent. At the same time, demands for winter heating will likely decrease, which can affect demand for natural gas and fuel oil, with less effect on electricity use. Increasing energy demands are compounded by existing trends, such as demographic shifts of the U.S. population to the south (with higher air conditioning demand) and an increase in square footage per person, requiring additional space heating and cooling.[43]

## Temperature Impacts

Thermal power plants will be affected by increasing air and water temperatures, as higher temperatures reduce the efficiency of cooling and can lead to lower power outputs. High heat events can also affect energy distribution systems, such as the failure of electric power transformers during heat waves, causing disruption of electricity supply.[44] Warmer water temperatures also have direct impacts on energy production. For example, regulatory constraints may limit the intake of cooling water from rivers, or may restrict the amount of water discharge from power plant cooling systems.[45]

Regional impacts will be greater in some energy production areas already experiencing changing conditions, such as the oil and gas industries on Alaska's North Slope. Temperatures in higher latitudes have been rising at a faster rate than in mid-latitudes, affecting the Arctic region with shorter winter seasons and thawing of permafrost. Both of these effects cause structural and operational problems for pipelines, airfields, and coastal structures associated with energy production.[46]

Increasing temperatures and rising levels of atmospheric $CO_2$ will affect bioenergy production, with regionally variable impacts to feedstock crops. For example, current U.S. production of ethanol depends largely on corn, which is vulnerable to high heat and drought conditions in the Midwest. However, future bioenergy fuels may rely more on a range of woody materials, which could benefit from changing climate conditions.[47] In addition, higher temperatures will likely lead to increased demand for irrigation, which affects water supply as well as energy consumption.

Higher temperatures are likely to affect hydroelectric energy, particularly in the western United States. With rising temperatures and more frequent droughts, evaporation of water from surface reservoirs will reduce water availability for hydroelectric power.

## Precipitation and Storm Impacts

Extreme weather events have direct and indirect impacts on energy infrastructure. Hurricanes, in particular, have had devastating effects on U.S. oil and gas production in recent years. In 2005, direct losses to the energy industry from hurricanes were estimated at $15 billion. Hurricanes Katrina and Rita closed many oil and gas pipelines and stalled nearly 20 percent of U.S. refinery production.[48]

Changes in precipitation that lead to reduced water availability will have negative impacts for all types of energy production (with the possible exception of solar and wind energy). As described above, large quantities of water are necessary for thermoelectric power production, oil and gas development, and generation of hydroelectric power. In areas with declining water supplies, existing power plants may see reduced capacity and siting of new facilities may be limited.[49]

Increased frequency and intensity of heavy precipitation will result in flooding that can damage energy infrastructure, such as pipelines and power lines, resulting in power outages. In addition, storm events and flooding can disrupt transportation of fuels for energy production. For example, nearly two-thirds of the coal used in U.S.

power plants is transported by rail; where railroad lines follow rivers, as in the Appalachian region, flooding can wash out rail beds.

Hydroelectric power is affected when the amount or timing of precipitation and runoff is altered. In regions with declining precipitation and lower river flows, hydroelectric production will likely be reduced. In addition, a shift toward more precipitation falling as rain instead of snow in some regions will reduce the amount of river flow in late spring and summer, when spring thaw would normally sustain or increase river flows.[50]

### Sea Level Rise Impacts

Energy production and distribution facilities are at risk for the direct and indirect effects of sea level rise. Power plants, refineries, and oil and gas pipelines may suffer equipment damage from saltwater inundation or coastal flooding from storm surge. The potential costs of repairing, retrofitting, or relocating coastal energy facilities may have a significant impact on energy prices.[51] In addition, distribution of energy may be disrupted by impacts to roads and railways due to sea level inundation and coastal flooding.

## 9.3. External Stressors

Climate change is one of many stressors that can affect natural and human-built infrastructure. Natural habitats are already challenged by a number of stressors, including habitat loss, altered hydrology, and other impacts that may be magnified or exacerbated by climate change. Human-built infrastructure is also subject to existing conditions and trends that affect the function and capacity of critical systems that provide transportation, energy, water, and communication services.

*Population growth* drives land development, which, in turn, requires infrastructure to support the growing population. Future development is a fundamental component of planning for long-range transportation and energy infrastructure needs. The increasing demand for transportation and energy services involves both a need for greater overall capacity and also greater geographic extent. Infrastructure must expand to areas of new growth while at the same time meeting the needs of densely populated urban areas. Delaware's population is projected to exceed one million by 2030, a 35 percent increase from 2000.[52]

Population growth creates additional demand on the transportation system to support both passenger and freight travel. Limitations of federal and state funding for road construction and repair will challenge transportation managers' ability to maintain existing roads while also adding new capacity. Congestion on heavily used roads and highways is an existing problem that is likely to worsen as population grows. Congestion and traffic demands are also affected by driving behavior, as well as the total number of drivers. When people drive more, the per capita measure of vehicle miles traveled (VMT) increases and higher emissions are generated. The United States has a significantly higher average VMT than does Europe or Canada, although this has declined since the economic downturn in 2007.[53] In Delaware, average VMT more than doubled between 1980 and 2005. However, the state's average VMT has declined in recent years, in spite of the increasing number of cars registered in the state.[54]

Population growth also drives increasing demand for energy in homes, businesses, and industries. Per capita energy consumption in the United States has been declining slowly over the past 25 years.[55] However, while there are reductions in energy use in some sectors due to technological efficiencies, other sectors may experience higher energy demands.

*Aging infrastructure* can add to costs and challenges in maintaining reliable, safe infrastructure. In many eastern U.S. cities, urban roads and bridges are subject to a greater volume of traffic than the 20th century demand for which they were designed. Some structures may be reaching the end of their functional lifespan and in need of replacement; other structures have been modified or expanded to accommodate increasing use. Most bridges are built to last roughly 50 years; of the 600,000 bridges in the United States today, the average age is 43 years. A 2008 survey of

U.S. bridges estimated that one in three urban bridges may be considered structurally deficient or functionally obsolete.[56]

Across the United States, infrastructure for energy transmission and distribution has not kept pace with new generation facilities. The American Society of Civil Engineers estimates that electricity demand has increased by approximately 25 percent since 1990, while construction of new transmission facilities has declined or been stagnant. Their report on U.S. infrastructure also identifies operational problems with maintaining voltage levels, as well as transmission constraints or "bottlenecks," that can lead to increasing costs and/or declining reliability in the energy system.[57]

*Land use changes* that accompany population growth have direct and indirect effects on infrastructure. Development of homes, businesses, and roads increases impervious surface area, such as buildings, concrete, and pavement. Impervious surfaces alter natural hydrology, resulting in higher volumes of stormwater runoff, increased erosion, and more frequent flooding. These impacts can increase the risk of damage or impairment of infrastructure components, such as bridge supports and poles for electric lines, and increase maintenance requirements and costs.

Land use changes have both environmental and societal effects on infrastructure. Shifts in growth patterns have consequences for planning and expanding services to new areas. For example, development spreading out to rural regions stresses the physical condition and capacity of local roads; in addition, safety problems can result when increased car traffic is sharing roadways with farming equipment.

## 9.4. Potential Impacts of Climate Change to Delaware's Infrastructure

The potential vulnerabilities of Delaware's infrastructure to climate change impacts can impair or disrupt the functions that help protect public health and safety, support economic activity, and enhance quality of life in our communities. As discussed above, infrastructure systems are highly interdependent; impacts to one component can affect other systems either directly or indirectly. In addition, natural environments provide ecosystem services that may be integrated with human-built infrastructure; therefore, impacts to ecosystem conditions can also affect infrastructure functions. The following summary describes some of the vulnerabilities that may affect all types of natural and human-built infrastructure in Delaware.

### 9.4.1. Climate Projections for Delaware

Delaware is likely to experience projected increases in annual and seasonal temperatures, high temperatures, and heavy precipitation, all of which show greater increases under higher as compared to lower scenarios and by end of century as compared to more near-term projections. The ***lower scenario*** represents a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide 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.

#### Annual and Seasonal Temperatures

- Temperature increases of 1.5 to 2.5°F are projected for 2020-2039 across all scenarios. By mid-century or 2040-2059, increases under lower scenarios range from 2.5 to 4°F and around 4.5°F for higher scenarios.

- Relatively greater changes are projected for spring and summer as compared to winter and fall. In winter and summer, projected increases in maximum and minimum temperature are similar.

#### Extreme Temperatures

- The number of very cold days (minimum temperature below 20°F) is projected to drop from 20 to 15 by 2020-2039, to just over 10 days per year by 2040-2059, and to a minimum of 10 days per year under lower scenarios and only 3 to 4 days per year under higher scenarios by 2080-2099.

- The number of hot days (maximum temperature over 95°F) is projected to increase from the current average of less than 5 days per year to as many as 15 to 30 days by mid-century.

- Energy demand for cooling is projected to increase by up to 130 percent by end of century, while energy demand for heating is projected to decrease by up to 40 percent by end of century (**Figure 9.1**).

### Precipitation Changes

- Precipitation is projected to increase, particularly in winter (**Figure 9.2**).

- By end of century, nearly every model simulation shows projected increases in the frequency of heavy precipitation events, indicating an increase in precipitation intensity (**Figure 9.2**).

## 9.4.2. Vulnerabilities to Impacts

Infrastructure and population density are not distributed equally across the state. Northern Delaware is a highly urbanized, densely populated region with a concentration of transportation, energy, and industrial facilities, including the Port of Wilmington, the I-95 corridor, and the majority of Delaware's petrochemical industry sites. These highly networked infrastructure systems can, on the one hand, provide some redundancy so that when one component fails, other components in the system can provide alternative or back-up function. On the other hand, when extreme events occur, a cascading effect can amplify the impacts to any part of the local infrastructure systems. In addition, Delaware's major infrastructure systems are part of larger, regional networks. For example, many of the state's industrial facilities depend on electrical distribution from neighboring states.

Central and southern Delaware represent a different landscape pattern, with lower-density communities connected by a north-south corridor of transportation and energy infrastructure. This geographic pattern presents a structure of a "main line" with "trunk lines" connecting to communities on the coast and to the rural communities in the western part of the state. As a result, services to the east or west of this north-south corridor can be affected by bottlenecks or disruptions in the system, so that homes and businesses farthest from the main line can be isolated. This vulnerability is evident in coastal communities that rely on a single road for ingress and egress.

Delaware's Atlantic coast and Inland Bays region supports a number of large communities that experience huge increases in summer population. Both residents and visitors in coastal regions are vulnerable to increased exposure to coastal storms and coastal flooding. In response to Hurricane Irene in 2011 and Hurricane Sandy in 2012, mandatory evacuations were required for all coastal communities in Delaware. This affected hundreds of residents and visitors in Sussex County within three-quarters of a mile of major waterways in Rehoboth Bay, Indian River Bay, Little Assawoman Bay, and Pepper Creek. In Kent County the mandatory evacuation affected areas within three-quarter of a mile of Delaware Bay, including Woodland Beach, Pickering Beach, Kitts Hummock, Bowers Beach, South Bowers Beach, and Big Stone Beach. New Castle County residents were also required to evacuate portions of Wilmington, New Castle, Delaware City, and areas south of the C & D Canal east of Route 9 including Port Penn, Augustine Beach, and Bayview Beach. Although emergency evacuations of this magnitude are uncommon, the dependence on infrastructure illustrates the potential vulnerability to coastal residents from increasing storms and flooding events.

Impacts from climate change are experienced differently by different populations of Delaware residents. Age, income, and transit-dependence are several factors that can increase vulnerability to climate change impacts that affect infrastructure. Older adults may have limited mobility or physical disabilities that make responding to extreme weather events more challenging. Senior citizens in retirement and coastal communities can be vulnerable in emergency situations, such

## Road Culverts – Upgrading Aging Infrastructure

Culverts are widely used to direct water away from roads, either for stream crossings or runoff management, to help reduce roadway flooding and help preserve the road bed from erosion. In many states with aging infrastructure, road culverts were not designed to handle the increasing volume of streamflows and surface runoff that can occur in extreme weather events. Climate change impacts, combined with land use changes that alter hydrology patterns, may increase the vulnerability of road drainage structures to damage. Failing culverts can affect the condition and function of roads, increase repair and maintenance costs, and add to water quality problems in adjacent waterways.

Newer designs and materials for culverts can improve their capacity and functional lifespan. For example, in some places galvanized steel pipe culverts were placed in locations where water is increasingly brackish as a result of sea level rise or exposure to storm surge. Replacement of older materials with high-density polyethylene pipes can reduce deterioration and maintenance needs. Replacing culverts with increased size and flow capacity can improve performance in extreme rain events and add long-term capacity for a changing climate.

as evacuations in response to flooding or coastal storms. Similarly, people who depend on public transit – those who are without cars or unable to drive – are often more vulnerable under conditions when transportation systems are disrupted. Low-income residents are also affected greatly by impacts to transportation and energy systems. Lack of access to work can have disproportionate impacts on low-wage workers. Low-income neighborhoods are also more likely to suffer from additional stressors, such as poor condition of aging infrastructure. In addition, communities with a high proportion of manufactured homes can be vulnerable to greater impacts from wind damage in severe storms.

### 9.4.3. Structural and Operational Impacts – Extreme Weather Events Impacts to Human-Built Infrastructure

Climate change impacts to the structural and operational use of infrastructure are particularly vulnerable to increasing frequency and/or intensity of extreme weather events. Back-to-back storms or cascading events can lead to the shutdown of public transit and power outages, dramatically increasing the vulnerability of residents and businesses dependent on infrastructure services. Although infrastructure managers typically have continuity plans[c] and emergency management procedures, these response strategies may need to be expanded or enhanced to prepare for greater variability in extreme weather events.

Climate impacts may be direct, such as physical damage to structures as a result of extreme weather events or sea level rise. Climate impacts may also have significant effects on the operability of infrastructure; for example, increasing salinity as a result of sea level rise may affect water use in power generation or industrial systems. Direct impacts can have significant costs for repair or replacement, or may require changes in technical design or materials. Impacts to operations that result in disruption of services can have wide-ranging and long-term impacts on economic productivity. In addition, both short-term and long-term impacts can affect public safety and economic productivity. Planning and operational decision making are essential to managing repair, recovery, and restoration of infrastructure services.

When infrastructure is damaged or impaired by weather-related impacts, the immediate focus is on the need to restore services with repairs to make the infrastructure operable. Taking a long-term approach to damage recovery can improve the resilience of infrastructure to future impacts.

[c] Continuity plans are a planning tool to ensure the continued performance of essential functions under a broad range of circumstances. These are used both by government agencies and businesses, and may be developed as part of disaster recovery plans.

For example, improving resilience could include reinforcement or replacement of structures, changes to the system location or design, or additional construction to add redundancy to the system. However, upgrading and improving culverts to meet higher capacity demands can be complicated by regulatory constraints. For example, federal emergency funds for road repairs in response to washouts may be limited to in-kind replacement. These restrictions may be changing as the Federal Highway Administration, Federal Emergency Management Agency, and others are adopting practices to plan for potential climate change impacts.[58]

Delaware often receives wintry-mix storm precipitation. Winter rain falling on snow can result in heavy, slushy snowpack, which sticks to roads and refreezes at night. These conditions can cause ice dams to plug drainage systems, leading to roadway flooding and overtopping of bridges and culverts. In addition, this heavy snow mix can be difficult to remove from roads with conventional snow plows, resulting in icy, bumpy, and dangerous roadways.[59]

### Impacts to Natural Infrastructure

Natural environments that provide valuable ecosystem services are also vulnerable to impacts from extreme weather events and increasing erosion, which may be exacerbated by sea level rise. Tidal wetlands in all coastal regions of Delaware are already declining where shoreline erosion rates exceed sediment accretion rates. Studies have indicated that Delaware's coastal wetlands have, historically, moved inland as sea level rises.[60] However, with rising sea levels and potentially greater intensity of coastal storms, further losses of wetland habitat may impair their ability to buffer inland areas, store floodwater, and act as a sink for nutrients and pollutants.

Beaches and dunes are also exposed to sea level rise and the associated impacts of coastal erosion and flooding. Barrier beaches in Sussex County are particularly vulnerable to loss of beach habitat, as coastal development blocks the landward migration of the beach and dune system. As a result, beaches and dunes decrease in width and height, thus reducing their function in providing a physical buffer that protects buildings and infrastructure on the shoreline and inland bay side of barrier beaches.

### Maintaining Coastal Buffers – Beach Nourishment

Adding sand to an eroding beach is a costly but effective method to maintain a safeguard between the ocean waves and shoreline structures, reducing storm damage and enhancing recreation opportunities. Increasing the beach width acts as a buffer to absorb wave energy from storms.

In Delaware, beach nourishment has been used as a management strategy for maintaining public beaches along the Atlantic coast, including in Rehoboth, Dewey, Bethany, South Bethany, and Fenwick Island since 1961. Beach nourishment projects typically involve pumping sand onto a beach directly by dredge pump from an offshore sand source (borrow site). Beach fill projects, where sand is hauled in by truck, have also been used in Delaware Bay beach communities, including Bowers Beach, South Bowers Beach, and Kitts Hummock.

Although there is increasing demand for beach nourishment projects to maintain public beaches and support the coastal tourism industry, there are also residential communities that look for beach replenishment strategies to protect homes from storm and flooding damage. Delaware's state policy is to consider economic costs and benefits in determining where, or whether, to pursue beach nourishment projects. A recent economic study focused on seven Delaware Bay beach communities evaluated the estimated costs and benefits of beach nourishment against "no action" and "retreat" alternatives. These beaches are vulnerable to impacts from increasing frequency and intensity of coastal storms as well as current erosion and flooding problems. Incorporating projected sea level rise will add a new dimension to short-term and long-term planning.

## 9.4.4. Roads and Dams – Increased Precipitation and Flooding

Because of Delaware's low-lying topography and location within three major watersheds, flooding is a frequent occurrence in many parts of the state. Changes in precipitation patterns may lead to a greater extent and/or frequency of inland

## Critical Transportation Infrastructure – Delaware's Early Warning System for Road Conditions

The Delaware Department of Transportation (DelDOT) manages a wide range of technologies for monitoring traffic flow, road and bridge conditions, and potential hazards that may require rapid response to keep transportation moving safely and efficiently. Transportation networks are one of the "critical infrastructure" systems that are in continuous operation, and damage or disruption to critical infrastructure can have significant impacts to public safety and economic activity.

Improving data collection and analysis can advance Delaware's ability to prepare for and respond to changing climate and weather extremes. Currently, DelDOT operates a system of 17 weather monitoring stations using sensors embedded in pavement or on towers or poles to monitor road surface and weather conditions along critical sections of the state's transportation system. The system collects real-time weather data, including air temperature, humidity, precipitation, wind, and visibility (both current conditions and 24-hour averages), and also records road surface conditions and temperatures.

Delaware transportation managers are evaluating ways to expand the existing monitoring system by adding data sensors that measure water levels and flows. By improving the data collection and analysis of both surface and hydrologic conditions, planners will be able to make better predictions of flooding hazards, provide early warning information to local emergency managers, and prepare for adjustments to traffic flows, such as detours and evacuation routes.

The combined data collection, analysis, and modeling are tools for a "decision support system" that can evaluate conditions, forecast impacts, and communicate risks to community leaders and emergency managers. In addition to contributing to emergency preparedness, this kind of decision-making process can help planners evaluate options for recovery and repair of damaged infrastructure after a severe weather event.

flooding and increase the potential vulnerability of infrastructure in flood-prone areas. With potential increases in precipitation falling in more intense storm events, the higher volume and velocity of surface runoff and streamflow can result in rapid erosion and scouring. This can erode roadway banks and pavements, undermine structural supports, and result in weakened or washed-out roads, rail, bridges, and culverts and other drainage structures.

Of the 48 regulated dams in Delaware, 42 are owned by the State of Delaware and managed by the state's Department of Transportation or the Department of Natural Resources and Environmental Control. Many of these dams are located adjacent to or integrated into state-managed roads and bridges. In extreme rain events, dams may be vulnerable to damage or failure. Thus, roads or bridges located on top, next to, or downstream from these structures are at risk of flooding or washout.

A potential shift toward more winter precipitation falling as rain instead of snow may alter the amount of snowpack in upstream portions of the Piedmont Basin. This may result in changes in the timing of spring thaw and shifts in seasonal flows and water levels that could increase flooding, particularly in urban areas of northern Delaware, where a high percentage of impervious surfaces already contributes to severe stormwater runoff problems.

Delaware already faces challenges from flooding and drainage problems, both in coastal areas and inland floodplains. Climate change impacts associated with sea level rise and extreme rain events are likely to result in more frequent and extensive flood problems that compound or magnify other stressors. Heavy precipitation events and resulting peak streamflows can exacerbate existing flooding problems. Delaware is already experiencing changes in streamflows. For example, floods that exceed the 10-year recurrence interval have become more frequent along the Brandywine Creek since the 1970s.[61] Flooding impacts to roads and rail lines also affect energy production, particularly for coal-fired power generation that relies on coal transport by rail. Transmission structures such as power lines and electrical substations are often built to withstand minor flooding; however, extreme weather events with high winds can cause significant damage and disruption to service.

Increased precipitation and associated flooding may increase the vulnerability of remediation sites and landfills associated with industrial facilities. Inundation from flooding may trigger the movement of hazardous chemicals or pollutants into groundwater or surface water, potentially affecting industrial operations. Increasing storm intensity may also increase the height of storm surge, causing greater extent of flooding than previously experienced.

## 9.4.5. Energy Production and Structural Safety – Increasing Temperatures

Rising summer temperatures and extended heat waves have been experienced in many parts of the United States in recent years. The summer of 2012 was the hottest summer on record, and also one of the driest. By late September 2012, more than 60 percent of the contiguous United States, including Delaware, was experiencing moderate to exceptional drought.[62] Increased variability of extreme temperatures is likely to have significant impacts on both natural and human-built infrastructure.

Under heat wave conditions, peak demands for electricity in summer months increase dramatically and vulnerability to power outages can affect wide regions. For example, in July 2012, a power outage during a record heat wave resulted in 1.7 million people across 10 states being without electricity for 2 days or more. Power outages may be triggered directly or indirectly by high heat events. Thermal stress or damage to energy infrastructure from heat-driven storms can impair electricity transmission. Higher air and water temperatures, or lack of available water for cooling, can affect operations and reduce electricity output. Power generators in Delaware and neighboring states (which provide electricity to meet in-state demand) are likely to experience local and regional shortages during extreme peak demand. Summer droughts also increase demand for irrigation, which in turn drives energy demands for pumping groundwater.

Power generation facilities can be affected by changes in water salinity and temperature. 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. Increased water temperatures during extended heat waves can trigger shutdown of power plants. For example, in August 2012 the Millstone Nuclear Power Station in Waterford, Connecticut, was forced to shut down for 12 days when Long Island Sound water temperatures exceeded the limit of 75˚F.

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. However, high heat conditions can complicate road maintenance and repair operations; health restrictions for outdoor workers may limit road work to nighttime hours to avoid high heat and ozone risks.

## 9.4.6. Transportation and Energy Facilities – Sea Level Rise

The potential effects of sea level rise from climate change have been extensively studied, particularly in the Mid-Atlantic coast region where rates of sea level rise are higher than the global average.[d] In Delaware, a vulnerability assessment conducted by Delaware Coastal Programs presented three scenarios for sea level rise by 2100 that are based on low, moderate, and high levels of future global warming.[e] The Low scenario is 1.6 feet (0.5 meter),

**d** The Mid-Atlantic region is described by Titus (2009) as the eastern U.S. coast from New York to North Carolina. Tide gauge observations over the 20th century indicate that relative sea level rise (the combination of global sea level rise and land subsidence) rates were higher than the global mean and generally ranged from 2.4 to 4.4 millimeters per year, or about 0.3 meters (1 foot). Over the same period, global average sea level rose approximately 1.7 millimeters per year. Source: Titus, J.G. (2009). *Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region.* U.S. Climate Change Science Program, Synthesis and Assessment Product 4.1., p. 2.

**e** Further discussion of sea level rise is found in the methodology section of Chapter 1, Introduction and Methodology.

**Table 9.4. Potential impacts of sea level rise to human-built infrastructure in Delaware**

| *Infrastructure Affected* | *Area in Delaware Affected* | *Potential Impacts Under Sea Level Rise Scenarios* |
|---|---|---|
| Roads and bridges; evacuation routes | Roads and bridges throughout the state, particularly in the Inland Bays area and around Lewes. Many Delaware Bay beach communities may be affected by sea level rise cutting off their primary access roads and evacuation routes. In New Castle County, portions of State Route 9 are also vulnerable to severe flooding from sea level rise. | Statewide, an estimated 12.6 miles of designated evacuation routes could be inundated under the Low scenario of one-half meter of sea level rise.[64] |
| Public bus transit | Primarily New Castle County, which has the largest concentration of DART bus service routes. Urban passengers and particularly transit-dependent residents are likely to be affected. | An estimated 36 to 94 miles of bus routes and 14 to 58 bus stops could be subject to inundation in New Castle County. (The range reflects the Low-to-High sea level scenarios of 1.6 to 4.9 feet, or 0.5 to 1.5 meters.)[65] |
| Passenger and freight rail lines | Passenger rail in northern New Castle County, especially Wilmington. Rail interchanges to central and southern Delaware; for example, the movement of coal to the Indian River Generating Station and grain to poultry growers in southern Delaware relies on freight rail connections north of the C & D Canal. | An estimated 8 to 21 miles of rail line in the Wilmington area (under the 1.6 to 4.9 feet sea level rise scenarios).[66] |
| Marine transport facilities | The Port of Wilmington is a major facility that could be significantly affected. Public boat ramps and piers throughout coastal Delaware are also at risk for intermittent or chronic flooding as a result of sea level rise. | An estimated 78 acres – approximately 36 percent – of the port's main facilities could be inundated under the Low scenario of 1.6 feet of sea level rise.[67]<br>60 percent of boating facilities statewide could be affected under the Low scenario.[68] |
| Energy and industrial facilities | Facilities located along the Delaware River and in the Inland Bays are vulnerable to inundation from sea level rise, and potential changes in salinity may affect industrial operations. | Between 16 and 25 percent of the acreage of heavy industrial lands in the coastal areas could potentially be affected under the three sea level rise scenarios.[69] |

Intermediate scenario is 3.3 feet (1 meter), and High scenario is 4.9 feet (1.5 meters).[63] Based on a spatial analysis of the three scenarios using a "bathtub model,"[f] the Delaware Sea Level Rise Vulnerability Assessment identified infrastructure resources that could be vulnerable to sea level rise over the next century. **Table 9.4** summarizes the potential impacts to human-built infrastructure, based on this assessment.

## Sources


**1** Hayhoe, K., Stoner, A., & Gelca, R. (2013). Climate Change Projections and Analysis for Delaware. Report dated December 2013.

**2** Oak Ridge National Laboratory. (2012). *Climate change and infrastructure, urban systems, and vulnerabilities.* U.S. Department of Energy, Science Office. Technical Report for the U.S. Department of Energy in Support of the National Climate Assessment. February 29. http://www.esd.ornl.gov/eess/EnergySupplyUse.pdf

**3** Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis.* Washington, DC: Island Press.

**4** Fischlin, A., Midgley, G. F., Price, J. T., Leemans, R., Gopal, B., Turley, C., … Velichko, A. A. (2007). Ecosystems, their properties, goods, and services. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press. pp. 211-272.


**f** A "bathtub model" is an inundation model that uses only two variables: land surface elevation and the inundation level (in this case, the three levels of sea level rise scenarios).

5 Delaware Natural Resources and Environmental Control. (2011). *Economic valuation of wetland ecosystem services in Delaware.* Division of Water Resources report prepared by Industrial Economic, Inc., for DNREC. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/Wetlandvalues.aspx

6 Tiner, R. W., Biddle, M. A. , Jacobs, A. D., Rogerson, A. B., & McGuckin, K. G. (2011). *Delaware wetlands: Status and changes from 1992 to 2007.* U.S. Fish and Wildlife Service, Cooperative National Wetlands Inventory Publication. Northeast Region, Hadley, MA, and the Delaware Department of Natural Resources and Environmental Control, Dover, DE. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/DelawareWetlandsStatusandTrends.aspx

7 National Center for Ecological Analysis and Synthesis. Retrieved on October 30, 2012 from http://www.nceas.ucsb.edu/featured/callaway

8 Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Delaware Forest Service report. Retrieved from http://dda.delaware.gov/forestry/index.shtml

9 Delaware Natural Resources and Environmental Control. (2011). *Economic valuation of wetland ecosystem services in Delaware.* Division of Water Resources report prepared by Industrial Economic, Inc., for DNREC. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/Wetlandvalues.aspx

10 Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Delaware Forest Service report. Retrieved from http://dda.delaware.gov/forestry/index.shtml

11 U.S. Environmental Protection Agency. (2012). *Reducing urban heat islands: Compendium of strategies.* Retrieved from http://www.epa.gov/heatisland/resources/pdf/TreesandVegCompendium.pdf

12 Delaware Department of Agriculture. (undated). *Delaware forest resource assessment.* Delaware Forest Service report. Retrieved from http://dda.delaware.gov/forestry/index.shtml

13 Carey, W. L., Maurmeyer, E. M., and Pratt, A. P. (2004). *Striking a balance: A guide to coastal dynamics and beach management in Delaware,* 2nd ed., Delaware Department of Natural Resources and Environmental Control, Document No. 40-07-01/04/08/06, 47 pp., Retrieved from http://www.dnrec.delaware.gov/swc/Pages/CoastalConsBeachPres.aspx

14 Kauffman, G., Homsey, A., McVey, E., & Mack, S. (2011). Economic value of the Delaware Estuary watershed. University of Delaware, Water Resources Agency report, dated May, to Delaware Department of Natural Resources and Environmental Control, Division of Watershed Stewardship. Retrieved from http://www.ipa.udel.edu/wra/research/delawareestuary.html

15 Kauffman, G., Homsey, A., McVey, E., Mack, S., & Chatterson, S. (2011). *Socioeconomic value of the Chesapeake Bay watershed in Delaware.* University of Delaware, Water Resources Agency report, dated March, to Delaware Department of Natural Resources and Environmental Control, Division of Watershed Stewardship. Retrieved from http://www.ipa.udel.edu/publications/DelChesapeakeWatershed.pdf

16 Delaware Natural Resources and Environmental Control. (2011). *Economic valuation of wetland ecosystem services in Delaware.* Division of Water Resources report prepared by Industrial Economic, Inc., for DNREC. Retrieved from http://www.dnrec.delaware.gov/Admin/DelawareWetlands/Pages/Wetlandvalues.aspx

17 Delaware Department of Transportation. (2010). *Delaware transportation facts 2010.* Retrieved from http://deldot.gov/information/pubs_forms/

18 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report dated July. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

19 Delaware Department of Transportation. (2010). *Delaware transportation facts 2010.* Retrieved from http://deldot.gov/information/pubs_forms/

20 Delaware Department of Transportation. (2010). *Delaware transportation facts 2010.* Retrieved from http://deldot.gov/information/pubs_forms/

21 Delaware Department of Transportation. (2010). *Delaware transportation facts 2010.* Retrieved from http://deldot.gov/information/pubs_forms/

22 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report dated July. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

23 Port of Wilmington. Retrieved on October 30, 2012 from http://portofwilmington.com/mainframesets/main_ourbusiness.htm

24 U.S. Energy Information Administration. (2012). *Delaware state energy profile.* Retrieved from http://www.eia.gov/beta/state/print.cfm?sid=DE

25 U.S. Energy Information Administration. (2012). *Delaware state energy profile.* Retrieved from http://www.eia.gov/beta/state/print.cfm?sid=DE

26 Oak Ridge National Laboratory. (2012). *Climate change and infrastructure, urban systems, and vulnerabilities.* U.S. Department of Energy, Science Office. Technical Report for the U.S. Department of Energy in support of the National Climate Assessment. February 29. http://www.esd.ornl.gov/eess/EnergySupplyUse.pdf

27 Peterson, T. C., McGuirk, M., Houston, T. G., & Horvitz, A. H. (2006). *Climate variability and change with implications for transportation.* National Oceanic and Atmospheric Administration & Lawrence Berkeley National Laboratory. Report dated December 6. Retrieved from http://onlinepubs.trb.org/onlinepubs/sr/sr290Many.pdf

28 Peterson, T. C., McGuirk, M., Houston, T. G., & Horvitz, A. H. (2006). *Climate variability and change with implications for transportation.* National Oceanic and Atmospheric Administration & Lawrence Berkeley National Laboratory. Report dated December 6. Retrieved from http://onlinepubs.trb.org/onlinepubs/sr/sr290Many.pdf

29 National Research Council. (2008). *Potential impacts of climate change on U.S. transportation.* Transportation Research Board Special Report 290. http://www.trb.org/Main/Blurbs/156825.aspx

30 National Research Council. (2008). *Potential impacts of climate change on U.S. transportation.* Transportation Research Board Special Report 290. http://www.trb.org/Main/Blurbs/156825.aspx

31 Peterson, T. C., McGuirk, M., Houston, T. G., & Horvitz, A. H. (2006). *Climate variability and change with implications for transportation.* National Oceanic and Atmospheric Administration & Lawrence Berkeley National Laboratory. Report dated December 6. Retrieved from http://onlinepubs.trb.org/onlinepubs/sr/sr290Many.pdf

32 U.S. Global Change Research Program. (2009). Transportation. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/transportation

33 National Research Council. (2008). *Potential impacts of climate change on U.S. transportation.* Transportation Research Board Special Report 290. http://www.trb.org/Main/Blurbs/156825.aspx

34 Hyman, R. C., Potter, H. R., Savonis, M. J., Burkett, V. R., & Tump, J. E. (2008). Why study climate change impacts on transportation? In M. J. Savonis, V. R. Burkett, and J. R. Potter (Eds.). *Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study, phase I.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Synthesis and Assessment Product 4.7, Washington, DC: Department of Transportation, Retrieved from http://library.globalchange.gov/products/assessments/sap-4-7-impacts-of-climate-change-and-variability-on-transportation-systems-and-infrastructure-gulf-coast-study

35 U.S. Global Change Research Program. (2009). Transportation. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/transportation

[36] Transportation Research Board. (2009). *Transportation's role in emergency evacuation and reentry: A synthesis of highway practice.* National Cooperative Highway Research Program. Retrieved from http://www.transport2012.org/transport-climate-change-publications/?page=8

[37] Gill, S. K., Wright, R., Titus, J. G., Kafalenos, R., & Wright, K. (2009). Population, land use, and infrastructure. In J. G. Titus, K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams (Eds.). *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. Washington, DC: U.S. Environmental Protection Agency, pp. 105-116.

[38] U.S. Global Change Research Program. (2009). Transportation. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/transportation

[39] Gill, S. K., Wright, R., Titus, J. G., Kafalenos, R., & Wright, K. (2009). Population, land use, and infrastructure. In J. G. Titus, K. E. Anderson, D. R. Cahoon, D. B. Gesch, S. K. Gill, B. T. Gutierrez, E. R. Thieler, and S. J. Williams (Eds.). *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. U.S. Washington, DC: Environmental Protection Agency, pp. 105-116.

[40] Oak Ridge National Laboratory. (2012). Climate change and infrastructure, urban systems, and vulnerabilities. U.S. Department of Energy, Science Office. Technical report for the U.S. Department of Energy in Support of the National Climate Assessment. February 29. http://www.esd.ornl.gov/eess/EnergySupplyUse.pdf

[41] Oak Ridge National Laboratory. (2012). *Climate change and infrastructure, urban systems, and vulnerabilities.* U.S. Department of Energy, Science Office. Technical report for the U.S. Department of Energy in Support of the National Climate Assessment. February 29. http://www.esd.ornl.gov/eess/EnergySupplyUse.pdf

[42] Bull, S. R., Bilello, D. E., Ekmann, J., Sale, J., & Schmalzer, D. K. (2007). *Effects of climate change on energy production and distribution in the United States.* in Effects of climate change on energy production and use in the United States. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC. Synthesis and Assessment Product 4.5. Retrieved from http://www.climatescience.gov/Library/sap/sap4-5/final-report/default.htm

[43] U.S. Global Change Research Program. (2009). Energy supply and use. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/energy-supply-and-use

[44] U.S. Global Change Research Program. (2009). Energy supply and use. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/energy-supply-and-use

[45] Oak Ridge National Laboratory. (2012). *Climate change and infrastructure, urban systems, and vulnerabilities.* U.S. Department of Energy, Science Office. Technical report for the U.S. Department of Energy in support of the National Climate Assessment. February 29. http://www.esd.ornl.gov/eess/EnergySupplyUse.pdf

[46] U.S. Global Change Research Program. (2009). Energy supply and use. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/energy-supply-and-use

[47] Bull, S. R., Bilello, D. E., Ekmann, J., Sale, J., & Schmalzer, D. K. (2007). Effects of climate change on energy production and distribution in the United States. In *Effects of climate change on energy production and use in the United States.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC. Synthesis and Assessment Product 4.5. Retrieved from http://www.climatescience.gov/Library/sap/sap4-5/final-report/default.htm

[48] U.S. Global Change Research Program. (2009). Energy supply and use. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/energy-supply-and-use

[49] Bull, S. R., Bilello, D. E., Ekmann, J., Sale, J., & Schmalzer, D. K. (2007). Effects of climate change on energy production and distribution in the United States. In *Effects of climate change on energy production and use in the United States.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC. Synthesis and Assessment Product 4.5. Retrieved from http://www.climatescience.gov/Library/sap/sap4-5/final-report/default.htm

[50] Bull, S. R., Bilello, D. E., Ekmann, J., Sale, J., & Schmalzer, D. K. (2007). Effects of climate change on energy production and distribution in the United States. In *Effects of climate change on energy production and use in the United States.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC. Synthesis and Assessment Product 4.5. Retrieved from http://www.climatescience.gov/Library/sap/sap4-5/final-report/default.htm

51 U.S. Global Change Research Program. (2009). Energy supply and use. *Global climate change impacts in the United States.* Retrieved from http://nca2009.globalchange.gov/energy-supply-and-use

52 Delaware Department of Transportation. (2010). *Moving the First State forward: Delaware long-range transportation plan.* Retrieved from http://deldot.gov/information/pubs_forms/delrtp/delrtp_102510.pdf

53 Transportation Research Board. (2012). *Climate change and transportation.* Transportation Circular E-C164. Retrieved from http://www.trb.org/Publications/Public/PubsTransportationResearchCirculars.aspx

54 Delaware Department of Transportation. (2010). *Delaware transportation facts 2010.* Retrieved from http://deldot.gov/information/pubs_forms/

55 Energy Information Administration. Retrieved October 18, 2012. http://www.eia.gov/emeu/25opec/sld020.htm

56 American Society of Civil Engineers. (2009). *2009 Report card on America's infrastructure.* Retrieved from http://www.infrastructurereportcard.org/report-cards

57 American Society of Civil Engineers. (2009). *2009 Report card on America's infrastructure.* Retrieved from http://www.infrastructurereportcard.org/report-cards

58 Croope, S. V., & McNeil, S. (2011). Improving resilience of critical infrastructure systems postdisaster. *Transportation Research Record: Journal of the Transportation Research Board,* Washington D.C.: Transportation Research Board of the National Academies, 2234: pp. 3-13.

59 McCleary, R. Delaware Department of Transportation. (personal communication, December 3, 2013).

60 Kraft, J. C. (1971). Sedimentary facies patterns and geologic history of a Holocene marine transgression. Geological Society of America Bulletin 82, 2131-2158.

61 Kauffman, G. J., University of Delaware, Water Resources Agency. (personal communication, September 10, 2013).

62 National Oceanic and Atmospheric Administration. *State of the climate: Drought.* National Climatic Data Center. Retrieved from http://www.ncdc.noaa.gov/sotc/drought/#national-overview

63 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July. Retrieved from http://www.dnrec.delaware.gov/coastal/Pages/SLR/DelawareSLRVulnerabilityAssessment.aspx

64 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July. pp. 108-109.

65 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July. pp. 110-111.

66 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's* high tide: Sea level rise vulnerability assessment for the State of Delaware. Delaware Coastal Programs report, July. pp. 115-116.

67 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July. pp. 113-114.

68 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July. pp. 117-118.

69 Delaware Department of Natural Resources and Environmental Control. (2012). *Preparing for tomorrow's high tide: Sea level rise vulnerability assessment for the State of Delaware.* Delaware Coastal Programs report, July. p. xii.

# DELAWARE

# Climate Change Impact Assessment

PREPARED BY

**Division of Energy and Climate**

Delaware Department of Natural Resources and Environmental Control

## Appendix:

### Climate Projections – Data, Models, and Methods

*(Katharine Hayhoe, Anne Stoner, and Rodica Gelca)*

### Climate Projection Indicators

# Appendix

# Climate Projections – Data, Models, and Methods

***Authors:*** *Dr. Katharine Hayhoe, Dr. Anne Stoner, and Dr. Rodica Gelca, ATMOS Research & Consulting*

This section describes the specific data sets and methods used to assess projected changes in Delaware climate in response to human-induced global change. These data sets, models, and methods include future scenarios, global climate models, long-term station records, and a statistical downscaling model. The methods and the assessment framework used here are consistent with—and, in general, represent updated versions of—those used in the 2007 Northeast Climate Impact Assessment,[1] the 2009 Second U.S. National Climate Assessment[2] and the upcoming 2013 Third U.S. National Climate Assessment.[3] (Note: For definitions of key terms, see Chapter 4.)

## A.1. Historical and Future Climate Scenarios

**The scenarios used in this analysis were the RCP 8.5 (higher) and 4.5 (lower) concentration pathways and SRES A1fi (higher) and B1 (lower) emission scenarios. These scenarios were chosen because they cover a broad range of plausible futures in terms of human emissions of carbon dioxide ($CO_2$) and other radiatively active species and resulting impacts on climate. Results shown in this report are based on the newer RCP scenarios only. Plots of results from both RCP and SRES scenarios are provided in the Excel files included with this Appendix.**

In historical climate model simulations, climate in each year is affected by external forcings or climate drivers (including atmospheric levels of greenhouse gases, solar radiation, and volcanic eruptions) consistent with observed values for that year. The historical forcings used by the global climate model (GCM) simulations in this project are the Coupled Model Intercomparison Project's "20th Century Climate in Coupled Models" or 20C3M total forcing scenarios.[4, 5] These simulations provide the closest approximation to actual climate forcing from the beginning of the historical simulation to the year 2000 for older CMIP3 simulations, and the year 2005 for newer CMIP5 simulations. Where multiple 20C3M simulations were available, the first was used here ("run 1" for CMIP3 and "r1i1p1" for CMIP5) unless complete daily outputs were not available for that simulation, in which case the next available was used.

The historical simulation provides the starting conditions for future simulations. To ensure the accuracy of the inputs used in the historical scenarios, it is customary in the climate modeling community for historical simulations to end at least 5 years before present. So although the CMIP3 GCM simulations were typically conducted after 2005, the CMIP3 historical total-forcing scenario ends and "future" scenarios begin in 2000. CMIP5 historical scenarios end in 2005 and "future" scenarios begin in 2006. In the future scenarios, most external natural climate drivers are fixed, and human emissions correspond to a range of plausible pathways rather than observed values.

Future scenarios depend on a myriad of factors, including how human societies and economies will develop over the coming decades; what technological advances are expected; which energy sources will be used in the future to generate electricity, power transportation, and serve industry; and how all these choices will affect future emissions from human activities.

To address these questions, in 2000 the Intergovernmental Panel on Climate Change (IPCC) developed a series of scenarios described in the *Special Report on Emissions Scenarios* (SRES).[6] These scenarios describe internally consistent pathways of future societal development and corresponding emissions. The carbon emissions and global temperature change that result from the SRES scenarios are shown in **Figure 1** (left).

At the higher end of the range, the SRES higher-emissions or fossil fuel–intensive scenario (A1FI or A1fi, for *fossil-intensive*) represents a world with fossil fuel–intensive economic growth and a global population that peaks mid-century and then declines. New and more efficient technologies are introduced toward the end of the century. In this scenario, atmospheric $CO_2$ concentrations reach 940 parts per million by 2100, more than triple preindustrial levels of 280 ppm. At the lower end, the SRES lower-emissions scenario (B1) also represents a world with high economic growth and a global population that peaks mid-century and then declines. However, this scenario includes a shift to less fossil fuel–intensive industries and the introduction of clean and resource-efficient technologies. Emissions of greenhouse gases peak around mid-century and then decline. Atmospheric $CO_2$ levels reach 550 parts per million by 2100, about double preindustrial levels. Associated temperature changes by end of century range from 4 to 9°F, based on the best estimate of climate sensitivity.

For this project, climate projections were based on the A1FI higher (dark red) and B1 (blue) lower scenarios. Because of the decision of IPCC Working Group 1 to focus on the A2, A1B, and B1 scenarios, only four GCMs had A1FI scenarios available. For other models, daily outputs were not available for all scenarios. **Table 1**, in the next section on Global Climate Models, summarizes the combinations of GCM simulations and emission scenarios used in this work.

In 2010, the IPCC released a new set of scenarios, called *Representative Concentration Pathways* (RCPs).[7] In contrast to the SRES scenarios, the RCPs are expressed in terms of $CO_2$ concentrations in the atmosphere, rather than direct emissions. The RCP scenarios are named in terms of their change in radiative forcing (in watts per meter squared) by end of century: +8.5 W/m$^2$ and +4.5 W/m$^2$.

**RCP scenarios** can be converted "backwards," into the range of emissions consistent with a given concentration trajectory, using a carbon cycle model (**Figure 1**, center). Four RCP scenarios were developed to span a plausible range of future $CO_2$ concentrations, from lower to higher. At the

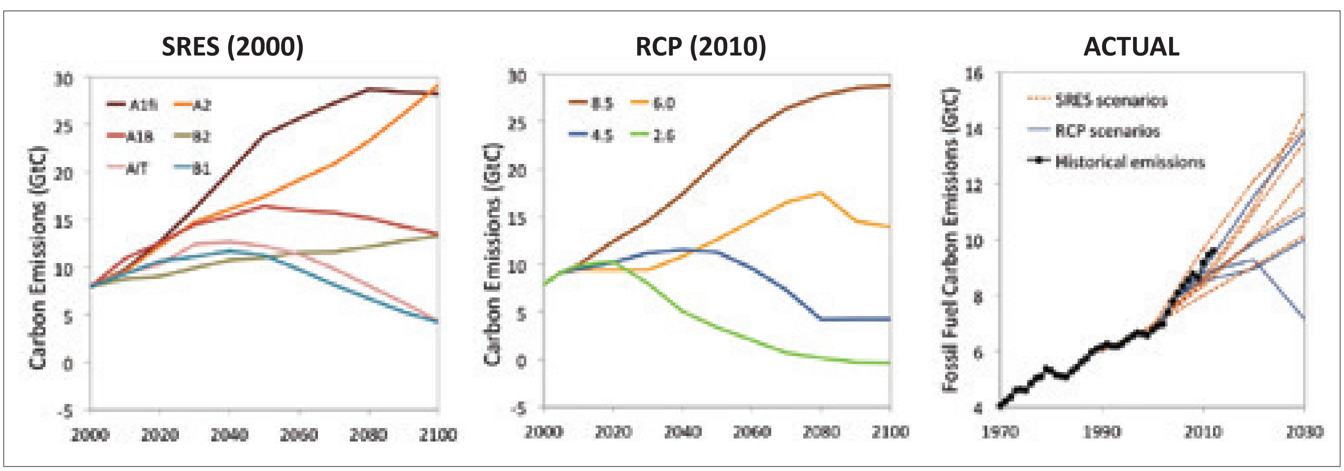


**Figure 1.** There are two families of future scenarios: the 2000 Special Report on Emission Scenarios (SRES, left) and the 2010 Representative Concentration Pathways (RCP, center). This figure compares 2000 SRES (left), 2010 RCP (center), and observed historical annual carbon emissions (right) in gigatons of carbon (GtC). At the top end of the range, the SRES and RCP scenarios are very similar. At the bottom end of the range, the RCP 2.6 scenario is much lower, because it includes the option of using policies to reduce CO2 emissions, while SRES scenarios do not.

higher end of the range, atmospheric $CO_2$ levels under the RCP 8.5 scenario reach more than 900 parts per million by 2100. At the lowest, under RCP 2.6, policy actions to reduce $CO_2$ emissions *below zero* before the end of the century (i.e., to the point where humans are responsible for a net uptake of $CO_2$ from the atmosphere) keep atmospheric $CO_2$ levels below 450 parts per million by 2100. Associated temperature changes by end-of-century range from 2 to 8°F, based on the best estimate of climate sensitivity.

In this Assessment, climate projections were developed for the RCP 8.5 higher (dark red) and 4.5 lower (blue) scenarios, because these closely match the SRES A1fi and B1 scenarios. Although the CMIP5 archive contains simulations from more than 40 models, a much smaller subset (only 16 individual models, from 13 modeling groups) archived daily temperature and precipitation for both the RCP 8.5 and 4.5 scenarios and even fewer of these models (9, total) represented updated versions of models already available in the CMIP3 archive. The CMIP5 models used in this study are summarized in **Table 1**.

As diverse as they are, neither the SRES nor the RCP scenarios cover the entire range of possible futures. Since 2000, $CO_2$ emissions have already been increasing at an average rate of 3% per year. If they continue at this rate, emissions will eventually outpace even the highest of the SRES and RCP scenarios (**Figure 1**, right).[8,9] On the other hand, significant reductions in emissions—on the order of 80% by 2050, as already mandated by the state of California—could reduce $CO_2$ levels below the lower B1 emission scenario within a few decades.[10] Nonetheless, the substantial difference between the higher and lower scenarios used here provides a good illustration of the potential range of climate changes that can be expected in the future, and how much these depend on future emissions and human choices.

## A.2. Global Climate Models

**To generate high-resolution daily projections of temperature and precipitation, this analysis used CMIP3 global climate model simulations from four different models, and CMIP5 simulations from nine different models. Plots of projections for CMIP5 models are provided in the Excel files included with this Appendix.**

**Table 1. CMIP3 and CMIP5 global climate modeling groups and their models used in this analysis. Those marked with a (+) have only 360 days per year. All other models archived full daily time series from 1960 to 2099 (for CMIP3 simulations) and 1950 to 2100 (for CMIP5 simulations).**

| *Origin* | *CMIP3 model(s)* | *CMIP3 scenarios* | *CMIP5 model(s)* | *CMIP5 scenario(s)* |
|---|---|---|---|---|
| National Center for Atmospheric Research, USA | CCSM3<br>PCM | A1FI, B1<br>A1FI, B1 | CCSM4 | 4.5, 8.5 |
| Centre National de Recherches Meteorologiques, France | | | CNRM-CM5 | 4.5, 8.5 |
| Commonwealth Scientific and Industrial Research Organisation, Australia | | | CSIRO-MK3.6.0 | 4.5, 8.5 |
| Geophysical Fluid Dynamics Laboratory, USA | GFDL CM2.1 | A1FI, B1 | - | - |
| Max Planck Institute for Meteorology, Germany | | | MPI-ESM-LR, MR | 4.5, 8.5 |
| UK Meteorological Office Hadley Centre | HadCM3+ | A1FI, B1 | HadGEM2-CC^+ | 4.5, 8.5 |
| Institute for Numerical Mathematics, Russian | | | INMCM4 | 4.5, 8.5 |
| Institut Pierre Simon Laplace, France | | | IPSL-CM5A-LR | 4.5, 8.5 |
| Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies, Japan | | | MIROC5 | 4.5, 8.5 |
| Meteorological Research Institute, Japan | | | MRI-CGCM3 | 4.5, 8.5 |

Future scenarios are used as input to GCMs, which are complex, three-dimensional coupled models that are continually evolving to incorporate the latest scientific understanding of the atmosphere, oceans, and earth's surface. As output, GCMs produce geographic grid-based projections of temperature, precipitation, and other climate variables and daily and monthly scales. These physical models were originally known as atmosphere-ocean general circulation models (AO-GCMs). However, many of the newest generation of models are now more accurately described as global climate models (GCMs) as they incorporate additional aspects of the earth's climate system beyond atmospheric and oceanic dynamics.

Because of their complexity, GCMs are constantly being enhanced as scientific understanding of climate improves and as computational power increases. Some models are more successful than others at reproducing observed climate and trends over the past century.[11] However, all future simulations agree that both global and regional temperatures will increase over the coming century in response to increasing emissions of greenhouse gases from human activities.[12]

Historical GCM simulations are initialized in the late 1800s, externally "forced" by the human emissions, volcanic eruptions, and solar variations represented by the historical scenario described above. They are also allowed to develop their own pattern of natural chaotic variability over time. This means that, although the climatological means of historical simulations should correspond to observations at the continental to global scale, no temporal correspondence between model simulations and observations should be expected on a day-to-day or even year-to-year basis. For example, although a strong El Niño event occurred from 1997 to 1998 in the real world, it may not occur in a model simulation in that year. However, over several decades, the average number of simulated El Niño events should be similar to those observed. Similarly, although the central United States suffered the effects of an unusually intense heat wave during summer 1995, a model simulation for 1995 might show that year as average or even cooler than average. However, a similarly intense heat wave should be simulated some time during the climatological period centered around 1995.

In this study, we used global climate model simulations archived by the Program for Climate Model Intercomparison and Diagnosis (PCMDI). The first collection of climate model simulations, assembled between 2005 and 2006, consists of models that contributed to phase 3 of the Coupled Model Intercomparison Project (CMIP3).[13] These are the results presented in the 2007 IPCC Third and Fourth Assessment Reports (TAR and AR4).

The CMIP3 GCM simulations used in this analysis consist of all model outputs archived by PCMDI with daily maximum and minimum temperature and precipitation available for the SRES A1fi and B1 scenarios. Additional simulations were obtained from the archives of the Geophysical Fluid Dynamics Laboratory, the National Center for Atmospheric Research, and the U.K. Meteorological Office. The list of GCMs used, their origin, the scenarios available for each, and the time periods covered by their output are given in **Table 1.**

From 2011 through the end of 2012, PCMDI began to collect and archive new GCM simulations that contributed to the fifth phase of CMIP and are used in the IPCC Fifth Assessment Report (AR5).[14] The CMIP3 and CMIP5 archives are similar in that most of the same international modeling groups contributed to both. Both provide daily, monthly, and yearly output from climate model simulations driven by a wide range of future scenarios. However, the archives are also different from each other in three key ways. First, many of the CMIP5 models are new versions or updates of previous CMIP3 models and some of the CMIP5 models are entirely new. Some of the CMIP5 models are "Earth System Models" that include both traditional components of the CMIP3 Atmosphere-Ocean General Circulation Models as well as new components such as atmospheric chemistry or dynamic vegetation. Second, the CMIP5 simulations use the RCP scenarios as input for future simulations, while the CMIP3 simulations use the SRES scenarios as input (**Figure 1**). Third, the CMIP5 archive contains many more output fields than the CMIP3 archive did.

The CMIP5 GCM simulations used in this project consist of nine sets of model outputs archived by the Earth System Grid with continuous daily maximum and minimum temperature and precipitation outputs available for historical and the RCP 8.5 future scenario and 14 available for historical and the RCP 4.5 future scenario. No additional simulations were obtained from individual modeling group archives. The full list of CMIP5 GCMs used, their origin, the scenarios available for each, and the time periods covered by their output are given in **Table 1.**

The GCMs used in this study were chosen based on several criteria. First, only well established models were considered, those already extensively described and evaluated in the peer-reviewed scientific literature. Models must have been evaluated and shown to adequately reproduce key features of the atmosphere and ocean system. Second, the models had to include the greater part of the IPCC range of uncertainty in climate sensitivity (2 to 4.5°C).[15] Climate sensitivity is defined as the temperature change resulting from a doubling of atmospheric $CO_2$ concentrations relative to preindustrial times, after the atmosphere has had decades to adjust to the change. In other words, climate sensitivity determines the extent to which temperatures will rise under a given increase in atmospheric concentrations of greenhouse gases.[16] The third and last criterion is that the models chosen must have continuous daily time series of temperature and precipitation archived for the scenarios used here (SRES A1FI and B1; RCP 8.5 and 4.5). The GCMs selected for this analysis are the only models that meet these criteria.

For some regions of the world (including the Arctic, but not the continental United States), there is some evidence that models better able to reproduce regional climate features may produce different future projections.[17] Such characteristics include large-scale circulation features or feedback processes that can be resolved at the scale of a global model. However, it is not valid to evaluate a global model on its ability to reproduce local features, such as the bias in temperature over a given city or region. Such limitations are to be expected in any GCM, because they are primarily the result of a lack of spatial resolution rather than any inherent shortcoming in the physics of the model. Here, no attempt was made to select a subset of GCMs that performed better than others, because previous literature has showed that it is difficult, if not impossible, to identify such a subset for the continental United States.[18,19]

## A.3. Statistical Downscaling Model

**This project used the statistical Asynchronous Regional Regression Model (ARRM). It was selected because it can resolve the tails of the distribution of daily temperature and precipitation to a greater extent than the more commonly used Delta and BCSD methods, but is less time-intensive and therefore able to generate more outputs as compared to a high-resolution regional climate model.**

Global models cannot accurately capture the fine-scale changes experienced at the regional to local scale. GCM simulations require months of computing time, effectively limiting the typical grid cell sizes of the models to 1 or more degrees of latitude and longitude per side. And although the models are precise to this scale, they are actually skillful, or accurate, to an even coarser scale.[20]

Dynamical and statistical downscaling represent two complementary ways to incorporate higher-resolution information into GCM simulations to obtain local- to regional-scale climate projections. Dynamical downscaling, often referred to as regional climate modeling, uses a limited-area, high-resolution model to simulate physical climate processes at the regional scale, with grid cells typically ranging from 10 to 50 km per side. Statistical downscaling models capture historical relationships between large-scale weather features and local climate, and use these to translate future projections down to the scale of any observations—here, both individual weather stations as well as a regular grid.

Statistical models are generally flexible and less computationally demanding than regional climate models, able to use a broad range of GCM inputs to simulate future changes in temperature and precipitation for a continuous period covering more than a century. Hence, statistical downscaling models are best suited for analyses that require a range of future projections that reflect the uncertainty in future scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes. If the study is more of a sensitivity analysis, where using one or two future simulations is not a limitation, or if it requires multiple surface and upper-air climate variables as input (and has a generous budget!), then regional climate modeling may be more appropriate.

In this project we used a relatively new statistical downscaling model, the Asynchronous Regional Regression Model, or ARRM.[21] ARRM uses asynchronous quantile regression, originally developed by Koenker and Bassett,[22] to estimate conditional quantiles of the response variable in econometrics. Dettinger et al.[23] was the first to apply this statistical technique to climate projections to examine simulated hydrologic responses to climate variations and change, as well as to heat-related impacts on health.[24]

ARRM expands on these original applications by adding (1) modifications specifically aimed at improving the ability of the model to simulate the shape of the distribution, including the tails, (2) piecewise rather than linear regression to accurately capture the often nonlinear relationship between modeled and observed quantiles, and (3) bias correction at the tails of the distribution. It is a flexible and computationally efficient statistical model that can downscale station-based or gridded daily values of any variable that can be transformed into an approximately symmetric distribution and for which a large-scale predictor exists. A quantile regression model is derived for each individual grid cell or weather station that transforms historical model simulations into a probability distribution that closely resembles historical observations (**Figure 2a**). This model can then be used to transform future model simulations into distributions similar to those observed (**Figure 2b**). More information on the ARRM method is provided in the peer-reviewed journal article, "An asynchronous regional regression model for statistical downscaling of daily climate variables," by Stoner et al. (2012).[25]

Both statistical and dynamical downscaling models are based on a number of assumptions,

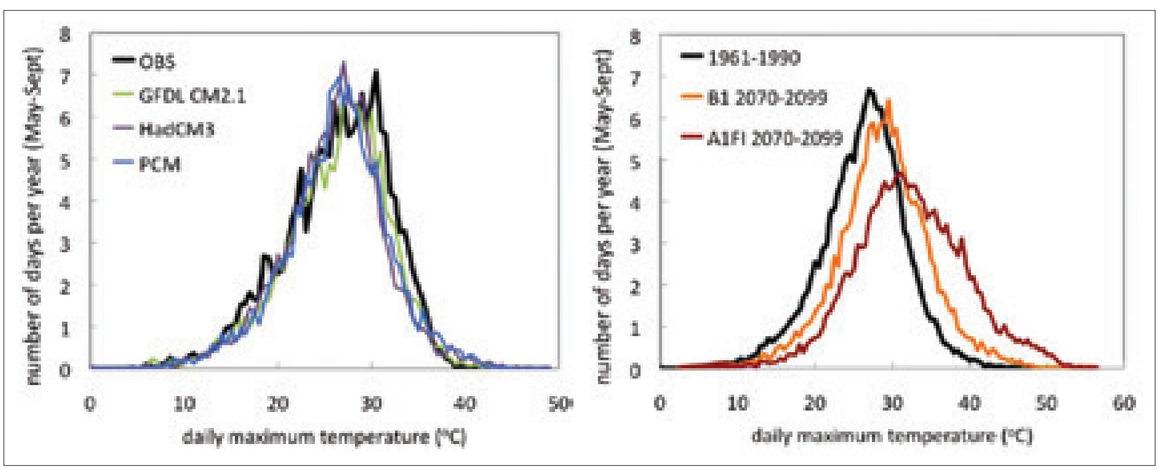


**Figure 2.** (a) Observed (black) and historical simulated distribution of daily maximum summer temperatures by three GCMs for a weather station in Chicago for evaluation period 1980-1999. (b) Historical simulated (black) and future projected daily maximum summer temperature under the SRES A1FI higher (red) and B1 lower (orange) emission scenarios.

some shared, some unique to each method. Two important shared assumptions are the following: first, that the inputs received from GCMs are reasonable—that is, that they adequately capture the large-scale circulation of the atmosphere and ocean at the skillful scale of the global model; and second, that the information from the GCM fully incorporates the climate change signal over that region. All statistical models are based on a crucial assumption often referred to as *stationarity*. Stationarity assumes that the relationship between large-scale weather systems and local climate will remain constant over time. This assumption may be valid for lesser amounts of change, but could lead to biases under larger amounts of climate change.

In a separate project, we are currently evaluating the stationarity of three downscaling methods, including the ARRM method used here. Preliminary analyses show that the assumption of stationarity holds true over much of the world for the lower and middle parts of the distribution. The only location where ARRM performance is systematically non-stationary (i.e., relationships based on historical observations and simulations do not hold true in the future) is at extremely high temperatures (at and above the 99.9th quantile) *along coastal areas*, with warm biases up to 6°C. This may be due to the statistical model's inability to capture dynamical changes in the strength of the land-sea breeze as the temperature differences between land and ocean are exacerbated under climate change; the origins of this feature are currently under investigation.

This bias has important implications for the climate projections generated for Delaware, because several of the station locations used in this study would be considered coastal. It suggests that estimated changes in days hotter than the 1-in-100 hottest historical day (e.g., the historical ~3 to 4 hottest days of the year) may be subject to temperature biases that increase in magnitude such that biases for the 1-in-1,000 hottest days (e.g., the hottest day in 3 years) may be as large as the projected changes in the temperature of those days by end of century under a higher emissions scenario. For precipitation, the ARRM method is characterized by a spatially variable bias at all quantiles that *is generally not systematic*, and varies from approximately -30 to +30%, depending on location.

## A.4. Station Observations

**Long-term weather station records were obtained from the Global Historical Climatology Networka and supplemented with additional records from the National Climatic Data Center cooperative observer programb and the state climatologist for Delaware.[27] All station data were quality-controlled to remove questionable data points before being used to train the statistical downscaling model.**

To train the downscaling model, the observed record must be of adequate length and quality. To appropriately sample from the range of natural climate variability at most of the station locations, and to produce robust results without overfitting, each station used in the analysis was required to have a minimum of 20 consecutive years of daily observations overlapping GCM outputs with less than 50% missing data after quality control. When these limits were applied, the number of usable stations for Delaware totaled 14 for maximum and minimum temperature and precipitation. The latitude, longitude, and station names of the weather stations for which downscaled projections were generated are provided in **Table 2** and are plotted in **Figure 3**.

Although GHCN station data have already undergone a standardized quality control,[28] these stations were additionally filtered using a quality control algorithm to identify and remove erroneous values that had previously been identified in the GHCN database as well as elsewhere. The quality control process consists of two steps: first, individual quality control for each station; and second, a nearest-neighbor approach to validate outliers identified relative to the climatology of each month.

[a] GHCN data is available online at: http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/

[b] NCDC-COOP data is available online at: http://www.ncdc.noaa.gov/land-based-station-data/cooperative-observer-network-coop


**Figure 3.** This report generated future projections for 14 weather stations in Delaware with long-term historical records. Weather stations that did not have sufficiently long and/or complete observational records to provide an adequate sampling of observed climate variability at their locations were eliminated from this analysis.

Individual quality control identified and replaced with "N/A" any values that failed one or more of these three tests:

1. Days when the daily reported minimum temperature exceeds the reported maximum.

2. Temperature values above or below the highest recorded values for North America (-50 to 70ºC) or with precipitation below zero or above the highest recorded value for the continental United States (915 mm in 24 h).

3. Repeated values of more than five consecutive days with identical temperature or nonzero precipitation values to the first decimal place.

In the second step of the quality control process, up to 10 "nearest neighbors" for each individual weather station were queried to see if the days with anomalously high and low values were also days in which anomalous values occurred at the neighboring station, plus or minus one day on either side to account for weather systems that may be moving through the area close to midnight. The resulting files were then scanned to identify any stations with less than 3,650 real

**Table 2. Latitude, longitude, and identification numbers for the 14 weather stations used in this analysis.**

| Station Name | Latitude | Longitude | Beginning of Record | GHCN ID |
|---|---|---|---|---|
| Bear | 39.5917 | -75.7325 | Apr 2003 | USC00071200 |
| Bridgeville | 38.75 | -75.6167 | Jan 1893 | USC00071330 |
| Dover | 39.2583 | -75.5167 | Jan 1893 | USC00072730 |
| Georgetown | 38.6333 | -75.45 | Sept 1946 | USC00073570 |
| Greenwood | 38.8161 | -75.5761 | Jan 1986 | USC00073595 |
| Lewes | 38.7756 | -75.1389 | Feb 1945 | USC00075320 |
| Middletown | 39.45 | -75.6667 | Sept 1952 | USC00075852 |
| Milford | 38.8983 | -75.425 | May 1893 | USC00075915 |
| Newark University Farm | 39.6694 | -75.7514 | Apr 1894 | USC00076410 |
| Selbyville | 38.4667 | -75.2167 | Jan 1954 | USC00078269 |
| Wilmington Porter | 39.7739 | -75.5414 | Jan 1932 | USC00079605 |
| Dover AFB | 39.1333 | -75.4667 | Jul 1946 | USW00013707 |
| Georgetown Sussex Airport | 38.6892 | -75.3592 | Feb 1945 | USW00013764 |
| Wilmington New Castle Airport | 39.6728 | -75.6008 | Jan 1948 | USW00013781 |

values and less than 200 values for any given month. After the quality control and filtering process was complete, a total of 14 stations were available to be downscaled using the ARRM model described previously and the GCM inputs listed in **Table 1.**

## A.5. Uncertainty

The primary challenge in climate impact analyses is the reliability of future information. A common axiom warns that the only aspect of the future that can be predicted with any certainty is the fact that it is impossible to do so. However, although it is not possible to *predict* the future, it is possible to *project* it. Projections can describe what would be likely to occur under a set of consistent and clearly articulated assumptions. For climate change impacts, these assumptions should encompass a broad variety of the ways in which energy, population, development, and technology might change in the future.

There is always some degree of uncertainty inherent to any future projections. To accurately interpret and apply future projections for planning purposes, it is essential to quantify both the magnitude of the uncertainty as well as the reasons for its existence. Each of the steps involved in generating projections—future scenarios, global modeling, and downscaling—introduces a degree of uncertainty into future projections; how to address this uncertainty is the focus of this section.

Another well-used axiom states that all models are wrong (but some can be useful). The earth's climate is a complex system. It is possible to simulate only those processes that have been observed and documented. Clearly, there are other feedbacks and forcing factors at work that have yet to be documented. Hence, it is a common tendency to assign most of the range in future projections to model, or scientific, uncertainty.

Future projections will always be limited by scientific understanding of the system being predicted. However, there are other important sources of uncertainty that must be considered; some even outweigh model uncertainty for certain variables and timescales.

Uncertainty in climate change at the global to regional scale arises primarily due to three different causes: (1) natural variability in the climate system, (2) scientific uncertainty in predicting the response of the earth's climate system to human-induced change, and (3) socioeconomic or scenario uncertainty in predicting future energy choices and hence emissions of heat-trapping gases.[29]

It is important to note that scenario uncertainty is very different, and entirely distinct, from scientific uncertainty in at least two important ways. First, although scientific uncertainty can be reduced through coordinated observational programs and improved physical modeling, scenario uncertainty arises due to the fundamental inability to predict future changes in human behavior. It can be reduced only by the passing of time, as certain choices (such as depletion of a nonrenewable resource) can eliminate or render certain options less likely. Second, scientific uncertainty is often characterized by a normal distribution, where the mean value is more likely than the outliers. However, scenario uncertainty hinges primarily on whether or not the primary emitters of heat-trapping gases, including traditionally large emitters such as the United States as well as nations with rapidly growing contributions such as India and China, will enact binding legislation to reduce their emissions or not. If they do enact legislation, then the lower emission scenarios become more probable. If they do not, then the higher scenarios become more probable. The longer such action is delayed, the less likely it becomes to achieve a lower scenario because of the emissions that continue to accumulate in the atmosphere. Hence, scenario uncertainty cannot be considered to have a normal distribution. Rather, the consequences of a lower versus a higher emissions scenario must be considered independently to isolate the role that human choices are likely to play in determining future impacts.

**Figure 4** illustrates how, over timescales of years to several decades, natural chaotic variability is the most important source of uncertainty. By mid-century, scientific or model uncertainty is the largest contributor to the range in projected temperature and precipitation change. By the end of the century, scenario uncertainty is most important for temperature projections, while model uncertainty continues as the dominant source of uncertainty in precipitation. This is consistent with the results of the projections discussed in this report, where there is a significant difference between the changes projected under higher versus lower scenarios for temperature-based and heavy precipitation indicators, but little difference for mean precipitation-based indicators.

The first source of uncertainty can be addressed by always averaging or otherwise sampling from the statistical distribution of future projections over a climatological period – typically, 20 to 30 years. In other words, the average winter temperature should be averaged over several decades, as should the coldest day of the year. No time stamp more precise than 20 to 30 years should ever be assigned to any future projection. In this report and accompanying data files, simulations are always averaged over multidecadal, climatological time periods: historical (1981-2010), near-term (2020-2039), mid-century (2040-2059) and end of century (2080-2099).

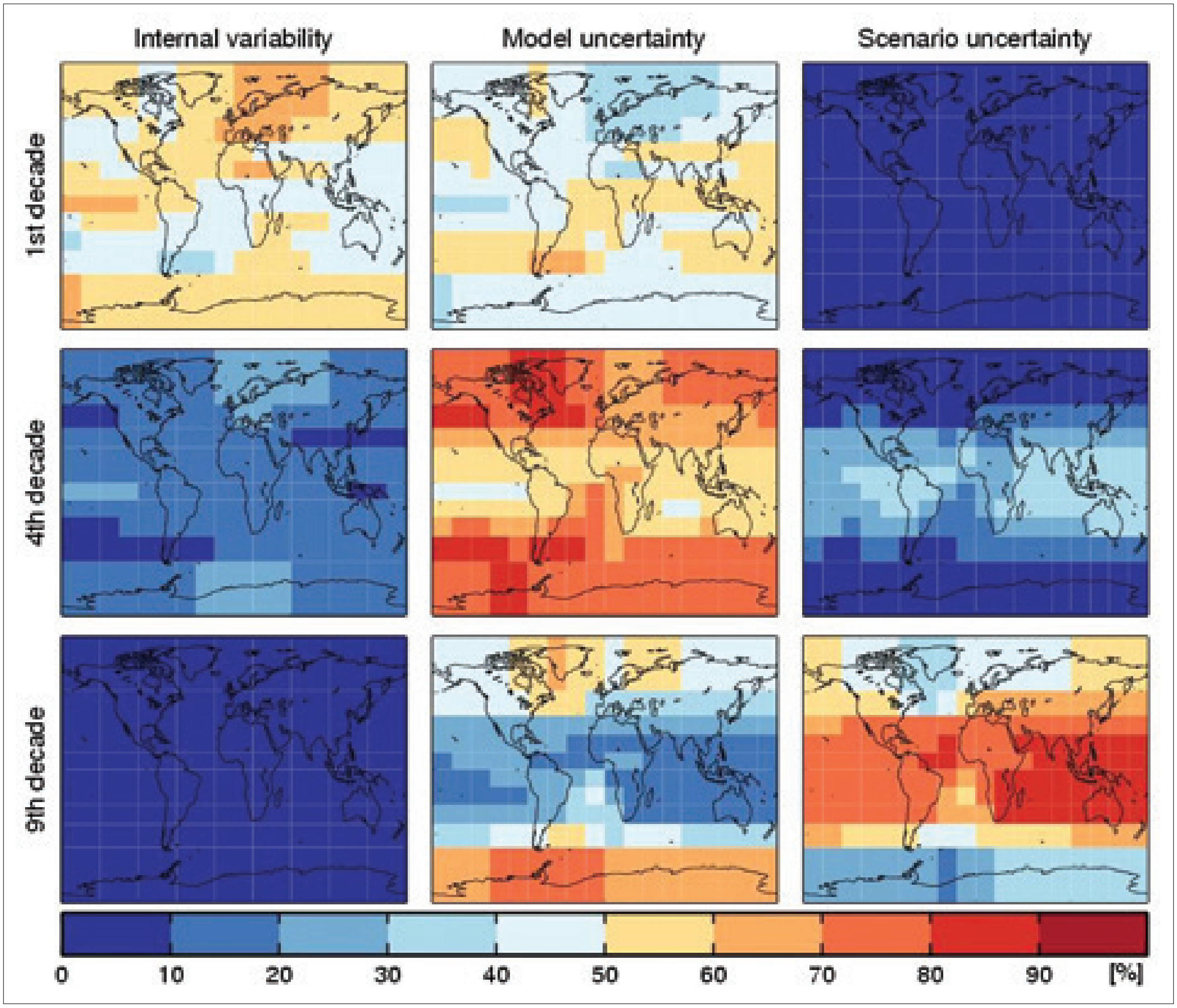


**Figure 4.** Percentage of uncertainty in future temperature projections one decade in the future (top row), four decades in the future (middle row) and nine decades in the future (bottom row) that can be attributed to natural variability (left column), model uncertainty (center column), and scenario uncertainty (right column). Source: Hawkins & Sutton, 2009.

The second source of uncertainty, model or scientific uncertainty, can be addressed by using multiple global climate models to simulate the response of the climate system to human-induced change (here, nine newer CMIP5 and four older CMIP3 models). As noted above, the climate models used here cover a range of climate sensitivity; they also cover an even wider range of precipitation projections, particularly at the local to regional scale.

Again, although no model is perfect, most models are useful. Only models that demonstratively fail to reproduce the basic features of large-scale climate dynamics (e.g., the jet stream or El Niño) should be eliminated from consideration. Multiple studies have convincingly demonstrated that the average of an ensemble of simulations from a range of climate models (even ones of varied ability) is generally closer to reality than the simulations from one individual model--even one deemed "good" when evaluated on its performance over a given region.[30, 31] Hence, wherever possible, impacts should be summarized in terms of the values resulting from multiple climate models, while uncertainty estimates can be derived from the range or variance in model projections. This is why most plots in this report show both multimodel mean values as well as a range of uncertainty around each value.

The third and final primary source of uncertainty in future projections can be addressed through generating climate projections for multiple futures: for example, a "higher emissions" future in which the world continues to depend on fossil fuels as the primary energy source (SRES A1FI or RCP 8.5), as compared to a "lower emissions" future focusing on sustainability and conservation (SRES B1 or RCP 4.5).

Over the next two to three decades, projections can be averaged across scenarios, because there is no significant difference between scenarios over that time frame due to the inertia of the climate system in responding to changes in heat-trapping gas levels in the atmosphere.[32] Past mid-century, however, projections should never be averaged across scenarios; rather, the difference in impacts resulting from a higher as compared to a lower scenario should always be clearly delineated. That is why, in this report, future projections are always summarized in terms of what is expected for each scenario individually.

# Appendix

# List of Bar Graphs for All Climate Indicators

**All temperature values in ˚F, all precipitation values in inches**

## TEMPERATURE INDICATORS

### Annual – Seasonal Temperature Indicators:

#### Maximum Temperatures

- Winter Maximum Temperature
- Winter Maximum Temperature Change
- Spring Maximum Temperature
- Spring Maximum Temperature Change
- Summer Maximum Temperature
- Summer Maximum Temperature Change
- Fall Maximum Temperature
- Fall Maximum Temperature Change
- Annual Maximum Temperature
- Annual Maximum Temperature Change

#### Minimum Temperatures

- Winter Minimum Temperature
- Winter Minimum Temperature Change
- Spring Minimum Temperature
- Spring Minimum Temperature Change
- Summer Minimum Temperature
- Summer Minimum Temperature Change
- Fall Minimum Temperature
- Fall Minimum Temperature Change
- Annual Minimum Temperature
- Annual Minimum Temperature Change

#### Average Temperatures

- Winter Average Temperature
- Winter Average Temperature Change
- Spring Average Temperature
- Spring Average Temperature Change
- Summer Average Temperature
- Summer Average Temperature Change
- Fall Average Temperature
- Fall Average Temperature Change
- Annual Average Temperature
- Annual Average Temperature Change

#### Temperature Range

- Winter Temperature Range
- Spring Temperature Range
- Summer Temperature Range
- Fall Temperature Range
- Annual Temperature Range

#### Standard Deviation of Temperature

- Standard Deviation of Winter Maximum Temperature
- Standard Deviation of Spring Maximum Temperature
- Standard Deviation of Summer Maximum Temperature
- Standard Deviation of Fall Maximum Temperature
- Standard Deviation of Annual Maximum Temperature
- Standard Deviation of Winter Minimum Temperature
- Standard Deviation of Spring Minimum Temperature
- Standard Deviation of Summer Minimum Temperature
- Standard Deviation of Fall Minimum Temperature
- Standard Deviation of Annual Minimum Temperature

## Other Temperature Indicators:

### Temperature Extremes

- Nights with Minimum Temperatures < 20˚F
- Changes in Nights with Minimum Temperatures < 20˚F
- Nights with Minimum Temperatures < 32˚F
- Changes in Nights with Minimum Temperatures < 32˚F
- Days with Maximum Temperatures > 90˚F
- Changes in Days with Maximum Temperatures > 90˚F
- Days with Maximum Temperatures > 95˚F
- Days with Maximum Temperatures > 100F
- Days with Maximum Temperatures > 105˚F
- Days with Maximum Temperatures > 110˚F
- Nights with Minimum Temperatures > 80˚F
- Nights with Minimum Temperatures > 85˚F
- Nights with Minimum Temperatures > 90˚F
- Number of 4+ Day Heat Waves per Year
- Longest Sequence of Days with Maximum Temperatures > 90˚F
- Longest Sequence of Days with Maximum Temperatures > 95˚F
- Longest Sequence of Days with Maximum Temperatures > 100˚F

### Growing Season

- Date of Last Frost in Spring
- Change in Date of Last Spring Frost (days)
- Date of First Frost in Fall
- Change in Date of First Frost in Fall (days)

### Energy-Related Temperature Indicators

- Mean Annual Cooling Degree-Days
- Mean Annual Heating Degree-Days

### Temperature Extreme Percentiles

- Nights with Minimum Temperatures < Historic 1-in-100 Coldest (1 percentile)
- Nights with Minimum Temperatures < Historic 1-in-20 Coldest (5th percentile)
- Days with Maximum Temperatures > Historic 1-in-20 Hottest (95th percentile)
- Days with Maximum Temperatures > Historic 1-in-100 Hottest (99th percentile)

# PRECIPITATION INDICATORS

## Annual – Seasonal Precipitation Indicators:

### Average Precipitation

- Winter Precipitation (inches)
- Winter Precipitation Change (%)
- Spring Precipitation (inches)
- Spring Precipitation Change (%)
- Summer Precipitation (inches)
- Summer Precipitation Change (%)
- Fall Precipitation (inches)
- Fall Precipitation Change (%)
- Annual Precipitation (inches)
- Annual Precipitation Change (%)

### 3-Month Precipitation Change

- January-March 3-Month Precipitation Change (%)
- February-April 3-Month Precipitation Change (%)
- March-May 3-Month Precipitation Change (%)
- April-June 3-Month Precipitation Change (%)
- May-July 3-Month Precipitation Change (%)
- June-August 3-Month Precipitation Change (%)
- July-September 3-Month Precipitation Change (%)
- August-October 3-Month Precipitation Change (%)
- September-November 3-Month Precipitation Change (%)
- October-December 3-Month Precipitation Change (%)
- November-January 3-Month Precipitation Change (%)
- December-February 3-Month Precipitation Change (%)

### 6- and 12-Month Precipitation Change

- January-June 6-Month Precipitation Change (%)
- February-July 6-Month Precipitation Change (%)
- March-August 6-Month Precipitation Change (%)

- April-September 6-Month Precipitation Change (%)
- May-October 6-Month Precipitation Change (%)
- June-November 6-Month Precipitation Change (%)
- July-December 6-Month Precipitation Change (%)
- August-January 6-Month Precipitation Change (%)
- September-February 6-Month Precipitation Change (%)
- October-March 6-Month Precipitation Change (%)
- November-April 6-Month Precipitation Change (%)
- December-May 6-Month Precipitation Change (%)
- January-December 12-Month Precipitation Change (%)

## Other Precipitation Indicators:

### Dry Days

- Annual Average Dry Days per Year
- Change in Dry Days per Year (%)
- Longest Dry Period of the Year (days)
- Change in Longest Dry Period (%)

### Precipitation Indices

- Precipitation Intensity (inches/day)
- Change in Precipitation Intensity (%)
- Standardized Precipitation Index

### Extreme Precipitation

- Days per Year > 0.5"
- Days per Year > 1"
- Days per Year > 2"
- Days per Year > 3"
- Days per Year > 4"
- Days per Year > 5"
- Days per Year > 6"
- Days per Year > 7"
- Days per Year > 8"
- Precipitation on Wettest 1 Day/Year (inches)
- Precipitation on Wettest 5 Days/Year (inches)
- Precipitation on Wettest 2 Weeks/Year (inches)
- Precipitation on Wettest 1 Day in 2 Years (inches)
- Precipitation on Wettest 5 Days in 2 Years (inches)
- Precipitation on Wettest Two Weeks in 2 Years (inches)
- Precipitation on Wettest 1 Day in 10 Years (inches)
- Precipitation on Wettest 5 Days in 10 Years (inches)
- Precipitation on Wettest Two Weeks in 10 Years (inches)
- Days per Year > Historical 2-day Maximum
- Days per Year > Historical 4-day Maximum
- Days per Year > Historical 7-day Maximum
- Percentage of Precipitation Falling as Rain vs. Snow (%)

## HUMIDITY HYBRID INDICATORS

### Dewpoint Indicators

- Winter Dewpoint Temperature (˚F)
- Winter Dewpoint Temperature Change (˚F)
- Spring Dewpoint Temperature (˚F)
- Spring Dewpoint Temperature Change (˚F)
- Summer Dewpoint Temperature (˚F)
- Summer Dewpoint Temperature Change (˚F)
- Fall Dewpoint Temperature (˚F)
- Fall Dewpoint Temperature Change (˚F)
- Annual Dewpoint Temperature (˚F)
- Annual Dewpoint Temperature Change (˚F)

### Relative Humidity

- Average Winter Relative Humidity (%)
- Change in Winter Relative Humidity (%)
- Average Spring Relative Humidity (%)
- Change in Spring Relative Humidity (%)
- Average Summer Relative Humidity (%)
- Change in Summer Relative Humidity (%)
- Average Fall Relative Humidity (%)
- Change in Fall Relative Humidity (%)
- Average Annual Relative Humidity (%)
- Change in Annual Relative Humidity (%)

### Heat Indices

- Summer Heat Index (˚F)
- Change in Summer Heat Index (˚F)
- Number of Hot Dry Days per Year
- Number of Cool Wet Days per Year

### Potential Evapotranspiration

- Winter Potential Evapotranspiration (mm)
- Spring Potential Evapotranspiration (mm)
- Summer Potential Evapotranspiration (mm)
- Fall Potential Evapotranspiration (mm)
- Annual Potential Evapotranspiration (mm)

## Sources
### (Endnotes)


1 Frumhoff, P.C., McCarthy, J. J., Melillo, J. M., Moser, S. C., & Wuebbles, D. J. (2007). *Confronting climate change in the U.S. Northeast: Science, impacts, and solutions.* Synthesis report of the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA: Union of Concerned Scientists (UCS).

2 U.S. Global Change Research Program (USGCRP). (2009). *Global climate change impacts in the United States.* Cambridge University Press. http://www.globalchange.gov/usimpacts/

3 Walsh, J., Wuebbles, D., Hayhoe, K., Kunkel, K., Somerville, R., Stephens, G., … Kennedy, J. (2014). Chapter 2: Our Changing Climate. In: *The Third U.S. National Climate Assessment.* In press.

4 Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., … Taylor, K. E. (2007). The WCRP CMIP3 multi-model dataset: A new era in climate change research. *Bulletin of the American Meteorological Society,* 88, 1383-1394.

5 Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of American Meteorological Society,* 93, 485–498. doi: http://dx.doi.org/10.1175/BAMS-D-11-00094.1

6 Nakicenovi, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S. … Dadi, Z. (2000). Intergovernmental Panel on Climate Change special report on emissions scenarios. Cambridge University Press, Cambridge, U.K.

7 Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P. … Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, 463, 747-756.

8 Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G., & Field, C. B. (2007). Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences,* 104(24), 10288-10293.

9 Myhre, G., Alterskjaer, K., & Lowe, D. (2009). A fast method for updating global fossil fuel carbon dioxide emissions. *Environmental Research Letters,* 4, doi:10.1088/1748-9326/4/3/034012

10 Meinshausen, M., Hare, B., Wigley, T. M. M., Van Vuuren, D., Den Elzen, M. G. J., & Swart, R. (2006). Multi-gas emissions pathways to meet climate targets. *Climatic Change* 75, 151-194.

11 Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., … Taylor, K. E. (2007). Cilmate models and their evaluation. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (Eds.)]. Cambridge University Press, Cambridge, U.K.

12 IPCC. (2007). Summary for policymakers. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (Eds.)]. Cambridge University Press, Cambridge, U.K.

13 Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., … Taylor, K. E. (2007). The WCRP CMIP3 multi-model dataset: A new era in climate change research. *Bulletin of the American Meteorological Society,* 88, 1383-1394.

14 Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of American Meteorological Society,* 93, 485–498. doi: http://dx.doi.org/10.1175/BAMS-D-11-00094.1

15 IPCC. (2007). Summary for policymakers. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (Eds.)]. Cambridge University Press, Cambridge, U.K.

16 Knutti, R., & Hegerl, G. (2008). The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience,* 1, 735-743.

17 Overland, J. E., Wang, M., Bond, N. A., Walsh, J. E., Kattsov, V. M., & Chapman, W. L. (2011) Considerations in the selection of global climate models for regional climate projections: The Arctic as a case study. *Journal of Climate,* 24, 1583-1597.

18 Knutti, R. (2010). The end of model democracy? *Climatic Change,* 102, 395-404.

19 Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., … Taylor, K. E. (2007). Climate models and their evaluation. In: *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (Eds.)]. Cambridge University Press, Cambridge, U.K.

20 Grotch, S., & MacCracken, M. (1991). The use of general circulation models to predict regional climatic change. *Journal of Climate,* 4, 286-303.

21 Stoner, A., Hayhoe, K., Yang, X., & Wuebbles, D. (2012). An asynchronous regional regression model to downscale daily temperature and precipitation climate projections. *International Journal of Climatology,* 33, 11, 2473-2494. Article first published online: 4 October 2012.

22 Koenker, R., & Bassett, G. (1978). Regression quantiles. *Econometrica*, 46, 33-50.

23 Dettinger, M. D., Cayan, D. R., Meyer, M. K., & Jeton, A. E. (2004). Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099. *Climatic Change,* 62, 283-317.

24 Hayhoe, K., Cayan, D., Field, C. B., Frumhoff, P. C., Maurer, E. P., Miller, N. L. … Verville, J. H. (2004). Emission pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences,* 101, 12423-12427.

25 Stoner, A., Hayhoe, K., Yang, X., & Wuebbles, D. (2012). An asynchronous regional regression model to downscale daily temperature and precipitation climate projections. *International Journal of Climatology,* 33, 11, 2473-2494. Article first published online: 4 October 2012.

26 Vrac, M., Stein, M., Liang, X., & Hayhoe, K. (2007). A general method for validating statistical downscaling methods under future climate change. *Geophysical Research Letters,* 34(18).

27 Leathers, D. J., University of Delaware, Office of the Delaware State Climatologist. [personal communication, August, 2013].

28 Durre, I., Menne, M. J., & Vose, R. S. (2008). Strategies for evaluating quality-control procedures. *Journal of Climate and Applied Meteorology,* 47, 1785-1791.

29 Hawkins & Sutton. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of American Meteorological Society,* 90, 1095.

30 Weigel, A., Knutti, R., Liniger, M., & Appenzeller, C. (2010). Risks of model weighting in multimodel climate projections. *Journal of Climate,* 23, 4175-4191.

31 Knutti, R. (2010). The end of model democracy? *Climatic Change,* 102, 395-404.

32 Stott, P., & Kettleborough, J. (2002). Origins and estimates of uncertainty in predictions of twenty-first century temperature rise. *Nature*, 416, 723-725.