2025 NEW JERSEY
SCIENTIFIC REPORT ON CLIMATE CHANGE

December 2025

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

COVER PHOTO: ATLANTIC CITY, NEW JERSEY

December 30, 2025

Fellow New Jerseyans,

We are pleased to present the 2025 New Jersey Scientific Report on Climate Change, an interdisciplinary update to the 2020 edition providing the latest and most reliable scientific information on the existing and projected future impacts of climate change on Garden State residents, businesses, institutions, and the natural and built environments upon which we all rely to sustain our families, communities, and economy. While grounded in the growing body of global, national, regional, and local climate science, this report is specific to New Jersey, the climate impacts we are confronting today, and those we must plan and prepare to confront in the years ahead. The goal of this report is simple: distill and share relevant climate science to inform and empower our fellow New Jerseyans and leaders across the public and private sectors to plan and prepare for the climate realities that affect us here at home in New Jersey.

The most recent and legitimate scientific explorations on the international, national, and state levels all agree, in no uncertain terms, that global atmospheric warming, caused largely by human activities, is leading to significant changes in climate patterns around the world. In New Jersey, we know well that climate change is real, here, and now. Warmer temperatures, rising sea levels, and more frequent and intense storms have become our new normal. We are experiencing increasingly mild winters, greater 'sunny day' coastal tidal flooding, periods of extended drought interrupted by sudden heavy rainfall, prolonged wildfire seasons, and more frequent extreme storms that lead to serious flooding along inland streams and rivers. Unfortunately, these conditions are only expected to worsen in the years ahead.

Climate shocks erode New Jersey beaches and coastlines, undermine critical infrastructure, threaten public health and safety, and damage and even destroy residential and commercial property. As documented in the 2025 report on the Economic Risks of Climate Change in New Jersey report, climate threats also wreak long-lasting economic damage. Indeed, parts of New Jersey continue to recover from Tropical Storm Ida of 2021, which demonstrates the cascading and long-lasting climate-related shocks that reverberate across New Jersey's local economies.

As our climate continues to change, it is vital that New Jerseyans understand what impacts are likely to occur, and when. By working together, we can plan for and adapt to those changes, helping to keep our communities safe and the economy strong. New Jersey's commitment to these issues as well as our leadership on climate science positions us well to prepare for a safe and vibrant economic future. We are fortunate that some of the best scientists and scientific institutions in the world call New Jersey home, and we thank them for contributing their expertise, data, and projections to this interdisciplinary report.

As the science and experience of climate change continues to evolve, DEP remains firmly committed to monitoring new developments and updating this report and other technical resources including the Climate Change in New Jersey: Impacts and Effects website. Together, informed by sound science and a willingness to make tough choices, we will build a more climate resilient New Jersey, secure and strengthen our economy, and protect the State and communities we love for future generations.

Onward,

Shawn M. LaTourette, Commissioner
New Jersey Department of Environmental Protection

ACKNOWLEDGMENTS

Development of this report would not have been possible without the contributions of many people within the New Jersey Department of Environmental Protection (DEP) and colleagues from other state agencies, including the Department of Health, the Department of Agriculture, and the Department of Human Services. Thank you to all the contributing authors for the content they developed and thank you to everyone within the DEP who provided guidance and support through the many phases of the report's development.

The Scientific Report includes a vast amount of knowledge on an extensive list of topics; however, it does not include all the available data, literature, and research and does not represent an inclusive list of all the areas that will be impacted by climate change. Any errors found within the report are the responsibility of the editors.

This work was made possible with financial assistance from the New Jersey Department of Environmental Protection and through the Coastal Zone Management Act of 1972, as amended, as administered by the Office of Coastal Management, National Oceanic and Atmospheric Administrator's Program through the New Jersey Department of Environmental Protection, Coastal Management Program.

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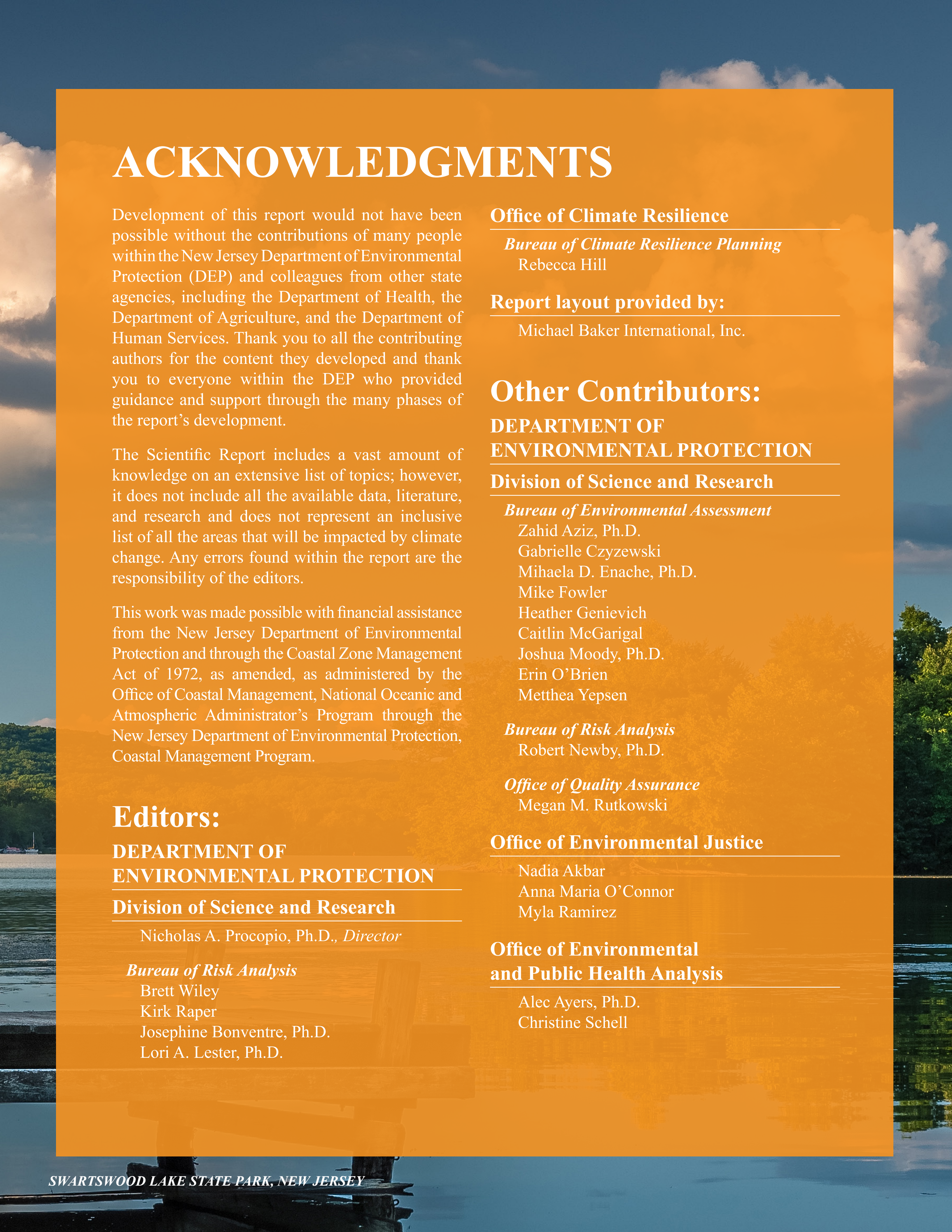

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Recommended Citation:
New Jersey Department of Environmental Protection. 2025. New Jersey Scientific Report on Climate Change. (Eds. B. Wiley, K. Raper, J. Bonventre, R. Hill, L.A. Lester, N.A. Procopio). Trenton, NJ. 275 pp.

EXECUTIVE SUMMARY

MOUNT TAMMANY, WARREN COUNTY, NEW JERSEY

Executive Summary

The New Jersey Department of Environmental Protection's 2025 Scientific Report on Climate Change summarizes the current state of knowledge regarding the effects of climate change on New Jersey's environment. This report collects the best available science and existing data regarding the current and anticipated environmental effects of climate change globally, nationally, regionally, and locally to present New Jersey-specific information to inform state and local decision-makers as they understand and respond to its impacts. These impacts are significant and wide-ranging, requiring a comprehensive and forward-thinking response by all levels of government, economic sectors, communities, and populations.

> ***"An atmosphere of that gas [carbon dioxide] would give to our earth a high temperature."***
> – Eunice Newton Foote, 1856

This updated Scientific Report is divided into seven chapters, in an effort to properly cover the issues relevant to New Jersey (see Table of Contents for complete layout). The report provides the latest data summaries available and introduces new sections on freshwater invertebrates and marine phytoplankton. New studies have been integrated into the narrative, including New Jersey-specific studies on precipitation, groundwater, and heat waves, among others. In addition, the most recent sea-level rise projections for New Jersey, published in November 2025, and the contents from the 2022 addendum, Climate Change Impacts on Human Health & Communities, have been integrated into this report in Chapters 4.3 and 6, respectively.

This report references four primary greenhouse gas emission scenarios:

- Low emission scenario (SSP1-2.6; RCP 2.6) – Global emissions of greenhouse gases are dramatically reduced (resulting in 2.9°F [1.6°C] by 2100); carbon dioxide (CO_2) emissions decline to net zero around 2070, followed by net negative emissions.
- Intermediate emission scenario (SSP2-4.5; RCP 4.5) – CO_2 emissions remaining around current levels until the middle of the century (corresponds with 4.7°F [2.6°C] by 2100), approximately consistent with interpretations of current global policy (as of November 2024), with global emissions slowly rising to about mid-century and then declining.
- High emission scenario (SSP3-7.0) – CO_2 emissions roughly double from current levels by 2100 (resulting in 6.8°F [3.8°C] by 2100), continued emissions growth throughout the century.
- Very High emission scenario (SSP5-8.5; RCP 8.5) – CO_2 emissions roughly double by 2050 (resulting in 8.5°F [4.7°C] by 2100), sustained growth in fossil fuel use at rates comparable to those of the 1990s and 2000s.

GREENHOUSE GASES

KEY FINDINGS:

- *As global CO_2 emissions continue to increase so will the anticipated increases in global temperature.*
- *From 1950 to 2023, the United States was the world's largest producer of CO_2 emissions, accounting for about 85% of CO_2 emissions in North America and 22% globally.*
- *Nationally, total emissions decreased 17% -- from 6,587 million metric tons carbon dioxide equivalent ($MtCO_2e$) in 2005 to 5,489 $MtCO_2e$ in 2022.*
- *In New Jersey, total emissions decreased 20% -- from 126.5 million metric tons carbon dioxide equivalent ($MtCO_2e$) in 2006 to 105.7 $MtCO_2e$ in 2022.*
- *New Jersey continues to reduce the state's greenhouse gas emissions through solar and other renewable sources of energy, which now provide 11% of in-state generation, up from less than 2% in 2006.*
- *Transportation has consistently been the largest source of emissions in New Jersey over the past 17 years but has recently experienced small reductions due to stringent vehicle emissions and fuel efficiency standards.*

Climate change is driven by increases in atmospheric levels of greenhouse gas concentrations and as these levels increase, additional heat is absorbed by Earth's atmosphere. Human activities, particularly the emissions of heat trapping greenhouse gases from the burning of fossil fuels and land use changes like deforestation, have increased atmospheric CO_2 concentrations by more than one third since the early 1900s and are now the primary driver of climate change. At the start of the Industrial Revolution, CO_2 levels were about 280 parts per million (ppm). Average annual CO_2 levels exceeded 400 ppm for the first time in 2016, and then surpassed 420 ppm in 2024, as reported at the National Oceanic and Atmospheric Administration's (NOAA) Mauna Loa Observatory. Given the role of CO_2 as a greenhouse gas, an increase of this magnitude is expected to result in an unprecedented increase in global temperature. The magnitude of this increase will primarily depend on global emissions of greenhouse gases and how Earth's climate system responds to this human-induced warming.

As atmospheric levels of CO_2 and other greenhouse gases increase, New Jersey will experience significant direct and secondary changes in its environment, including increases in:

- Temperature
- Variability in precipitation
- Frequency and intensity of storms
- Sea-level rise
- Ocean acidification
- Associated impacts to ecological systems, natural resources, human health, and the economy

New Jersey is acting to reduce in-state emissions of greenhouse gases and other climate pollutants. For example, the State continues to establish policies to reduce emissions from stationary and mobile sources while expanding its renewable energy resources. This has helped the state achieve a 2.6% average annual decrease in emissions in the energy sector since 2006 (NJDEP 2025a). More information about New Jersey's actions to meet its climate and energy goals can be found in the Global Warming Response Act 80x50 Progress Reports, and the 2024 Energy Master Plan (EMP).

TEMPERATURE

KEY FINDINGS:

- *New Jersey continues to warm faster than the rest of the Northeast region and the world.*
- *Since 1895, New Jersey's annual temperature has increased by 4.1°F.*
- *Average annual temperatures in New Jersey are projected to increase by 3.7–6.2°F by 2100.*
- *New Jersey is experiencing more frequent and hotter heat waves.*

While the Earth's surface has warmed by approximately 2.6°F (1.4°C) since the late 19th century, the warming trend has accelerated in recent decades, with 2023 and 2024 being the warmest years on record. Each year from 2015 to 2024 has individually ranked among the ten warmest years ever recorded. Globally, ocean heat content reached a record high in 2025, and sea surface temperatures have hit record highs in the tropical and North Atlantic, the tropical Indian Ocean, sections of the western Pacific, and parts of the Southern Ocean. In the United States, the Northeast has experienced temperature increases between 1°F and 3°F since 1901 and is projected to warm by 3.6°F (2°C) over the pre-industrial (1850-1900) average by 2035, regardless of future emissions.

New Jersey is warming faster than both the global and regional averages, with a 4.1°F (2.3°C) rise in average annual temperature from 1895 to 2024. Winters are warming nearly twice as fast as summers, and 15 of the state's 20 warmest years have all occurred since 2000. The frequency of heat waves has increased, while nighttime temperatures during these events have warmed, reducing the opportunity for overnight cooling. Urban areas in New Jersey are especially vulnerable due to the heat island effect caused by dense infrastructure and limited green space. Looking ahead, New Jersey is projected to warm by 3.7–6.2°F under an intermediate emission scenario (SSP2-4.5) and 5.8–8.6°F under a high emission scenario (SSP3-

7.0) by 2100. This continued warming is expected to intensify heat waves, reduce the number of freezing days, and increase risks to public health, infrastructure, and ecosystems.

PRECIPITATION

KEY FINDINGS:

- *Annual precipitation in New Jersey has increased by 2.8 inches per century since 1895.*
- *Annual precipitation in New Jersey is expected to increase by an average of 6 to 7% by 2100.*
- *The intensity and frequency of precipitation events have increased and are expected to continue increasing due to climate change.*
- *By the end of the century, the amount of precipitation that occurs during a 1% storm is expected to increase across the state, but most notably by 20% to 25% in northern counties.*
- *Droughts may occur more frequently due to the expected changes in precipitation patterns.*
- *The size and frequency of floods will increase as annual precipitation increases.*
- *Tropical storms have the potential to increase in intensity due to the warmer atmosphere and warmer oceans that will occur with climate change.*

As temperatures increase, Earth's atmosphere can hold more water vapor which leads to a greater potential for precipitation. A warmer atmosphere means storms have the potential to be more intense and occur more often. Currently, New Jersey receives an average of 46 inches of precipitation each year. Analysis of statewide annual precipitation data from 1895 to 2024 shows an increasing rate of 6.2% per century (2.8 inches per century). By 2100, annual precipitation in New Jersey could increase by 6% to 7%.

The amount and timing of precipitation events is expected to become increasingly variable, resulting in greater potential for more frequent and prolonged dry periods and increases in the number of flood events. In New Jersey, extreme precipitation amounts have already increased at most weather stations by 2.5% or more, with 100-year storms increasing by more than 10% in some places. Precipitation intensity is projected to increase over time throughout the state, including more intense rain events, less snow, and more rainfall, with the largest increases in northern counties. Projections under an intermediate emission scenario (RCP 4.5) indicate a 50% chance that 100-year, 24-hour storms will increase in amounts of up to 22% in some counties and a 17% chance of increasing by up to 50%.

In New Jersey, extreme storms typically include coastal nor'easters, snowstorms, spring and summer thunderstorms, tropical storms, and on rare occasions hurricanes. Most of these events occur in the warmer months of the spring, summer, and fall, with nor'easters occurring between September and April. From 1958 to 2021, storms that resulted in the heaviest 1% of daily events have increased in amounts by 60%, which is greater than anywhere else in the United States. As temperatures increase so will the energy in a storm system, increasing the chance for more intense tropical storms, including those reaching Category 3, 4, and 5.

SEA-LEVEL RISE

KEY FINDINGS:

- *Sea levels are rising in New Jersey more than two times faster than the global average.*
- *By 2050, there is a 50% chance that sea-level rise will meet or exceed 1.3 feet and a 17% chance it will meet or exceed 1.7 feet. Those levels are projected to increase to 2.9 and 3.8 feet by the end of the century.*
- *The inclusion of rapid ice sheet loss processes increase estimated sea-level rise projections to 1.9 feet by 2050, 2.8 feet by 2070, and 4.5 feet by 2100.*

- *The rate of sea-level rise is likely to increase from the current rate of 0.2 inches/year up to 0.46 inches/year by mid-century and up to 0.56 in/yr by late century.*
- *"Sunny day flooding" will occur more often across the entire coastal area of New Jersey due to sea-level rise.*
- *It is extremely likely that Atlantic City will experience "sunny day flooding" 131 days a year, and a 50% chance it will experience 326 days a year, by 2100.*

Flooding caused by more intense rain events and storms will be exacerbated in the coastal area by rising sea levels. In New Jersey, sea levels are rising faster than the global and regional averages due to changes in the Gulf Stream, localized land subsidence, and continued geologic influences as land slowly adjusts to the loss of the North American ice sheet at the end of the last ice age. Prior to the industrial revolution, rates of sea-level rise in New Jersey are estimated at about 0.08 inches per year (2 mm/yr). In Sandy Hook, Atlantic City, and Cape May, the rate of sea-level rise has been approximately 0.17, 0.17, and 0.2 inches per year, respectively, since records began in the 20th century. The rate of sea-level rise has increased over more recent intervals. For example, the recent rate of sea-level rise from 1993-2021 for Atlantic City was 0.2 inches per year (5 mm/yr). The rate of sea-level rise will continue to increase, with the amount of greenhouse gases emitted tied to future rates.

Updated 2025 New Jersey-specific sea-level rise scenarios are available with projected increases relative to the year 2005. By 2050, New Jersey will likely experience a 0.9 to 1.7-foot increase (all emission scenarios), 1.5 to 2.5-foot increase by 2070 (intermediate emission scenario [SSP2-4.5]), and potentially a 2.2 to 3.8-foot increase by 2100 (intermediate emission scenario [SSP2-4.5]). An extended likely range is considered separately, which incorporates the potential for devastating rapid ice sheet loss processes in modeling, resulting in estimated sea-level rise under an intermediate emission scenario (SSP2-4.5) of up to 1.9 feet by 2050, 2.8 feet by 2070, and 4.5 feet by 2100.

Understanding how sea-level rise will change in the future is vital to New Jersey's coastal zone because low-lying coastal areas are already experiencing tidal flooding, even on sunny days in the absence of precipitation events. In Atlantic City, tidal flooding events have already increased from happening less than once per year in the 1950s to an average of twelve times per year between 2007 and 2024. By 2100, under an intermediate emission scenario (SSP2-4.5), it is extremely likely (greater than a 95% chance) that high-tide flooding will occur in Atlantic City at least 131 days a year with a 50% chance it will occur 326 days per year.

OCEAN ACIDIFICATION

KEY FINDINGS:

- *Since the start of the Industrial Revolution, ocean pH levels have declined, and the ocean is now 30% more acidic.*
- *If CO_2 emissions continue at current rates, ocean pH levels are expected to fall, creating an ocean that is more acidic than has been seen for the past 20 million years.*
- *Southern New Jersey counties rank second in the United States in economic dependence on shelled mollusks, which will suffer from increasing ocean acidity.*

New Jersey will not only be impacted by higher reaching tides, but also by the chemistry of the ocean as the CO_2 concentration increases. CO_2 is not only detrimental as a greenhouse gas, but also for its role in ocean acidification. In the most basic terms, CO_2 dissolves in seawater, beginning a chain reaction leading to more acidic conditions.

Since the Industrial Revolution, the ocean has become 30% more acidic and ocean pH levels will continue to decline along the coast of New Jersey. In response to this increase in acidity, shellfish and coral species will build weaker shells. Ocean acidification also affects the success of hatching, larval development, organ development, immune response, metabolic processes, and olfaction (smell) in marine species.

New Jersey is at increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests, with southern New Jersey counties ranking second in the United States in economic dependence on shelled mollusks. While New Jersey is not predicted to see unfavorable acidification conditions for shellfish until 2100, given the state's dependence on shellfish resources, there will be high social and economic impacts.

AIR QUALITY

Key Findings:

- *A warming climate contributes to an increase in air pollution, despite the numerous measures to reduce ground-level ozone precursors and other sources of air pollution.*
- *Increases in air pollution will reduce visibility, damage to crops and forests, and adversely impact human health.*

As temperature, precipitation, sea-level rise, and ocean acidification increase, so will the impacts to New Jersey's air, water, habitats, and wildlife. Despite on-going efforts to reduce emissions that lead to ground-level ozone, New Jersey's air quality will be negatively affected by changes in meteorological conditions, a phenomenon often called the ozone-climate penalty, which refers to the worsening of air quality as a result of a warming climate. Impacts of ground-level ozone, as well as particulate matter, will be particularly high for dense urban areas. In addition, increases in wildfires, both locally and across the continent, can lead to the release of $PM_{2.5}$ and ozone precursors that can be transported long distances and impact air quality far from the source. As concentrations of ground-level ozone and particulate matter increase, New Jersey is likely to experience an increase in the human health impacts attributed to both.

WATER RESOURCES: SUPPLY AND QUALITY

Key Findings:

- *Water supplies will be stressed from the increase in the growing season and extreme temperatures expected due to climate change.*
- *Rising sea levels may lead to increased saltwater intrusion in New Jersey aquifers where wells are over pumped.*
- *Freshwater intakes and aquifer recharge areas may be threatened if sea-level rise pushes the salt front further upriver.*
- *Communities with aging combined sewer infrastructure may be further challenged as sea-level rise and/or increased rain events submerge discharge points that are currently above the waterline.*
- *Surface and groundwater quality will be impaired as increased nutrients and contaminants enter waters due to runoff from more intense rain events.*
- *Climate change impacts, such as warmer temperatures, create favorable conditions for cyanobacteria blooms, which can produce toxins affecting water quality.*

Climate change is significantly impacting water resources in New Jersey by altering critical factors such as temperature, precipitation, and sea-level rise. These changes are affecting both the availability and quality of water across the state.

Groundwater, which supplies 30% of New Jersey's water needs, is particularly vulnerable. Changes in precipitation and rising temperatures are altering recharge rates, potentially leading to shifts in groundwater availability and quality. While some model projections indicate more water will be available for groundwater recharge in 2050 than in the 1990s, other studies have concluded that with increased precipitation, evapotranspiration will increase due to more plant growth resulting in less recharge. Additionally, increased storm intensity may result in greater percentages of precipitation running off rather than recharging. There is also a heightened risk of saltwater intrusion into coastal aquifers due to sea-level rise and increased groundwater pumping, which threatens freshwater supplies in these areas.

Surface water, which accounts for 70% of the state's water use, faces challenges from increased variability in streamflow patterns. This variability is driven by more frequent and intense precipitation events, which can lead to both flooding, and conversely, periods of low flow due to flash droughts. Such changes can stress reservoir systems that are crucial for managing water supply, making it essential to enhance management strategies to handle future variability and potential shortages. Additionally, models show that with 1.0 meter (3.3 feet) of sea-level rise the salt front moves to river mile 100, the point reached at the height of the drought in the 1960s, and with 1.6 meters (5.2 feet) it moves to river mile 104, about six miles from the drinking water intakes.

Water quality is also at risk due to climate change. Increased precipitation and storm events can lead to higher nutrient loads and sedimentation in waterways, degrading water quality and impacting aquatic ecosystems. Stormwater management systems will likely need to be upgraded to handle more intense rainfall and prevent flooding and pollution.

Additionally, climate change is exacerbating the risk of harmful algal blooms (HABs) in New Jersey's water bodies. Warmer temperatures and increased nutrient inputs create favorable conditions for the growth of cyanobacteria, leading to more frequent and prolonged HABs. These blooms degrade water quality and pose health risks to the public, necessitating increased monitoring and management efforts.

UPLAND FORESTS

KEY FINDINGS:

- *Upland forests in low-lying coastal areas are vulnerable to the impacts of sea-level rise, storm surge, and saltwater intrusion, which can cause a direct loss of forested land area.*
- *Pests opportunistic in warmer temperatures are expected to disperse and adversely affect forest resources. The persistence of the Southern pine beetle in New Jersey represents an early example of the destruction of invasive pests that can occur due to climate change impacts.*
- *Wildfire seasons are likely to be lengthened and occur outside typical seasons.*
- *The frequency of large fires may increase due to hotter and longer dry periods.*

Climate change is expected to bring changes to New Jersey's forests, wetlands, terrestrial, freshwater, and marine systems. Upland forests are likely to be stressed by rising temperatures, instances of drought, and the increased disturbances from insects and disease. This stress is expected to be amplified by the non-climate stressors that forests already face from human decisions, increasing forest density, and the competition for limited resources.

As New Jersey's climate becomes more similar to southern conditions and temperature zones shift northward, more stress will be placed on the moisture tolerant species, like maples, in New Jersey forests, whereas the drought tolerant species, like oaks and pines, will be better suited for these changes. Additionally, upland forests in low-lying coastal areas are vulnerable to the impacts of sea-level rise which can cause a direct loss of forested land area, as well as storm surge and saltwater intrusion which can create conditions to which forests are intolerant, creating "ghost forests".

Pest species are expected to take advantage of warmer temperatures and disperse into forests that have not before experienced the pressure of these pests. New Jersey pine forests will specifically be impacted by the invasive southern pine beetle. This beetle has the potential to kill tens of thousands of acres as thermal controls move north. Other pests are likely to experience range shifts, increased vigor, and increased impact to New Jersey forests due to climate change. Additionally, forests will be more stressed from the impacts of climate change, allowing pests and disease to more easily spread, increasing tree mortality.

New Jersey forests could also experience impacts from a longer wildfire season, fires that may occur outside of the typical season, and increased occurrence of large fires. Climate change conditions and more impactful insect infestations lead to an increased likelihood of tree stress and mortality, providing an increased fuel source for wildfires. As development expands into wildland areas, including forests, the risk of wildfire will continue to increase across the state. Of particular concern is the Pinelands area of southern New Jersey which is the most susceptible to forest fire and has a tremendous propensity towards burning.

WETLANDS

KEY FINDINGS:

- *Some freshwater wetlands may be lost due to inundation with saltwater.*
- *An estimated 61% of monitored tidal wetlands in New Jersey are not gaining elevation at a rate that is greater than or equal to recent rates of sea-level rise. Thus, some are expected to be lost to increasing rates of sea-level rise over time.*
- *Increased flooding and salinity are projected to lead to a loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100.*
- *Atlantic white cedar, a globally rare species, is expected to lose habitat in New Jersey because of rising sea levels.*

New Jersey's freshwater and coastal wetlands are vulnerable to the effects of climate change which will impact the functions and ecosystem services they provide.

Freshwater wetland ecosystems are expected to be affected by increases in salinity from rising sea levels and alterations to hydrology from climate change effects (e.g., flooding, drought). As a result, some freshwater wetlands may be lost or substantially altered. Saltwater inundation has already caused New Jersey to experience "ghost forests," or stands of dead trees, surrounded by transitional marshes. Atlantic white cedar, a globally rare species, grows in low-lying coastal areas but is completely intolerant of saltwater, making it extremely susceptible to rising seas and is expected to continue to lose habitat in New Jersey.

Tidal wetlands are already being negatively impacted by current rates of sea-level rise, and 61% of monitored salt marshes in the state are not gaining elevation at a rate that equals or exceeds recent rates of local sea-level rise, indicating substantial vulnerability. In response to increased flooding, high salt marsh habitat shifts towards low marsh ecosystems, giving way to species that are more resilient to sea-level rise. This is expected to lead to the loss of habitat for species like ribbed mussels and crabs, and the eventual conversion of marsh habitat to mud flats and open water.

While it is possible for marshes to migrate inland as sea-levels rise, 29% of potential migration areas in New Jersey are blocked by roads and other development. Increased flooding, salinity, and sea-level rise may lead to the loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100.

TERRESTRIAL CARBON SEQUESTRATION

KEY FINDINGS:

- *The loss of coastal wetland and forest habitats to climate change will result in carbon losses and increase New Jersey's net greenhouse gas emissions.*

Wetland and forest habitats are carbon sinks that serve as an important component of New Jersey's mitigation of greenhouse gas emissions. The sequestration ability of New Jersey forests and wetlands is threatened by sea-level rise and other climate change factors such as the southern pine beetle. Forests killed by beetles will regrow and over time will adapt in response to this disturbance, but this regrowth and adaptation is a long process and the carbon losses from such an event will cause forests to become a net carbon emitter.

TERRESTRIAL SYSTEMS

KEY FINDINGS:

- *Climate change is likely to further facilitate expansion of invasive plant species.*
- *29% of New Jersey's bird species are vulnerable to climate change, including the American Goldfinch which is the state bird of New Jersey.*
- *Saltmarsh Sparrows, a globally endangered species, may reach quasi-extinction population numbers by 2040 due to habitat loss from sea-level rise.*
- *Many insect species, including ones that are listed as Species of Greatest Conservation Need, will experience range shifts towards the poles as temperatures increase.*

Changes to New Jersey habitats will impact many plant and animal species.

New Jersey is home to more than 2,000 native plant species, several globally rare communities such as sea-level fens and Atlantic white cedar, a little over 860 rare or endangered species, and several plant species such as Hammond's yellow spring beauty and bog asphodel which are found nowhere else in the world. Warmer temperatures will push plants to flower earlier, will not provide needed periods of cold weather, and will likely result in declines in reproductive success of plant and pollinator species. Unique habitats like the maritime forests found on New Jersey's barrier islands and endangered species like the Nantucket serviceberry are the most vulnerable to sea-level rise.

Bird species are good indicators of ecological change and are early responders to climate change threats. According to the Audubon Society, 29% of New Jersey's 248 bird species are vulnerable to climate change, including the American Goldfinch which is the state bird of New Jersey. Shorebirds like Red Knots and Saltmarsh Sparrows are more highly vulnerable to climate change than other bird species because they migrate, breed, or winter in areas that will be severely affected by climate change such as the low-lying, coastal areas of New Jersey. Saltmarsh Sparrows, a globally endangered species, may reach quasi-extinction population numbers by 2040 because of habitat loss from sea-level rise.

Moreover, climate change related changes to temperature regimes are pushing many northern species of insects out of the southern edge of their range in New Jersey, particularly in the northern part of the state. For example, New Jersey has recently lost several species of listed, Species of Greatest Conservation Need, and rare butterflies to the northern retreat of their range. Spotted lanternflies will likely continue to extend their range throughout the Northeastern and Southeastern United States as temperatures continue to warm. Conservation managers will need to allow for more fluidity as the spatial distribution of animal species changes.


DELAWARE WATER GAP, NEW JERSEY

FRESHWATER SYSTEMS

Key Findings:

- *Freshwater fish, like brook trout, that need cold-water habitats are expected to lose habitat as water temperatures increase due to climate change.*
- *As waters warm, New Jersey's waterways are becoming more hospitable to invasive fish species.*
- *As sea level rises, saltwater intrusion of coastal freshwater lakes can result in fish kills.*
- *Reptiles with temperature-dependent sex determination could experience changes in sex ratios as New Jersey temperatures increase.*
- *Many species of freshwater invertebrates will be affected by changes in the water cycle and decreasing habitat availability due to climate change.*

Freshwater fish will also be impacted by climate change. Fish, like the brook trout, that require cold water habitats are expected to lose habitat as water temperatures increase and will be replaced by warmer-water tolerant fish. Accounts of New Jersey trout streams are already showing this cold-to-warm-water tolerant species shift and most current cold-water fisheries are projected to be warm-water fisheries by 2100 regardless of greenhouse gas emission scenario. In addition, droughts will likely promote crowding, increased competition, physiological stress, and mortality for freshwater fish populations. As waters warm and flow patterns become altered, invasive species such as the northern snakehead and flathead catfish, already established and expanding their range in New Jersey, have a distinct advantage. Coastal freshwater lakes are being significantly impacted by saltwater intrusion, which can result in fish kills.

Reptile and amphibian populations in New Jersey may experience shifts in distribution, range, reproductive ecology, and habitat availability. Increased temperatures could lead to changes in mating, nesting, reproductive, and foraging behaviors of species, including a change in the sex ratios in reptiles with temperature-dependent sex determination. Increased storms and extreme temperatures could contribute to unusual mass mortality and cold stunning events in diamondback terrapins. An increase in droughts throughout New Jersey will decrease the availability of freshwater habitats such as vernal ponds for amphibians, and sea-level rise may further decrease the amount of available habitat.

Many species of freshwater invertebrates will be affected by increased temperature, altered precipitation patterns, and rising sea level. For example, one recent study of 15 species of dragonflies in the Northeast found that climate change would decrease habitat availability for all 15 species by 2080. If climate change impacts result in the reduction of invertebrate abundances and diversity as some studies have indicated, it could be expected to cause reductions in numerous ecosystem services and to reduce the availability of food sources for numerous other species.

MARINE SYSTEMS

Key Findings:

- *Current climate changes could result in more "dead zones" from hypoxic events, which are of particular concern for summer flounder which is commonly fished in New Jersey.*
- *Many commercially important shellfish species including mussels and oysters will develop thinner and frailer shells due to ocean acidification.*
- *As temperatures increase, environmental conditions in New Jersey estuaries may improve for invasive species like the clinging jellyfish.*
- *The effects of climate change will reduce available habitat for submerged aquatic vegetation.*

New Jersey's marine mammal populations will be impacted by the shift in distribution of prey sources due to the ocean warming. Finfish will be impacted through shifts in species spatial distribution, altered food availability, decreased survival due to changes in acidity and dissolved oxygen levels, and loss of habitat.

Profitable fisheries could experience declines as water quality changes in bays and estuaries, potentially impacting some recreationally fished species in New Jersey. Summer flounder and black seabass may be impacted as the potential for hypoxic events increase in New Jersey. New Jersey's shellfish industry will be impacted as shellfish species, including mussels and oysters, develop thinner and frailer shells due to ocean acidification.

New Jersey is likely to experience the spread of non-native and invasive plant and animal species if new climates and habitats allow them to outcompete native species and rapidly reproduce and adapt. Clinging jellyfish serve as an example where climate change improved environmental conditions for an invasive species. Similarly, fisherman are now reporting fish species like sheepshead, cobia, and triggerfish earlier in the year and with increasing regularity. These species were once late summer visitors to New Jersey waters.

The effects of climate change can also have major implications on rooted aquatic plants, known as submerged aquatic vegetation, by increasing metabolic stressors and altering distributions throughout the state. Submerged aquatic vegetation meadows also serve as a mechanism to capture and store CO_2, sequestering oceanic organic carbon. Climate change will cause submerged aquatic vegetation habitats to experience changes in distribution, productivity, and structure.

The potential impacts of climate change on marine phytoplankton are a new update to this report. As the thermal dynamics of New Jersey's coast change, so will the population size and habitat distributions of marine phytoplankton.

HUMAN HEALTH, AGRICULTURE, AND COMMUNITIES

Key Findings

- *The extreme weather events predicted for New Jersey, including heat waves and heavy precipitation, can lead to both immediate and long-term effects on cardiovascular, respiratory, and gastrointestinal systems, as well as on mental health and behavior.*
- *Climate change is anticipated to worsen air quality from both natural and human-made sources, which may lead to greater instances of cardiovascular disease, respiratory illnesses, and cancers in vulnerable populations.*
- *Climate impacts are threat multipliers, worsening the population's pre-existing and chronic health conditions such as asthma and cardiovascular diseases. Consequences of climate change in human health are not restricted to physical problems, such as respiratory and cardiovascular disease, but also have a tremendous impact on mental health, lives lost and individuals harmed, and housing and the built environment.*
- *Infectious diseases spread by arthropods, insects, and microbial contamination of food and water supplies are expected to become more prevalent as climate change increases the environmental conditions that are more favorable for pathogens and their hosts.*
- *The productivity of crops and livestock are expected to change due to climate-induced changes in temperature and precipitation patterns.*
- *New Jersey may become unsuitable for specialty crops like blueberries and cranberries in the future as higher temperatures reduce necessary winter chill periods.*

- *Population displacement because of sea-level rise, flooding events, and resource insecurity may add to the cumulative detrimental effects of climate change on mental health as individuals cope with the environmental and personal consequences of climate change.*
- *Climate change is increasingly an environmental justice issue, as overburdened communities bear the brunt of the crisis.*

Changes in temperature, precipitation, sea-level rise, and extreme weather can directly and indirectly lead to detrimental effects on human health, agriculture, and New Jersey communities.

Adverse health effects include acute and chronic cardiovascular and respiratory conditions; vector-, food-, and waterborne diseases; resource insecurity; economic hardship; community displacement; and can contribute to negative mental health conditions. The climate crisis disproportionally harms vulnerable populations (e.g., children, elderly, and the chronically ill) and households that are economically and socially disadvantaged. It is anticipated that the effects on the human population will be significant, and the strain on existing infrastructure, including medical and public health services, will grow. Severe storms and extreme temperatures will affect agricultural production, threatening food supplies. Flooding and sea-level rise will decrease water quality as well as adversely impact agriculture. Pollution from wildfires and ground level ozone will diminish air quality. Pathogens, through various mechanisms, are anticipated to become a greater public health concern.

These changes may limit the use of water supplies for some industrial, agricultural, or recreational uses. This is of particular concern to New Jersey's agriculture sector which may be impacted by a longer growing season, wetter conditions in the early season, delayed spring plantings, warmer and drier conditions mid-season, and increased need for irrigation to sustain the health of crops, pastureland, and livestock. New Jersey crops and livestock may see a decrease in growth and productivity due to increased dry spells, heat waves, and sustained droughts. The productivity of New Jersey dairy cows is predicted to reduce resulting in loss to the industry. By mid-century, New Jersey may become unsuitable for blueberries and cranberries. New Jersey farmers will increase use of pesticides as agricultural pests and weeds will move northward, resulting in additional environmental concerns.

Climate change will act as a threat multiplier for Environmental Justice communities, exacerbating existing stressors such as air pollution while adding new threats such as infectious diseases. These communities are also more vulnerable to the effects of extreme weather events, as they may lack adequate infrastructure, health, income, and resources to prepare for and recover from natural disasters. Food insecurity is worsened by climate injustices, which increase the already high frequency of chronic illnesses in impoverished areas.

Importantly, these factors will not be isolated, but rather, will be a collective challenge to our ways of living. Understanding how these challenges posed by climate change threaten human health and communities is essential to establishing strategies and environmental and public health policies that can effectively and equitably protect and improve health outcomes.

Science Informs Policy

As described above, New Jersey is experiencing many challenges as the climate shifts and will continue to experience more.

In 2021, consistent with the information summarized in this scientific report, the New Jersey Department of Environmental Protection, as part of the Interagency Council on Climate Resilience, released the Statewide Climate Change Resilience Strategy. This policy framework promoted immediate and long-term adaptation and resilience strategies to protect New Jersey's natural resources, communities, infrastructure, and economy. Building from the Resilience Strategy, in 2024 the New Jersey Extreme Heat Resilience Action Plan was released to focus on mitigating the effects of extreme heat through the actions of state departments and agencies. In 2025, the New Jersey Statewide Flood Resilience Initiatives report was released to highlight projects and programs led by state agencies aimed at reducing flood risk.

New Jersey is committed to reducing the emissions of greenhouse gases and other climate pollutants pursuant to the Global Warming Response Act and plans for adaptation consistent with the Statewide Climate Change Resilience Strategy. Through these actions, the state is in a place to be a leader and model for how to address climate change in the rest of the United States and the world. Considering the fluid nature of the best available science regarding the effects of climate change on New Jersey's resources, this science report will be updated regularly to incorporate newly evolving scientific knowledge as it becomes available.

TRENTON, NEW JERSEY

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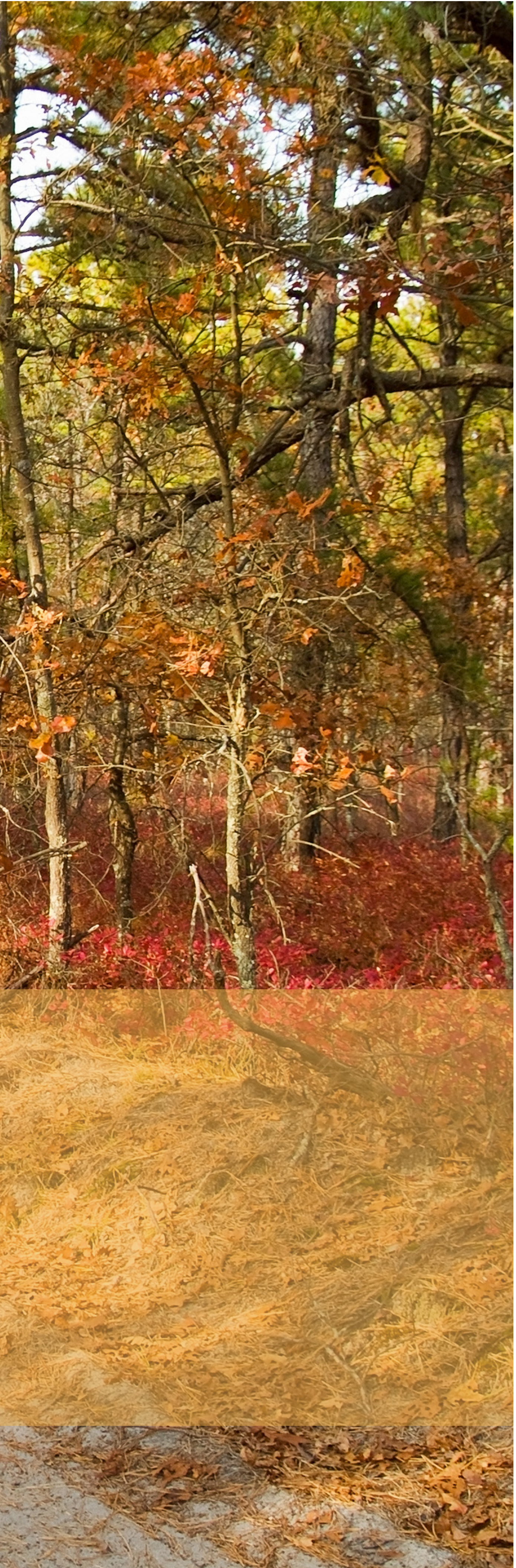
CHAPTER 1

INTRODUCTION



In the past two decades, there have been important advancements in the scientific understanding of climate change and its anticipated impacts on the environment. Reports from the New Jersey Climate Change Resource Center, The National Oceanic and Atmospheric Administration (NOAA), and many other federal and non-governmental organizations detail some of the anticipated impacts of climate change in New Jersey. The 2020 New Jersey Scientific Report on Climate Change was the first state-led assessment detailing the effects climate change will likely have on the natural resources within the state. This update to the 2020 report incorporates several recent New Jersey specific studies, as well as the latest reports from federal and international sources.

On October 29, 2019, New Jersey Governor Philip D. Murphy signed Executive Order No. 89 into effect. Among other things, this Executive Order established, for the first time, the position of Chief Resilience Officer as well as the Office of Climate Resilience within the Department of Environmental Protection (DEP). Executive Order No. 89 also called for the DEP to develop a Scientific Report on Climate Change for the State of New Jersey (Scientific Report) within six months of its issuance and to provide updates every two years. In 2022, DEP developed an addendum to the 2020 report that covers Climate Change Impacts on Human Health & Communities. In 2023, DEP released an online web resource called Climate Change in New Jersey: Impacts & Effects, which summarizes and updates information from the 2020 report and 2022 addendum.

The Office of Climate Resilience and the Division of Science and Research led the DEP's effort to develop the Scientific Report and this 2025 update. To inform the content of the Scientific Report, experts from within the DEP's programs were consulted. This Scientific Report is based on the best available science and existing data regarding the current and anticipated environmental effects of climate change in New Jersey. In order to accomplish this goal, the DEP identified the existing science that would help further New Jersey's understanding of how climate change will likely affect the environment within the state and summarized it into this report.

INTRODUCTION

This Scientific Report is divided into seven chapters in an effort to properly cover issues relevant to New Jersey. Chapter 2 introduces a broad discussion of the issues as reported in numerous global, national, and regional-scale climate change reports. Subsequent chapters provide a more focused discussion of specific impacts of climate change as identified in current research. Chapter 3 provides a discussion of the primary driver of climate change, greenhouse gases. Chapter 4 details the major impacts and effects of climate change on New Jersey including temperature, precipitation, sea level rise, and ocean acidification. Chapter 5 discusses climate change impacts to New Jersey's many resources, including air, water, and ecological systems. Chapter 6 examines impacts on humans (i.e., health, agriculture, and communities). Chapter 7 identifies research and data gaps and concludes the report.

1.1 Purpose

The purpose of this report is to further New Jersey's understanding of how climate change will likely affect the environment within the state by fulfilling articles 2a and 2b of Executive Order 89. This language directs the Chief Resilience Officer and the Climate and Flood Resilience Program, now known as the Office of Climate Resilience to:

"Develop a Scientific Report on Climate Change based on existing data and the best available science regarding the current and anticipated environmental effects of climate change in New Jersey, including but not limited to increased temperatures, sea level rise, increased frequency or severity of rainfall, storms and flooding, increased forest fires, and increased frequency and severity of droughts, anticipated by scientists at least through 2050."

and to:

"Deliver the Scientific Report on Climate Change to the Governor within 180 days of the effective date of this Order and update and supplement the report as necessary, but at least every two (2) years to reflect the latest available climate change science."

Climate change is expected to have far-reaching impacts, affecting every area of the state in different ways. Foremost, this report will leverage existing studies to inform decision-makers at all levels on how environment and natural resources may be affected by future climate conditions and associated hazards. This report will also inform State policies, plans, and programs, and give guidance ensuring New Jersey is taking the appropriate actions in order to respond to the anticipated impacts of climate change. This report will also link existing scientific research with an anecdotal understanding to highlight where there are research gaps and additional studies warranted.

1.2 Background, Climate Change Science

Greenhouse gases occur naturally in the atmosphere and are essential to the survival of life on Earth as they allow for the retention of some of the Sun's warmth within the atmosphere (United Nations 2020). Without greenhouse gases, Earth would be significantly colder and uninhabitable. Climate change can perhaps most simply be described as the human fingerprint on greenhouse gases (United Nations 2025). This fingerprint is causing the Earth's climate to change faster now than it has at any other point in the history of modern civilization (USGCRP 2023). The issue of climate change can be seen as a defining moment for our time (United Nations 2025) and its impacts are global in scope as well as unprecedented in scale. The World Economic Forum (World Economic Forum 2025) identifies environmental impacts including extreme weather, biodiversity losses, and critical change to earth systems as the most severe types of global risks to occur over the next 10 years (Figure 1.1). A failure to take sufficient climate action to mitigate these risks is expected to result in a more severe global impact.

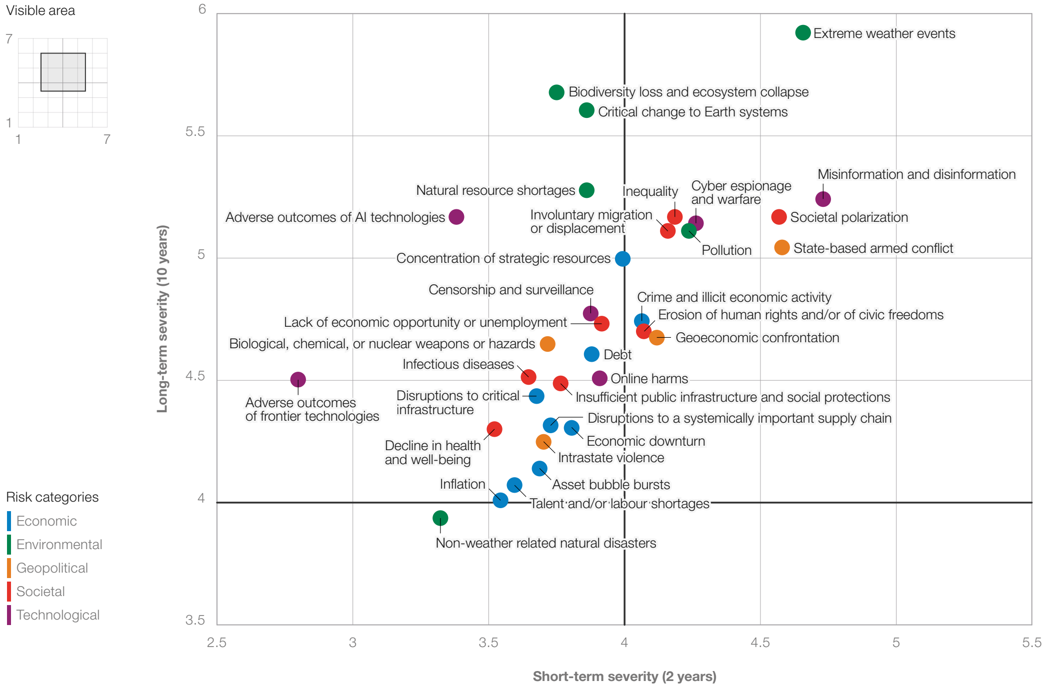


Figure 1.1. The Global Risk Landscape 2025. This represents survey data on the perceived threat of various global risks that could negatively impact global gross domestic product, human populations, or natural resources over short-term (2 year) and long-term (10 year) periods. This shows that some of the most concerning environmental risk categories are perceived to have a higher severity over the long-term (World Economic Forum 2025).

Researchers around the world have conducted thousands of studies that have documented increases in the temperature at the Earth's surface, in the atmosphere, and in the oceans (IPCC 2021a, USGCRP 2023). This current warming trend is of particular significance because it is unequivocally a result of human activities since the industrial era (US EPA 2025a). While each aspect of the climate system includes strong evidence to support this, when taken together, human influence is the only convincing explanation for the observed warming trend that is occurring at an unprecedented rate (IPCC 2021a, USGCRP 2023). Human activities driving climate change include the emissions of heat trapping greenhouse gases, largely from fossil fuel combustion, but also from deforestation and other land use changes (US EPA 2025a).

There have been seven cycles of glacial advance and retreat in the last 650,000 years (NASA 2020). The last interglacial period ended about 11,700 years ago, marking the beginning of the modern climate era with human civilization emerging around 6,000 years ago. These climate shifts through geological time are attributed to very small variations in Earth's orbit which change the amount of solar energy absorbed at its surface and are recorded in ice cores drawn from ice sheets in Greenland and Antarctica, as well as from mountain glaciers. These ice cores record a paleoclimatic record of Earth's atmosphere in response to changing climates. This same evidence can be found in tree rings, ocean and lake sediments, coral reefs, and the layering of sedimentary rocks. These records demonstrate that current warming is occurring roughly ten times faster than the average rate since the end of the last interglacial period (NASA 2020).

Industrialization, deforestation, and large-scale agriculture have contributed to greenhouse gas levels in the atmosphere not seen in three million years (United Nations 2020). The cumulative level of greenhouse gases continues to rise with growing populations, economies, and standards of living. A few well-established scientific links have been presented in a global body of research.

INTRODUCTION

First, greenhouse gas concentrations in Earth's atmosphere are directly linked to average global temperature. Second, greenhouse gas concentrations have been rising steadily, in concert with average global temperature, since the Industrial Revolution. Lastly, one of the most abundant greenhouse gases, CO_2, has been added to the atmosphere through the combustion of fossil fuels at unprecedented rates. Carbon dioxide is a minor component of the atmosphere but plays an extremely important role in regulating the greenhouse effect. Carbon dioxide is released into the atmosphere naturally through processes such as respiration in plants and animals and in volcanic eruptions. It is also introduced through human activities like the burning of fossil fuels and land use changes including deforestation (NASA 2020). Human activities have increased atmospheric CO_2 concentrations by more than a third since the early 1900s (Bereiter et al. 2015). Carbon dioxide is the most important "forcing" factor of climate change as it contributes to the greatest change in atmospheric energy fluctuations (IPCC 2018a). Other greenhouse gases include water vapor, methane, nitrous oxide, and chlorofluorocarbons (CFCs). Unlike other greenhouse gases, water vapor is controlled by the atmosphere itself, so it is considered a function of climate instead of "forcing" climate change.

Since the 2020 Scientific Report on Climate Change, emission scenarios have evolved. Previously, the most widely used model scenarios were Representative Concentration Pathways (RCPs) that project changes in radiative forcing, or changes to the atmospheric energy (heat) balance associated with climate change. In the most recent Sixth Assessment Report (AR6), a new framework of five baseline Shared Socioeconomic Pathways (SSPs) was introduced (see Table 1.1) (Riahi et al. 2017). These scenarios combine qualitative narratives—depicting potential societal developments—with quantitative projections of key socioeconomic factors such as population growth, gross domestic product, and urbanization. Each baseline assumes no implementation of climate policy, with mitigation and adaptation addressed separately through various emissions targets and associated radiative forcing levels projected for the year 2100. In essence, each global SSP scenario explores how specific radiative forcing outcomes could emerge based on the distinct characteristics of its baseline pathway. While there is not a clear overlap between the two, the projected outcomes of SSP scenarios can be compared to those from the earlier RCP scenarios. While some SSP scenarios are designed to reach the same radiative forcing levels by the end of the century, the trajectories leading to those levels can vary greatly depending on the underlying socioeconomic pathway. Furthermore, the atmospheric compositions of key greenhouse gases—such as carbon dioxide, methane, and nitrous oxide—as well as aerosols, may vary between the RCP and SSP frameworks. These variations lead to differences in long-term projections, including the timing and magnitude of changes in greenhouse gas concentrations, radiative forcing, global temperatures, and other climate-related impacts. Projected outcomes of each SSP are compared in Figure 1.2 and Table 1.2.

Climate modeling is a critical tool for understanding the Earth's climate system, projecting future changes, and guiding policy decisions (IPCC 2023). These models simulate the complex interactions of physical, chemical, and biological processes that drive the climate, capturing variables such as temperature, precipitation, sea level rise, and extreme weather events under different greenhouse gas emission scenarios. By incorporating both natural processes and socio-economic factors, climate models allow scientists to assess the climate's response to varying levels of emissions and to evaluate potential mitigation and adaptation strategies. They also account for key feedback mechanisms—such as permafrost thaw, ice-albedo feedback, and ocean carbon uptake—that can amplify or dampen climate change effects.

The four primary scenarios used in AR6 are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (IPCC 2021a). The SSP1-2.6 scenario, which reaches 2.6 W/m^2 of radiative forcing by 2100, is a revised version of the RCP 2.6 pathway and was developed to represent a trajectory consistent with the 2°C climate target. Similar to its predecessor, it assumes the implementation of climate mitigation measures. SSP2-4.5, an update to the RCP 4.5 scenario, projects a radiative forcing of 4.5 W/m² by 2100 and represents a middle pathway for future greenhouse gas emissions. This scenario assumes that climate mitigation measures are actively implemented. Reaching 7 W/m² of radiative forcing by 2100, the SSP3-7.0 scenario falls in the upper part of the middle range of all projected pathways. It was newly introduced after the RCP framework to fill the gap between RCP 6.0 and RCP 8.5. The SSP5-8.5 scenario represents radiative forcing of 8.5 W/m² by 2100 and is the upper bound of the range described in the scientific literature. It serves as an updated version of the CMIP5 scenario RCP 8.5, now integrated with socioeconomic drivers to reflect a more comprehensive high-emissions pathway. This report includes studies that may reference RCPs or SSPs, due to the recent changes in standard pathways.

- Low emission scenario (SSP1-2.6; RCP 2.6) – Global emissions of greenhouse gases are dramatically reduced (resulting in 2.9°F [1.6°C] by 2100); CO2 emissions decline to net zero around 2070, followed by net negative emissions (IPCC 2023).
- Intermediate emission scenario (SSP2-4.5; RCP 4.5) – CO2 emissions remaining around current levels until the middle of the century (corresponds with 4.7°F [2.6°C] by 2100) (IPCC 2023), approximately consistent with interpretations of current global policy (as of November 2024), with global emissions slowly rising to about mid-century and then declining (Kopp et al. 2025).
- High emission scenario (SSP3-7.0) – CO2 emissions roughly double from current levels by 2100 (resulting in 6.8°F [3.8°C] by 2100) (IPCC 2023), continued emissions growth throughout the century (Kopp et al. 2025).
- Very High emission scenario (SSP5-8.5; RCP 8.5) - CO2 emissions roughly double by 2050 (resulting in 8.5°F [4.7°C] by 2100) (IPCC 2023), sustained growth in fossil fuel use at rates comparable to those of the 1990s and 2000s (Kopp et al. 2025).

Table 1.1. Description of the mitigation and adaptation challenges for the five baseline Shared Socio-economic Pathway (SSP) narratives. These baseline pathways are used in conjunction with different emissions targets and approximate radiative forcing values, in development of the current standard scenarios (Riahi et al. 2017).

Baseline Pathways	Mitigation Challenges	Adaptation Challenges	Description
SSP1	low	low	**"Taking the Green Road"** involves resource efficiency and rapid technological and social developments towards sustainability
SSP2	intermediate	intermediate	The **"Middle of the Road"** path involves some limited developments towards resource efficiency, policies that reduce emissions, and sustainability.
SSP3	high	high	The **"Rocky Road"** pathway is characterized by slow developments for adaptation and a "regional rivalry" regarding advancements of energy and land policy
SSP4	low	high	The **"Road Divided"** pathway is characterized by inequality, wherein regions with low tech economies are less adaptable despite successes in technological advancements that help mitigation at the global level.
SSP5	high	low	The **"Taking the Highway"** path is fueled by intensive resource use but also has rapid developments for adaptation.

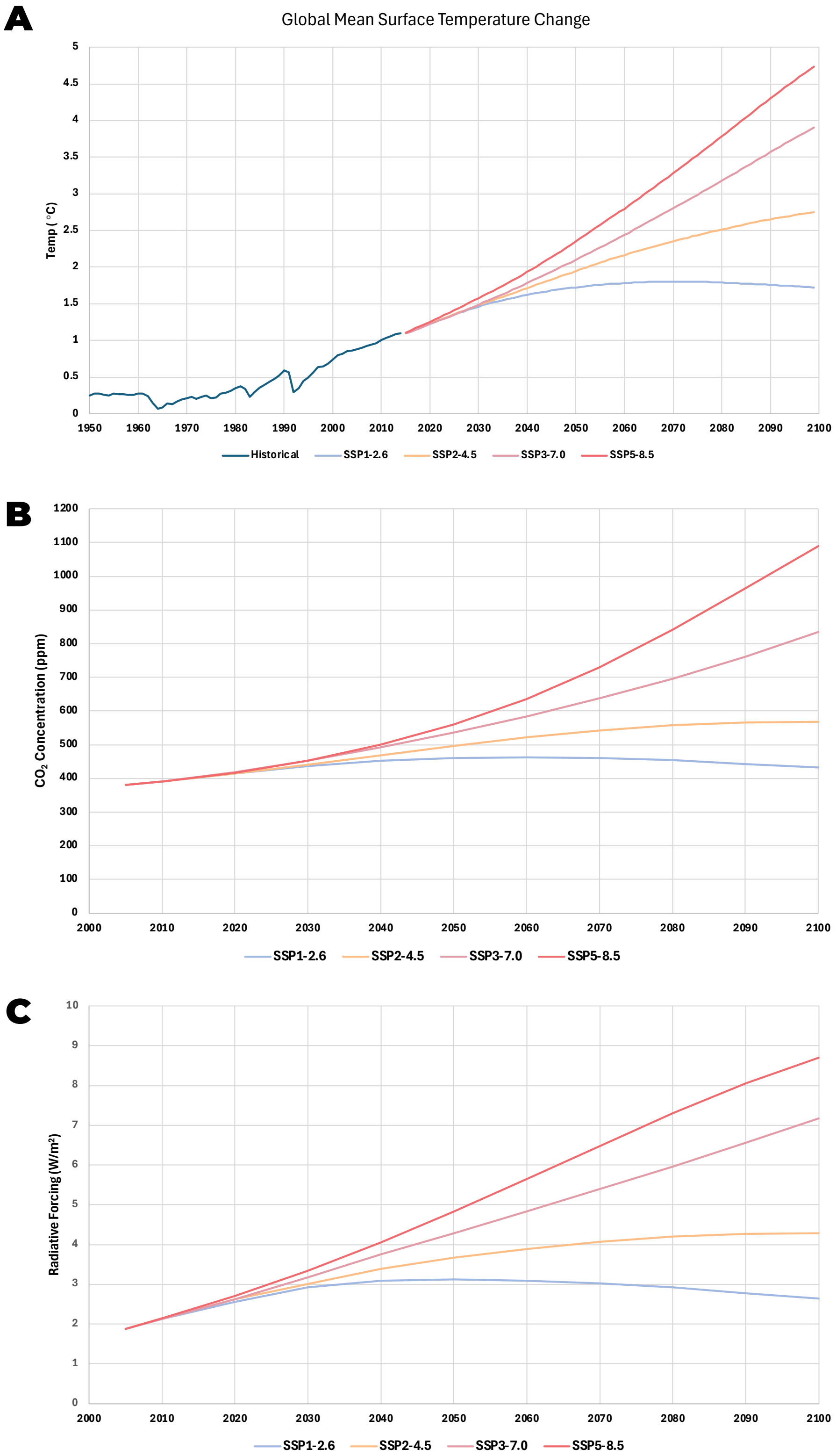


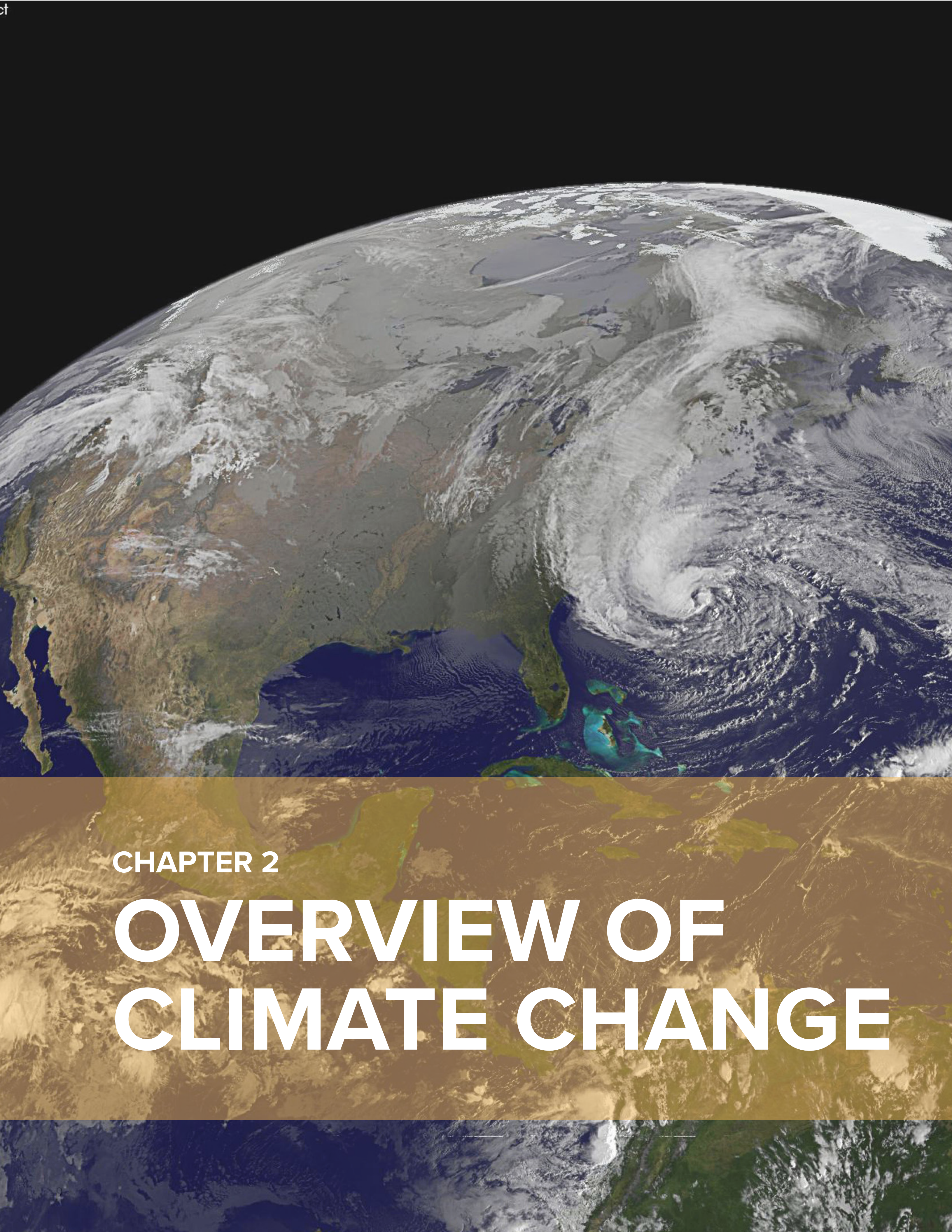
Figure 1.2. Projections of global mean surface temperature change (panel A), atmospheric CO_2 concentration (panel B), and total radiative forcing (panel C) through 2100 based on each SSP scenario. Data are available from the SSP Database (Version 2.0). Scenarios and projections follow (Riahi et al. 2017).

Table 1.2. Global Mean Temperature Increases (°F) by 2100 Associated With Each Shared Socio-economic Pathway (SSP) Model Scenario (IPCC 2023). Temperature increases are relative to 1995-2014 reference period (Kikstra et al. 2022).

Scenario	Likely Range – Low	Average Temperature Increase	Likely Range – High
SSP1-1.9	0.3	1.0	1.7
SSP1-2.6	0.8	1.7	2.8
SSP2-4.5	2.3	3.3	4.8
SSP3-7.0	3.5	5.0	6.8
SSP5-8.5	4.4	6.4	8.7

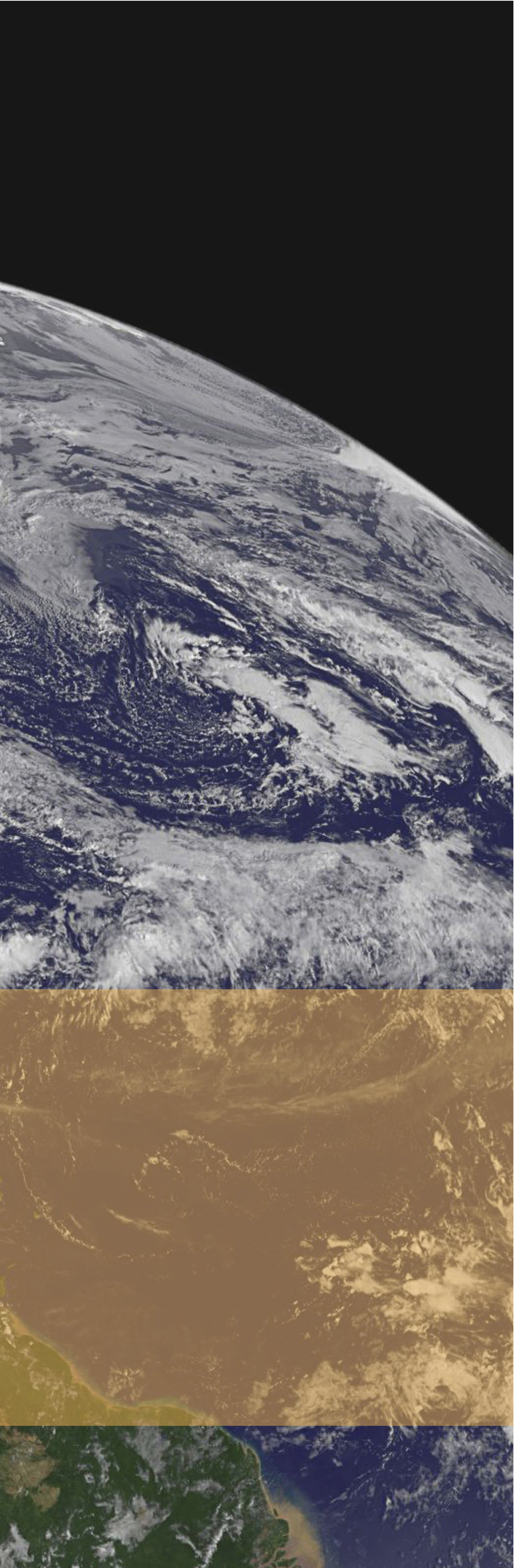
> *"Climate change is expected to have far-reaching impacts, affecting every area of the state in different ways."*

JERSEY CITY SKYLINE



CHAPTER 2

OVERVIEW OF CLIMATE CHANGE



2.1 Global

Global climate is changing rapidly when compared to the pace historically set by natural variations in climate (Hayhoe et al. 2018). According to NASA's Vital Signs, the average global temperature has risen by about 2.6°F (1.4°C) above the 1850-1900 average from 1880-2024 (NASA 2025a). Paleo-temperature records can be reconstructed by analyzing ancient sediments for lipids produced by cold-adapted and warm-adapted organisms. Synthesis of paleo-temperature evidence indicates that the recent decades are the warmest in at least 2000 years, and the period 2011-2020 was warmer than the last multi-century warm period that occurred about 6,500 years ago (IPCC 2021b).

Human activities are unequivocally responsible for observed increases in greenhouse gas emissions, which are virtually certain to be the primary driver of climate change (IPCC 2021a, Marvel et al. 2023). There is not credible evidence to support natural explanations for this warming, as there are no known natural processes that have the potential to cause the currently observed warming trend (IPCC 2021b, Marvel et al. 2023). Earth's climate can be expected to continue changing through this century and beyond due to already committed warming from greenhouse gas emissions. Looking forward, future warming and its numerous impacts and effects will primarily depend on global emissions of greenhouse gases and the natural response of Earth's climate system to this human-induced warming. The future of humanity and nature depends on our choices. A very high warming scenario without significant emissions reductions from current levels could see annual average global temperatures increase by more than 10°F (5.7°C) by the end of the century, compared to pre-industrial temperatures (IPCC 2021b). According to the Climate Action Tracker's analysis of 2030 emissions targets, the temperature by the end of the century is projected to rise to 4.7°F (2.6°C) (Climate Action Tracker 2024). Additionally, the Rhodium Climate Outlook projects warming of 4.9°F (2.7°C) with a very likely range of 3.6–6.7°F (2.0–3.7°C) by 2100, consistent with SSP2-4.5 and current policy trends (Larsen et al. 2024).

OVERVIEW OF GLOBAL AND REGIONAL CLIMATE CHANGE

Given the mounting evidence that human activities were altering atmospheric composition, the countries of the world set up the *Intergovernmental Panel on Climate Change* (IPCC) in 1988 to synthesize and evaluate the state of scientific understanding about climate change, resultant impacts, and the potential for limiting further change. Since its creation, the Intergovernmental Panel on Climate Change has completed six comprehensive assessments (IPCC 1990, 1995, 2001, 2007, 2013, 2021a), produced a number of additional reports, and stimulated substantial growth in research on climate change. In the Physical Science Basis of the Sixth Assessment Report (AR6), the IPCC stated, *"It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time, in particular for temperature extremes"* (IPCC 2021a).

The rate at which atmospheric CO_2 is increasing has accelerated, rising from approximately 1.6 parts per million per year (ppm/yr) in the 1980s to over 2.5 ppm/yr during the period of 2014 and 2023. Currently, atmospheric CO_2 concentrations exceed 425 ppm (NOAA Global Monitoring Lab 2025), marking the highest levels in at least 800,000 years (Tripati et al. 2009, IPCC 2021b). Similarly, the concentration of atmospheric CH_2 has seen a rise in its growth rate, increasing from 9.1 parts per billion per year (ppb/yr) during 2014–2018 to 13.2 ppb/yr from 2019-2023 (NOAA Global Monitoring Lab 2025). Over the past decade, atmospheric N_2O has been growing at an average rate of about 1.1 ppb/yr (NOAA Global Monitoring Lab 2025).

The increase in greenhouse gases in Earth's atmosphere causes other changes in addition to rising temperatures. Over the past 50 years, the world's oceans have absorbed greater than 90% of the excess heat (Venegas et al. 2023) and a quarter of the CO_2 produced annually from human activities (Hayhoe et al. 2018). These changes are causing the oceans to warm and become more acidic, respectively, resulting in rising sea surface temperatures and sea levels, and changing patterns of precipitation, winds, nutrients, and ocean circulation. Due to the size of the ocean and the capacity to store heat, climate change from human-caused emissions of CO_2 and other greenhouse gases will continue to persist for decades to millennia. Furthermore, feedback loops within Earth's climate system have the potential to accelerate anthropogenic (human-caused) change (Hayhoe et al. 2018, IPCC 2021a).

As global temperature increases into the future, the frequency and intensity of extreme high temperature events are very likely to increase as well (Marvel et al. 2023). Heavy precipitation events will also very likely continue to increase in their frequency and intensity globally (IPCC 2021a). However, the


LONG BEACH ISLAND, NEW JERSEY

observed and projected trends for some other types of extreme events, such as floods, droughts, and severe storms for example, are more variable regionally.

2.2 National

Based on the Fifth National Climate Assessment (NCA5) by the United States Global Change Research Program in 2023, it can be said with very high confidence that the average annual temperature throughout the United States has increased by 2.5°F (1.39°C) since 1970 relative to 1901–1960 (Marvel et al. 2023). The average annual temperature in the contiguous United States is projected to rise and extreme temperatures are projected to increase even more than average temperatures (Marvel et al. 2023). These projections are particularly important to be aware of because the urban heat island effect will strengthen in the future as the structure, spatial extent, and population density of urban areas changes and grows (Rosenzweig et al. 2005).

In addition to temperature, the instances of heavy precipitation events in most parts of the United States have increased in intensity and in frequency over the period 1958-2021 (Marvel et al. 2023). There are, however, significant regional differences in trends across the country. The largest regional increase in heavy precipitation events has occurred in the Northeastern United States (Marvel et al. 2023). Collectively, these changes to temperature and precipitation will make the current environment feel much like that of other regions of the country, mostly those more southern and western (Fitzpatrick and Dunn 2019).

Not only will climate change affect the way it feels to live in regions around the United States, but it will impose new challenges to survival due to greater frequencies of natural disasters. From 1980 to 2024, the United States has sustained 403 weather and climate-related disasters (National Centers for Environmental Information 2025) where the overall costs of damages per event reached or exceeded $1 billion (including Consumer Price Index adjustment to 2024). During 2024, the United States experienced an active year of billion-dollar disaster events, including 27 weather and climate disaster events that each sustained losses exceeding $1 billion (National Centers for Environmental Information 2025). These disasters included seventeen severe storms, five tropical cyclones, two winter storms, and one wildfire.

A report by Climate Central produced a nationwide analysis of new homes in areas vulnerable to coastal flooding in all 24 coastal states and Washington, DC (Climate Central 2019). This report showed, on average, how many homes will become exposed to annual ocean flooding in the coming decades, depending on the choices the world makes today regarding greenhouse gases. If only moderate cuts are made to current day greenhouse gas emissions, around 17,800 existing homes built after 2009 will face at least a 10% flood threat on average each year by 2050. These moderate cuts would be roughly in line with those of the Paris agreement on climate, whose targets the international community is not on track to meet. The figures are more than two times higher for 2100 and three times higher if emissions continue unchecked.

2.3 Regional

Regional assessments predict that the Northeastern United States will be especially vulnerable to impacts of climate change and the potential ecological, economic, and public health impacts could be devastating (Frumhoff et al. 2007). The United States NCA5 presents observed and projected changes for the northeast region of the United States, reporting that average annual temperatures in the region have increased by more than 2°F (1.1°C) above the 1901-1960 average in the Northeastern United States (Marvel et al. 2023). Analysis of available regional data from NOAA's Climate at a Glance online resource shows an increase of 3°F (1.7°C) from 1895 to 2024 (NOAA 2025a). The number of days per year with temperatures above 95°F (35°C), as well as the number of nights exceeding 70°F (21°C), is projected to increase through the southern portion of the region (including Maryland, Delaware, southwestern West Virginia, and New Jersey) when compared with the 1991-2020 climate normal (Marvel et al. 2023). Temperatures off the coast and open ocean along the Northeast Continental Shelf have warmed by 0.06°F (0.03°C) per year over the period 1982–2016, which is three times faster than the 1982–2013 global average rate of 0.018°F (0.01°C) per year (Dupigny-Giroux et al. 2018).

The United States National Climate Assessment also reported that precipitation increased by over 10% or five inches (roughly 0.4 inches per decade) between 1895 and 2011 (Melillo et al. 2014, Huang et al. 2017). The Northeast has seen a greater recent increase in extreme precipitation events than any other region in the United States (Marvel et al. 2023). From 1958 to 2021, the Northeast received about a 60% increase in the amount of precipitation falling during events that are considered very heavy events (by definition, the heaviest 1% of all daily events).

Despite a trend toward more precipitation occurring since 1970, the Northeastern United States is seeing longer periods without rainfall during longer growing seasons (Frumhoff et al. 2007, Krakauer et al. 2019). The result is a drier growing season, especially during the summer months, when temperatures and evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) are highest. Additionally, drier conditions are exacerbated by reduced recharge from spring snowmelt as observations indicate that precipitation is transitioning to more rain and less snow in the Northeastern United States since 1970 (Frumhoff et al. 2007).

Higher temperatures allow for additional moisture in the atmosphere (NASA 2022) which contributes to more overall precipitation in some areas, especially in much of the Northeast (Frumhoff et al. 2007). Precipitation (as rain, rather than snow) and runoff are likely to increase in the Northeastern United States in both winter and spring. Such areas, where total precipitation is expected to increase the most, would also experience the largest increase in heavy precipitation events. Projections also indicate that spring snow melts may begin up to 14 days earlier under high emission scenarios. Reduced stream flows late in the season due to earlier runoff, higher water temperatures, and reduced soil moisture in the summer and fall will stress human and environmental systems.

Sea-level rise is documented throughout the world, and it is an indicator of Earth's heat balance (Blunden et al. 2019). Sea level rose in the contiguous United States by approximately 12 inches (30 cm) from 1920-2020, exceeding the global average (May et al. 2023). Although there are local and regional influences on sea level that are not related to anthropogenic climate change (such as geological subsidence that exists in New Jersey), sea-level rise occurs due to two main reasons: ice melting on land (leading to increased water volume) and thermal expansion (the expansion of the ocean as it warms) (Blunden et al. 2019, Kopp et al. 2025). Consistent with the observed trend, sea-level rise will lead to more frequent and extensive coastal flooding. By the end of the 21st century, several northeastern states will have notable portions of their projected populations at risk of adverse effects from sea-level rise (Hauer et al. 2016).

The Mid-Atlantic region of the ocean includes the area from Cape Hatteras in North Carolina to Cape Cod in Massachusetts (Dupigny-Giroux et al. 2018). The extent that climate change may possibly impact this region has been studied extensively over the past decade (Colgan et al. 2018). Climate-related changes that are likely to occur have been identified with ever increasing confidence. These changes include sea-level rise and changes to marine and coastal ecosystems, with the breadth and depth of information varying across the region. The increased potential for more intense tropical storms (Huang et al. 2017) along with increased likelihood for severe thunderstorms and other weather hazards such as lightning, heavy rain, hail, and tornadoes (Diffenbaugh et al. 2013) make it clear that threats from climate change are clear and present in the Mid-Atlantic.

> *“Regional assessments predict that the Northeastern United States will be especially vulnerable to impacts of climate change and the potential ecological, economic, and public health impacts could be devastating.”*

SATELLITE IMAGE OF NEW YORK-NEW JERSEY AREA

CHAPTER 3

GREENHOUSE GASES: THE PRIMARY DRIVER OF CLIMATE CHANGE

The atmosphere is composed of many gases critical for life on Earth, some of which are designated greenhouse gases. Spurred by the industrial revolution, human activity has caused a drastic increase of greenhouse gases over the last two centuries. This increase in emissions is the primary driver of climate change and has had expansive negative impacts over time, imposing a myriad of threats including but not limited to human health, food security, economic activity, and ecosystem services. It is critical to expand our knowledge of greenhouse gases to support climate mitigation strategies that reduce emissions, bolster natural and engineered sinks, and dampen the trajectory of long-term impacts.

Chapter 3 is divided into the following sections:

GREENHOUSE GASES:
THE PRIMARY DRIVER OF CLIMATE CHANGE

KEY FINDINGS

- **As global CO2 emissions continue to increase so will the anticipated increases in global temperature.**
- **From 1950 to 2023, the United States was the world's largest producer of CO2 emissions, accounting for about 85% of CO2 emissions in North America and 22% globally.**
- **Nationally, total emissions decreased 17% -- from 6,587 million metric tons carbon dioxide equivalent (MtCO2e) in 2005 to 5,489 MtCO2e in 2022.**
- **In New Jersey, total emissions decreased 20% -- from 126.5 million metric tons carbon dioxide equivalent (MtCO2e) in 2006 to 105.7 MtCO2e in 2022.**
- **New Jersey continues to reduce the state's greenhouse gas emissions through solar and other renewable sources of energy, which now provide 11% of in-state generation, up from less than 2% in 2006.**
- **Transportation has consistently been the largest source of emissions in New Jersey over the past 17 years but has recently experienced small reductions due to stringent vehicle emissions and fuel efficiency standards.**

3.1 Greenhouse Gas Global Cause-Effect Chain—Basic Background

The principles of the greenhouse effect have been understood for more than a century (Foote 1856, Tyndall 1859) and can be summarized as follows: the Sun emits intense amounts of solar radiation that is either absorbed by Earth's surface and atmosphere or is reflected back into space (Wolff et al. 2020). The atmosphere and Earth's surface (land, ocean, and ice) reflect back into space thirty percent (30%) of this solar energy (Pielou 2001). A portion of the absorbed solar energy is further absorbed by greenhouse gases and warms Earth's atmosphere, while some is reflected back into space (Wolff et al. 2020). These naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Without these gases, Earth would be as much as 60°F (33°C) colder (Pielou 2001).

The primary climate pollutant emitted as a result of human activities is CO_2. Scientists have been able to reconstruct a record of atmospheric CO_2 concentrations dating back 800,000 years using ice cores drilled in Antarctica to depths of approximately 3 km, or nearly 2 miles (Lüthi et al. 2008). Peaks in CO_2 concentration occurred during warm interglacial periods, followed by dips during cold glacial periods (Lindsey 2019). Over this period of 800,000 years, the concentration of CO_2 did not exceed 300 parts per million (ppm), until recently (Figure 3.1).

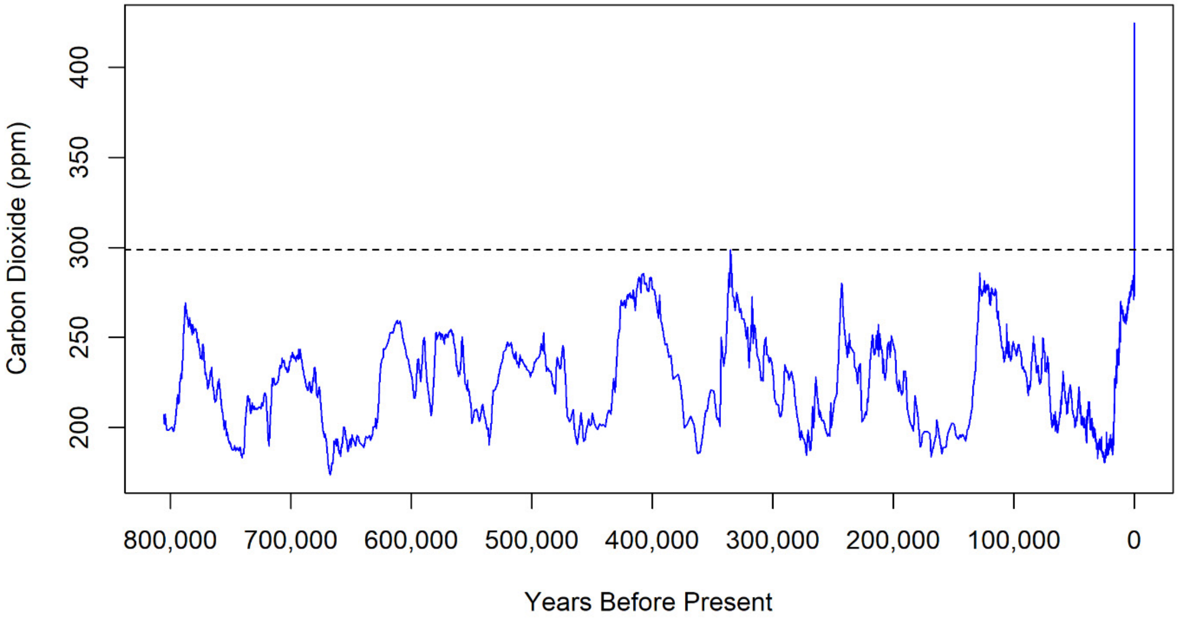


Figure 3.1. Atmospheric CO2 Concentrations in Parts Per Million (ppm) for the Previous 800,000 Years. High points represent warm interglacial periods, while valleys represent colder glacial periods. The timepoint 0 is 1950. The dashed line at 296 ppm represents the historic maximum prior to the industrial age. The historic CO2 concentrations are reconstructed from composite air gas trapped in Antarctic ice cores while recent CO2 concentrations are atmospheric levels reported from the Mauna Loa, Hawaii observation station. The ice core data is available at https://www.ncdc.noaa.gov/paleo/study/17975 (Bereiter et al. 2015) and the Mauna Loa data are available at https://gml.noaa.gov/ccgg/trends/data.html (Lan et al. 2025).

The concentration of carbon dioxide in the atmosphere began increasing rapidly at the start of the Industrial Revolution more than two centuries ago. At that point, CO_2 levels were about 280 ppm (IPCC 2001). Since then, billions of tons of carbon dioxide and other greenhouse gases have been emitted into the atmosphere, far more than natural removal processes (described in the next section, Chapter 3.2, and shown in Figure 3.3) can keep pace with. This buildup, as seen in Figure 3.2 for CO_2, results in higher concentrations of climate gases in the atmosphere, leading to greater amounts of heat being trapped. Average annual CO_2 levels exceeded 400 ppm for the first time in 2016, and then surpassed 420 ppm in 2024, as reported at the National Oceanic and Atmospheric Administration's (NOAA) Mauna Loa Observatory (Lan et al. 2025). Given the role of CO_2 as a greenhouse gas, continued additions of this magnitude will result in an unprecedented increase in global temperature.

> ***"Regional assessments predict that the Northeastern United States will be especially vulnerable to impacts of climate change and the potential ecological, economic, and public health impacts could be devastating."***

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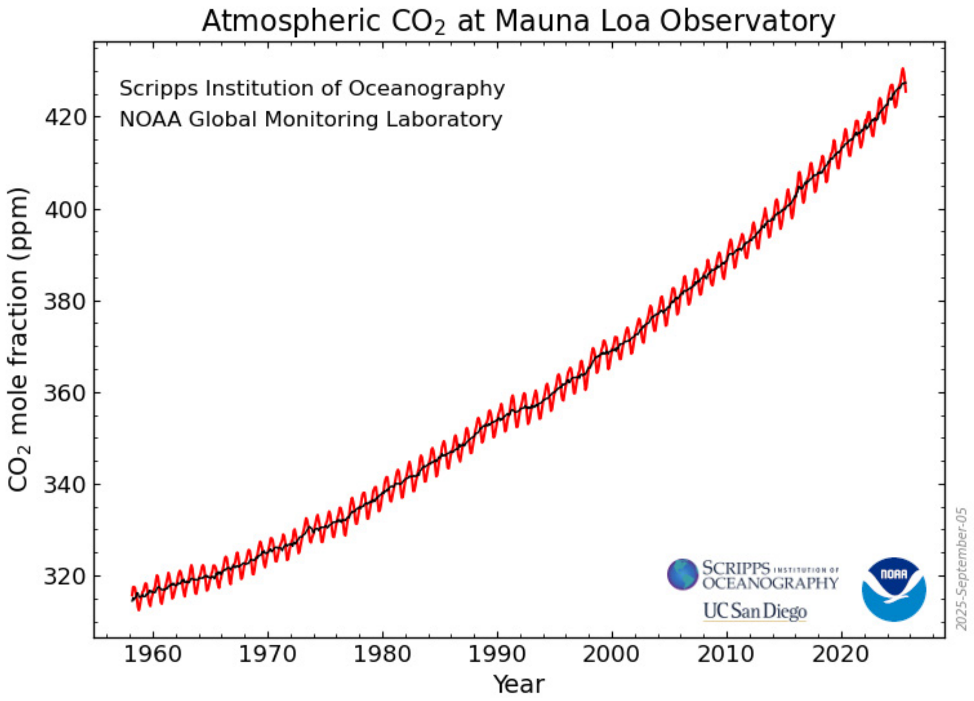

Figure 3.2. Keeling Curve - Carbon Dioxide Concentration (NOAA Global Monitoring Lab 2025)**.** The figure shows the average monthly carbon dioxide concentration from 1958-2025 (in red), with a moving average of seven adjacent seasonal cycles (in black) that removes the season cycle. Figure and data available from the NOAA Earth System Research Laboratories; https://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html (Lan et al. 2025).

The increasing concentration of CO_2 was first observed more than 60 years ago (Le Treut et al. 2007). But quickly thereafter, other human-sourced greenhouse gases were also recognized as significant contributors to climate change, including methane (CH_4), nitrous oxide (N_2O), ozone (O_3), many halogenated gases (especially chlorofluorocarbons [CFC-11 and CFC-12]), among others.

3.2 Greenhouse Gas and Biogeochemical Cycles

Biogeochemical cycles on land and in the oceans are key components of Earth's climate system. These cycles are defined by fluxes of chemical elements across various parts of Earth: from non-life to life, from soils to plants, and from the atmosphere to land to sea. The surface fluxes of the precursors, or building blocks, of many greenhouse gases are decisively influenced by biogeochemical and physical processes and are sensitive to changes in climate and atmospheric composition. Of critical importance, biogeochemical processes help control atmospheric concentrations of the main greenhouse gases - CO_2, CH_4, and N_2O. Vegetation, soils, and permafrost on the land, taken together, contain at least five times as much carbon as the atmosphere, and the oceans contain about fifty times more carbon than the atmosphere (see Figure 3.3 for a schematic of the carbon cycle) (Le Quéré et al. 2018). Thus, future climate change will be determined not only by anthropogenic (human-caused) emissions but also by the strength of the feedbacks between all aspects of Earth's climate system. This includes how much carbon, such as CO_2 and CH_4, is sequestered through natural ecosystems as part of the global carbon cycle, as well as the nitrogen cycle, which determines how N_2O is dispersed throughout Earth's systems. While human-caused emissions are the dominant influence on the present-day carbon cycle, climate projections now take some of these feedbacks into account (USGCRP 2018).

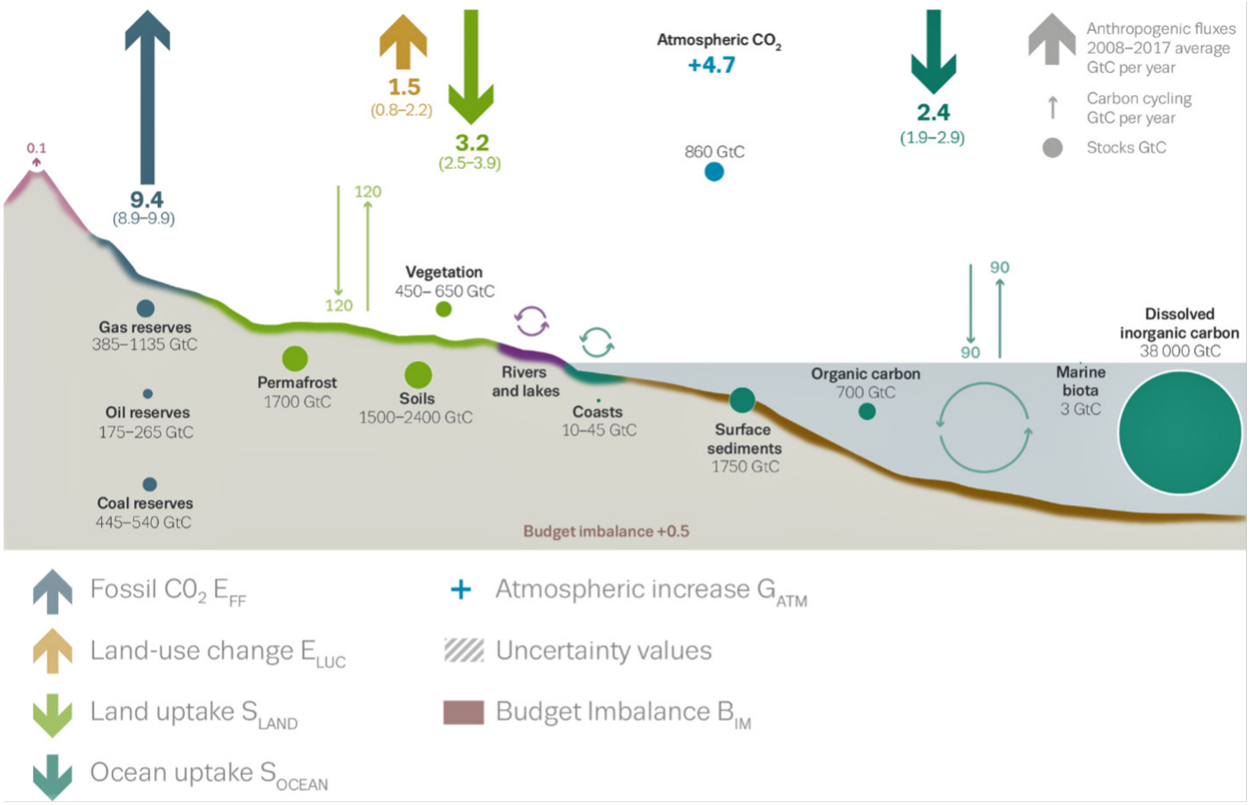

Figure 3.3. The Global Carbon Cycle. The schematic represents the overall influence on the global carbon cycle from anthropogenic (human-caused) activities, averaged globally for the decade 2008-2017. The natural background cycles are represented by the thin arrows, and the thick arrows, representing anthropogenic disruptions, are factored into natural cycles to calculate total fluxes. This schematic includes carbon stocks at the coasts, coastal marine sediments GtC (gigatons of carbon), E_{FF} (fossil CO_2 emissions), E_{LUC} (land-use change emissions), S_{OCEAN} and S_{LAND} (ocean and land CO_2 sinks), G_{ATM} (growth rate in atmospheric CO_2 concentration), and B_{IM} (budget imbalance). Source: Earth System Science Data (Le Quéré et al. 2018).

Large-scale modifications of biogeochemical cycles are occurring due to human activities both in the United States and elsewhere, with impacts and implications now and into the future. Global CO_2 emissions constitute the primary driver of human-caused climate change (Galloway et al. 2014). However, accelerated alterations to other element cycles, especially nitrogen, phosphorus, and sulfur, also influence climate. These can directly affect climate or serve as indirect factors that affect the carbon cycle, magnifying or reducing the impacts of climate change. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight. For example, small particles known as aerosols that are created naturally and anthropogenically can reflect sunlight.

According to the Third National Climate Assessment, human activities cause carbon, nitrogen, and phosphorus to enter the environment from Earth's crust and atmosphere. This transfer is now occurring 36, 9, and 13 times, respectively, faster than what occurred from geological sources during pre-industrial times (Galloway et al. 2014). These increases come mostly from the burning of fossil fuels, changes to land-cover, production of cement, fertilizer extraction, and production for agriculture. In addition to CO_2, which is the most abundant heat-trapping greenhouse gas, Methane (CH_4) and Nitrous Oxide (N_2O) are increasing in the atmosphere.

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Global warming potential has been developed as a tool to facilitate comparisons among greenhouse gases, as different gases react differently based on their unique properties. Global warming potential is a measure of the energy that a gas absorbs over a particular period of time (usually 100 years), compared to CO_2 (NJDEP 2020a). A twenty-year time horizon is sometimes used to study short-lived climate pollutants like methane (lifetime in atmosphere 12 years). This approach ignores any impacts after 20 years, making the apparent impact of long-lived carbon dioxide (lifetime in atmosphere from centuries to millennia) smaller in comparison to the short-lived gas. CH_4 and N_2O have high global warming potential values, as a given mass of these gases will cause many times more impact than the equivalent mass of CO_2. To allow for the comparison of warming impact across different gases, emissions of non-CO_2 gases are converted to "CO_2 equivalent" or CO_2e. This is calculated by multiplying mass by the specific global warming potential.

From 1950 to 2023, the United States was the world's largest producer of anthropogenic CO_2 emissions, accounting for about 85% of CO_2 emissions in North America and 22% globally (Global Carbon Project 2024). Carbon is not only released into the atmosphere in the form of CO_2 but can also be taken out of the atmosphere and stored in carbon sinks. Carbon sinks can store carbon for short or long periods of time and are integral to ecosystems. Ecosystems that serve as carbon sinks span the marine and terrestrial environment including wetlands and forest. The southeastern, south central, and Pacific northwestern regions of the United States have the largest rates of carbon removal from the atmosphere and sequestration into biomass. Despite this, North America remains a net source of CO_2 as emissions from human activities are more than three times greater than the rate of sequestration that occurs in ecosystems, as seen in Figure 3.4. For more information on carbon sequestration in New Jersey upland forests and wetlands, see Chapters 5.3 and 5.4, respectively .

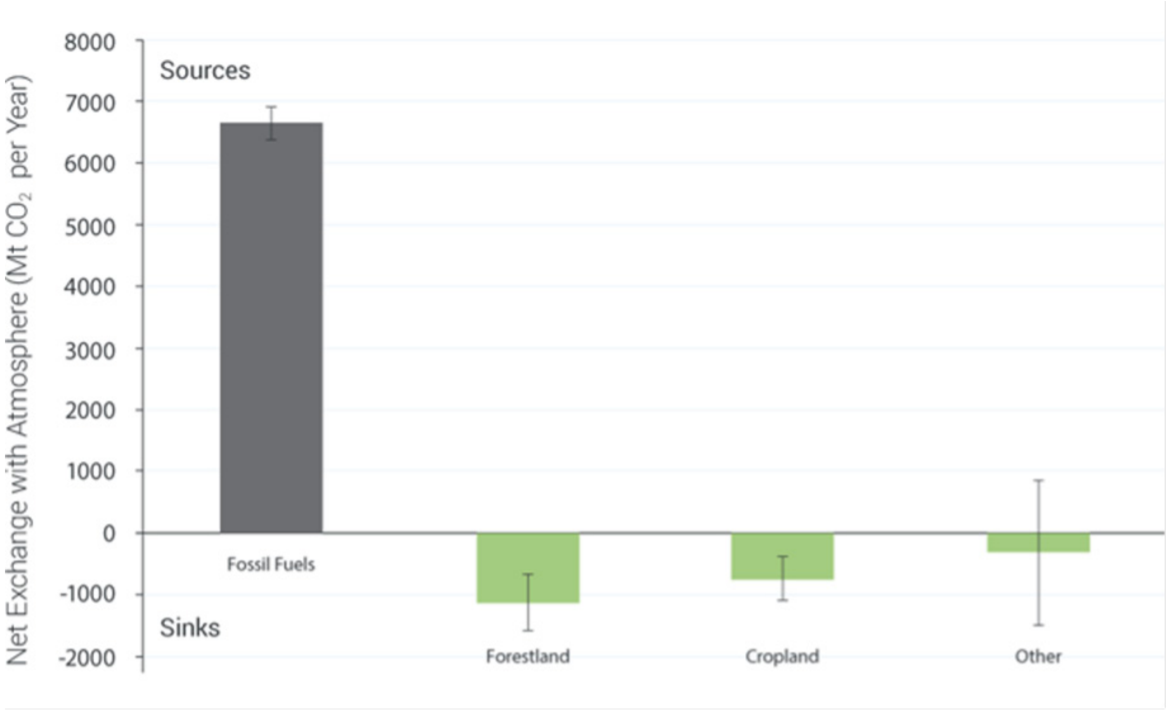

Figure 3.4. North American Carbon Dioxide (CO_2) Sources and Sinks: Magnitude, Attribution, and Uncertainty. The figure shows the amount of atmospheric CO_2 in metric tons of CO_2 (y-axis) that is released (a source) or sequestered (a sink) in North America from 2010 (95% confidence interval) (King et al. 2012).

Nationally, CO_2 accounted for 80% of warming emissions in 2022, CH_4 11%, N_2O 6%, and fluorinated gases 3%, when using the potential global warming over 100 years (GWP_{100}). Combustion of fossil fuels was in turn responsible for 93% of gross CO_2 emissions, with transportation and electricity generation being the most significant sources. Since 2005, national emissions have generally trended downward, punctuated by dips and rebounds associated with economic recessions and recoveries. Total emissions in 2005 were 6,587 million metric tons carbon dioxide equivalent ($MtCO_2e$), but by 2022 emissions had dropped to 5,489 $MtCO_2e$, a 17% decrease.

3.3 Greenhouse Gas Emissions in New Jersey

The New Jersey *Global Warming Response Act*, the State's cornerstone legislation guiding its response to climate change, mandates that greenhouse gas emissions be reduced to 80 percent of 2006 levels or less by 2050. It also requires the Department of Environmental of Protection (DEP) to establish an inventory of statewide greenhouse gas emissions to track the state's progress towards meeting the 2050 mandated reductions (Senate and General Assembly of the State of New Jersey 2007). Pursuant to this mandate, the DEP has regularly published Greenhouse Gas Inventory Reports from 2008 onward. Due to lags in data availability, New Jersey and federal inventories are released up to three years after the end of the calendar year. All inventories can be found at: https://dep.nj.gov/ghg/nj-ghg-inventory/

New Jersey's total gross greenhouse gas emissions in 2022 reached 105.7 $MtCO_2e$ based on GWP_{100}. Estimates based on GWP_{20}, or global warming potential over 20 years, are 128.8 $MtCO_2e$ total gross emissions; 120.7 $MtCO_2e$ total net emissions, 8.1 $MtCO_2e$ carbon sequestration; 38.6 $MtCO_2e$ transportation sector; 18.1 $MtCO_2e$ electricity sector; 15.2 $MtCO_2e$ residential; 10.2 $MtCO_2e$ commercial; 9.0 $MtCO_2e$ industrial (including fuel consumption and emissions from chemical processes). Black carbon emissions in 2020 were 6.1 $MtCO_2e$, of which 1.4 $MtCO_2e$ came from the transportation sector. However, it is also estimated that the state's land sector (forests and associated land cover) sequestered the equivalent of 8.1 $MtCO_2e$, resulting in net emissions of 97.6 $MtCO_2e$ for the year. The bulk of the state's greenhouse gas emissions are from energy consumption related to transportation, electric generation, space heating, cooking and industrial applications. These energy emissions represented 86% of total gross emissions. The remaining emissions (14%) arose from activities other than energy consumption, including waste management, agriculture, leaks from the natural gas transmission and distribution network, and releases of refrigerant gases from refrigeration and air conditioning. These non-energy sector emissions consisted of mostly non-CO_2 greenhouse gases, including CH_4, N_2O and the highly warming halogenated/fluorinated gases.

The transportation sector has consistently been the largest source of greenhouse gas emissions in the state, emitting 38.4 $MtCO_2e$ in 2022. The electricity generation sector accounted for 18.1 $MtCO_2e$; the residential sector 15.2 $MtCO_2e$; commercial sector 10.2 $MtCO_2e$; and industrial sector (including emissions from fuel combustion and from chemical processes) 8.9 $MtCO_2e$. Figure 3.5 shows the sectoral distribution of the greenhouse emissions in 2022.

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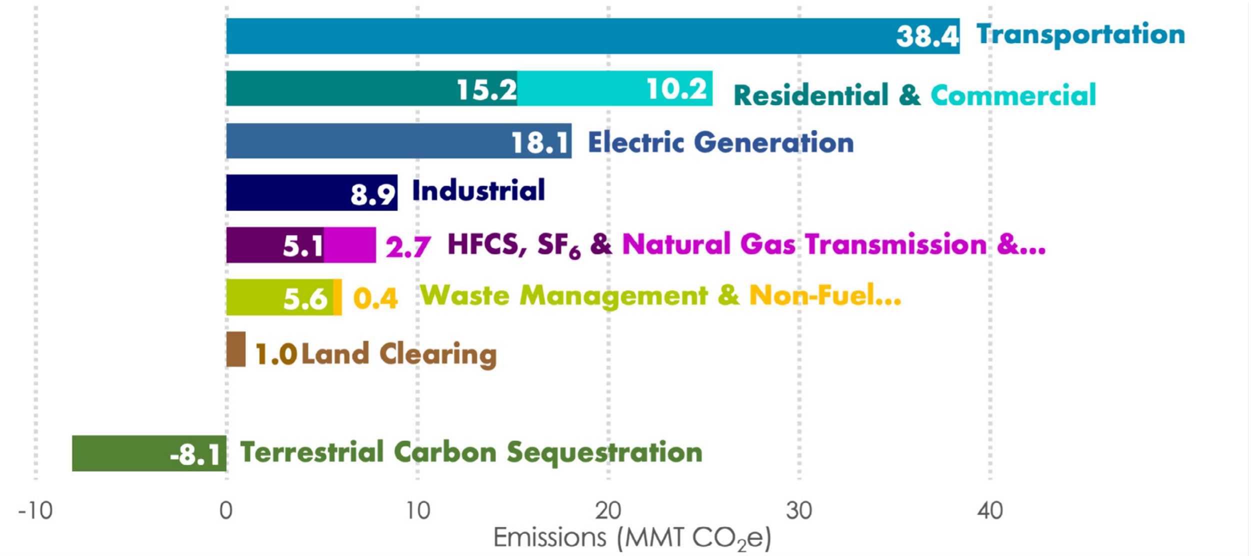


Figure 3.5. New Jersey Greenhouse Gas Sources and Sinks by Sector. This figure shows the distribution of greenhouse gas emission sources and sinks by sectoral distribution in 2022. This is based on a 100-year time period (NJDEP 2025a).

Non-energy sources include those that release climate pollutants other than CO_2. These include the electric transmission and distribution system (using SF_6 as an insulator), the natural gas transmission and distribution system (releasing CH_4), and agriculture (enteric fermentation, manure, and soil management, releasing CH_4 and N_2O). Halogenated gases are also a significant non-CO_2 climate pollutant. Together, these four categories contributed 8.3 $MtCO_2e$ to 2022 emissions. The waste management sector, comprised of solid waste landfills and wastewater treatment facilities, accounted for 5.6 $MtCO_2e$, including emissions from in-state municipal waste landfills (2.5 $MtCO_2e$ methane); in-state industrial waste landfills (0.4 $MtCO_2e$ methane); out-of-state disposal (1.9 $MtCO_2e$ methane); and wastewater treatment plants (0.8 $MtCO_2e$ methane and nitrous oxide). Land clearing contributed 1.0 $MtCO_2e$ (carbon dioxide) as a result of lost carbon in biomass and soil removed or disturbed. These non-energy categories contributed a total of 14.9 $MtCO_2e$ based on GWP_{100}. Using GWP_{20}, emissions were 20.3 $MtCO_2e$ from halogenated gases, electric transmission, and non-fuel agriculture; 16.4 $MtCO_2e$ from waste management; and 1.0 $MtCO_2e$ from land clearing, for an overall total of 37.7 $MtCO_2e$.

Black carbon, or soot, also acts as a climate pollutant because it absorbs sunlight, thereby warming the atmosphere and any surfaces on which the material collects. Black carbon emissions for 2020, the most recent year for which estimates are available, were 1.7 $MtCO_2e$, of which 0.4 $MtCO_2e$ came from the transportation sector. As black carbon is a solid rather than a gas and behaves quite differently in the environment, it is accounted for separately in the state greenhouse gas inventory.

Over the past 17 years, transportation has consistently been the largest source of emissions but has experienced small reductions as progressively more stringent vehicle emission and fuel efficiency standards have been adopted (Figure 3.6). The electricity sector has also seen reductions, largely due to the transition from low-efficiency coal-fired power plants to modern combined cycle natural gas and renewable energy sources. Industrial emissions have decreased as the makeup of the state's industrial sector has shifted. However, emissions from the residential and commercial sectors have remained largely unchanged.

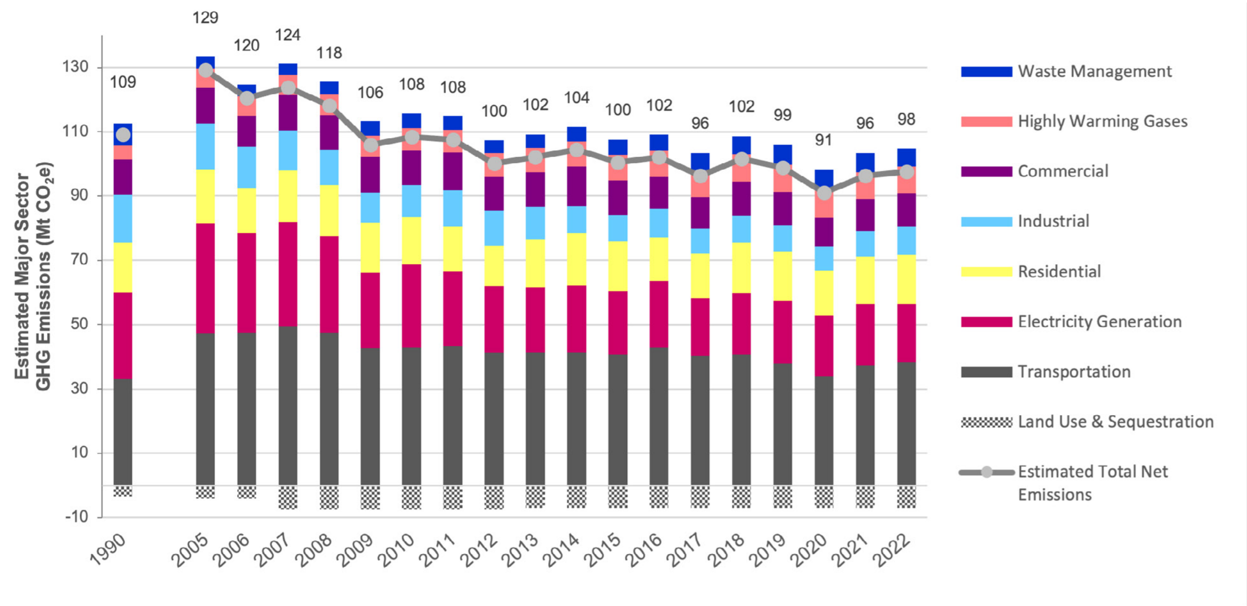
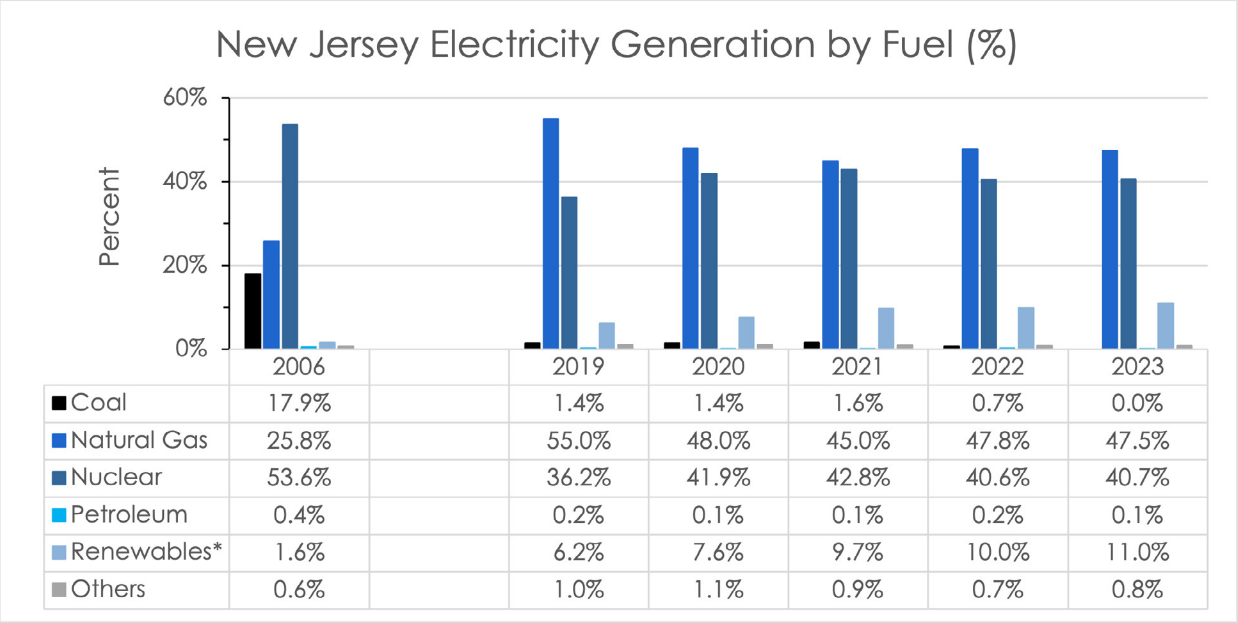


Figure 3.6. New Jersey Greenhouse Gas Emission Trends by Sector. This figure shows the estimated greenhouse gas emissions in million metric tons (MtCO$_2$e) for major sector activities from 2005 to 2022 compared to 1990 based on GWP$_{100}$ (NJDEP 2025a). This is based on a 100-year period.

Looking to the future, clean, renewable electricity supply is central to the state's strategy for reducing climate emissions. Referring to Figure 3.6, the bulk of emissions come from combustion of fossil fuels. For many of these applications, alternatives based on electricity instead of combustion are readily available. Electric passenger vehicles can replace gas-powered cars, SUVs, and pickup trucks. Heat pumps can replace gas fired furnaces and other fossil-powered heating systems, even industrial boilers. And electricity generation itself can be based on a range of emissions-free technologies. Furthermore, each of these alternatives is poised to make advances by way of innovation and cost reduction, therefore putting the electric sector at the center of the climate transition.

New Jersey's electricity generation sector has already shifted towards clean energy (Figure 3.7) (US Energy Information Administration 2024a, NJBPU 2025a). In 2023, New Jersey-based nuclear power provided over 40% of in-state generation, despite the closure of the Oyster Creek nuclear generating station in 2018. Solar and other renewables now provide 11% of in-state generation, up from less than 2% in 2006. Coal, responsible for 18% of the state's power as recently as 2006, has been fully eliminated. What fossil generation remains is nearly all powered by natural gas and emits about half the CO$_2$ for the same amount of electric generation as coal. As a result, New Jersey produces power at a considerably lower emission rate. Further, while New Jersey imports some of its electricity (typically 10%-20% annually, based on the difference between in-state generation and retail sales), the neighboring states that provide that power have seen their electric supplies transition towards cleaner sources as well. According to 2023 data, Pennsylvania, which is by far the greatest electricity exporter in the region, now obtains 91% of its power from nuclear and natural gas, compared to 88% in New Jersey, with only 5% of its power coming from coal. Notably, New Jersey generation estimates include small, behind-the-meter solar photovoltaic energy installations not tracked by the United States Energy Information Administration. If small, behind the meter solar photovoltaic energy is not included, the fraction of power coming from natural gas and nuclear in New Jersey increases to 95%. Pennsylvania estimates do not include small, behind-the-meter solar photovoltaic energy. Renewables make up most of the balance (US Energy Information Administration 2024b, US Energy Information Agency 2025). Therefore, it is likely that the emissions created by each megawatt of imported power are similar to that for in-state generation. In effect, New Jersey has benefited not only from clean energy policies within the state, but from clean energy policies throughout the Mid-Atlantic region.



	2006		2019	2020	2021	2022	2023
■ Coal	17.9%		1.4%	1.4%	1.6%	0.7%	0.0%
■ Natural Gas	25.8%		55.0%	48.0%	45.0%	47.8%	47.5%
■ Nuclear	53.6%		36.2%	41.9%	42.8%	40.6%	40.7%
■ Petroleum	0.4%		0.2%	0.1%	0.1%	0.2%	0.1%
■ Renewables*	1.6%		6.2%	7.6%	9.7%	10.0%	11.0%
■ Others	0.6%		1.0%	1.1%	0.9%	0.7%	0.8%

**includes small-scale and behind-the-meter solar*

Figure 3.7. New Jersey Electricity Generation Fuel Mix. Comparing electricity generation by fuel source in 2006, and 2019 through 2023, coal has dropped from nearly 18% to zero, and renewables now supply 11% of in-state generation (US Energy Information Administration 2024a, NJBPU 2025a).

Despite these advances, New Jersey will likely need to expand its commitment to renewable energy if it is to meet its 2050 mandated reduction. This would include new renewable generation that would expand electricity production and replace fossil fueled generation. The state has also sought to identify achievable and affordable pathways to meet these goals. In particular, the New Jersey 2019 Energy Master Plan, 2020 Global Warming Response Act 80x50 Report, and the upcoming 2025 Energy Master Plan focus on specific steps to be taken, and timelines for implementation, that will bring the state to an 80% reduction or further by 2050. These studies have all reached similar conclusions: the fastest and least expensive pathway, based on comprehensive assessments of economy-wide costs, starts by significantly expanding renewable electricity generation (solar, wind, and battery storage) and leveraging that power to supply electrified alternatives: electric vehicles for transportation, and heat pumps for homes and commercial spaces. These three sources (on-road transportation, residential and commercial applications, and electricity generation) accounted for 75% of the state's gross emissions in 2022. Decreasing emissions from these sources will bring the state close to its 80% reduction goal (Senate and General Assembly of the State of New Jersey 2007).

3.4 Air Quality and Greenhouse Gas Emissions in New Jersey

There are interactions between air quality and greenhouse gas concentrations driven by climate change. As discussed in Chapter 5.1, two primary impacts on air quality in New Jersey due to climate change are increased levels of ground-level ozone due primarily to increased temperatures and higher levels of $PM_{2.5}$ due to increases in wildfires.

Research has identified and described the phenomenon of an *ozone-climate penalty*. The expected increase in global mean temperatures associated with climate change leads to higher tropospheric (the lowest layer of Earth's atmosphere which resides at the surface of Earth) ozone concentrations in already polluted regions, potentially eroding the benefits of expensive emission controls. Ozone-climate penalty is "the deterioration of air quality due to a warming climate, in the absence of anthropogenic (human-caused) polluting activities" (Fu and Tian 2019). This phenomenon is particularly relevant to New Jersey since ground-level ozone is the only National Ambient Air Quality Standard the state continues to be in non-attainment of, and a warming climate is expected to increase ozone production in New Jersey. The National Ambient Air Quality Standards are set by the United States Environmental Protection Agency for six common air pollutants (including ozone and $PM_{2.5}$). Non-attainment means that air pollution levels are above the national ozone health-based National Ambient Air Quality Standard established by the Federal Clean Air Act and United State Environmental Protection Agency (NJDEP 2020b) National studies of the ozone-climate penalty have stated that increases in ozone concentrations due to climate change are predicted to result in a significant increase in additional ozone-related illnesses and premature deaths per year. Based on the national results seen in these studies, the impacts for New Jersey are generally more severe than many other states.

In addition to ozone, another important air pollutant for New Jersey is particulate matter. Particulate matter smaller than 2.5 microns in diameter ($PM_{2.5}$) is associated with serious chronic and acute health effects including premature death, lung cancer, chronic obstructive pulmonary disease (COPD), cardiovascular disease, and asthma development and exacerbation. Air quality in New Jersey has recently been impacted by highly elevated $PM_{2.5}$ levels from climate-change enhanced wildfires in North America. For example, during the spring and summer of 2023, record-breaking Canadian wildfires transported smoke and high levels of fine particulates to the Northeastern United States, including New Jersey. Researchers have modeled the quantitative contribution to $PM_{2.5}$ related mortality due to the additional wildfire smoke attributable to anthropogenic climate change for the continental United States. Study results indicate that the climate change component of health impacts due to the increased wildfire $PM_{2.5}$ to all states, including New Jersey, have been significant in the past and are following an increasing trend.

3.5 New Challenges—Role of Short-Lived Climate Pollutants/Forcers

The existing metrics of the *Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC)* focus on the effects of six main greenhouse gases – carbon dioxide (CO_2), methane (CH_4); nitrous oxide (N_2O); hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (United Nations 1997). However, a notable portion of total global atmospheric forcing (or energy associated with global climate change) is caused by short-lived climate pollutants with atmospheric lifetimes of less than 20 years. These were excluded from the Kyoto metrics because their contributions were not well understood at that time. For instance, the Kyoto metrics do not account for black carbon, which is now recognized as a major pollutant contributing to climate warming globally.

GREENHOUSE GASES: THE PRIMARY DRIVER OF CLIMATE CHANGE

The Intergovernmental Panel on Climate Change (IPCC), Sixth Assessment report, makes clear that black carbon and HFCs are significant contributors to global atmospheric forcing along with CO_2 and CH_4, and ultimately play critical roles in global warming (Figure 3.8) (IPCC 2021a).

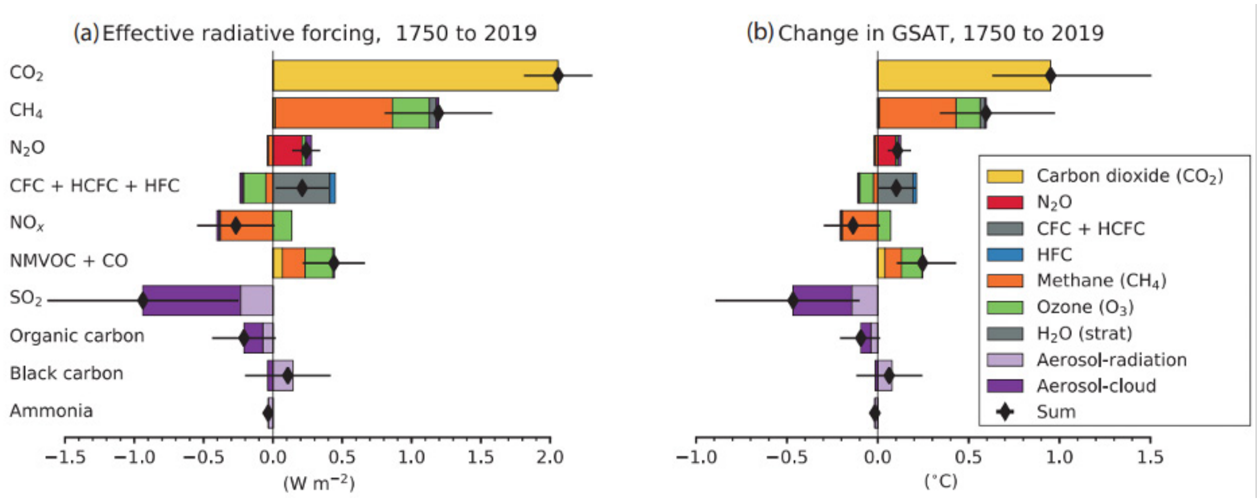


Figure 3.8. Radiative Forcing Estimates. Contribution to effective radiative forcing ERF (a) from component emissions between 1750 to 2019 and (b) global mean surface air temperature (GSAT) change. Estimates from 2019 are relative to 1750 based on CMIP6 models. Values are global average ERF; the black diamonds represent best estimates of the net radiative forcing with corresponding uncertainty intervals (5-95%) (IPCC 2021a).

Other highly warming climate pollutants trap heat in the atmosphere more effectively than CO_2. Although these materials are only emitted in relatively small amounts compared to CO_2 in terms of mass, they have a significant and measurable contributions to climate change due to their high global warming potential per molecule. Highly warming climate pollutants, including methane, halogenated gases, nitrous oxide, and black carbon, accounted for 15.8 $MtCO_2e$, or 15% of New Jersey's total greenhouse gas emissions in 2022 (NJDEP 2025a) based on GWP_{100}. Using GWP_{20}, the total is 43.1 $MtCO_2e$, or 32% of total gross emissions. Each climate pollutant has its own physical and chemical characteristics, and arises from different activities, which in turn shape the strategies available for emissions reduction:

Methane (CH_4) is a gas emitted during the formation, mining, and transport of coal, natural gas, and oil. Emissions also result from agricultural practices and decay of organic waste in landfills.

Nitrous oxide (N_2O) is a gas emitted during agricultural and industrial activities, wastewater treatment, and in trace amounts from combustion of fossil fuels and solid waste. Small amounts can also be released from use in medical products (e.g., as an aerosol propellant).

Halogenated gases have highly reactive elements chlorine, fluorine, or bromine in their molecular structure and include hydrofluorocarbons (HFCs), per- and polyfluoroalkyl substances (PFAS), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Fluorinated gases also include chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), both of which are scheduled for phase out of use under the 1987 Montreal Protocol (USEPA, accessed 2019). Sources of fluorinated gases (F-gases) include industrial and commercial operations including leaks from electronics and metals cleaning and refrigeration systems; heat pumps and air conditioning equipment; semiconductor, magnesium, and aluminum manufacturing; and insulation in electrical transmission and distribution equipment. In New Jersey, most of the emissions of halogenated gases are associated with their uses in, and releases from, air conditioning and refrigeration systems. Sulfur hexafluoride is also a halogenated gas used as an insulating fluid in high-voltage electrical equipment. The global warming potential for these gases can be in the thousands or tens of thousands. Halogenated gases came into widespread use as replacements for ozone-depleting substances (ODS) such as fluorocarbons that are now banned from use (Gallagher et al. 2014).

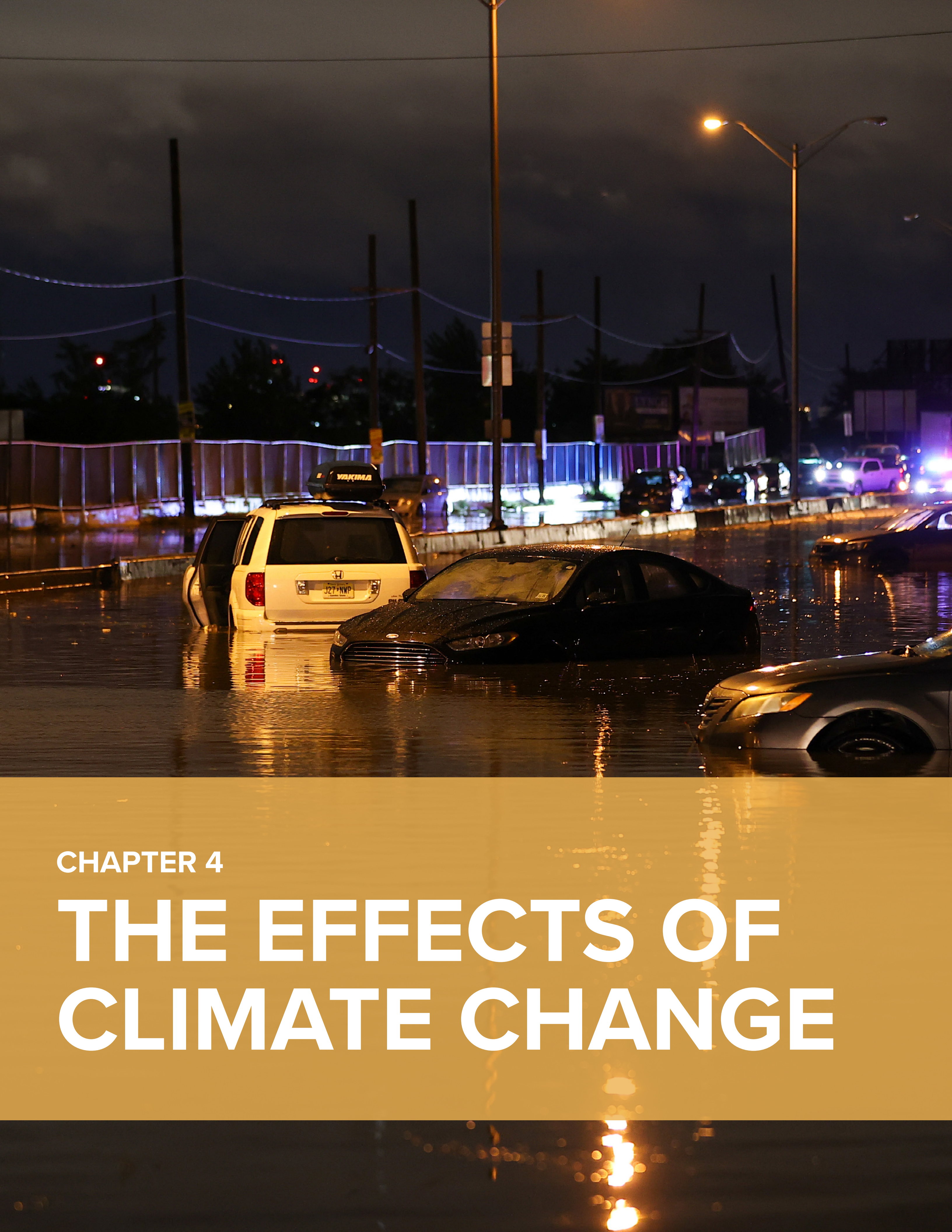
Black carbon is the light-absorbing component of soot and is the product of incomplete combustion. While globally the largest sources of black carbon are cook stoves and wood burning, in New Jersey, the primary sources are older diesel engines and forest fires. It warms the atmosphere directly by absorbing solar radiation. It has indirect effects such as influencing cloud formation. Furthermore, black carbon deposition increases surface melt of snow and ice, leading to reduced snowpack. Black carbon typically remains in the atmosphere for days to weeks, as opposed to CO_2, which can stay in the atmosphere for centuries and even millennia. While in the atmosphere, black carbon has a GWP_{100} of 910 (GWP_{20} is 3,200) (Bond et al. 2013). Once it returns to Earth's surface through rain or air deposition, its climate impacts are mostly relevant to the cryosphere, or regions of frozen water.

3.6 Impact of Changes in Greenhouse Gas Concentrations

As discussed throughout this chapter, greenhouse gas concentrations and their future trajectories will have a direct effect on how quickly Earth warms. This warming will lead to changes in our climate and result in temperature changes (Chapter 4.1), precipitation changes including floods and drought (Chapter 4.2), sea-level rise (Chapter 4.3), and ocean acidification (Chapter 4.4). These, in turn, lead to multiple impacts in air quality (Chapter 5.1), water resources like drinking water and water quality (Chapter 5.2), ecological systems including upland forests (Chapter 5.3), wetlands (Chapter 5.4), other ecosystems (Chapter 5.6-5.8), and human health, agriculture, and communities (Chapter 6).

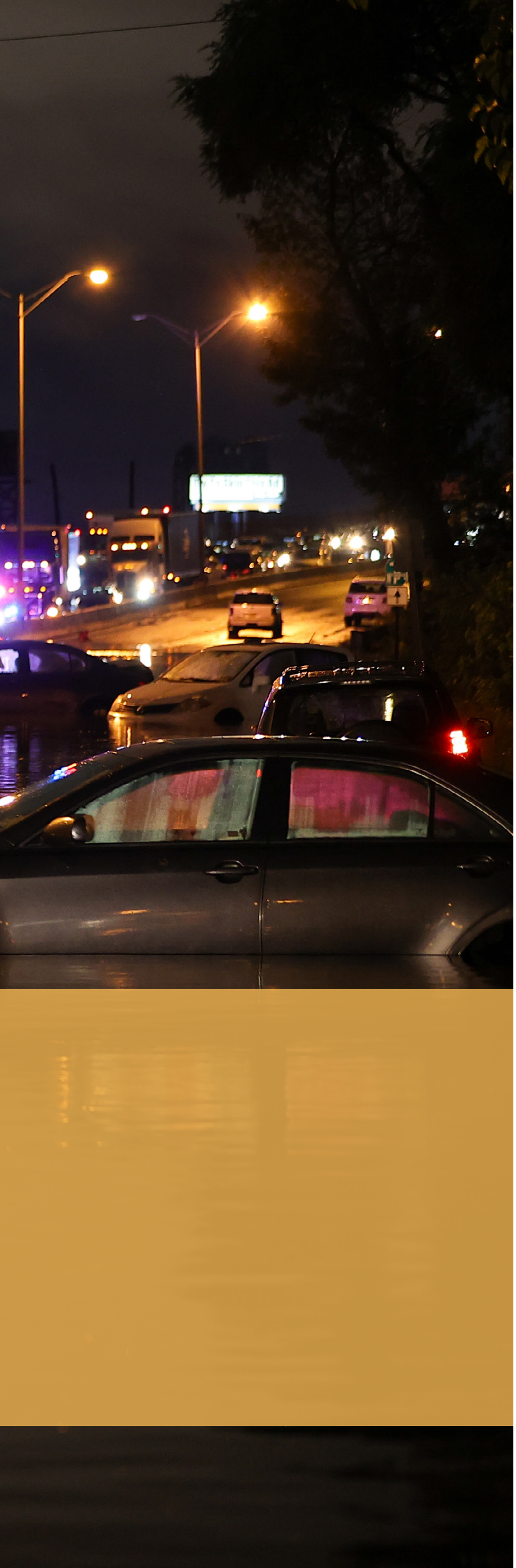
Subsequent chapters of this report detail and elaborate on the impacts briefly discussed here in the context of New Jersey.


NEWARK, NJ



CHAPTER 4

THE EFFECTS OF CLIMATE CHANGE



The following chapter provides details about the direct effects of climate change, such as temperature, precipitation, sea-level rise, and ocean acidification being experienced globally, regionally, and in New Jersey. The chapter discusses each effect individually, describes what New Jersey is currently experiencing, provides insight into what can be expected into the future, and what current and future impacts will be for the state.

Chapter 4 is divided into the following sections:

4.1 Temperature

4.2 Precipitation

4.3 Sea-Level Rise

4.4 Ocean Acidification

CHAPTER 4.1

TEMPERATURE

KEY FINDINGS

- **New Jersey continues to warm faster than the rest of the Northeast region and the world.**
- **Since 1895, New Jersey's annual temperature has increased by 4.1°F.**
- **Average annual temperatures in New Jersey are projected to increase by 3.7–6.2°F by 2100.**
- **New Jersey is experiencing more frequent and hotter heat waves.**

4.1 Temperature

There is strong evidence that increasing concentration of atmospheric carbon dioxide (CO_2) and other greenhouse gases from the emissions of human activities, as well as natural climate variability have warmed Earth's surface by over 2.6°F (1.4°C) from the late 19th century average (1850-1900) from 1880 through 2024 (NASA 2025a). This temperature increase has contributed to an increase in precipitation, intensity of some weather events like heat waves and tropical cyclones, ecological changes, and a rise in global sea level. Continued greenhouse gas emissions at or above current rates are expected to cause further warming and alter the global climate system, likely inducing greater changes than those observed during the 20th century. According to the Climate Action Tracker's analysis of 2030 emissions targets, the temperature by the end of the century is projected to rise to 4.7°F (2.6°C), with a greater than 99.7% likelihood of surpassing 2.7°F (1.5°C). Including binding long-term targets, 3.8°F (2.1°C) of warming is projected by end of century, likely staying below 4.1°F (2.3°C), with a greater than 94.3% probability of exceeding 2.7°F (1.5°C) (Climate Action Tracker 2024). Further detail on temperature projections and the impact of these projected temperature increases on New Jersey are outlined in this chapter.

The urbanization of large portions of New Jersey results in large expanses of asphalt and concrete, and the loss of forests, fields, and other open spaces. These conditions make heat waves especially pronounced and lead to increased impacts in densely populated urban areas. This phenomenon is called the heat island effect (Carnahan and Larson 1990). Urban heat islands result from a combination of dense construction, lack of green space, and the heat generated from traffic congestion. Additionally, many cities act as an artificial valley, trapping heat between high-rises, resulting in higher temperatures on the sidewalk than on a roof, in a city park, or outside the city. Urban heat islands are a growing concern as summer temperatures increase. An analysis of heat waves in New Jersey over the period of 1994-2023 shows there has been a significant decline in diurnal temperature range (Wiley and Lester 2025). Of particular concern is warming overnight temperatures that do not allow populations to cool off after a hot day. This phenomenon can lead to negative health outcomes that range from heat exhaustion to less direct impacts such as declines in mental health. For more information on health impacts, see Chapter 6.

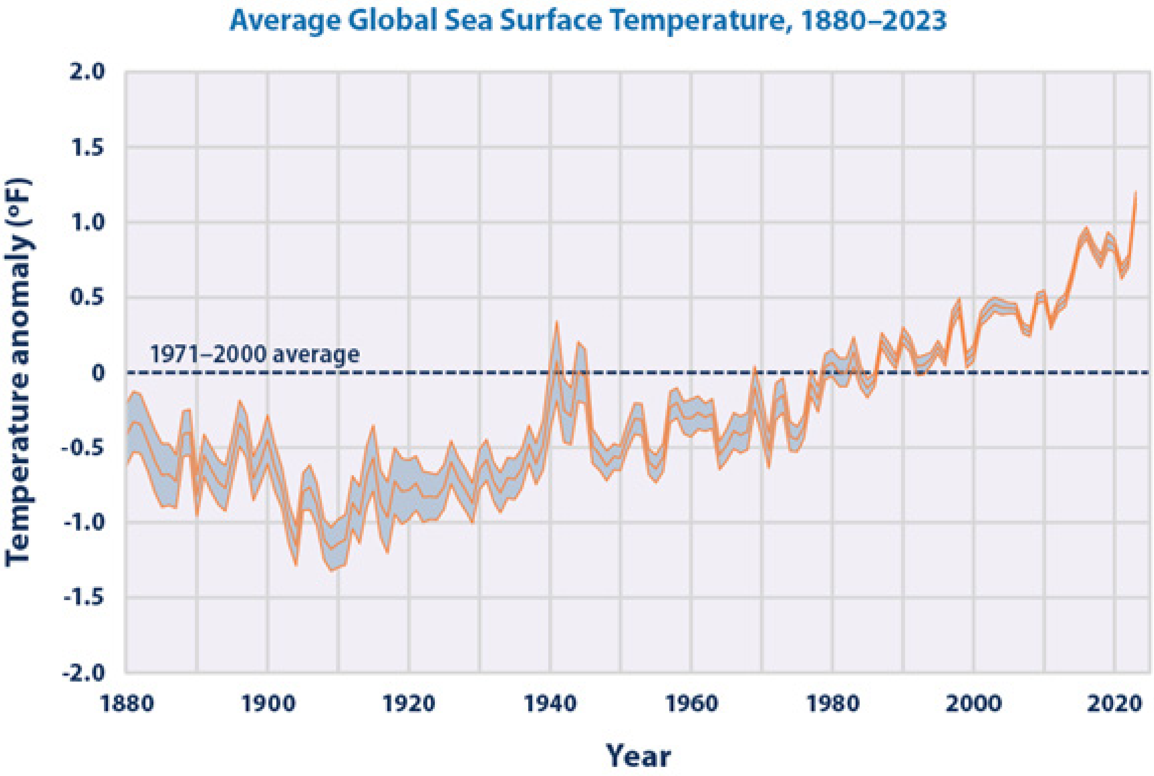
4.1.1 Global Temperatures

The two warmest years since records began in the mid-1800s occurred in 2023 and 2024 (WMO 2025), influenced in part by strong El Niño conditions in the last six months of 2023 and the first few months of 2024 (NOAA National Centers for Environmental Information 2020, Blunden and Boyer 2024, NOAA 2025b). In fact, each year from 2015 to 2024 has individually ranked among the ten warmest years ever recorded (NASA 2025b, WMO 2025). Broad swaths of the world reported record or near-record warmth in 2023. It was the warmest year for China and continental Europe, second warmest year for India and Russia, and third warmest year for Canada. Across the Arctic, the annual surface temperature was the fourth highest in the 124-year record, including a record warm summer (July–September) (Blunden and Boyer 2024).

In addition to warming air temperatures, global sea surface temperatures are also rising (Figure 4.1). This is in conjunction with rapidly increasing ocean heat content, as changes in the total amount of heat stored in the ocean are based on measurements of ocean temperatures at different depths. Averaged over the full depth of the ocean over the surface of the Earth, the 1993–2024 heat-gain rates were approximately 0.66 to 0.74 Watts (Joules/sec) per square meter (Dahlman and Lindsey 2025). As a result of this trend, in 2025, the heat content anomaly reached a new record high rate of 22.29 x 10^{22} Joules above the 1955-2006 average heat content in the top half mile of the ocean (Dahlman and Lindsey 2025). Resulting from the aforementioned rapid increase in ocean heat, sea-surface temperatures hit record highs in the tropical and North Atlantic, the tropical Indian Ocean, sections of the western Pacific, and parts of the Southern Ocean (WMO 2025). From 1901 through 2023, the average global sea surface temperature rose an average of 0.14°F (0.08 °C) per decade, which is a total of 1.8°F (1.0°C) since the beginning of the last century (Figure 4.1) (US EPA 2024a). In addition to the global trend, regional sea surface temperatures are influenced by natural variability, human-induced emissions of heat-trapping gases, and particulate pollution (Ting et al. 2019).

In Figure 4.1, the global sea surface temperature anomaly evident in the early 1940s is due to extremely cold winters in Europe, while temperatures were exceptionally high in other parts of the world such as Alaska, Canada, and Central Asia (Brönnimann 2005). After reconstructing and modeling the atmosphere, this global temperature anomaly has been attributed to a strong and prolonged El Niño event. As global air temperatures continue to rise, global sea surface temperatures are also expected to continue rising.

CAPE MAY, NEW JERSEY


Average Global Sea Surface Temperature, 1880–2023

Data source: Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S., & Zhang, H.-M. (2024). *NOAA Extended Reconstructed Sea Surface Temperature (ERSST), version 5* [Data set]. Retrieved February 1, 2024, from https://doi.org/10.7289/V5T72FNM

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 4.1. Average Global Sea Surface Temperature Anomaly, 1880-2023. The center orange line represents the difference between the annual average and the 1971-2000 average. The shaded region reflects the uncertainty in the data due to the number of measurements collected and the precision of the methods used (US EPA 2024a).

4.1.2 Regional Temperatures

The United States National Climate Assessment presents observed and projected climate changes for the Northeast region of the United States, reporting that temperatures in the region increased by 1°F (0.6°C) in West Virginia to 3°F (1.7°C) in New England since 1901 (Dupigny-Giroux et al. 2018). By 2035, it is expected that the average temperature in the Northeast will be 3.6°F (2°C) warmer than the pre-industrial (1850-1900) average, regardless of future emissions (Hayhoe et al. 2018). By 2100, downscaled global climate model data indicate a potential increase in mean annual temperature of 2.6°F (1.4°C) to 7.6°F (4.2°C) for New England and Upstate New York compared to the 1971-2000 baseline (Janowiak et al. 2018). The Mid-Atlantic region could experience a nearly 190% increase in the average number of days with temperatures above 90°F by mid-century — rising from 16.5 to 47.7 days. By the end of the century, that number could surge by more than 300% above the 1991-2020 baseline, reaching 68.1 days under a high emission scenario (SSP3-7.0) (Grocholski et al. 2024). The number of days below freezing is decreasing overall (Broccoli et al. 2020, Climate Central 2023). Further, the rate of warming in the winter season is nearly two times faster than summer in some northern states (Marvel et al. 2023). It should be noted that some of the expected additional days above temperature thresholds (e.g., 32°F and 90°F) include days that currently average just below those levels.

Table 4.1. Northeastern State Trends, 1900-2020. Comparing data for the 2002–2021 period to the average for the period of 1901–1960, a large area of the Northeast has experienced a warming of average annual temperatures of more than 2°F (NOAA 2022). This includes New Jersey.

State	Temperature Trend (+/- °F)	Timeframe
West Virginia	+1	1900-2020
Pennsylvania	+2	1900-2020
Maryland	+2.5	1900-2020
New Jersey*	+3.5	1900-2020
Delaware	+3	1900-2020
New York	+2.5	1900-2020
Connecticut	+3.5	1900-2020
Rhode Island	+4	1900-2020
Massachusetts	+3.5	1900-2020
Vermont	+3	1900-2020
New Hampshire	+3	1900-2020
Maine	+3.5	1900-2020

**for the most up-to-date temperature data see Chapter 4.1.3*

4.1.3 New Jersey Temperatures

The Office of the State Climatologist at Rutgers University reports statewide temperature and precipitation records back to 1895. These data show a statistically significant increase in New Jersey's average annual temperature of 4.1°F (2.3°C) from 1895 to 2024 (Figure 4.2) (Office of the New Jersey State Climatologist 2025a). New Jersey is warming faster than the Northeast region (3°F [1.7°C]) and the world (2.2°F [1.2°C]) when compared over the same time period (NOAA 2025a). The rate of warming in New Jersey has increased since 1970. In analyzing data from the New Jersey State Climatologist through the end of 2024, several trends were observed: fifteen of the twenty warmest calendar years on record have occurred since 2000 while the ten coldest years all occurred before 1941. While 2012 remains the warmest year on record

> ***"…fifteen of the twenty warmest calendar years on record have occurred since 2000 while the ten coldest years all occurred before 1941…"***

with an average temperature of 55.9°F (13.3°C), the average annual temperature in 2024 was a close second at 55.7°F (13.2°C). The average annual temperature in 2024 was 3.8°F (2.1°C) above the long-term annual average of 51.9°F (11.1°C) from 1895 – 2024 and 2.1°F (1.2°C) above the 30-year normal of 53.6°F (12°C) from 1991-2020.

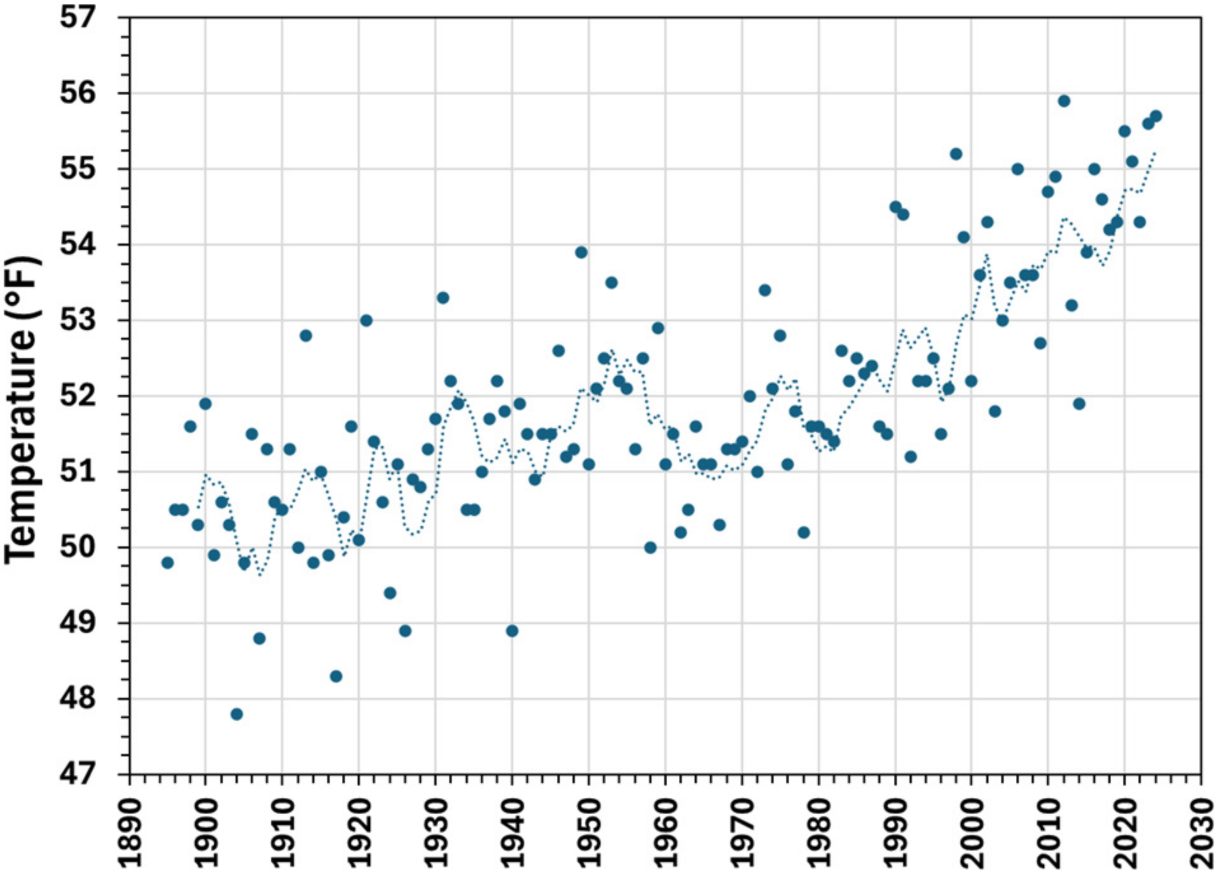


Figure 4.2. New Jersey 12-Month Average Air Temperature from 1895 to 2024. Points represent the average annual temperature, and the dashed line represents a five-year average of those points. Data from the (Office of the New Jersey State Climatologist 2025a).

New Jersey has also seen heat-related trends as another indicator of a warming climate, as demonstrated in a recent study that analyzed heat wave trends in the state (Wiley and Lester 2025). Three measures were used in the analysis: heat wave length, heat wave frequency, and heat wave temperature range. Twelve stations were chosen for their completeness of record and location to get as even a distribution throughout the state as possible. From the results, it was found that heat wave frequency and heat wave temperature range have experienced significant changes (an increase and decrease, respectively). When the heat wave temperature range decreases, the difference between high and low temperatures is smaller which means that conditions stay warmer. Duration of heat waves did not experience a significant change over the 30-year period of the analysis. Overall, there was found to be a trend toward more heat waves and less daily cooling associated with each one.

For the seasonal analyses, winter months include December, January, and February, while summer months include June, July, and August. Recently, many more unusually warm months have occurred in the state than unusually cold months. When assessing each month's top five warmest average temperatures, 48 out of 60 (80%) have occurred since 1990, while none of the months in that same period recorded a top five coldest average temperature. The last top five coldest temperature months occurred in December 1989 (Office of the New Jersey State Climatologist 2020). Overall, the five warmest winters on record have occurred since 1998, and the thirteen warmest summers on record have occurred since 1999.

Monthly average temperature data from the New Jersey State Climatologist (Office of the New Jersey State Climatologist 2025a) were analyzed for long-term trends and seasonal variation within each of three regional climate divisions of New Jersey (Figure 4.3). To determine the change in temperature over time, the linear slope was calculated over the 129-year period (1895 to 2024) for each division (Table 4.2).

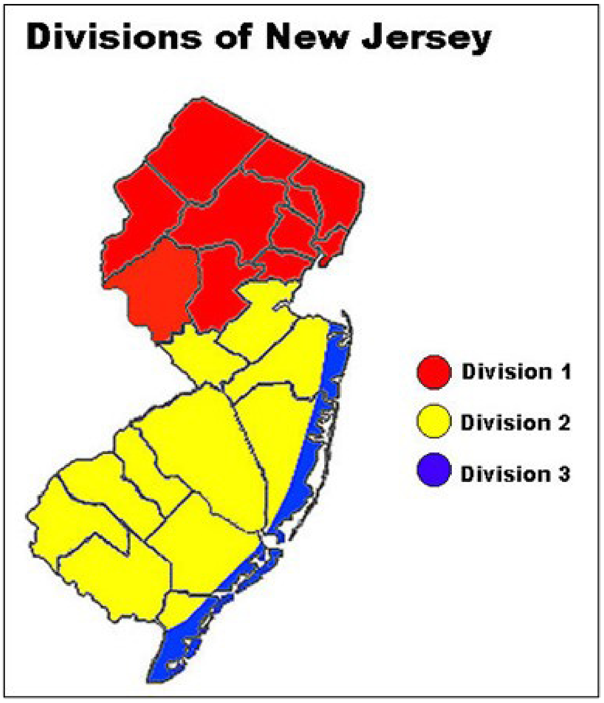


Figure 4.3. Regional Climate Divisions of New Jersey for Temperature Analysis (Office of the New Jersey State Climatologist 2025a).

Table 4.2. Annual and Seasonal Increases in Air Temperatures Over the Period 1895 to 2024 (Office of the New Jersey State Climatologist 2025a). The change in temperature was determined from the linear slope of the entire period of record.

	°C	°F				
	Annual	Annual	Winter	Spring	Summer	Fall
Statewide	2.3	4.1	5.6	3.5	3.6	3.4
Division 1 North	2.3	4.2	6.0	3.6	3.5	3.5
Division 2 South	2.2	4.0	5.4	3.4	3.6	3.3
Division 3 Coast	2.5	4.6	5.8	4.0	4.2	3.9

Statewide, average annual temperature in New Jersey has increased by 4.1°F (2.3°C) over this period. Temperature increases vary geographically within the state. In the coastal region (Division 3), the average annual temperature has increased by 4.6°F (2.5°C) since 1895, with the northern region (Division 1) increasing by 4.2°F (2.3°C), and the southern region of the state (Division 2) increasing by 4.0°F (2.2°C). Seasonally, winter shows the greatest temperature increase (December, January, and February). In the northern region, the average winter temperature increased by 6.0°F (3.3°C) since 1895, followed by the coastal region at 5.8°F (3.2°C), and the southern region at 5.4°F (3.0°C).

4.1.4 Statewide Temperature Projections

Given a continued rise in global greenhouse gas concentrations, a continued warming trend in New Jersey is very likely. Global climate models that factor in future greenhouse gas emissions are used to project the magnitude of future temperature increases. Projections published by NOAA's National Centers for Environmental Information are based on the low (SSP1-2.6; defined as "lower" by the author), intermediate (SSP2-4.5), and very high (SSP5-8.5; defined as "higher" by the author) emission scenarios, as adapted from (Runkle et al. 2022) (Figure 4.5). Less warming is expected under the lower emission scenario, with end-of-century projections ranging 2.2-8.2°F warmer than the 1901–1960 average. The very high emission scenario is projected to bring a temperature increase of 7.4-14.8°F warmer than the 1901-1960 average. The intermediate emission scenario, which most closely aligns with current estimates, leads to end-of-century projections ranging from about 4.1°F to 10°F above the 1901–1960 average. Analysis by Rutgers University reported that under an intermediate emission scenario (SSP2-4.5), the average annual temperatures in New Jersey are projected to increase 3.7–6.2°F (2.1–3.4°C) (10th–90th percentile of model projections) by the end of the 21st century relative to the 1991–2020 average. Under a high emission scenario (SSP3-7.0), temperatures are expected to increase 5.8–8.6°F (3.2–4.8°C) by 2100 (Davies et al. 2025). These are the numbers that are used in temperature projections in this report. Similar projections are offered by the New York City Panel on Climate Change who suggests that localized annual average temperatures will increase from 4°F to 8°F (2.2°C to 4.4°C) higher than the 1981-2010 climate normal by 2050 (Braneon et al. 2024). The most recent 10-year (2015-2024) average annual temperature is currently about 3.7°F (2.1°C) above the 1901-1960 period average (Office of the New Jersey State Climatologist 2025a).

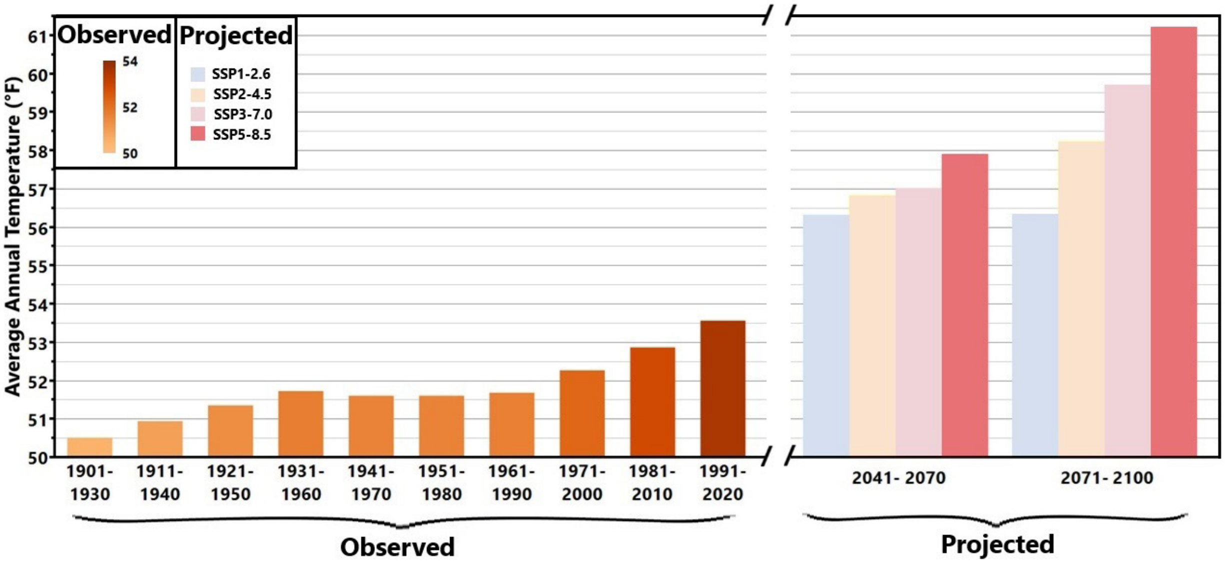


Figure 4.4. Observed and Projected average annual temperatures in New Jersey. Average annual temperatures observed in New Jersey over 30-year periods, known as climate normals, are shown as orange bars that are increasingly dark with higher temperature (Office of the New Jersey State Climatologist 2025a). The projected estimates for average annual temperature in mid-century (2041-2070) and end of century (2071-2100) are shown in colorful grouped bars that depict low (light blue), intermediate (yellow), high (pink), and very high (red) emission scenarios. The projected estimates derive from downscaled climate model data outputs at 1 km resolution (Wang et al. 2016, AdaptWest Project 2022).

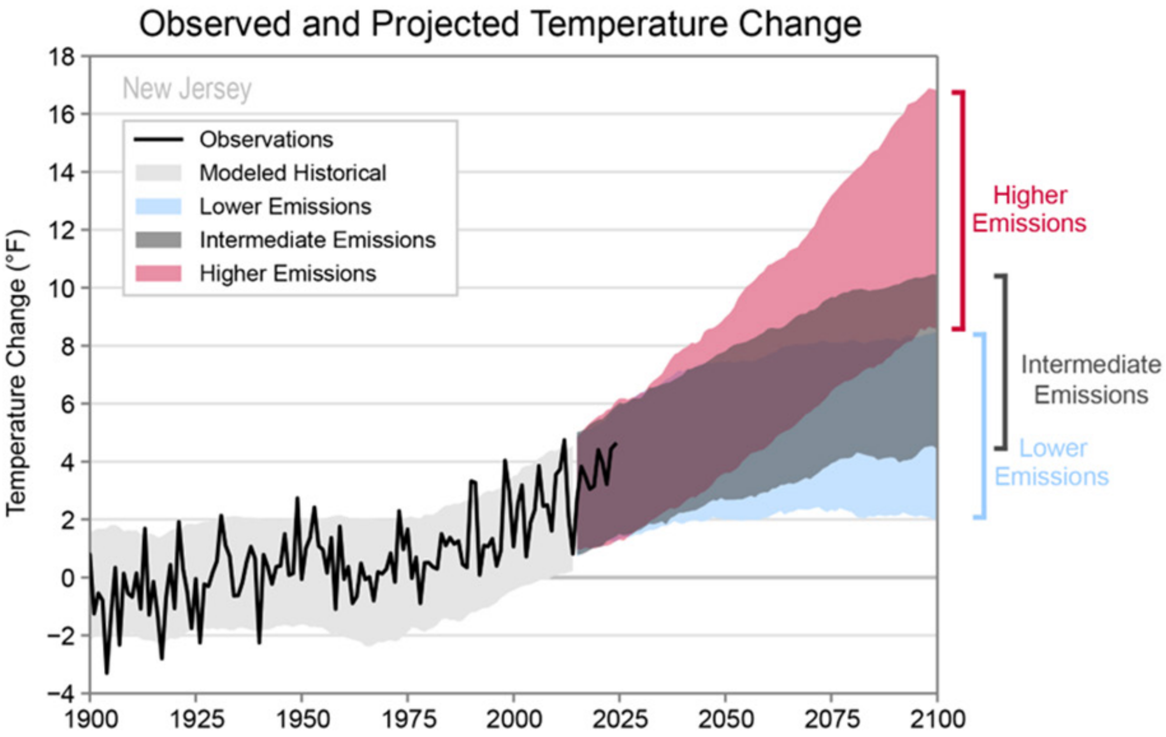


Figure 4.5. Observed and Projected Changes (Compared to the 1901-1960 Average) in Near-Surface Air Temperature for New Jersey. Observed data are for 1900-2024. Projected changes for lower (SSP1-2.6), intermediate (SSP2-4.5), and higher (SSP5-8.5) emission scenarios are for 2015-2100. Adapted from (Runkle et al. 2022).

In New Jersey, warming temperatures will produce many detrimental effects. For one, heat waves are expected to become more intense (Runkle et al., 2022) and impact larger areas with more frequency and longer duration by 2050 (Lyon et al., 2019). A multi-model analysis of 100°F heat index found that by midcentury, the frequency of heat index, or apparent temperature, values over 100°F is projected to increase threefold in the Northeast under an intermediate emission scenario (RCP 4.5) (Dahl et al. 2019). These temperature extremes lead to heat waves that cause a number of adverse impacts; namely increases in energy consumption, reduced power plant efficiency, air pollution, negative effects on human health, and increased water loss through evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) (Mazdiyasni and AghaKouchak 2015). While warming temperatures can have positive outcomes such as longer growing seasons (Frumhoff et al. 2007), these potential benefits may be offset by side effects such as greater precipitation extremes and increases in drought conditions (Gautam et al. 2023).

Further, the number of days below freezing will likely decrease (Runkle et al. 2022, Climate Central 2023) as winters warm nearly two times faster than summer in some northern states (Marvel et al. 2023). Although it is likely that there will be fewer intense cold waves, which are defined by rapid falls in temperature and extreme low temperatures for an extended period (FEMA 2023), extreme cold events are still possible even in a warming climate (Ye et al. 2025). Combined with the potential for stronger winds and increased precipitation from winter storms, the risk of exposure to these elements during the cold season will remain a threat going forward (Conlon et al. 2011).

CHAPTER 4.2

PRECIPITATION

KEY FINDINGS

- **Annual precipitation in New Jersey has increased by 2.8 inches per century since 1895.**
- **Annual precipitation in New Jersey is expected to increase by an average of 6 to 7% by 2100.**
- **The intensity and frequency of precipitation events have increased and are expected to continue increasing due to climate change.**
- **By the end of the century, the amount of precipitation that occurs during a 1% storm is expected to increase across the state, but most notably by 20% to 25% in northern counties.**
- **Droughts may occur more frequently due to the expected changes in precipitation patterns.**
- **The size and frequency of floods will increase as annual precipitation increases.**
- **Tropical storms have the potential to increase in intensity due to the warmer atmosphere and warmer oceans that will occur with climate change.**

4.2 Precipitation

The amount of water vapor in the atmosphere is influenced by factors such as regional weather patterns, atmospheric temperature, and regional geography. The amount of precipitation that may fall is dependent on the amount of water vapor available in the atmosphere and other necessary weather conditions. Locally, precipitation is dictated by continental influences, such as inland mountains, as well as coastal influences that include offshore conditions (Marquardt Collow et al. 2016). Cooler temperatures and greater amounts of precipitation occur at higher elevations around the more mountainous areas of the region.

In New Jersey, the amount and frequency of precipitation vary over short and long periods of time. While average annual precipitation totals have already increased significantly over the observational record (Robinson et al. 2022), climate change is expected to exacerbate the intensity of rainfall events and extend the duration of drier periods (IPCC 2021b, Payton et al. 2023). Such changes could have immediate impacts to public safety due to increased flooding, water supply availability, water quality, stormwater infrastructure, and ecological impacts.

4.2.1 Global and Regional Atmospheric Conditions

Radiation from the Sun evaporates water from Earth's ocean, freshwater, and land surfaces (Trenberth 2011). Water vapor circulates throughout the troposphere (the layer of the atmosphere closest to the land surface) by winds. As the water vapor moves higher into the troposphere it combines with particles, forming the droplets of clouds. The water then returns to Earth's surface as a form of precipitation (i.e., rain, snow, hail). Precipitation falling on land that does not infiltrate to groundwater will remain as runoff on the surface, ultimately flowing back to the oceans via streams and rivers. Water is also returned to the atmosphere from plants through transpiration and from open water and soils by evaporation (evapotranspiration). Evapotranspiration rates are greatest during warm, sunny, and windy days, typically in the late spring through early fall, when plants are actively growing and environmental conditions are favorable.

4.2.2 Changes in Global and Regional Atmospheric Conditions

As carbon dioxide (CO_2) levels increase, the temperature of Earth's atmosphere also increases (Guilbert et al. 2015, USGCRP 2023) (see Chapter 4.1). As air temperatures increase, the atmosphere has a greater capacity for saturation of water vapor. For every 1.8°F (1.0°C) increase in air temperature, the atmosphere can hold up to approximately 7% more moisture (Trenberth 2011). This results in hydrologic intensification, an increased rate of water transfer to and from land surfaces, including changes to precipitation and evapotranspiration that can result in increased frequencies of flooding and drought-like conditions (Ficklin et al. 2022). More moisture in the atmosphere provides the means for storms to be more intense (Guilbert et al. 2015) and increases the chances of extreme rainfall events (Coumou and Rahmstorf 2012, Marquardt Collow et al. 2016, Douville et al. 2021). However, this does not mean increases in moisture for all areas. While model simulations for arid and semi-arid regions of the world have indicated an increase in atmospheric water vapor over the four decades prior to 2024, observations indicate this increase has not occurred (Simpson et al. 2024). There has been an increase in water vapor–holding capacity, as described, but the availability of moisture to meet the increased atmospheric demand is lower than modeled in arid/semi-arid regions.

A warmer atmosphere will also contribute to the warming of the oceans. Although the main source of ocean heat is solar radiation; clouds, water vapor, and greenhouse gases all additionally emit the heat they have absorbed and some of this heat is absorbed into the ocean (Dahlman and Lindsey 2025). During summer and fall, some of the most intense precipitation events in the Northeastern region of the United States (Northeast) are from tropical cyclones (Marquardt Collow et al. 2016, Howarth et al. 2019). Since tropical cyclones are fueled by the energy found in ocean waters, a warmer atmosphere and warmer oceans will provide the potential for tropical storms to increase in intensity (Coumou and Rahmstorf 2012, Bhatia et al. 2019). These factors are likely to affect the Northeast and cause conditions that have the potential to be more intense than those seen during Extratropical Cyclone Sandy (hereafter referred to as Superstorm Sandy) in 2012 (Lau et al. 2016). Additionally, with heightened oceanic water levels caused by sea-level rise, the compounding effect results in an increased flooding impact risk during storm surges (Marvel et al. 2023).

While changes in global circulation patterns will likely have significant impacts on local precipitation patterns, it remains difficult to estimate localized precipitation changes due to the spatial and temporal (time) variability of global atmospheric drivers (Guilbert et al. 2015). If the concentration of greenhouse gases from emissions continues to rise as expected, the eastern United States can expect to see an increase in the number of days where the atmospheric conditions would be supportive of severe thunderstorms and other hazards such as lightning, heavy rain, hail, and tornadoes (Diffenbaugh et al. 2013, Allen 2018, Trapp et al. 2019, Haberlie et al. 2022).

4.2.3 Observed Changes in Precipitation Patterns

Precipitation can be monitored in many ways, with two of the most common ways being the average annual precipitation occurring in a defined area and precipitation from extreme events. Extreme precipitation events are those that result in very heavy rain or snowfall, usually within a short period of time and represent the heaviest 1% of all daily precipitation events, often referred to as the 100-yr storm (Marvel et al. 2023).

Climate change has caused the eastern United States to become wetter (Kirchmeier-Young and Zhang 2020). In the Northeast, extreme precipitation increases have occurred in all seasons (Huang et al. 2017) and extreme precipitation has increased more in this region than anywhere else in the United States (Whitehead et al. 2023).

4.2.3.1 Annual Precipitation in New Jersey

Over the long-term observational record from 1895 to 2024, New Jersey receives an average of 45.6

inches (115.7 cm) of precipitation annually (Office of the New Jersey State Climatologist 2025b), which includes all types of precipitation events (e.g., rain, snow, hail). This statewide average varies over time and geography. There is a north to south gradient in annual precipitation totals due to geographical differences in the inland and coastal areas (Agel et al. 2015, Runkle et al. 2022). The north to central portion of the state averages 47.2 inches (119.9 cm) of precipitation annually, while the coastal and southern regions average 44.3 and 44.6 inches, (112.5 cm and 113.3 cm) respectively (Office of the New Jersey State Climatologist 2025b). This spatial variation occurs due to the rapid change in elevation at the fall line along the I-95 corridor. The moist air is lifted by the topography in northern New Jersey, which cools the air, condensing the water vapor, thereby enhancing precipitation in the region. This occurs because cooler air at higher elevations does not hold as much condensation as warmer air at lower elevations (Marquardt Collow et al. 2016). Meanwhile, coastal areas experience less precipitation due to the maritime atmosphere being stabilized by the Atlantic Ocean.

Assessing long-term precipitation trends over time is fundamental for projecting future precipitation levels. Analysis of statewide precipitation data from 1895 to 2024 shows a weakly significant increase in the total annual precipitation at a rate of 6.2% per century (2.8 inches per century) (Office of the New Jersey State Climatologist 2025b). The increase over time is largely driven by seasonal increases in the spring and fall (Robinson et al. 2022). Evaluating this data in short-period averages (e.g., five- and ten-year periods) accounts for interannual variability that is commonly associated with precipitation patterns. Statistical results using these short-period averages show significant increases over the same 130-year period (Figure 4.6).

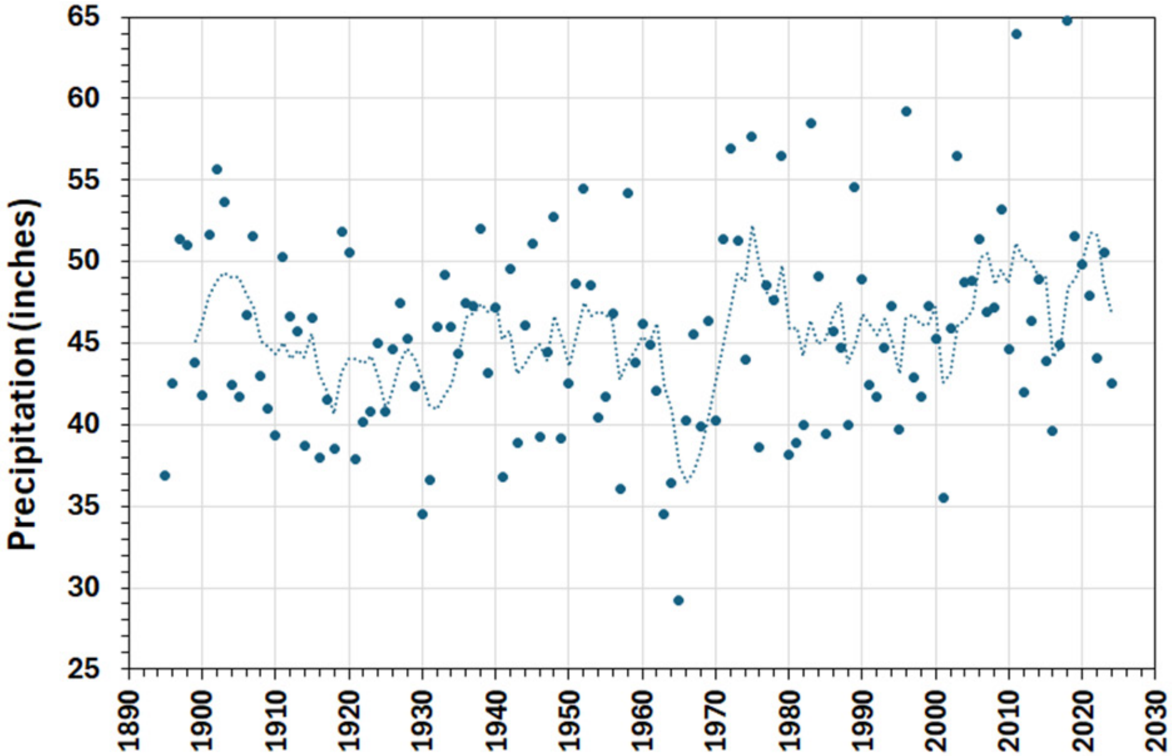


Figure 4.6. Statewide Annual Precipitation in Inches (1895 – 2024). Points represent the statewide annual precipitation, and the dashed line represents a five-year average of the data based on year of interest and the previous four years. Data acquired from the (Office of the New Jersey State Climatologist 2025b).

Recent decades include particularly large increases in annual precipitation in New Jersey. This is apparent when assessing changes in 30-year averages, known as climate normals. Climate normals are updated every ten years based on guidance from the World Meteorological Organization, with the latest update averaging 47.6 inches of average annual precipitation for the period 1991-2020. The last three (1971-2000, 1981-2010, and 1991-2020) are the only climate normals that have exceeded 46 inches in statewide average annual precipitation, with the most recent averaging 2 inches above the long-term average (1895-2024). This is partly explained by more extreme events occurring in recent years. For example, four of the ten wettest years on record occurred in the last 30 years, while only one of the ten driest years on record occurred during this period (Robinson et al. 2022). The years 2011 and 2018 are the only two instances in the long-term record where the annual amount of precipitation exceeded 60 inches (Office of the New Jersey State Climatologist 2025b). The wettest year on record was 2018, which totaled approximately 65 inches (165.1 cm) of precipitation, more than 42% (19 inches or 48.8 cm) above the long-term average. Dry years, defined here as those with precipitation of five or more inches (12.7 cm) below the current long-term average, have decreased in frequency. Such dry years have occurred only three times between 1991-2024, where previous climate normal periods had between six and twelve occurrences per normal period (Office of the New Jersey State Climatologist 2025b).

4.2.3.2 Extreme precipitation

Extreme precipitation is commonly described in terms of frequency and intensity. Frequency can be evaluated using return periods, or recurrence intervals, for extreme precipitation, which describe an average or estimated average amount of time (e.g., 100 years) between events of similar precipitation intensity for a given area. Precipitation intensity is the amount of rain, snow, or other precipitation that falls over a given period of time (e.g. inches per hour). Just as with annual precipitation, the frequency and intensity of precipitation events is characterized by large variability over time and by geography (e.g., between inland and coastal areas). Extreme precipitation, defined as the top 1% of the heaviest precipitation events for an area based on historical records (Marvel et al. 2023), can include coastal nor'easters, snowstorms, spring and summer thunderstorms, tropical storms, and on rare occasions hurricanes (Runkle et al. 2022).

Precipitation events in the Northeast often occur as persistent multiday events (two to five days); however, the most intense precipitation usually occurs within several hours over the course of a single day (Agel et al. 2015). While there is large variability when considering precipitation trends, analysis of data shows an increase in intensity and frequency of heavy precipitation events (Agel et al. 2015, Whitehead et al. 2023). Even when using different data sources and periods of analysis, the historical record of daily precipitation in the United States supports the claim that there is a statistically significant upward trend in heavy precipitation that is occurring in the Northeast (Agel et al. 2015, Hoerling et al. 2016, Marvel et al. 2023). Extreme precipitation events are becoming more intense, occurring more frequently, and are projected to continue in this trend (Huang et al. 2017, Marvel et al. 2023).

Several studies have found increases in the frequency and amount of heavy precipitation in the Northeast over the last century (Colle et al. 2015, Marquardt Collow et al. 2016, Howarth et al. 2019, DeGaetano 2021a, Kim et al. 2022, Marvel et al. 2023). From 1958-2021, total precipitation amounts during extreme precipitation events (heaviest 1%) have increased in the Northeast by about 60%, which is more than any other region in the country (Marvel et al. 2023). Over the same time period, the number of daily events that exceeded 2, 3, 4, and 5 inches of precipitation have all significantly increased in the Northeast (Whitehead et al. 2023). From 1997 to 2014, more than four times the number of daily rainfall events with approximately 6 inches or more occurred compared to the 1979-1996 period (Howarth et al. 2019). In New Jersey, extreme precipitation amounts have already increased at

Return Periods for Extreme Storms

Accurately predicting when or where precipitation amounts will occur is a very difficult proposition. Precipitation frequency analysis provides estimates for the potential frequency of rainfall amounts in a given area using historical data, which can be estimated using a range of return periods (e.g., 1,10, 100, 1000 years) and durations (e.g., minutes, hours, days). Return periods most commonly refer to a 24-hour duration, because most weather stations collect daily records rather than hourly records. However, return periods are sometimes misunderstood. A 100-year storm has an annual exceedance probability of 1%, meaning the 1-in-100 chance of having a storm event exceed that estimated precipitation depth is the same chance each year regardless of whether that depth was exceeded in any previous year at a given location. For this reason, some organizations, including the Federal Emergency Management Agency (FEMA), now refer to a so-called 100-year storm as a 1% storm.

The National Weather Service's NOAA Atlas 14 has provided the standard for site-specific precipitation frequency estimates across the United States. Such estimates are used to assist with planning for regulatory requirements, public safety, and developing critical infrastructure (e.g., hospitals, stormwater management, water treatment facilities). For example, NOAA Atlas 14 provides an estimate of 8.2" of precipitation in Trenton, New Jersey for a 24-hour, 100-year storm. According to this estimate, the next storm to reach 8.2" of rainfall within 24 hours can be described as a 100-year storm. However, precipitation events have become more intense in recent decades, and that pattern is projected to continue due to climate change. Precipitation frequency analyses in NOAA Atlas 14 rely on assumptions of an unchanging climate and risk underestimating precipitation intensity and the associated hazards (DeGaetano 2021a, Kim et al. 2022, 2023).

most weather stations by 2.5% or more, with 100-year storms increasing by more than 10% in some places (DeGaetano 2021a).

The frequency of multi-day precipitation events has also increased over time. Nationally, there has been a significant increase in the occurrence of two-day precipitation events from the period of 1901-1960, to the period of 1961-2017 (USGCRP 2017). The same study points to a 40% increase in the likelihood of three-day precipitation events since 1900. A recent study using weather station data in and around New Jersey compared extreme rainfall amounts reported in NOAA Atlas 14 over the period 1950-2000 to a reanalysis for 1950-2019 (DeGaetano 2021a). The results show that 1% storm rainfall amounts during multi-day (2, 3, 4, 7, 10, and 20-day) events have increased at 77 to 100% of stations with amounts increasing, on average, by 3 to 8%, including some individual stations increasing by as much as 21%. This trend underscores the need to reanalyze precipitation intensity conditions in the state on a consistent basis.

While annual precipitation totals in New Jersey have slightly increased over time, the distribution of precipitation events throughout each year is a key factor in the potential environmental impacts (e.g., flooding, drought) (Robinson et al. 2022). One recent study in New Jersey documented that the majority of weather stations, especially those located in the southern coast and the northwest, are now receiving greater contributions to annual totals from moderate and heavy storm events since 2000 when compared to 1950-1999 (Robinson et al. 2022). With the increases in extreme precipitation amounts in the Northeast (Whitehead et al. 2023), there is potential for prolonged dry periods occurring in between extreme precipitation events.

Extreme precipitation days in the Northeast can occur in any month, but the majority occur in the warmer months during the spring, summer, and fall (Agel et al. 2015, Howarth et al. 2019, Kunkel et al. 2020). From 1979-2014, 92% of events with ~6 inches of precipitation or more in the Northeast occurred during spring, summer, and fall, with increasing frequencies of this type of extreme event, especially in the fall (Howarth et al. 2019). In most years, New Jersey experiences at least one coastal storm, but has experienced as many as five to ten storm events in some years (Runkle et al. 2022). Damaging nor'easters are most common between September and April and bring strong winds, heavy rain or snow, and often result in coastal flooding (NOAA 2020a). Seasonal and interannual variability masks long-term changes, making it more challenging to separate climate induced changes from natural fluctuations.

As described previously, there is also spatial variability in extreme precipitation patterns due to geography. Coastal stations experience more extremes in the spring than inland stations, while inland stations experience more extremes in the summer than coastal stations. Overall, more extreme events were recorded in coastal areas than inland from 1901-2014 (Huang et al. 2017). In more recent years (1979-2008), on an annual basis, the Northeast coastal areas experience a greater intensity of extreme precipitation events than inland areas, but inland areas experience more extreme precipitation days (Agel et al. 2015, Teale and Winter 2024). Over the observational period from 1950-2017, the intensity of wet days in the Northeast increased by approximately 1.2 in/day (30 mm/day) in inland areas and 2.4 in/day (60 mm/day) at the coast (Agel and Barlow 2020).

4.2.4 Precipitation Projections

There are difficulties in predicting whether annual precipitation or the number of extreme precipitation events will increase because of the various meteorological interactions that drive precipitation patterns (Marquardt Collow et al. 2016). It is generally accepted that warmer atmospheric and sea-surface temperatures will increase the potential energy in a storm system, ultimately increasing the potential for more intense tropical storms (Huang et al. 2017, 2021, Knutson et al. 2019, IPCC 2021a).

Since the Intergovernmental Panel on Climate Change's (IPCC) First Assessment Report was published, there has been compelling evidence that more heavy precipitation events would occur as global water cycling intensified as a symptom of global warming (Hoerling et al. 2016, Krakauer et al. 2019). While uncertainties and variations still exist, climate models have improved. The IPCC's Sixth Assessment Report (2021) reinforces early models' assertions that as greenhouse gas forcing increases, radiative forcing (or changes to the atmospheric energy [heat] balance associated with global climate change) will lead to more heavy precipitation events.

As Earth warms and additional water vapor moves to the atmosphere, changes in timing and intensity of heavy precipitation events will become more likely. Studies have observed increases in the intensity of extreme precipitation in North America, which have now been robustly attributed to human influence (Kirchmeier-Young and Zhang 2020). Extreme precipitation events are observed to be increasing throughout the contiguous United States, with the largest increase occurring in the northeast region (Marquardt Collow et al. 2016, Marvel et al. 2023). Wright et al. (2019) also present a significant increase of over 130% has occurred in the frequency of extreme rainfall events that exceed the 10-year, 24-hour storm between 1950 and 2017 in the Northeast. Not only are increases anticipated in the intensity of precipitation events and the frequency at which they will occur (Broccoli et al. 2020, Whitehead et al. 2023), precipitation events are also anticipated to show more variation in timing and spatial distribution due to climate change (Payton et al. 2023). This is important, as the potential for increases in precipitation can lead to increased flooding events and even more droughts with potential to impact public safety and infrastructure (Broccoli et al. 2020).

In recent years, there have been advances that enable scientists to better attribute individual extreme events to climate change (CarbonBrief 2024, World Weather Attribution 2025). In addition, there is data that indicates that the increased occurrence of such events may be attributed to changes in climate (Wuebbles et al. 2014, Huang et al. 2021). The number of Category 3, 4, and 5 North Atlantic hurricanes has increased since 1951, most likely due to higher sea surface temperatures occurring in the region where Atlantic hurricanes form. According to recent modeling, it is likely that the proportion of these very intense hurricanes will increase with warming. Additionally, there is high confidence that the rate at which tropical cyclones intensify will increase and that rainfall rate in these storms will continue to increase with warming (Kopp et al. 2025). Projections to estimate the change in frequency and severity of extratropical cyclones (nor'easters, for example) contain a large amount of uncertainty due to how models predict storm tracks and how well weather patterns, such as El Niño – Southern Oscillation, are simulated (Colle et al. 2015, Kopp et al. 2019). While much of the evidence indicates an increase in precipitation associated with extratropical cyclones, there is low confidence regarding future changes in ETCs due to the limited body of evidence (Kopp et al. 2025).

Besides increases in sea surface temperature, there are additional climate variations that could occur that would increase the potential for more intense hurricanes. One such change relates to vertical wind shear, which is the magnitude and directional difference between winds in the lowest region of Earth's atmosphere, the troposphere. Vertical wind shear along the east coast of the United States provides a natural protective barrier from hurricanes making land fall (Ting et al. 2019). Greenhouse gas forcing has the potential to reduce vertical wind shear and degrade that natural barrier, providing favorable conditions for more intense hurricanes.

4.2.4.1 Projections for New Jersey and the Northeast

Climate projections predict that the total annual precipitation in the Northeast region of the United States could increase up to 15 percent by the end of the century depending on the location and warming scenario (Marvel et al. 2023). The New York City Panel on Climate Change estimates that annual precipitation in the area could increase between 4% to 11% by 2050 and 5 to 21% by 2100 (Braneon et al. 2024).

Climate normals provide a helpful framework for comparing change over time, as they account for interannual variability and are typically updated every ten years. These multidecadal time periods are similarly useful for summarizing climate model projection data. In Figure 4.7, New Jersey's climate normals from the observational record (Office of the New Jersey State Climatologist 2025b) are plotted alongside projected climate normals for four different emission scenarios in mid-century (2041-2070) and end of century (2071-2100) periods (Wang et al. 2016, AdaptWest Project 2022). In comparison with New Jersey's observed 1991-2020 annual precipitation average (47.6 inches [120.8 cm]) (Office of the New Jersey State Climatologist 2025b), downscaled climate model data for intermediate (SSP2-4.5) and high (SSP3-7.0) emission scenarios show annual precipitation in New Jersey may increase on average by 3.0 to 3.8 inches (7.6 to 9.6 cm), respectively, indicating a 5.9% to 7.3% increase by the end of the century (2071-2100) depending on emissions (Wang et al. 2016, AdaptWest Project 2022).

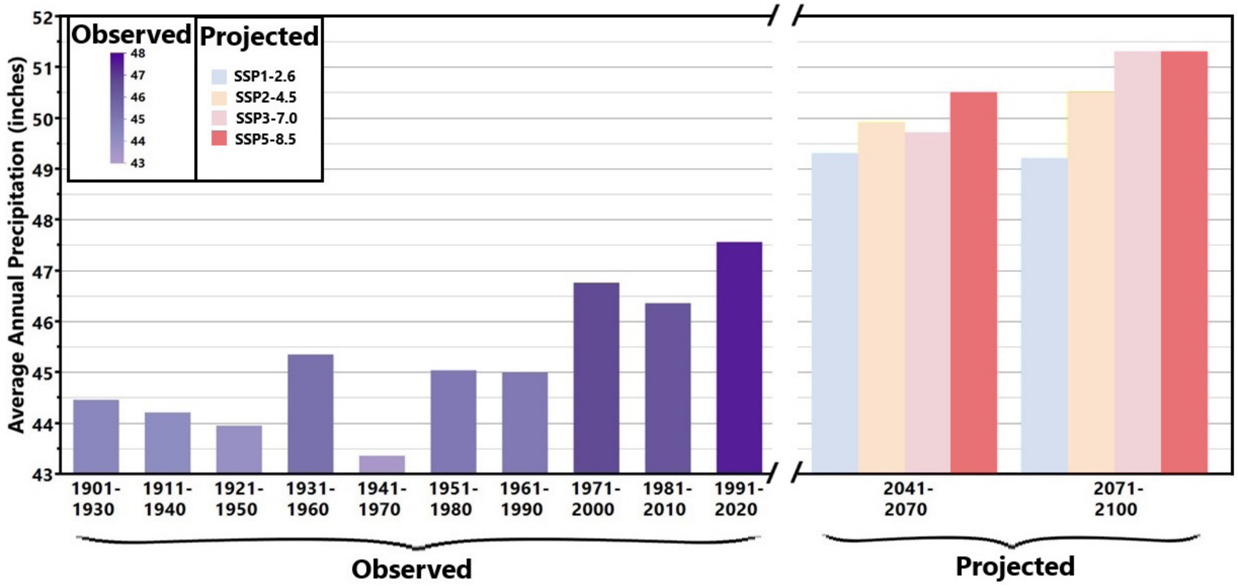


Figure 4.7. Observed and Projected average annual precipitation in New Jersey. Average annual precipitation observed in New Jersey over 30-year periods, known as climate normals, are shown as purple bars that become increasingly dark with higher values. The projected estimates for average annual precipitation in mid-century (2041-2070) and end of century (2071-2100) are shown in colorful grouped bars that depict low (light blue), intermediate (yellow), high (pink), and very high (red) emission scenarios. The projected estimates derive from downscaled climate model data outputs at 1 km resolution (Wang et al. 2016, AdaptWest Project 2022).

A recent New Jersey specific study (DeGaetano 2021b) used projections from 47 downscaled climate model simulations to estimate the change in magnitude of future extreme rainfall events under both intermediate (RCP 4.5) and very high emissions (RCP 8.5) scenarios for mid-century (2020-2069) and late-century (2050-2099) time periods. Modeled data were applied to the NOAA Atlas 14 methodology to estimate intensity for several return periods and durations, which were ratioed against the historical trends reported in NOAA Atlas 14 to compute change factors. The authors determined that precipitation intensity is highly likely to increase over time throughout the state, with the largest increases in northern counties. Under an intermediate emission scenario (RCP 4.5), the 100-year, 24-hour storm projections show a 50% chance of increasing in precipitation amounts

> ***"…variability in the amount and timing of precipitation events is anticipated, including projected increases in heavy precipitation events within a single day."***

by up to 22% in some counties and a 17% chance of increasing by up to 50%. Grid-based results were aggregated at the county level for display in Figure 4.8. See the interactive New Jersey Extreme Precipitation Projection Tool online to explore these results online.

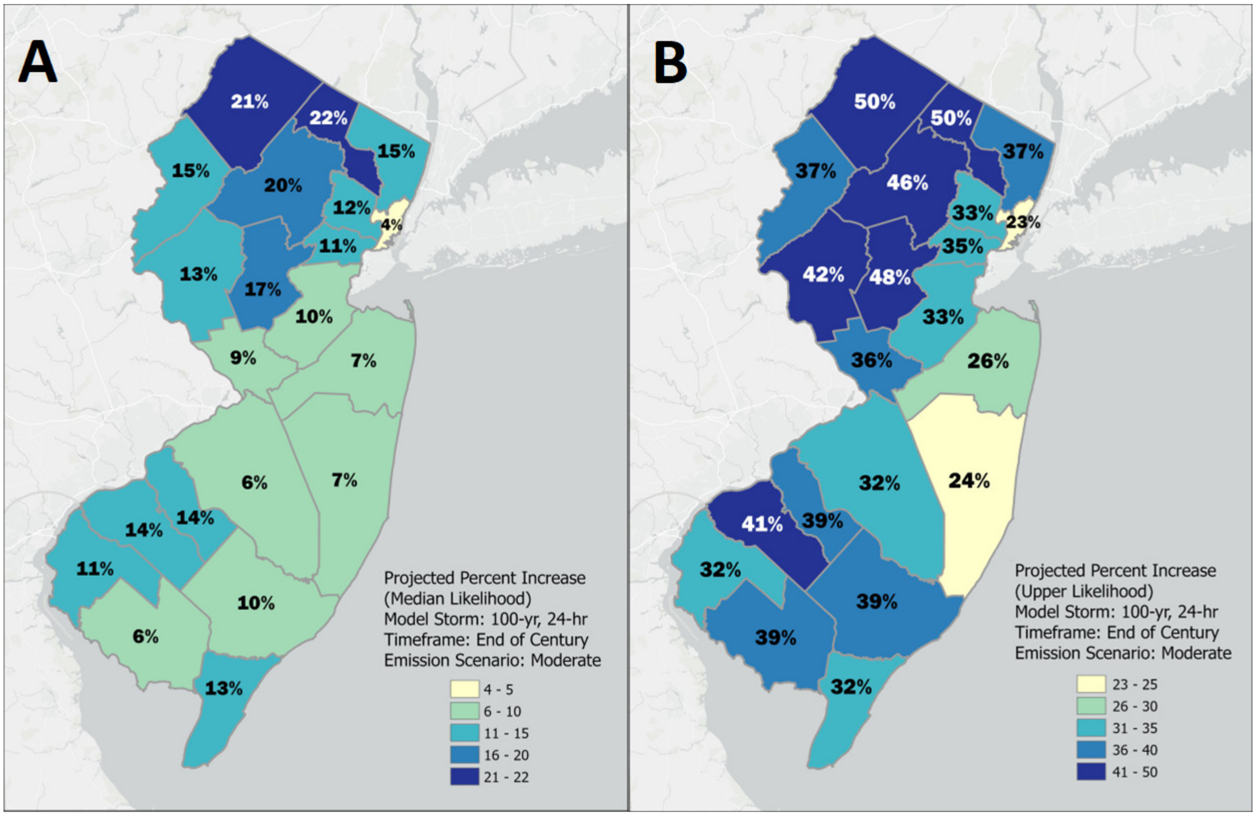


Figure 4.8. Projected percent increases by county at the end of the century. Projected end of century (2050-2099) increase in rainfall amounts (%) associated with the 100-year storm above the 1950-1999 reference period across New Jersey by county. These projections are based on the RCP 4.5 emission scenario, representing the (A) median (50% chance) and (B) upper likelihood (17% chance) of occurrence (DeGaetano 2021b).

Seasonal patterns in New Jersey are also projected to change over time. Under an intermediate emission scenario (RCP 4.5), New Jersey may see seasonal increases in precipitation in winter and spring (Demaria et al. 2016, Runkle et al. 2022). This may be partly explained by winters warming nearly two times faster than summer in some northern states, a trend expected to result in winter precipitation falling as rain rather than snow (Marvel et al. 2023). Such changes have implications for seasonal runoff. Additionally, variability in the amount and timing of precipitation events is anticipated (Marvel et al. 2023), including projected increases in heavy precipitation events within a single day (DeGaetano 2021b). Furthermore, the changing climatic conditions are expected to lead to longer and more persistent wet and dry periods throughout the Northeast region (Hayhoe et al. 2007, Guilbert et al. 2015).

4.2.5 Drought

Drought is a prolonged period of abnormally low precipitation with respect to local and regional averages, leading to a shortage of water. Increased evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) and reduced soil moisture amplified by warmer and drier conditions over an extended growing season (Wuebbles et al. 2014) has the potential to cause more frequent, severe, and prolonged droughts (Trenberth 2011, Payton et al. 2023).

Drought and heat wave conditions are occurring more frequently across the United States and are having significant impacts on ecosystems and society (Mazdiyasni and AghaKouchak 2015, Bruhwiler et al. 2023). Impacts include:

- reduced water supply capacity
- reductions in gross primary productivity, which leads to shortages in food production and increased prices
- economic losses from potential impacts to livestock, transportation by river, hydropower production, bioenergy, and energy consumption

Changing temperature and precipitation norms, if occurring simultaneously, can cause significant impacts (Mazdiyasni and AghaKouchak 2015, Bruhwiler et al. 2023). For example, a heat wave in conjunction with extended periods of dry weather in the summer season can cause drought and significant societal and environmental consequences despite the impact of either event occurring alone.

The consumption of water for potable use, agriculture needs, and non-agricultural irrigation has been increasing in some regions in the state. Changes in precipitation patterns and particularly extended periods of low rainfall is likely to make droughts more frequent, adding stress to local water supplies (NJDEP 2024a).

There are three main types of drought that effect the United States: meteorological drought (average precipitation in a region), hydrological drought (how decreased precipitation affects streamflow, soil moisture, and groundwater recharge), and agricultural drought (when water supply cannot meet crop demands). Drought conditions, even short lived, can bring long-term changes to the water supply. If a state has adequate water storage to get through a particular drought or dry season, there may not necessarily be negative socioeconomic impacts. However, enduring changes in precipitation patterns, streamflow, and discharge can alter a state's ability to maintain sufficient surface and groundwater storage (Strzepek et al. 2010, Aziz 2023, NJDEP 2024a).

In New Jersey, a water-supply drought is declared when the volume of water needed is greater than what is available. The 2024 season did not meet this requirement despite the issuance of a drought warning. The most recent water-supply drought was initiated in October 2016 for the northeastern, northwestern, and central drinking water supply regions in New Jersey. This was one of the warmest and driest summers on record throughout much of the Northeastern United States. Additionally, historically low winter snowfall preceding the summer of 2016 exacerbated drought conditions and led to record low streamflow in some regions (Sweet et al. 2017). The drought period during fall 2024 was remarkable in having the most consecutive days without any measurable precipitation at several stations, with these record counts ranging from 38 to 42 days (Office of the New Jersey State Climatologist 2024). The statewide average for October 2024 was a mere 0.02 inches, which was the driest month ever recorded and 4.17" below the 1991–2020 normal October.

Drought frequency has decreased In the Northeast over the period 1901-2015, while changes in average intensity and duration of droughts were more variable (Krakauer et al. 2019). The likelihood of dry extremes decreased less than anticipated, considering the increases in annual and extreme precipitation amounts in the region. This increase in dry and wet extremes are indications that the region may already be exhibiting hydrologic intensification trends associated with climate change (Krakauer et al. 2019). This may be related to flash droughts, which develop rapidly and can intensify over short time scales due to factors such as precipitation deficits, extremely high temperatures, and high wind speeds (Otkin et al. 2018, 2022) that can lead to increases in evaporative demand and reductions in soil moisture. Due to warmer conditions and more frequent heat waves, much of the United States is becoming increasingly vulnerable to the development of flash droughts (Marvel et al. 2023). One study determined that from 1981-2018, there was a significant increase in the frequency of flash droughts in the eastern United States due to high evaporative demand (Lesinger and Tian 2022).

If short-term droughts become more frequent in the summer, which has been indicated by climate models, it could pose serious challenges to farmers and water resource managers in the Northeast region of the United States (Runkle et al. 2017, Sweet et al. 2017).

4.2.6 Flooding

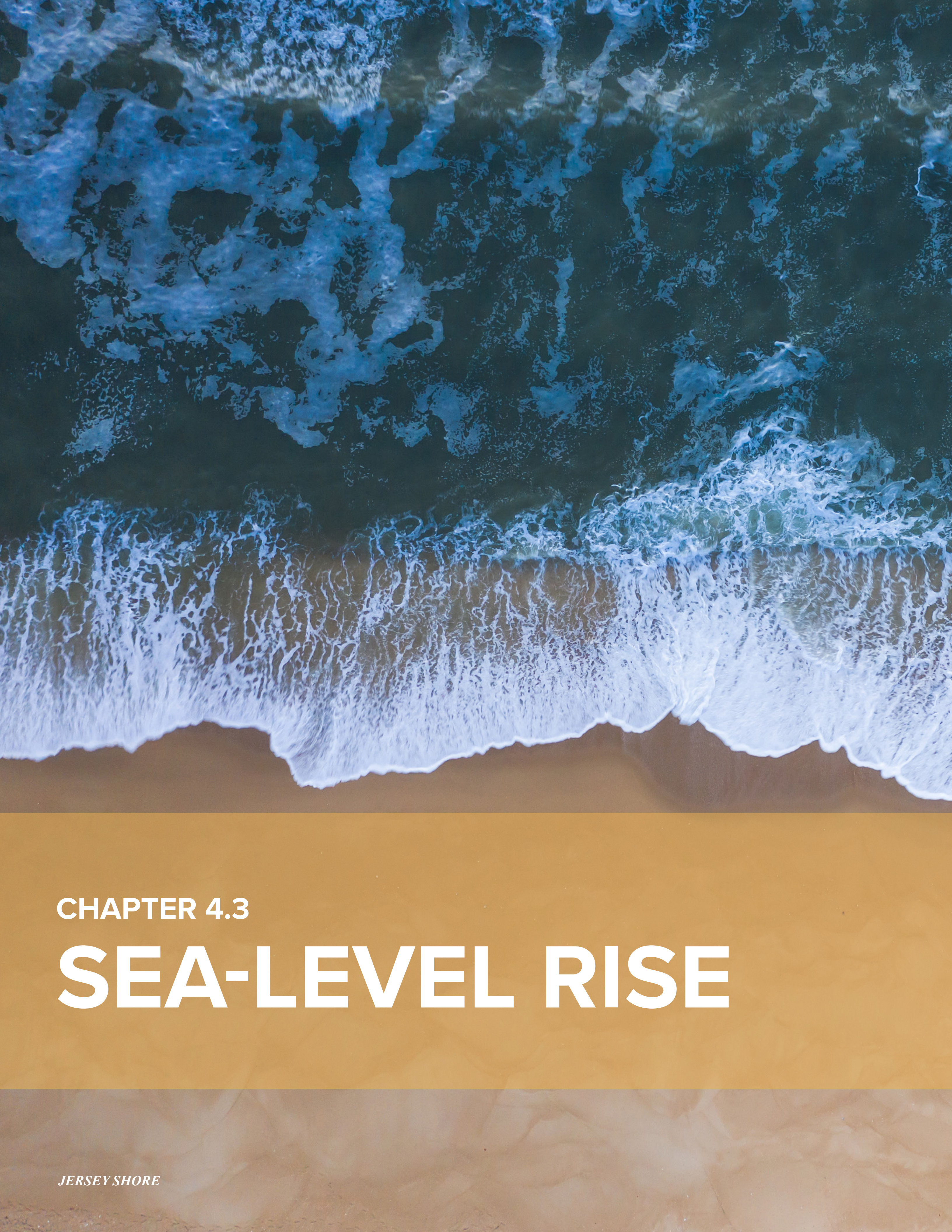
Extreme weather events resulting in heavy precipitation, localized thunderstorms, or rapid melting of snow often lead to flooding. Floods occur when waterways exceed their banks and the surrounding flood plain is inundated for a period of time. Major floods are characterized as events that have caused extensive inundation of structures and roads, significant evacuations of people and/or transfer of property to higher elevations. An increase in more frequent and intense rain events will increase the potential for flooding (Tabari 2020, Davenport et al. 2021). This risk of flooding also increases during periods of drought when the soil is too dry to absorb large amounts of rain in a short period of time.

Flooding risk due to climate change will be different for the various regions of the United States, but it is expected that the Northeast will be susceptible to increased seasonal flooding (Runkle et al. 2022). As annual precipitation and extreme precipitation have increased in the Northeast, so too has the size and frequency of floods (Wuebbles et al. 2014, Guilbert et al. 2015, Collins 2019). Regional trends analyses indicate flooding events generally occur during the same seasons, with a subset of sites showing increased flooding events in the spring with little evidence for seasonal shifts (Collins 2019). However, this study indicates that there are some watersheds within the Northeast where the number of flooding events from June to October increased between 1941-2013. These months historically have a low number of flood events, suggesting that flood potential in warmer months is increasing. There is limited understanding of how flooding has and will change seasonally. Any change to the timing of floods will have implications for communities, flood plain infrastructure, and habitats, and may be indicative of climatic changes resulting in floods.

In the New England and Mid-Atlantic regions of the Northeastern United States, climate-induced increases in the magnitude and frequency of floods have been observed (Collins 2019). When compared against observations from 1950-1999, New Jersey's extreme rainfall amounts from 1950-2019 have increased at more than 75% of stations analyzed, including increases of more than 10% for some stations (DeGaetano 2021a). Several major floods have occurred in New Jersey since 2000, including in 2000, 2004, 2005, 2006, 2007, 2010, 2011 (Hurricane Irene), 2012 (Superstorm Sandy), 2016 (coastal storm Jonas), and 2021 (remnants of Hurricane Ida) (USGS 2025).

In addition to the flooding risk from increases in precipitation, coastal areas are particularly vulnerable to flooding from storm surge and increased intensity of coastal storms and will most likely be faced with worsening conditions as sea levels rise (Colle et al. 2015, Mayo and Lin 2022). For additional discussion on sea-level rise please refer to Chapter 4.3.

> ***"As annual precipitation and extreme precipitation have increased in the Northeast, so too has the size and frequency of floods."***



CHAPTER 4.3

SEA-LEVEL RISE

JERSEY SHORE

KEY FINDINGS

- **Sea levels are rising in New Jersey more than two times faster than the global average.**
- **By 2050, there is a 50% chance that sea-level rise will meet or exceed 1.3 feet and a 17% chance it will meet or exceed 1.7 feet. Those levels are projected to increase to 2.9 and 3.8 feet by the end of the century.**
- **The inclusion of rapid ice sheet loss processes increase estimated sea-level rise projections to 1.9 feet by 2050, 2.8 feet by 2070, and 4.5 feet by 2100.**
- **The rate of sea-level rise is likely to increase from the current rate of 0.2 inches/year up to 0.46 inches/year by mid-century and up to 0.56 in/yr by late century.**
- **"Sunny day flooding" will occur more often across the entire coastal area of New Jersey due to sea-level rise.**
- **It is extremely likely that Atlantic City will experience "sunny day flooding" 131 days a year, and a 50% chance it will experience 326 days a year, by 2100.**

4.3 Sea-Level Rise

Sea level is not static over time or space, but varies in response to several factors, including atmospheric temperatures, ocean circulation patterns, and glacial extent. Today, sea levels are rising at increasing rates due to human influence, which presents substantial risks to numerous human and ecological resources in New Jersey, the United States, and around the world (IPCC 2021a, Sweet et al. 2022, Kopp et al. 2025). Several potential impacts of sea-level rise are documented throughout this report, including impacts to public safety in the face of coastal inundation and increased flooding, reduced water supply and water quality, and ecological impacts, among others. Addressing risks imposed by rising seas is essential to protecting the public and our resources.

Temperature is a primary driver of global sea level change because it exhibits strong effects on the major mechanisms, including the melting or formation of landlocked ice (glaciers, ice caps, and ice sheets), the physics of thermal expansion (where warmer ocean water takes up more space), and changes to water storage on land, such as changes in precipitation, aquifer withdrawal, and dam construction (Kopp et al. 2025).

4.3.1 Measuring Sea-level Change

Sea-level change is estimated using evidence from the geological record, as well as by direct measurements using modern technologies. Scientific understanding of sea level change in the geologic record is informed by numerous lines of evidence, including rock stratigraphy, fossil records, tree rings, ice cores, and sediment cores. This allows scientists to conceptualize long-term variability of sea-level change over the geologic record in order to better understand currently observed sea-level rise and the potential mechanisms involved in modeling projections of future sea-level rise. Modern technologies, such as water level sensors and satellite altimetry, provide extensive observational datasets that form the basis for understanding current rates of sea-level rise.

4.3.2 Historic Rates of Sea-level Rise

Geologic evidence indicates that during warmer, interglacial periods, water volume has increased enough for sea level to have risen by as much as 66 feet (20 m) above current levels (Poore et al. 2000).

Conversely, during the last glacial maximum period that ended about 20,000 years ago, sea level had fallen to 427 feet (130 m) lower than the current level, which has since risen to current levels at variable rates in response to naturally occurring atmospheric warming conditions (Yokoyama et al. 2018). About 6000 years ago, the rate of increase slowed down to a more consistent and stable pace that has continued into modern times (Fox-Kemper et al. 2021).

One key distinction about the modern era is that the Earth's climate is warming from human influences (see Chapter 3), which is causing sea-level rise to accelerate over the last century to a rate that is more rapid than any time in at least 3000 years (IPCC 2021b). The current rate of sea-level rise is increasing in response to ongoing atmospheric warming that has resulted from a rapid increase of greenhouse gas emissions largely produced by humans over the industrial age (IPCC 2021a, Walker et al. 2022). Global sea levels will continue to rise for decades and centuries into the future due to committed warming from previously released emissions, but the extent of long-term sea-level rise is dependent on how humans manage greenhouse gas emissions going forward (Fox-Kemper et al. 2021, Kopp et al. 2025).

Global average sea level was relatively stable for 1800 years prior to the industrial age, with varying rises and falls at rates ranging from ± 0.1 in/decade (± 0.2 mm/year) (Walker et al. 2021). The global sea-level rise rate from 1900-2018 is estimated at 0.7 ± 0.2 inches per decade (1.7 ± 0.5 mm/yr) (Fox-Kemper et al. 2021). However, sea-level rise is not consistent around the globe. The primary factors contributing to global sea-level rise include thermal expansion of the oceans due to increased water temperatures and melting terrestrial glaciers and polar ice sheets. Additional factors influencing regional and local sea-level rise include changes in ocean circulation, vertical land movement (subsidence due to natural sediment compaction and groundwater withdrawals), isostatic rebound (adjustment of land surface to the loss of ice sheets at the end of the last interglacial period), as well as local coastal morphology (Miller et al. 2009, Horton et al. 2018, Kopp et al. 2025). A combination of these factors will dictate local or regional rates of sea-level rise.

Temperature and sea-levels are increasing at a greater rate in New Jersey than in other parts of the world. In New Jersey, the average annual temperature has increased by about 4.1°F (2.3°C) since the late 19th century (Office of the New Jersey State Climatologist 2025a) and is predicted to increase by 3.7–6.2°F (2.1-3.4°C) above the 1991–2020 normal by 2100 under an intermediate emission scenario (SSP2-4.5) (Davies et al. 2025). The rate of sea-level rise in the Northeastern United States has been higher than the global rate over the last several decades and is expected to continue to be amplified. Average rates of sea-level rise at National Oceanic and Atmospheric Administration (NOAA) tide stations in New Jersey are provided in Table 4.3. Notably, the rate of sea-level rise increases over more recent intervals. Local estimates of sea-level rise are available from the New Jersey Climate Change Resource Center's Science and Technical Advisory Panel (STAP) report prepared by Rutgers University (Kopp et al. 2025). The DEP uses the STAP's estimate of 0.20 ± 0.04 in/yr (5.0 ± 1.0 mm/yr) for Atlantic City from 1993-2021 to represent New Jersey's recent sea-level rise trend, as compared to the 0.17 ± 0.01 in/year (4.25 ± 0.2 mm/yr) trend over the long-term record shown in Table 4.3. This recent sea-level rise trend in the STAP report includes a detailed breakdown of the contributing factors (e.g., thermal expansion, glacial isostatic adjustment, melting ice sheets).

Table 4.3. New Jersey Sea-level Trends. Long-term sea-level rise trends for Sandy Hook, Atlantic City, and Cape May since records began in the 20th century (NOAA 2025c). Rates are provided in multiple units plus or minus the 95% confidence interval.

Station	Years	Rate of sea-level rise		
		inches/decade	feet/century	mm/year
Sandy Hook	1932-2024	1.69 ± 0.07	1.40 ± 0.06	4.28 ± 0.19
Atlantic City	1911-2024	1.67 ± 0.06	1.39 ± 0.05	4.25 ± 0.15
Cape May	1965-2024	2.01 ± 0.17	1.68 ± 0.14	5.11 ± 0.44

Pre-industrial sea-level rise in New Jersey was approximately 0.08 in/yr (2 mm/yr) (Stanley et al. 2004, Miller et al. 2009, Walker et al. 2022). A recent study in Dennis Creek, New Jersey used foraminifera (fossils of tiny sea creatures) to reconstruct rates of sea-level rise over the last 1500 years, which indicates an accelerating increase in the rate of sea-level rise from about 0.06 inches/year (1.4 mm/yr) in the 16th century to 0.17 inches/year (4.2 mm/yr) in the 20th century (Walker 2024). These studies suggest that anthropogenic factors have contributed to a more than doubling of the historic rate of rise. The contributing factors to higher rates of sea-level rise in the Northeast and New Jersey include changes in the Gulf Stream (Sweet et al. 2022), localized subsidence, and continued geologic influences as solid Earth slowly adjusts to the loss of the North American ice sheet at the end of the last ice age (Kopp et al. 2025).

4.3.3 Basis and Selection of Sea-Level Rise Projections

Sea-level rise models are used to produce estimated projections of sea level changes for a range of future warming scenarios. These models are constructed in various ways, incorporating observational datasets (e.g., modern and geologic evidence), climate inputs (e.g., future temperature scenarios, ocean circulation patterns), and potential physical mechanisms (e.g., thermal expansion, ice sheet melt, land motion). Projections outlined in the Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force report (Sweet et al. 2022) and the 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2021a) were reviewed but do not offer localized projections. Each report uses a slightly different approach and thus offers different sea-level rise projections. After careful deliberation, DEP determined to use the projections provided by the STAP because of its New Jersey-specific focus (Kopp et al. 2025).

The 2025 STAP report provides sea-level rise projections specific to New Jersey, which align with the IPCC AR6 Shared Socioeconomic Pathway (SSP) emission scenarios and include consideration of the most current science and understanding of Arctic and Antarctic ice-sheet conditions (see Chapter 1.2 for details about SSPs). The low emission scenario (SSP1-2.6) optimistically assumes low greenhouse gas emissions leading to a 2.9°F (1.6°C) temperature increase by 2100. The intermediate emission scenario (SSP2-4.5) assumes a 4.7°F (2.6°C) increase in average global temperature by 2100, exceeding the limit set by the 2015 Paris Climate Agreement. Achieving even this intermediate scenario would require a dramatic cut in current greenhouse gas emissions. Finally, there is a high emission scenario (SSP3-7.0) that assumes a 6.8°F (3.8°C) increase in average global temperatures. In determining the relative sea level changes in New Jersey, the STAP report accounts for such factors as glacial isostatic adjustment, sediment compaction, movement of land ice to the oceans, and changes in ocean circulation, temperature, and salinity.

The New Jersey projections are based on a probabilistic model that associates likelihood of occurrence (or probability) of sea-level rise heights and rates over time with decadal estimates directly tied to low (SSP1-2.6), intermediate (SSP2-4.5), and high (SSP3-7.0) future climate scenarios to the year 2150 (Kopp et al. 2025). For example, given a specific emission scenario, a 50% likelihood, or a central estimate, of sea-level rise scenario suggests that there is a 50% chance that sea-level rise will meet or exceed a given level at a certain point in time. As such, the central estimate for 2070 under an intermediate emission scenario represents a 50% probability that sea-level rise will meet or exceed 1.9 feet (0.6 meters). The central estimate includes an inherent risk that future sea-level rise may still exceed the given level. A likely range, consistent with definitions by the IPCC, is also presented. The likely range includes projections between the 17th and 83rd percentile and thus represents a 66% probability that future sea-level rise will be within that range. For example, the likely range for 2070 under a high emission scenario represents a 66% probability that sea-level rise will be between 1.5 feet (0.46 meters; lower end) and 2.5 feet (0.76 meters; upper end). An extended likely range is included separately, which incorporates rapid ice sheet loss processes into the models. When planning for low risk tolerance (e.g., critical infrastructure), consideration should be given to the extended likely range estimates, to account for these unknown likelihood, high-impact processes. The STAP projections represent a change from the 19-year average from 1995-2014 and can be interpreted as having a baseline sea level in the year 2005.

4.3.4 Sea Level Rise Projections for New Jersey

The sea-level rise values in Table 4.4 and Figure 4.9 represent projections made by the STAP to the year 2150 (Kopp et al. 2025). The Atlantic City tide gauge station was selected to represent the New Jersey coast because it maintains the longest tide gauge data record in the state. By 2100, under an intermediate emission scenario, the likely range of sea-level rise for Atlantic City is 2.2 to 3.8 feet (0.67 to 1.16 meters) above a 2005 baseline, with an extended likely range of up to 4.5 feet (1.37 meters). Data are also available for Sandy Hook and Cape May within the 2025 STAP report.


BARNEGAT LIGHT, NEW JERSEY

Table 4.4. New Jersey sea-level rise estimates, above the 1995-2014 baseline (ft). *Sea-level rise (SLR) estimates are reported here for Atlantic City, NJ. All values are 19-year means of sea-level measured with respect to a 1995-2014 mean (i.e., 2005 baseline). Low (blue), intermediate (orange), and high (red) emission scenarios above correspond to SSP1-2.6, SSP2-4.5, and SSP3-7.0, respectively. Projections through 2050 do not project to low, intermediate, or high projections because differences in sea-level rise projections between emission scenarios are minor through the year 2050, where the range of projected sea-level rise is less than 0.2 ft across emission scenarios. Rows correspond to different projection probabilities. For example, the 'Likely Range' rows correspond to at least a 2-in-3 (66-100% chance) chance of sea-level rise from the relevant projections considered, consistent with the terms used by the Intergovernmental Panel on Climate Change* (Kopp et al. 2023)*. 'Extended Likely Range' projections include potential effects from unknown-likelihood, high-impact ice sheet instability processes. Low end and likely range rows do not incorporate these processes. However, most experts agree the actual 83rd percentile falls between the 83rd percentile of projections that exclude potential rapid ice-sheet loss processes and those that fully incorporate potential rapid ice-sheet loss processes. As such, the "Extended Likely Range" projections can be considered within the likely range and within the high-end projections.*

	Across Emissions Scenarios		**Low Emissions (SSP1-2.6)**			**Intermediate Emissions (SSP2-4.5)**			**High Emissions (SSP3-7.0)**		
Degrees of Warming (°C)†	**1.7 †** *(1.4-2.1)*	**1.9 †** *(1.5-2.5)*	**1.7 †** *(1.3-2.4)*	**1.6 †** *(1.2-2.3)*	**1.5 †** *(1.1-2.3)*	**2.3 †** *(1.8– 3.0)*	**2.6 †** *(2.0-3.6)*	**2.8 †** *(2.1-4.0)*	**2.8 †** *(2.2- 3.5)*	**3.8 †** *(3.0-5.0)*	**5.1 †** *(3.9-7.0)*
Year	**2040**	**2050**	**2070**	**2100**	**2150**	**2070**	**2100**	**2150**	**2070**	**2100**	**2150**
Extremely Likely to be Exceeded, Both Excludes and Includes Rapid Ice Sheet Loss											
> 95% Chance SLR Exceeds	0.5	0.7	1.1	1.3	1.7	1.2	1.8	2.5	1.3	2.1	3.2
Likely Range, Excludes Rapid Ice Sheet Loss											
> 83% Chance SLR Exceeds	0.7	0.9	1.3	1.8	2.3	1.5	2.2	3.1	1.6	2.6	3.9
~50% Chance SLR Exceeds	1	1.3	1.8	2.4	3.5	1.9	2.9	4.5	2	3.3	5.5
<17% Chance SLR Exceeds	1.3	1.7	2.3	3.3	4.9	2.5	3.8	6.3	2.6	4.3	7.7
Extended Likely Range, Includes Rapid Ice Sheet Loss											
<17% Chance SLR Exceeds	1.4	1.9	2.5	3.7	5.8	2.8	4.5	12	3	5.2	16.2
Extremely Unlikely to be Exceeded, Includes Rapid Ice Sheet Loss											
< 5% Chance SLR Exceeds	1.7	2.3	3.2	5.1	9.4	3.5	6.2	17.9	3.9	7.5	20.2

† Estimated degrees of warming relative to late nineteenth century (1850-1900) levels provided for each year and emission scenario using the format "median (5th – 95th percentile range)." Estimated degrees of warming for 2040 and 2050 are reported using the format "median of the intermediate emission scenario (5th percentile from SSP1-2.6 – 95th percentile from SSP3-7.0)".

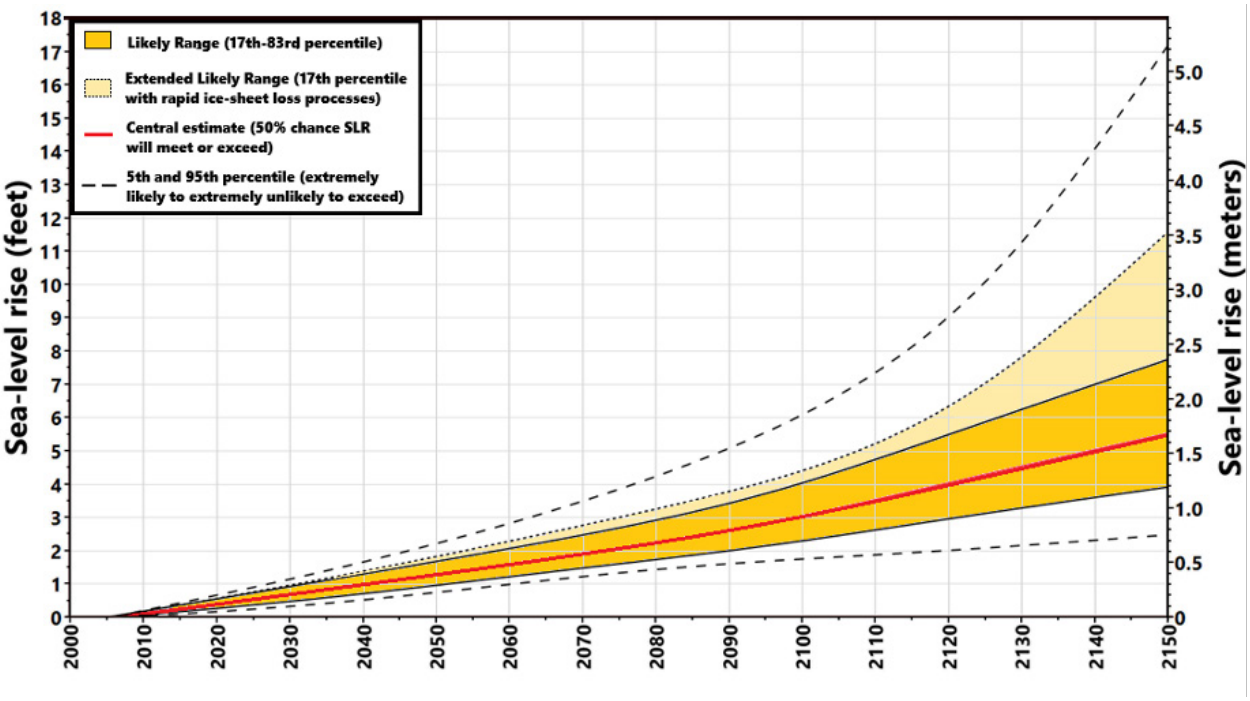


Figure 4.9. Diagram of Sea-Level Rise Projections Curve Under Intermediate Emission Scenario SSP2-4.5 (Kopp et al. 2025)**.** There is a 50% chance that future sea-level rise will exceed the level displayed by the red line, and a 66% chance (17th to 83rd percentile, the likely range) that sea-level rise levels will be between the solid black lines (i.e., tan area). For example, there is a 66% chance that in 2070, under an intermediate emission scenario, sea-level rise in New Jersey will be between 1.5 feet (0.46 meters) and 2.5 feet (0.76 meters).

Increasing rates of sea-level rise are also expected. The local rate of sea-level rise will likely increase beyond the current rate, which is 0.2 ± 0.04 inches/year (5.0 ± 1.0 mm/yr) at the Atlantic City tide gauge from 1993-2021 (Kopp et al. 2025). The projections for increasing rates of sea-level rise depend on the greenhouse gas emission scenario. Sea-level rise rates under low, intermediate, and high emission scenarios are described below for mid-century (2040-2060) and late century (2080-2100) periods:

- Under a low emission scenario (SSP1-2.6), mid-century rates have a likely range of 0.22 to 0.43 in/yr (6.3 – 11 mm/yr). Late century rates have a likely range of 0.13 to 0.41 in/yr (3.4 – 10.3 mm/yr). Extended likely range projections that include rapid ice-sheet loss processes result in higher rates of up to 0.49 and 0.53 in/yr (12.5 and 13.4 mm/yr) for mid-century and late century, respectively.
- Under an intermediate emission scenario (SSP2-4.5), mid-century rates have a likely range of 0.3 to 0.46 in/yr (7.5 – 11.9 mm/yr). Late century rates have a likely range of 0.22 to 0.56 in/yr (5.6 – 14.3 mm/yr). Extended likely range projections that include rapid ice-sheet loss processes result in higher rates of up to 0.59 and 0.85 in/yr (14.9 and 21.5 mm/yr) for mid-century and late century, respectively.
- Under a high emission scenario (SSP3-7.0), mid-century rates have a likely range of 0.32 to 0.49 in/yr (8.1 – 12.5 mm/yr). Late century rates have a likely range of 0.32 to 0.72 in/yr (8.2 – 18.3 mm/yr). Extended likely range projections that include rapid ice-sheet loss processes result in higher rates of up to 0.65 and 1.19 in/yr (16.4 and 30.1 mm/yr) for mid-century and late century, respectively.

4.3.5 Coastal Flooding

Especially in low-lying coastal areas, New Jersey is already experiencing tidal flooding on sunny days, even in the absence of precipitation events. This occurrence of high tide floods has increased in recent years (Kopp et al. 2025). In Atlantic City, New Jersey, the frequency of tidal flooding events has increased from an average of less than one per year in the 1950s to an average of twelve per year from 2007 to 2024 (Figure 4.10).

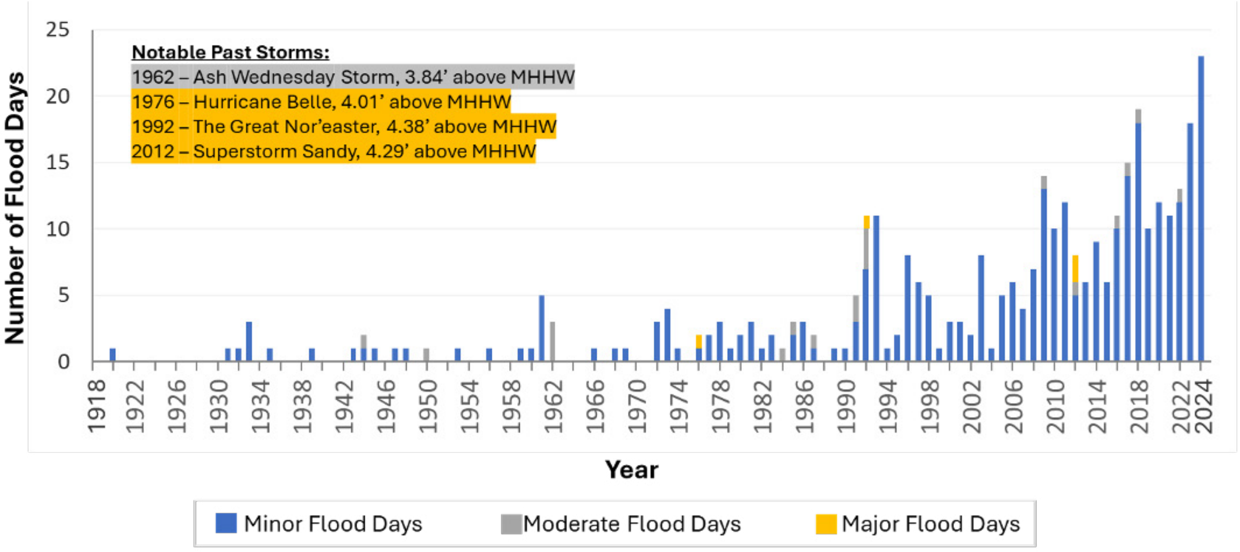


Figure 4.10. Historical High Tide Flood Frequency (number of Flood Days) for Atlantic City, New Jersey. Flood events are recorded based on calendar year, not meteorological year. Major flood event names, as well as a notable moderate flood event name, are superimposed and color coded on the upper left corner (NOAA 2025d). The number of high-tide flooding days has continued to rise in Atlantic City, New Jersey since 1930 (Kopp et al. 2025).

Future high-tide flooding days in Atlantic City under an intermediate emission scenario were modeled with alarming results (Kopp et al. 2025). By the year 2100, it is extremely likely (>95% chance) that Atlantic City will experience high-tide flooding at least 131 days a year, and likely (50% chance) that Atlantic City will experience high-tide flooding 326 days per year. This study highlighted one particularly vulnerable area of New Jersey, but similar projections of "sunny day flooding" and increased flooding from storms is expected across the entire coastal area of the state, including locations such as Sandy Hook and Cape May.

In addition to flooding solely from increased sea levels, an increase of tropical cyclone formation along the southeast coast and moving northward to impact the Northeast has the potential to compound for more damaging storm surge impacts in coastal areas (Kopp et al. 2025). By 2070, under an intermediate emission scenario (SSP2-4.5) there is a 50% chance that Atlantic City, New Jersey will experience annual flood events with water levels of at least 6.3 ft above the 1995-2014 baseline, which was the measured storm surge height during Superstorm Sandy in 2012 (Kopp et al. 2025). This century, the time between Sandy-level flooding events is expected to decrease 3 to 17 fold (Lin et al. 2016).

For a more detailed breakdown on the science of sea-level rise in New Jersey, see the 2025 STAP report, "New Jersey's Rising Seas and Changing Coastal Storms."

CHAPTER 4.4

OCEAN ACIDIFICATION

KEY FINDINGS

- **Since the start of the Industrial Revolution, ocean pH levels have declined, and the ocean is now 30% more acidic.**
- **If CO_2 emissions continue at current rates, ocean pH levels are expected to fall, creating an ocean that is more acidic than has been seen for the past 20 million years.**
- **Southern New Jersey counties rank second in the United States in economic dependence on shelled mollusks, which will suffer from increasing ocean acidity.**

4.4 Ocean Acidification

Earth is over 70% water, and roughly 97% of that water can be found in the oceans which are being threatened by climate change. Carbon dioxide (CO_2) has detrimental effects on the environment not only as a greenhouse gas, but also in its lesser-known role in ocean acidification. In the most basic terms, ocean acidification occurs because CO_2 dissolves in seawater, beginning a chemical reaction that leads to more acidic conditions. Many marine organisms will be negatively impacted by ocean acidification, particularly species who rely on calcium carbonate to build shells and skeletons, such as many shellfish and corals. As these organisms are often at the base of the food chain, their loss will adversely impact higher level marine trophic levels. Additionally, the economies and communities that rely on those organisms will also be impacted. See Chapter 5.8.2 and Chapter 5.8.3 for more details about how Finfish and Invertebrates, respectively, will be impacted by ocean acidification.

4.4.1 The Chemistry of Ocean Acidification

In addition to the adverse effects discussed up to this point in Chapter 4, excess CO_2 also causes significant harm through effects neither seen nor felt, but occurring underwater (NOAA Ocean Acidification Program 2025). When CO_2 from the atmosphere is absorbed by seawater, several chemical reactions occur resulting in increased concentrations of hydrogen ions (H+) in seawater which leads to ocean acidification (Orr et al. 2005, Doney et al. 2009). The measurement of acidity is referring to the concentration of free H+ in aqueous solution and is described in terms of pH (NOAA 2025e). These chemical reactions are collectively referred to as ocean acidification (NOAA 2025e).

Seawater naturally contains less CO_2 than the atmosphere (NOAA Ocean Acidification Program 2025) and substances, such as CO_2, will naturally move from an area of greater concentration to an area of lesser concentration. In this way, increased global concentrations of atmospheric CO_2 are driving corresponding increases in concentrations of dissolved CO_2 (called partial CO_2 or pCO_2) in surface ocean waters (NOAA Ocean Acidification Program 2025). The reaction begins when CO_2 is absorbed by seawater (H_2O) and forms carbonic acid (H_2CO_3). H_2CO_3 then dissociates, or breaks apart, to form bicarbonate (HCO_3-) and H+ (Ferguson et al. 2015). The free H+ are increasing the acidity (lowering the pH) of the ocean. Furthermore, the additional H+ react with carbonate ions to form more HCO_{3-}, which causes a decrease in the availability of carbonate ions in the system (Jewett and Romanou 2017). This process can be seen in Figure 4.11.

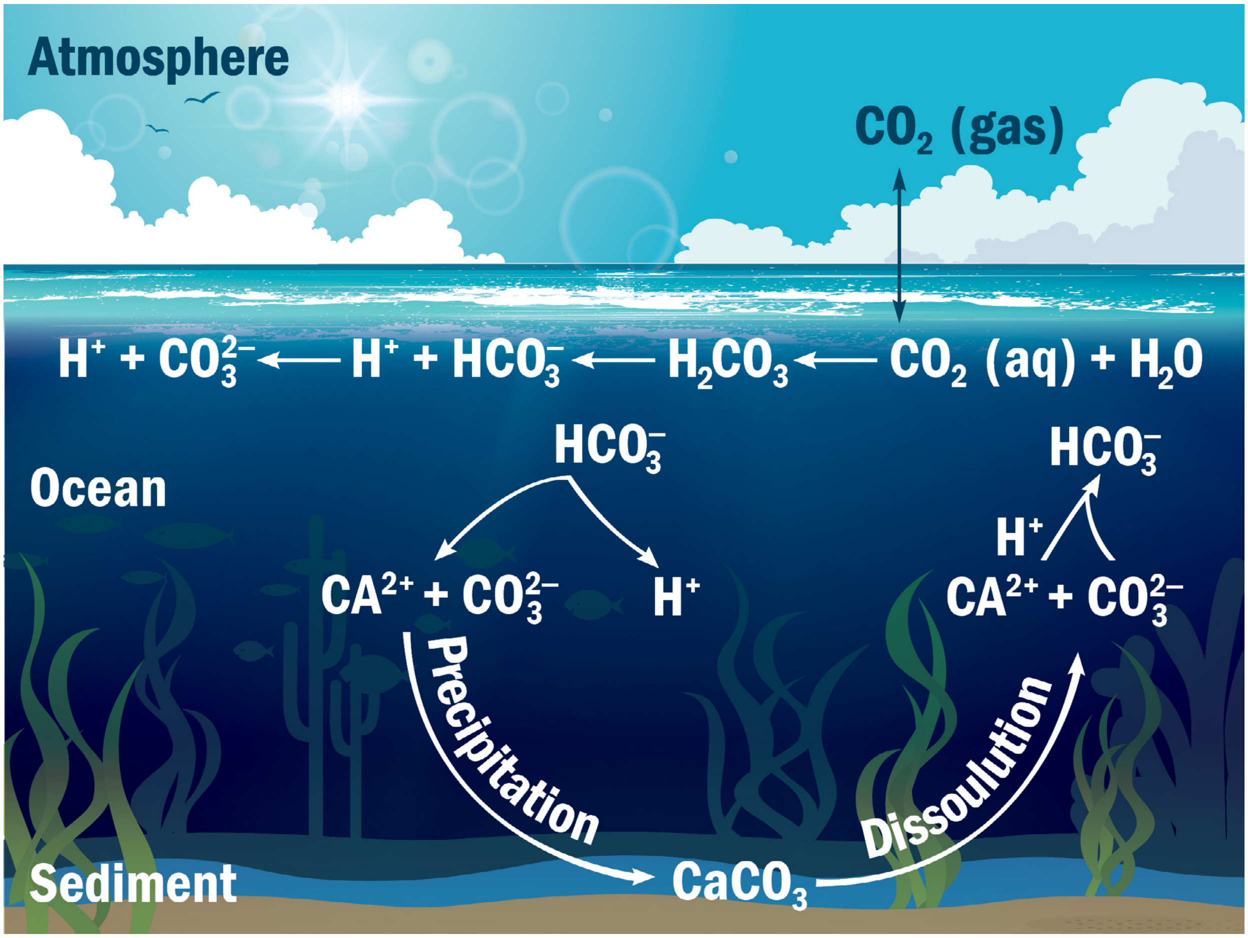
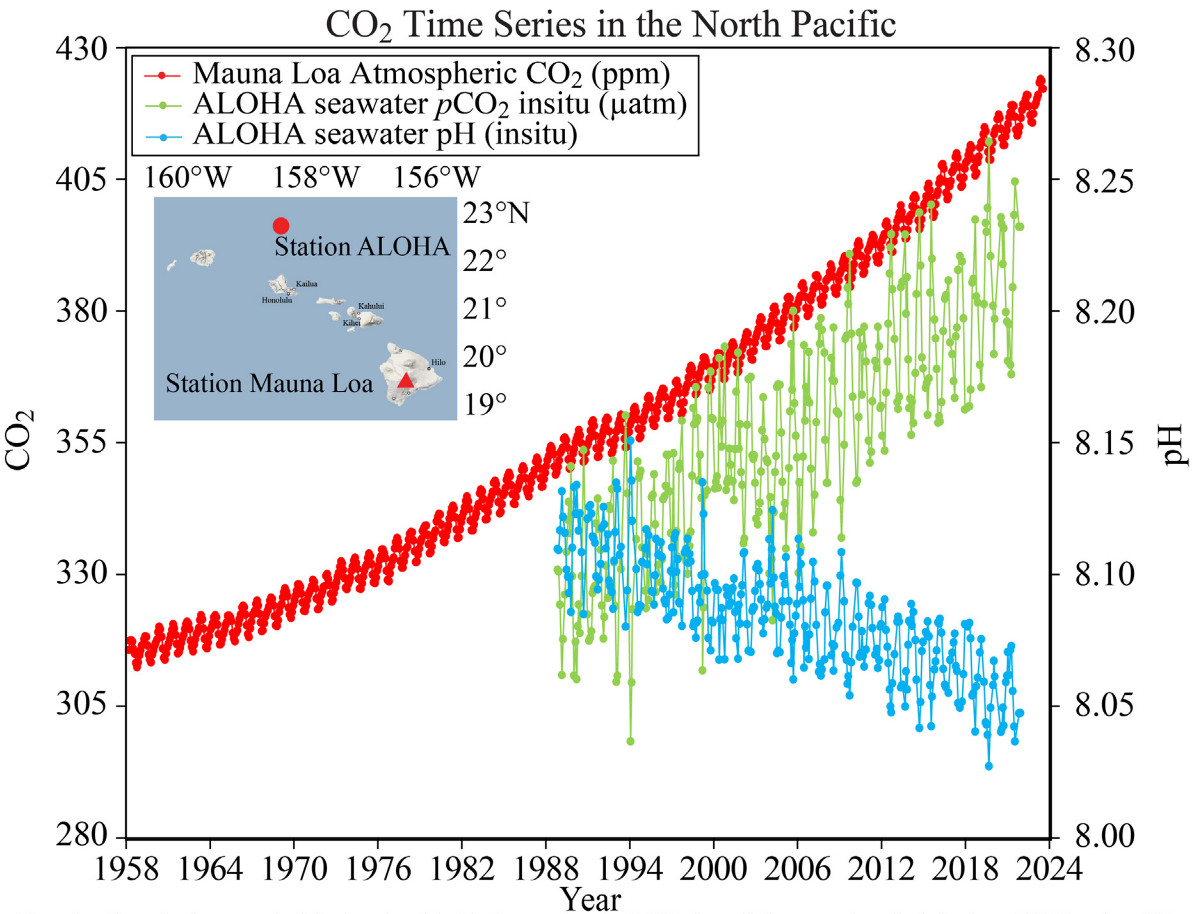


Figure 4.11. Process Contributing to Ocean Acidification. The Chemical Reaction That Leads to Ocean Acidification with the Introduction of CO_2 Into the Ocean.

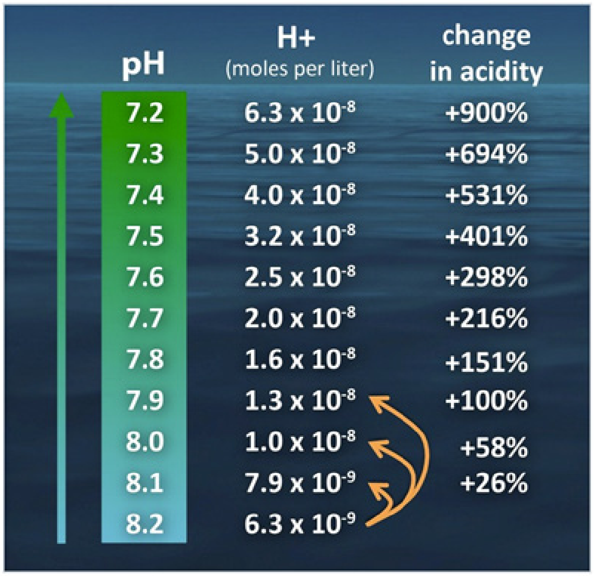
The concentration of carbonate ions in the ocean affects the saturation state and the availability of the calcium carbonate minerals that many shell-building species need to build their skeletons. A lower calcium carbonate concentration may dramatically effect a wide range of important species that rely on shell formation for survival, including bivalves (oysters, clams, mussels, scallops, and surfclams), lobsters, crabs, sea urchins, plankton, and coral reefs (Dupigny-Giroux et al. 2018, NOAA 2025e). Fisheries and aquaculture industries rely on many of the species that will suffer from increasing ocean acidity (Dupigny-Giroux et al. 2018). Another factor of importance is the ability of seawater to maintain the aragonite saturation state (when seawater can support formation of aragonite). Aragonite is a mineral form of calcium carbonate used by corals, bivalve larvae, and other mollusks to build their exoskeletons (Ekstrom et al. 2015). The aragonite saturation state decreases as ocean acidification advances and can be used as a measure and proxy for calcifying conditions; making it an ecologically relevant marker of ocean acidification.

Increasing levels of atmospheric CO_2 from the burning of fossil fuels, changes in land use, other human activities, and natural releases are having a direct effect on ocean carbonate chemistry (Jewett and Romanou 2017, NOAA 2025e). Since the industrial revolution, atmospheric concentrations of CO_2 have increased from around 280 to over 400 parts per million (ppm) (Figure 4.12) (NOAA Ocean Acidification Program 2025). The surface of the world's oceans are tightly linked with the atmosphere and the ocean has absorbed roughly 30% of global emissions of CO_2 since the preindustrial era ended (Feely et al. 2004, Gruber et al. 2019). This exchange of CO_2 with the ocean helps in part to regulate atmospheric concentrations, but at a cost to ocean life (NOAA Ocean Acidification Program 2025). Since the industrial age, pH levels have declined by 0.1 pH units, from a global average of 8.2 to 8.1. This may not seem like very much, but the pH scale is logarithmic, so this decrease of 0.1 represents a 30% increase in acidity in the ocean (NOAA 2020b). If CO_2 emissions continue at current rates, ocean pH levels are expected to fall another 0.3 to 0.4 pH units by the end of the century to 7.8 or 7.7, representing another 120% drop and creating an ocean that is more acidic than has been seen for the past 20 million years (Ocean Portal Team 2018). This logarithmic change in pH and the percent change in ocean acidity is presented in Figure 4.13. It is not only surface ocean waters that have become more acidic over the last 150 years, CO_2 is also penetrating into the waters of the deep ocean (Jewett and Romanou 2017). If not for this ocean uptake of CO_2, atmospheric levels would be increasing at an even greater rate than they are at present (NOAA Ocean Acidification Program 2025).



Data: Mauna Loa (https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_mlo.txt) ALOHA (https://hahana.soest.hawaii.edu/hot/hotco2/HOT_surface_CO2.txt)
ALOHA pH & pCO_2 are calculated at in-situ temperature from DIC & TA (measured from samples collected on Hawaii Ocean Times-series (HOT) cruises)
using co2sys (Pelletier, v25b06) with constants: Lueker et al. 2000, KSO4: Dickson, Total boron: Lee et al. 2010, & KF: seacarb

Figure 4.12. Time Series of CO_2 at Mauna Loa and Ocean pH and pCO_2 at ALOHA, Hawaii (NOAA PMEL 2022).



pH	H+ (moles per liter)	change in acidity
7.2	6.3×10^{-8}	+900%
7.3	5.0×10^{-8}	+694%
7.4	4.0×10^{-8}	+531%
7.5	3.2×10^{-8}	+401%
7.6	2.5×10^{-8}	+298%
7.7	2.0×10^{-8}	+216%
7.8	1.6×10^{-8}	+151%
7.9	1.3×10^{-8}	+100%
8.0	1.0×10^{-8}	+58%
8.1	7.9×10^{-9}	+26%
8.2	6.3×10^{-9}	

Figure 4.13. Percent change in acidity. Ocean acidification is based on the measurement of acidity, which refers to the concentration of free H+ in aqueous solution. The pH scale is logarithmic, so a decrease in pH of 0.1 from 8.1 to 8.0 represents a 30% increase in acidity (NOAA 2020b).

4.4.2 Localized Drivers in the Coastal Zone

As described above, ocean acidification is a result of the chemical reaction that leads to more acidic ocean conditions. In addition to the absorption of CO_2 from the atmosphere, there are local factors that play a part in ocean acidification. These factors include upwelling of naturally acidic, colder subsurface waters from deeper depths (Jewett and Romanou 2017), freshwater river inputs, and influx of nutrient run-off from the land, such as nitrogen and organic carbon (NOAA Ocean Acidification Program 2025). The variables that impact open ocean acidification are shown in Figure 4.14.

Freshwater flows from many rivers tend to be naturally more acidic than ocean water and thereby factor into lower pH levels observed in coastal waters, versus the pH of the open ocean. Additionally, freshwater inputs area additional drivers of acidification by contributing varying amounts of dissolved inorganic carbon, dissolved and particulate organic carbon, and total alkalinity, and other nutrients from riverine and estuarine sources (Jewett and Romanou 2017), such as stormwater runoff and wastewater treatment effluent. Excess nutrients from pollution and fertilizers cause increased phytoplankton or algal growth (Jewett and Romanou 2017, NOAA Ocean Acidification Program 2025). The resultant algal blooms then die and are eaten by bacteria, which consume oxygen and respire CO_2, increasing acidification (see Chapter 5.2.4 for more information about Harmful Algal Blooms).

There are indications that pH in portions of major estuaries in the United States have already decreased to a point of harming invertebrates. Larval and juvenile stages of invertebrates are especially sensitive to lower pH which can weaken their shells, making them more susceptible to predation and decreased growth rates. Thus, small changes in estuarine pH that might result from acidification could have large impact on the estuarine food chain. The pH has declined substantially in Chesapeake Bay. In some regions, it has declined to such low values that juvenile oyster shells dissolve (Waldbusser et al. 2011). The pH has also declined significantly in portions of the Puget Sound in Washington State (Feely et al. 2010, Pacella et al. 2024). In this case, scientists have estimated that acidification currently accounts for 24-29% of the change in pH from pre-industrial levels. Based on future projections of coastal acidification under a scenario where CO_2 doubles, the contribution could increase to 49-82% of the pH decrease.

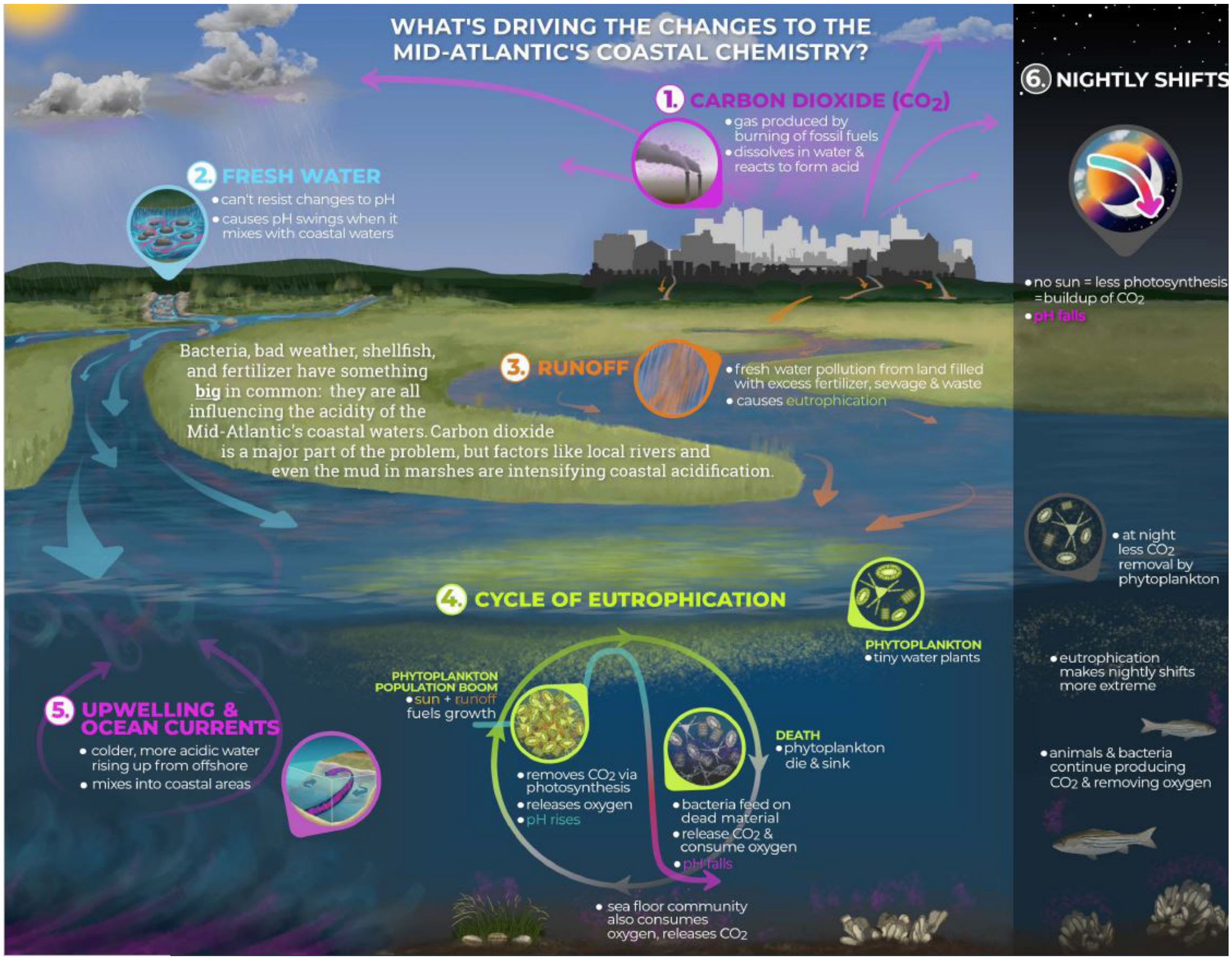


Figure 4.14. What's Driving the Changes to the Mid-Atlantic's Coastal Chemistry? The figure visualizes open ocean and coastal acidification factors in the Mid-Atlantic (VOCAL 2022).

4.4.3 Ocean Acidification in the Mid-Atlantic

For the purposes of this section, the Mid-Atlantic is the region south of Long Island Sound, New York to Virginia, bordered by the Northeast Continental Shelf, a broad continental shelf several hundred miles offshore (Goldsmith et al. 2019). The coastal states in this region (New York, New Jersey, Delaware, Maryland, and Virginia) frequently work together cooperatively to manage and study the shared ocean resources of the region. The Mid-Atlantic Coastal Acidification Network (MACAN) is co-coordinated by the Mid-Atlantic Council on the Ocean (MARCO) and the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) to address ocean acidification.

In 2019 a MACAN study reviewed and summarized current acidification and ecological research, identified research gaps, and provided recommendations for further studies to improve understanding in the Mid-Atlantic region (Saba 2019). Current insights from acidification research in the region support many of facts discussed in the previous section including indications that the aragonite saturation state will be reduced further because of increased ocean acidification and reduced calcifying conditions challenge the ability of bivalves, lobsters, crabs, sea urchins, plankton, and coral reefs to deposit shell material. It has also been observed that increased acidification affects the success of hatching, larval development, organ development, immune response, acid-base regulation, metabolic processes, and olfaction (smell) in calcifying as well as non-calcifying species. Marine life responses to acidification in the Mid-Atlantic are highly variable and species-specific, with the potential for acclimation or adaptation leading to relative "winners" and "losers" in a future acidic ocean. Groups of organisms that can expect neutral to negative impacts from ocean acidification include corals, crustaceans, mollusks, echinoderms, bony finfish, and calcified algae. Younger, larval stage shelled organisms tend to be more at risk than adults due to reduced growth and impaired development. Adult shelled organisms, however, tend to be susceptible to changes in behavior and metabolism that can make them easy prey and increase physiological stress. As further summarized by Saba et al. (2019), studies are inconclusive as to whether rooted vascular plants, collectively termed submerged aquatic vegetation, could benefit from ocean acidification. Short-term increases in the amount of CO_2 dissolved in tissue of submerged aquatic vegetation can yield higher rates of photosynthesis. However, elevated amounts of dissolved CO_2 may also enhance the vulnerability of submerged aquatic vegetation to grazing, disease, and decomposition through the decreases in phenolic compounds, compounds that help reduce biotic and abiotic stressors.

Furthermore, MACAN compiled a review of current monitoring, available technology, existing infrastructure, and areas of ecological and economic importance in order to inform the development of collaborative monitoring in the Mid-Atlantic (Goldsmith et al. 2019). This paper highlighted the significance of ocean acidification in the Mid-Atlantic by detailing the unique topography, geography, economy, seasonality, and ecological variability of the region. This densely populated, urbanized, and developed Mid-Atlantic coastline washes nutrients and other pollutants into its estuarine systems, exacerbating ocean acidification. Extreme precipitation events as well as overall annual precipitation amounts are predicted to increase for the Mid-Atlantic. In some locations, this will cause more naturally acidic freshwater to run off into the ocean. This region also faces an above average risk from sea-level rise and storm surge, creating the potential for compounding impacts associated with rising sea water temperatures, ocean acidification, and higher precipitation amounts that can threaten vulnerable aquatic species and dependent communities.

4.4.4 Ocean Acidification in New Jersey

Regions along the northern west coast and northern east coast of the United States are expected to experience the earliest impacts from ocean acidification (Ekstrom et al. 2015) (see Figures 4.15 and 4.16). The long-term economic impacts of ocean acidification are predicted to be the most severe not just in regions where seawater will acidify soonest, but also where communities rely heavily on local shellfish industries for their livelihoods (NRDC 2015). New Jersey is not predicted to see unfavorable conditions to shellfish resulting from anthropogenic ocean acidification until 2100 according to global ocean models (Ekstrom et al. 2015), however, New Jersey is at an increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests (NRDC 2015), and is expected to see a high social impact as conditions evolve (NRDC 2015, Ekstrom et al. 2015) (Figure 4.16). The 2025 Economic Risks of Climate Change in New Jersey report further discusses the economic impact from likely increases to mortality rates due to weaker and more shell deformities in calcifying organisms, disruptions in supply chains due to impacts from sea-level rise to low-lying mariculture infrastructure, reductions in catch volumes from coastal storms and high ocean temperatures, and the resulting price increases (NJDEP 2025b).

New Jersey has both a thriving commercial fishing industry and aquaculture community. A 2015 study found that in the United States, southern New Jersey counties rank second in economic dependence on the shelled mollusks. Communities that are highly dependent on shellfish resources are either already experiencing effects of ocean acidification or will be in the near future (NRDC 2015, Ekstrom et al. 2015).

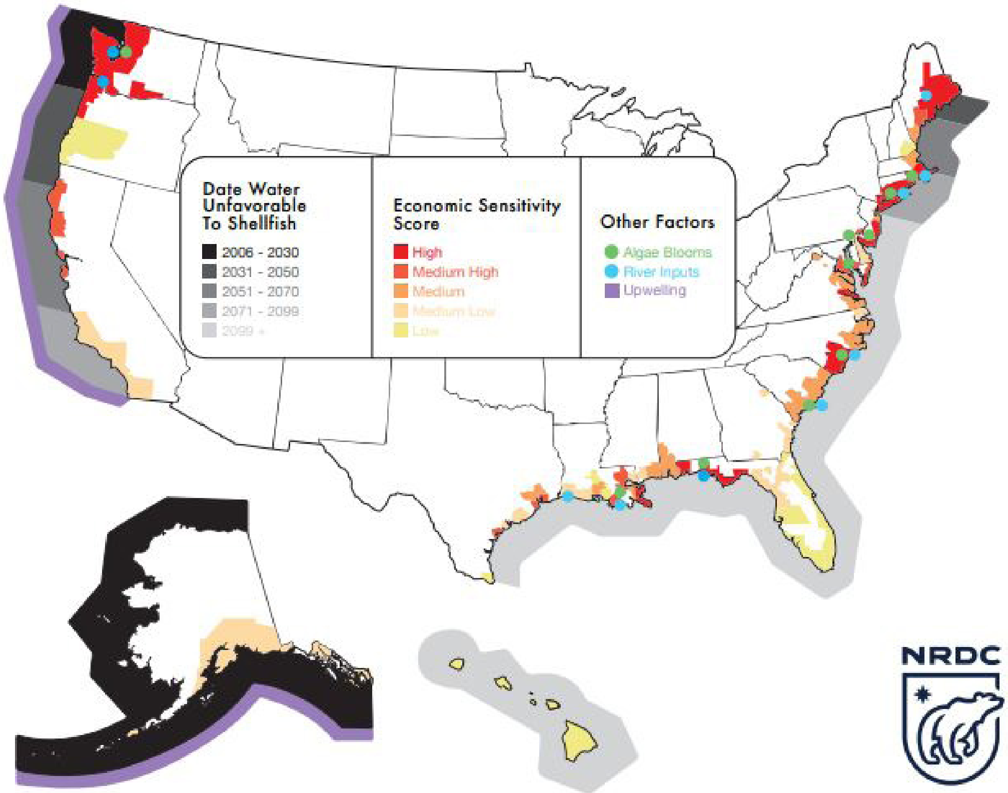


Figure 4.15. Vulnerability Ranking of United States Communities to Ocean Acidification. The most severe long-term economic impacts from ocean acidification are expected in the areas where the ocean is acidifying the soonest (black) and where there is a high reliance on shellfish for livelihood (red). Adapted from (NRDC 2015, Ekstrom et al. 2015).

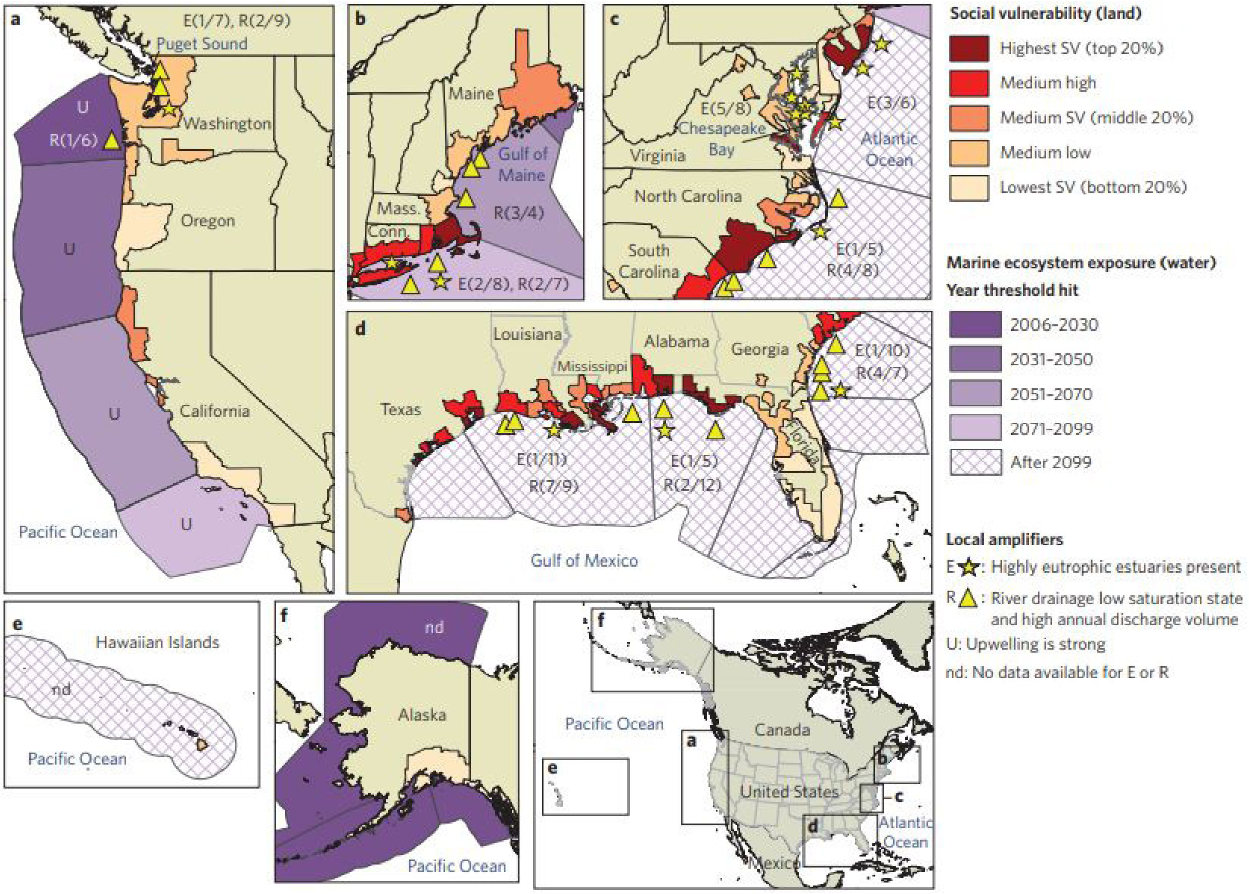


Figure 4.16. Exposure and Vulnerability of United States Communities to Ocean Acidification. The social vulnerability and marine ecosystem exposure is shown for regions of the United States: (a) the Pacific Northwest, (b) the Northeast, (c) the Mid-Atlantic, (d) Southeast and Gulf, (e) Hawaiian Islands, and (f) Alaska (Ekstrom et al. 2015).

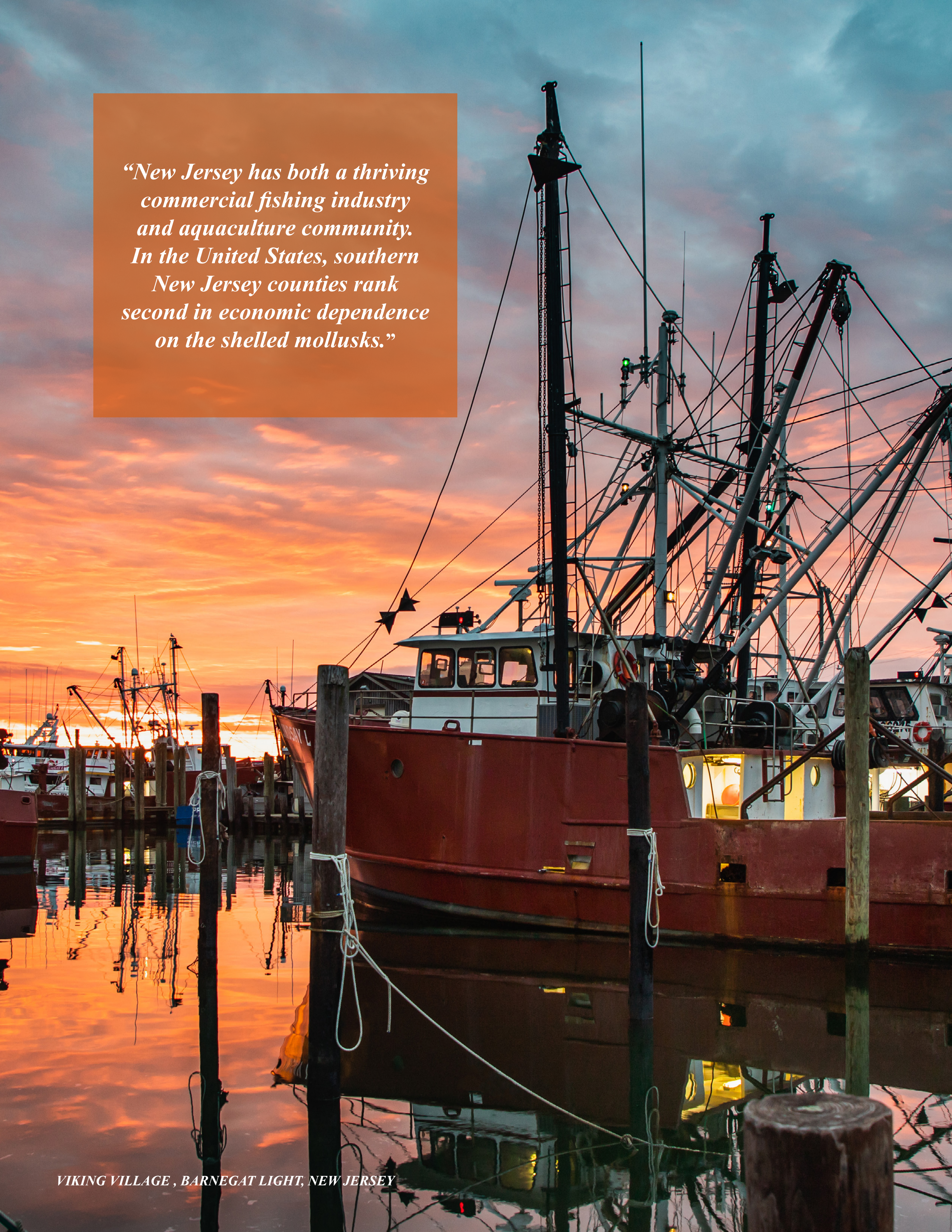
In New Jersey, local amplifiers of ocean acidification include periodic summer upwelling events that can occur off of New Jersey's coasts and transport deeper, colder, and more acidic water up to the surface (Goldsmith et al. 2019). This low pH, low aragonite-soluble seawater can impair shellfish production. Not only are shell-building species at risk, but so too are fish populations that depend on estuaries during part of their life cycles, including summer flounder (*Paralichthys dentatus*). The ecological impacts of ocean acidification on marine organisms require further research.

Poorly buffered rivers (those least able to resist changes in pH), such as coastal drainages from the Pinelands region of the state, introduce relatively more acidic freshwater to coastal waters, reducing both pH and the availability of carbonate minerals needed by shellfish to build their shells. The effects on developing oysters, for example, have already been seen on the West Coast of the United States, suggesting that commercial shellfisheries along the east coast and New Jersey are at risk as similar conditions arise (Weis et al. 2015). Also, excess nutrients such as nitrogen make their way into coastal New Jersey waters from farms, lawn chemicals, and poorly maintained sewage systems (NRDC 2015). Alternatively, the increase in river alkalinity over time in New Jersey has helped to offset some of the new sources of acidity in river and estuarine systems (Kaushal et al. 2013).

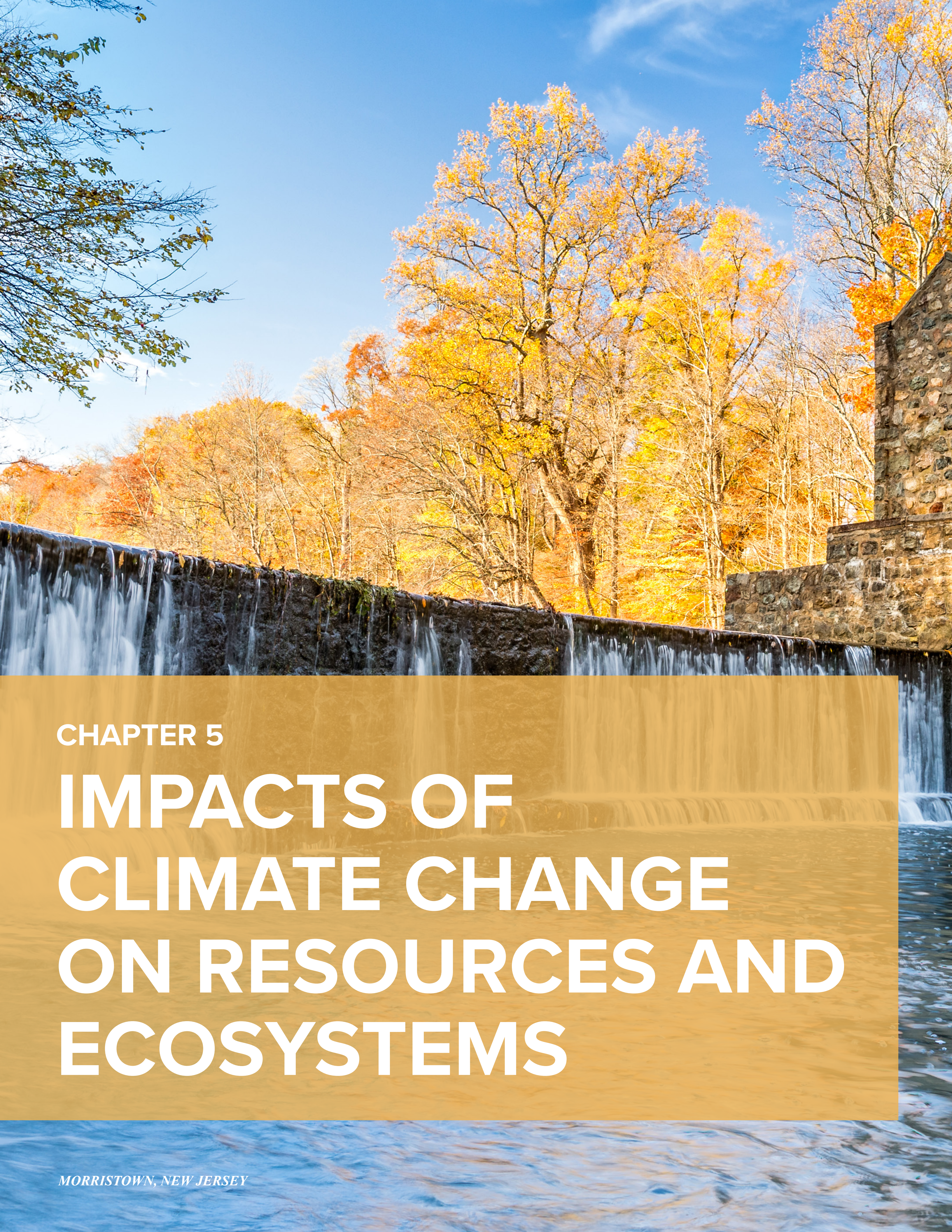
Despite decades of ongoing ocean monitoring in New Jersey, there is a lack of consistency both in sampling technology and methods that make developing a clear picture of the level of acidification of ocean waters difficult. New Jersey ocean waters have been monitored for pH and dissolved oxygen since the mid-1990s to some extent, and more extensively since the early 2000s (Weis et al. 2015). Monitoring stations with sensors from the National Estuarine Research Reserve System are included in the Atlantic coast database with data that does not extend prior to the 2000s. The DEP has conducted submersible glider studies since 2011 in order to look at ocean chemistry over an extensive area, with data available through 2020 (NJDEP 2025c). NOAA has taken oceanic samples in the Mid-Atlantic area including New Jersey, as well as its regional estuaries since the 1970s, but sampling did not include ocean pH until the mid- to late-2000s. New Jersey's most comprehensive dataset is from the Barnegat Bay and includes pH and dissolved oxygen data from the 1970s to present (Weis et al. 2015).

The New Jersey area is uniquely susceptible to the impacts of ocean acidification. New Jersey's marine ecosystems, and particularly fisheries, are economically and ecologically important resources that provide services for local communities and the much wider populations they support (Murray et al. 2015).

> ***"New Jersey has both a thriving commercial fishing industry and aquaculture community. In the United States, southern New Jersey counties rank second in economic dependence on the shelled mollusks."***



VIKING VILLAGE , BARNEGAT LIGHT, NEW JERSEY



CHAPTER 5

IMPACTS OF CLIMATE CHANGE ON RESOURCES AND ECOSYSTEMS

MORRISTOWN, NEW JERSEY

This chapter will discuss how the primary driver of climate change, greenhouse gas emissions, will impact and affect New Jersey's environmental and natural resources as well as ecological communities. The impacts of climate change on natural resources in New Jersey, particularly from increasing temperatures, changing precipitation patterns, and rising sea-levels, are already apparent. The following sections describe these impacts of climate change on New Jersey's air quality, water quality and quantity, forests, wetlands, and wildlife species in terrestrial, freshwater, and marine systems.

Chapter 5 is divided into the following sections:

CHAPTER 5.1

AIR QUALITY

NEAR PORT NEWARK, NEW JERSEY

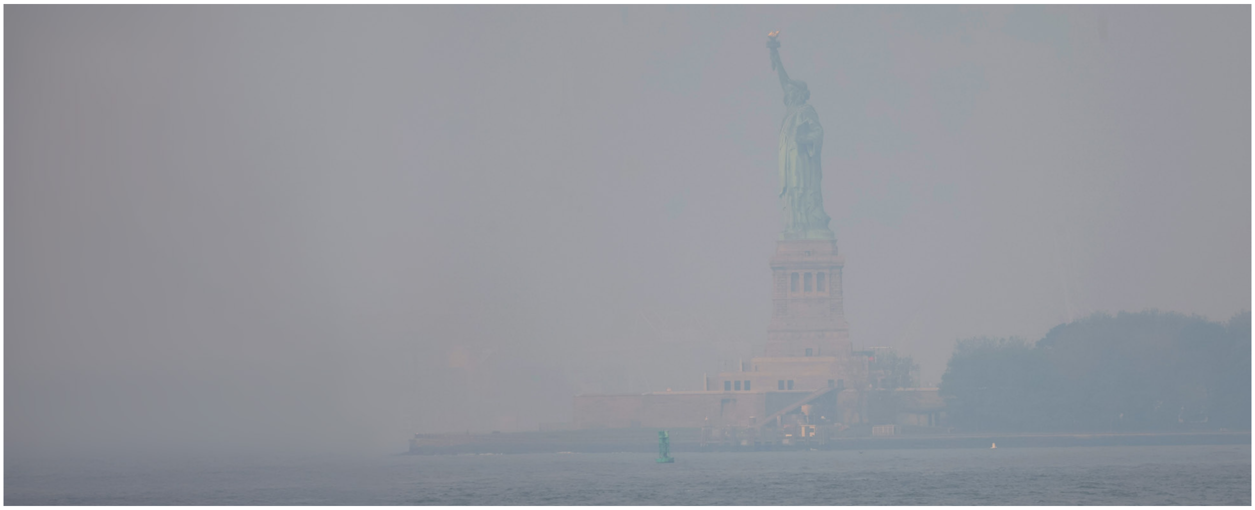
KEY FINDINGS

- **A warming climate contributes to an increase in air pollution, despite the numerous measures to reduce ground-level ozone precursors and other sources of air pollution.**
- **Increases in air pollution will reduce visibility, damage to crops and forests, and adversely impact human health.**

5.1 Air Quality

The quality of air affects all aspects of life. When air is polluted, it can cause adverse health effects on humans and the environment. Air pollutants can be found indoors and outdoors, and in urban, suburban, and rural areas. National health-based standards exceed air pollution levels for over 100 million United States residents, including all New Jersey residents (Nolte et al. 2018). The effects of climate change will not only contribute to an increase in air pollution but will also lead to increased respiratory and cardiovascular health problems and an even greater number of premature deaths (refer to Chapter 6.2). In addition, higher air pollution levels will result in increased environmental degradation such as reduced visibility and damage to crops and forests.

The chemical and physical processes that generate, transport, and eliminate air pollution will be affected by climate change. The changes to these processes are likely to increase levels of air pollutants (outdoor and indoor) as well as increase exposures to aeroallergens (i.e., airborne substances that cause allergic reactions, discussed further in Chapter 6.2.2). The primary pathways by which climate change will influence air pollution are summarized in Figure 5.1, which highlights the chemical and physical interactions that create, remove, and transport air pollution (Nolte et al. 2018). Human activities and natural processes release precursors for ground-level ozone and particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$), including methane (CH_4), carbon monoxide (CO), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), organic carbon (OC), black carbon, and dimethyl sulfide (DMS) (a compound present in the oceans); and direct atmospheric pollutants, including mineral dust, sea salt, pollen, spores, and food particles (Fiore et al. 2015).



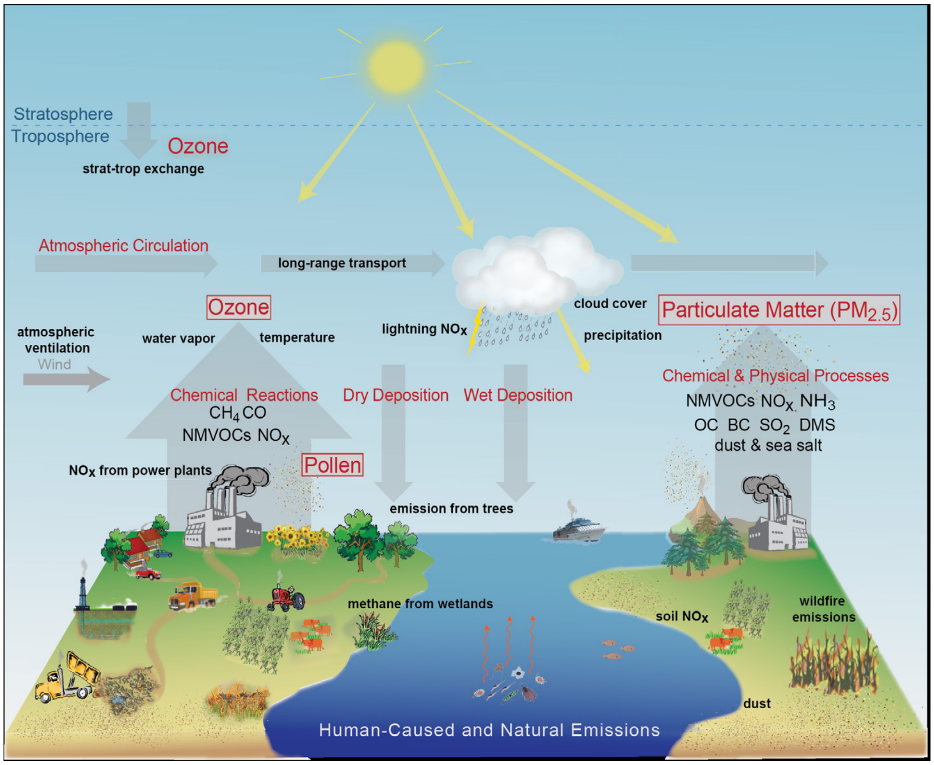


Figure 5.1. Air Quality and Climate Connections. This figure shows the primary pathways by which climate change will influence air pollution. The black bold text shows when climate change will alter the chemical and physical interactions that create, remove, and transport air pollution, which are shown in red text and gray arrows (Nolte et al. 2018).

5.1.1 Outdoor Air Quality

Outdoor pollutants that threaten air quality include ground-level ozone, particulate matter, aeroallergens, greenhouse gases (see Chapter 3), and various other hazardous air pollutants. This section will focus on the mechanisms by which climate change can alter the chemical and physical production of ground-level ozone, particulate matter, and common aeroallergens. For information regarding the human health impact of these outdoor pollutants, refer to Chapter 6.2.

5.1.1.1 Ground-Level Ozone

Ozone is a colorless and odorless gas that is formed in the layer of the atmosphere called the stratosphere (i.e., the layer of the atmosphere 6-30 miles above Earth's surface) (NOAA 2008), which provides protection from the harmful ultraviolet rays of the Sun. Ozone can also be created in Earth's lower atmosphere, or troposphere, by chemical reactions of pollutant gases, known as the 'precursor pollutants', NOx and VOCs interacting with heat and sunlight, as seen in Figure 5.2 (NJDEP 2022a). This ground-level ozone will be the focus of this section of the report. The atmospheric conditions that generate high ozone levels are high temperatures, sunlight, and stagnant air masses. When these conditions also result in elevated levels of particulate matter and/or other gases, the combination of pollutants may appear visually as haze or smog, which is why ground-level ozone is sometimes referred to as smog. The primary ozone precursor pollutants are NOx and VOCs. Sources of NOx emissions can be natural, but the primary source is human-made emissions from motor vehicles that use internal combustion engines (gasoline and diesel), construction equipment, power plants, and industrial, commercial, and residential fuel combustion (NJDEP 2024b). The primary sources of human-made VOCs are household cleaners, paints and solvents, motor vehicles, lawn and garden equipment, and gasoline stations, but can also be emitted from trees and plants (NJDEP 2024b).

Figure 5.2. How Ozone is Formed. Ground-level ozone is formed when oxides of nitrogen (NOx) and volatile organic compounds (VOCs) react in the presence of sunlight (NJDEP 2022a).

For decades, New Jersey has implemented numerous measures to control emissions of ozone precursors and has made significant progress in the reduction of ozone levels. However, the entire state currently is classified as “nonattainment”, meaning air pollution levels are above the national ozone health-based air standard of 70 parts per billion (ppb) established by the Federal Clean Air Act and United States Environmental Protection Agency (US EPA) (NJDEP 2025d).

Many factors contribute to ground-level ozone concentrations at any given time and location, and extensive studies have been performed that evaluate how climate change will impact ground-level ozone air pollution. These factors can be broadly separated into two categories: sources that emit ozone precursor pollutants (e.g., NOx and VOCs) and meteorological conditions that are conducive to ozone formation (Fann et al. 2016). The primary climate change impacts on ozone formation are expected to result from changes to meteorological conditions, often referred to as the ozone-climate penalty, which is “the deterioration of air quality due to a warming climate, in the absence of anthropogenic (human-caused) polluting activities” (Fu and Tian 2019). This means that even as emissions are reduced, ozone formation may still increase due to the warmer climate, suggesting that it will be more difficult in the future for New Jersey to meet and maintain federal health-based air quality standards.

Meteorological conditions influencing ozone levels include air temperatures (especially heat waves), humidity (water vapor), cloud cover, precipitation, regional stagnation, wind trajectories, and the amount of vertical mixing in the atmosphere (Fu and Tian 2019). Additional ozone related processes that are impacted by climate change include wildfires (NOx and VOC source), lightning (NOx source), stratospheric ozone transport, soil NOx emissions, background methane levels, and the release of VOCs from vegetation. An important feedback effect is the increase in NOx emissions from fossil fuel power plants generating electricity when the demand for electricity increases due to higher temperatures and increased humidity levels as a result of climate change. In addition, the anticipated increase in future electricity demand from data centers and electrification of the transportation/residential/commercial/industrial sectors could add to this feedback effect, potentially causing increased levels of harmful air pollution from electric generation facilities that are not either zero emission or very stringently controlled. The scientific consensus is that the impact of climate change due to the above-mentioned processes will tend to generally increase ground-level ozone levels.

Additionally, climate change is expected to play a role in increases in the frequency and severity of wildfires (Nolte et al. 2018). The air pollution from wildfire smoke degrades air quality and increases adverse health effects for tens of millions of United States residents. Wildfire smoke impacts air quality in New Jersey from both in-state and upwind wildfires as far away as the western United States and Canada. The degraded air quality due to wildfire smoke increases incidences of premature deaths, respiratory illnesses, reduced visibility, and outdoor activity disruptions.

Changing wind patterns is another example of meteorological conditions being affected by climate change and leading to impacts on ozone (Fann et al. 2016). For New Jersey, and over much of the United States, the worst ozone episodes occur when ozone and ozone precursor pollutants accumulate in a specific location when the local air mass does not change over a period of several days. Parts of the United States are already seeing an increase in frequency of this type of episode, and it is expected to become even more common in the future.

To better understand how meteorology influences ozone formation compared to the effects of changes in emissions of ozone precursors, researchers use quantitative modeling that simulates regional chemical transport over multiple years (Fann et al. 2016). These models show that large portions of the United States, including New Jersey and surrounding states, are likely to see higher levels of ozone due to direct meteorological impacts from climate changes such as accelerated rates of photochemical reactions and increased occurrence of stagnate air mass events. High concentrations of ground-level ozone have been associated with a range of adverse human health effects, discussed in Chapter 6.2.1.1.

Recent modeling provided quantitative estimates of the projected change in temperature, ozone, and ozone-related premature deaths in 2030 for the United States (Fann et al. 2015, 2016). Study results shown in Figure 5.3 resulted in an increase in daily 8-hour maximum ozone and an increase in 1.8°F (1°C) to 7.2°F (4°C) in average daily maximum temperatures. While the change in air quality across the United States will be specific to regional conditions, the increase in ozone concentration due to climate change is predicted to result in a significant increase in additional ozone-related illnesses and premature deaths per year. The economic value of these additional premature deaths, respiratory related hospital admissions, acute respiratory symptoms, and missed days of school illnesses were also estimated by the authors of this study (Fann et al. 2015). These nationwide costs were estimated to range from $320 million to $1.4 billion for the GISS/RCP 6.0 scenario and from $3.6 to $15 billion for the CESM/RCP 8.5 scenario in 2030.

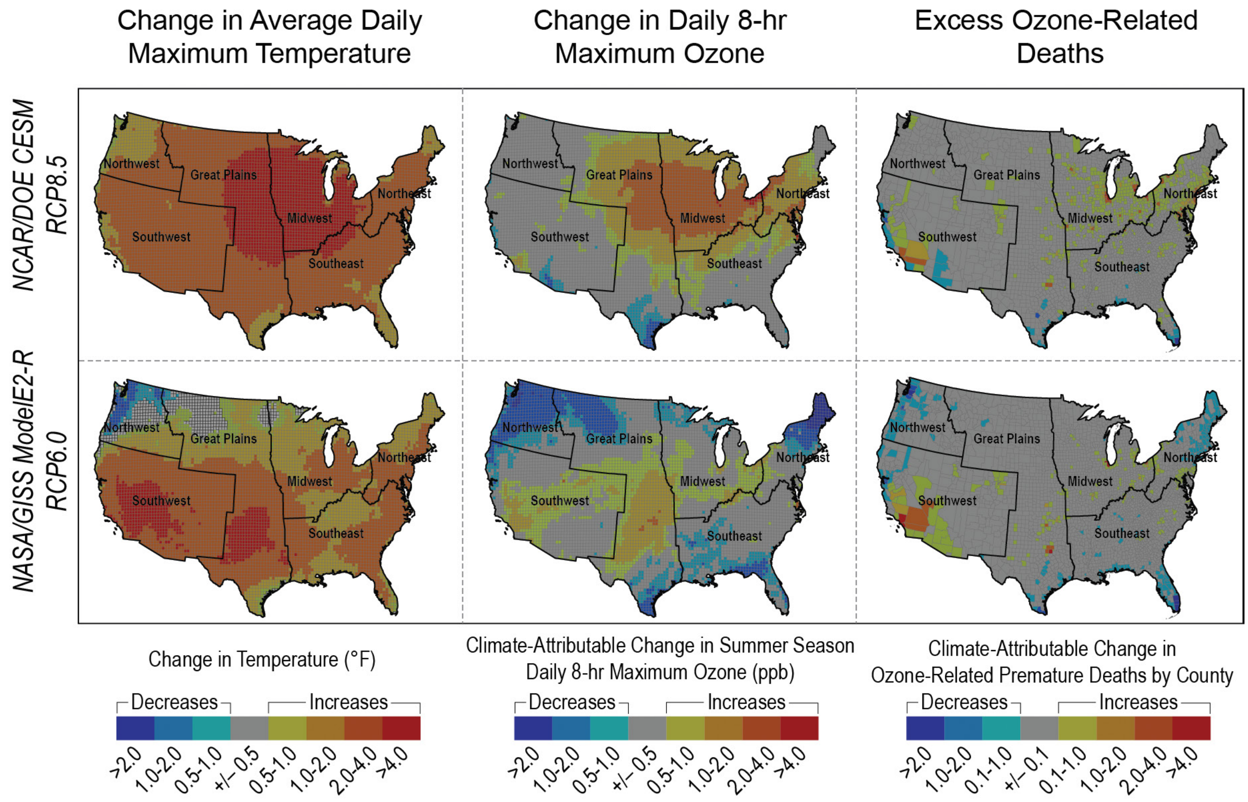


Figure 5.3. Projected Change in Temperature, Ozone, and Ozone-Related Premature Deaths in 2030. Projected changes in average daily maximum temperature (degrees Fahrenheit), summer average maximum daily 8-hour ozone (parts per billion), and excess ozone-related deaths (incidences per year by county) in the year 2030 relative to the year 2000, following two global climate models and two greenhouse gas concentration pathways. The top panels are based on the National Center for Atmospheric Research/Department of Energy (NCAR/DOE) Community Earth System Model (CESM) following RCP 8.5 (a very high greenhouse gas concentration pathway), and the bottom panels are based on the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) ModelE2-R following RCP6.0 (an intermediate greenhouse gas concentration pathway) (Fann et al. 2016).

Based on the national results seen in these studies, the impacts for New Jersey are generally more severe than many other states. The specific impacts for New Jersey can be estimated. For the two cases analyzed, average New Jersey temperatures will increase by about 2 - 4°F (1.1 - 2.2°C), and ozone levels will increase by up to 2-4 ppb. It should be noted that numerous important climate change-impacted processes that increase ozone levels were not included in the above analysis. For example, emissions from electrical generation units and wildfires were held constant between the current and future periods.

In New Jersey, the ozone monitoring season currently lasts from March 1 to October 31, peaking from June 1 through August 31. Ozone is mainly a problem during the daytime (2 p.m. to 8 p.m.) in summer months when temperature and sunlight are at their peaks (NJDEP 2024b). As explained above, meteorological conditions have a significant effect on ozone formation and as climate change results in higher temperatures and drying conditions, New Jersey will likely see an increase in ozone. The Department of Environmental Protection currently measures ozone at 16 sites around the state and has seen a substantial decrease over the last 23 years in the number of ozone exceedances of the declining 8-hour standard, as seen in Figure 5.4. In addition, since 1997 monitoring sites have also shown a decrease in the annual 4th-highest maximum ozone concentrations for the 8-hour periods, as seen in Figure 5.5.

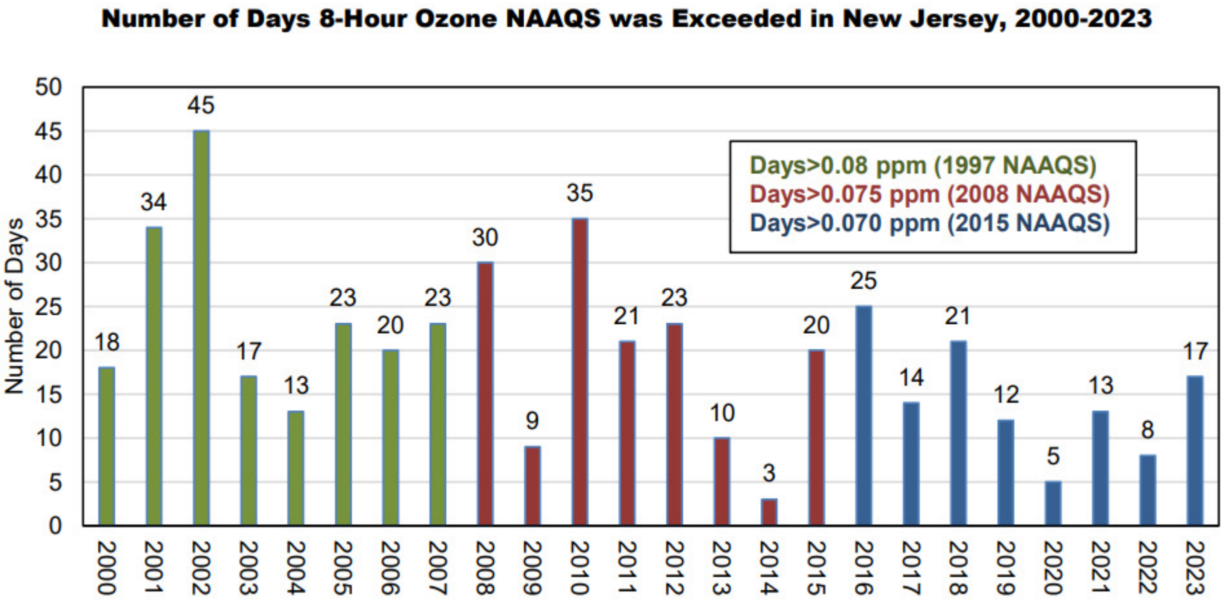


Figure 5.4. Number of Days 8-Hour Ozone National Ambient Air Quality Standard (NAAQS) was Exceeded in New Jersey, 2000-2023. This chart shows the total number of days the 8-hour average ozone NAAQS was exceeded in New Jersey since 2000 (NJDEP 2024b).

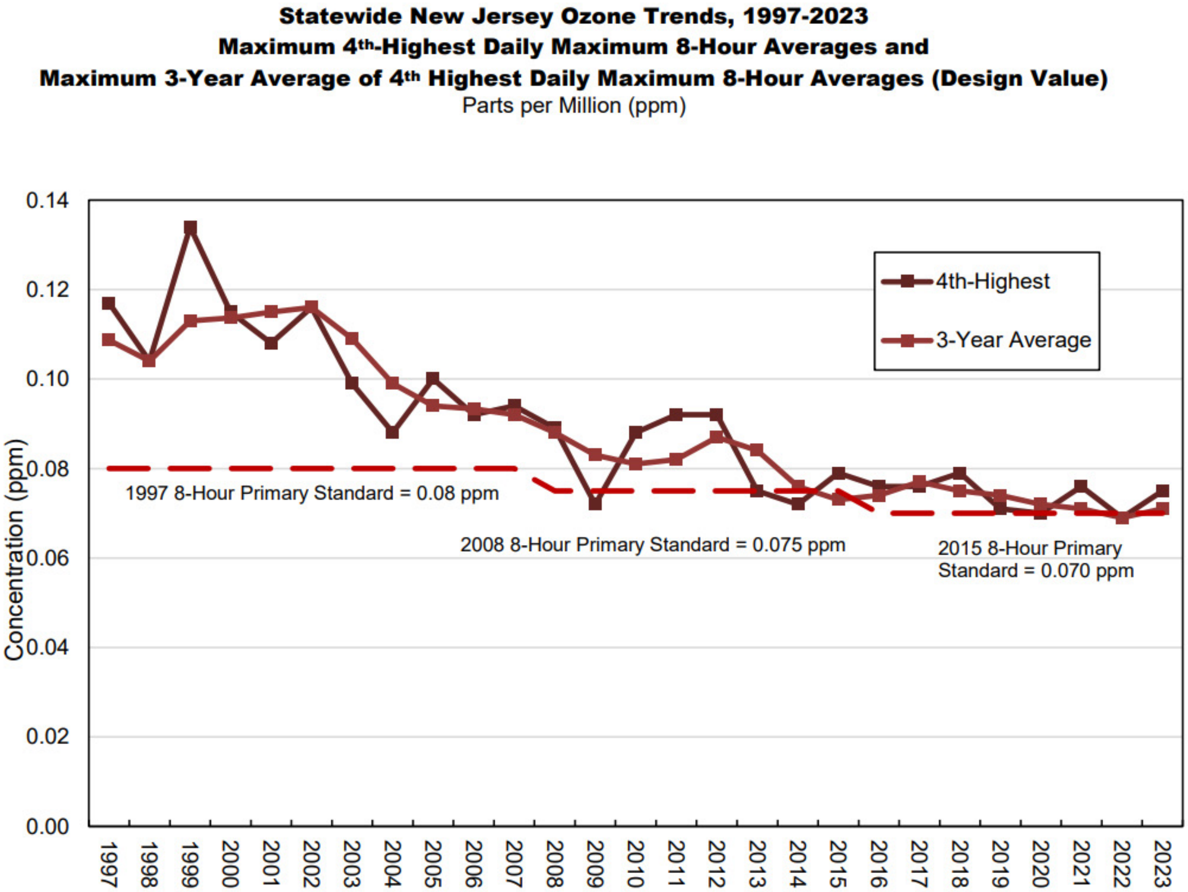


Figure 5.5. Statewide New Jersey Ozone Trends, 1997-2023. This figure shows the maximum value from all DEP air monitoring stations of the annual 4th-highest daily maximum 8-hour average concentration and the maximum ozone design value (3-year averages of the annual 4th-highest) from all DEP stations for each year since 1997 (NJDEP 2024b).

Ground-level ozone is not only harmful to human health but is also harmful to the environment (NJDEP 2016). Plant life is particularly susceptible, and an increase in ozone exposure has the potential to cause losses in crops and forests.

Climate-change enhanced wildfire smoke impacts both ozone and particulate matter air quality in New Jersey from both in-state and upwind wildfires as far away as the western United States and Canada. During the spring and summer of 2023, numerous wildfires had devastating impacts on air quality across the United States. The plumes of smoke produced by these fires extended for hundreds of miles, impacting several regions. Wildfires originating from Canada and the Midwest United States significantly contributed to New Jersey's degraded air quality during this period. While much smaller in size, local fires also contributed to the impacts on New Jersey's air quality. Due to the transported emissions from these wildfires, New Jersey recorded multiple ambient air quality exceedances of the current 70 parts per billion (ppb) 8-hour average ozone National Ambient Air Quality Standard (NAAQS) (NJDEP 2025e).

The Clean Air Act (CAA) section 319(b) and US EPA regulations allow for the exclusion of air quality monitoring data influenced by exceptional events from use in determinations of exceedances or violations of the NAAQS, as these occurrences are considered not to be representative of typical air quality conditions. New Jersey prepared ozone exceptional event demonstration analyses for April

13, 2023, June 2, 2023, and June 29-30, 2023. New Jersey formally submitted their exceptional event demonstrations to the US EPA on May 28, 2024, and supplemental information on December 14, 2024 (NJDEP 2025e). The 2023 exceptional events echo a previous New Jersey ozone exceptional event that occurred during May 2016, that was caused by the emissions from a catastrophic wildfire originating in Fort McMurray, Alberta, Canada. Wildfire fueled exceptional events like these are expected to continue to increase in frequency and severity, as the 2023 Canadian wildfire season was recorded to be the most destructive in the nation's history, and the 2024 wildfire season ranked among the worst over the past 50 years (NOAA 2025f).

5.1.1.2 Particulate Matter

In addition to ozone, another important air pollutant for New Jersey is particulate matter (PM). In the atmosphere, PM consists of very small solid or liquid phase matter that is either directly emitted or formed from other pollutants, including ozone precursors (Fann et al. 2016). Sulfate, nitrate, ammonium, organic carbon, elemental carbon, sea salt, and dust are all examples of the many types of PM. These particles, also known as aerosols, are especially harmful to human health. Particulate matter smaller than 2.5 microns (µm) in diameter ($PM_{2.5}$) is associated with serious chronic and acute health effects including premature death, lung cancer, chronic obstructive pulmonary disease (commonly referred to as COPD), cardiovascular disease, and asthma development and exacerbation. It is still unclear if changes in $PM_{2.5}$ or ozone will be the dominant driver of air quality-related health effects due to climate change (Fann et al. 2016, Nolte et al. 2018).

Historically, many New Jersey counties have experienced $PM_{2.5}$ pollution levels that have exceeded federal health-based air quality standards. New Jersey has taken many actions to address $PM_{2.5}$ pollution and as a result, the entire state was determined by the US EPA to have met the health standard in 2013 (US EPA 2013). However, compliant levels may not occur in populated areas as localized exposure can be orders of magnitude higher than spatially averaged values. Despite this, concentrations of $PM_{2.5}$ remain higher than they would be without human-caused, or anthropogenic, sources. Consequently, $PM_{2.5}$ will continue to cause significant health effects for New Jersey residents because there is no safe level of $PM_{2.5}$ that will not cause negative human health effects (see Chapter 6.2.1.2). In addition, effective May 6, 2024, the US EPA revised the primary annual $PM_{2.5}$ standard by lowering the level from 12.0 $\mu g/m^3$ to 9.0 $\mu g/m^3$ in recognition of the current understanding of the severe health effects associated with this air pollutant (US EPA 2024b).

Meteorological conditions and emissions also affect $PM_{2.5}$ levels in the atmosphere (Fann et al. 2016, Nolte et al. 2018). While regulatory controls are expected to continue to reduce emissions of SO_2, NOx, and black carbon in the United States, $PM_{2.5}$ concentrations are still expected to increase, due to various factors, including wildfires, dust generation from droughts, and heat-induced evaporation volatilization of natural and anthropogenic substances. Meteorological changes due to climate change that will cause increases in $PM_{2.5}$ levels include increased humidity, increased stagnation events, and increased biogenic emissions. However, increases in precipitation and enhanced atmospheric mixing could result in local decreases in $PM_{2.5}$ levels at certain times (Fann et al. 2016).

As discussed later in this report, the number and magnitude of wildfires are expected to increase in North America, including in New Jersey (see Chapter 5.3.5) because of climate change (Fann et al. 2016). Wildfires are currently a major source of $PM_{2.5}$, especially in the western United States, during the summer months (Fann et al. 2016, Nolte et al. 2018). Release of $PM_{2.5}$ and ozone precursors from wildfires can be transported significant distances and cause impacts to air quality in these downwind locations.

The contribution of human-caused climate change to the increased mortality and associated economic burden due to wildfire $PM_{2.5}$ exposure in the continental United States during the 15-year period between 2006 and 2020 was recently estimated by researchers (Law et al. 2025). The paper includes the quantitative contribution to $PM_{2.5}$ related mortality due to the additional wildfire smoke attributable to anthropogenic climate change. The researchers combined results from climate projections, climate-wildfire models, wildfire smoke models, machine learning model methods, and health impact modeling, on a national scale. The study concluded that across the United States, climate change contributed to approximately 15,000 wildfire particulate matter deaths over a 15-year period, and a cumulative economic burden of $160 billion (Law et al. 2025). These impacts are based exclusively on mortality estimates from wildfire $PM_{2.5}$ and do not include any estimations for morbidity impacts due to climate change-related $PM_{2.5}$ wildfire emissions. It is additionally noted that a significant portion of the mortalities and associated economic burdens occurred in the most recent years of the observation period (Law et al. 2025). This indicates that the health effects from impacts from wildfire $PM_{2.5}$ due to climate change are accelerating over time.

The study included state-level estimates for mortality and economic burdens caused by wildfire $PM_{2.5}$ due to climate change. According to the study, New Jersey has seen climate change contribute to an annual average of 5.1 wildfire particulate matter deaths over the 15-year period due to wildfire smoke attributed to climate change (Law et al. 2025). Using results presented in the supplemental data provided with the paper, it can be estimated that New Jersey's cumulative economic burden associated with these deaths was $782 million. As with the national impacts, a significant portion of deaths and associated economic impacts occurred in the most recent portions of the period studied.

Air quality in New Jersey has recently been impacted by elevated $PM_{2.5}$ levels from climate-change enhanced wildfires in North America. For example, during the spring and summer of 2023, record breaking Canadian wildfires transported smoke and high levels of fine particulates to the Northeastern United States, including New Jersey. New Jersey recorded multiple ambient air quality exceedances of the most recent $PM_{2.5}$ annual standard of 9 $\mu g/m^3$. Smoke from the Canadian wildfires significantly contributed to New Jersey's degraded air quality during the summer of 2023, resulting in historically high $PM_{2.5}$ concentrations measured in New Jersey, with air quality monitors recording levels greater than 98th percentile of the highest $PM_{2.5}$ concentrations typically observed during the last five years (2019 – 2023) (NJDEP 2025e).

The Clean Air Act Section 319(b) and US EPA regulations allow for the exclusion of air quality monitoring data influenced by exceptional events from use in determinations of exceedances or violations of the national ambient air quality standards as these occurrences are considered to be not representative of usual air quality conditions. New Jersey prepared $PM_{2.5}$ exceptional event demonstration analyses for June 6, 7, 8, 29, and 30, 2023. New Jersey formally submitted their exceptional event demonstrations to the US EPA on December 11, 2024.

5.1.1.3 Aeroallergens

An aeroallergen is any airborne substance that triggers an allergic reaction caused by hypersensitivity of the immune system to certain substances. Examples of aeroallergens include tree, grass, and weed pollen; indoor and outdoor molds; and other allergenic proteins associated with animal dander, dust mites, and cockroaches. People in the United States are most commonly affected by the pollen from ragweed. Allergic diseases resulting from aeroallergens include hay fever and allergic asthma (Fann et al. 2016) (see Chapter 6.2.2). Allergy symptoms can be exacerbated by the changes in local weather patterns, such as rainfall and changes to minimum and maximum temperatures (Fann et al. 2016).

There is substantial evidence that supports the conclusion that climate change and rising CO_2 concentrations affect major facets of aeroallergen biology (Nolte et al. 2018). These facets include production rates, timing of releases, and the potential for the severity of allergic reactions to aeroallergens. Changes in seasonal exposure times for allergenic pollen have been observed and correlate with rising CO_2 levels, higher temperatures, and altered precipitation patterns. Trends show climate change has extended the growing season for some allergenic pollens by lengthening the frost-free period (Fann et al. 2016). Increases in CO_2 and temperature result in acceleration of flowering, increased pollen production and floral numbers, as well as allergenicity of pollen. These changes result in more exposure to aeroallergens, which in many cases cause increases in allergic disease. As discussed in Chapter 4.1.3, out of the 20 warmest years since 1895, 15 have occurred from 2000-2024 (Davies et al. 2025), while the ten coldest years all occurred before 1941 (Office of the New Jersey State Climatologist 2025a). This is supported by the observation that annual precipitation over the most recent 10-year period in New Jersey was 8% above the long-term average.

5.1.2 Indoor Air Quality

Climate change is likely to worsen indoor air problems as outdoor air can enter buildings through open windows, under doors, or through cracks in the building (Fann). When air infiltrates a building this way, it bypasses filtration systems exposing inhabitants to air pollutants. Poor indoor air quality is linked with adverse respiratory and other health effects (see Chapter 6.2.2).

Outdoor weather conditions can also affect indoor air quality through the same infiltration described above. As droughts and dust storms become more frequent, dust particles carrying dust-borne pathogens are more likely to infiltrate buildings and increase the allergic potential of indoor air (Fann et al. 2016). In addition, as climate change results in weather events of increased severity and increases in humidity, the effect is an increase in potential water/moisture damage to buildings and a higher potential for dampness and condensation indoors, creating more ideal environments for mold and bacteria growth. More extreme weather events could cause additional power outages, disabling any control systems meant to regulate indoor air conditions such as temperature, humidity or circulation (Runkle et al. 2017), further worsening these conditions. This was the case in 2012, when New Jersey experienced Superstorm Sandy, and more recently when the state was devastated by flooding from Hurricane Ida which occurred on September 1, 2021. Powerful storm surges and the accompanying rainfall caused substantial damage and allowed water to infiltrate structures in the impacted area. The conditions the storm created were ideal for numerous molds and bacteria. Power loss rendered heating, ventilation, and air conditioning systems useless, making it difficult for many buildings to maintain indoor temperature, humidity and keep up ventilation, filtration, and circulation. Additionally, the use of portable generators to power appliances in lieu of normal power supply can lead to carbon monoxide poisoning if used improperly. As discussed previously in this report (Chapter 4.2.4), it is generally believed that climate change related factors such as ocean temperatures and increasing sea levels will strengthen storms and their impacts.

"Air quality in New Jersey has recently been impacted by air pollution from wildfires in the western United States and Canada."

CHAPTER 5.2

WATER RESOURCES: SUPPLY AND QUALITY

STOKES STATE FOREST, NEW JERSEY

KEY FINDINGS

- **Water supplies will be stressed from the increase in the growing season and extreme temperatures expected due to climate change.**
- **Rising sea levels may lead to increased saltwater intrusion in New Jersey aquifers where wells are over pumped.**
- **Freshwater intakes and aquifer recharge areas may be threatened if sea-level rise pushes the salt front further upriver.**
- **Communities with aging combined sewer infrastructure may be further challenged as sea-level rise and/or increased rain events submerge discharge points that are currently above the waterline.**
- **Surface and groundwater quality will be impaired as increased nutrients and contaminants enter waters due to runoff from more intense rain events.**
- **Climate change impacts, such as warmer temperatures, create favorable conditions for cyanobacteria blooms, which can produce toxins affecting water quality.**

5.2 Water Resources: Supply and Quality

Climate change has been shown to have a multitude of effects on our planet. Of particular concern to New Jersey water supply and water quality managers are temperature (Chapter 4.1), precipitation (Chapter 4.2), and changes to sea level (Chapter 4.3). These three factors have a significant effect on the amount of available water, where and when it is available, and on its quality. The factors can place additional or new stresses on the treatment and infrastructure for drinking water, wastewater, stormwater, on aquatic ecosystems, and any designated uses of the waters. It is thus critical to update procedures within any planning process to ensure that the most recent scientific consensus, data, and models are considered.

Throughout the United States, aging public water supply infrastructure and demands are vulnerable to the consequences of climate change. According to the 2024 Statewide Water Supply Plan, New Jersey citizens withdraw on average 1.8 billion gallons of water per day, with 70% coming from surface water, 20% from groundwater from unconfined aquifers (water table aquifer; aquifers where water can directly recharge from precipitation), and 10% from confined aquifers (aquifers where recharge is restricted by impermeable layers) (NJDEP 2024a). On average from 2016 through 2020, about 70% of the withdrawals were used for potable (drinking water) supply, with power generation, commercial/industrial/mining, and agricultural/irrigation making up the remaining 30%. Sub-annual use patterns vary depending upon the specific use type and socio-economic factors. In addition, the fraction of consumptive use (water that is lost to evaporation, transpiration, etc., and not discharged at any location) and depletive use (withdrawal of water from a source where once used, the water is not discharged back to the same resource so as to be usable within the same watershed) varies by season, use type, and individual user. Even with these variations, withdrawals have generally been sustainable due to a combination of abundant rainfall (on average), physiography (allows water storage), adequate management, and regulatory actions. Additionally, apart from power generation, total water use has remained relatively stable over the last decade (NJDEP 2024a). While New Jersey receives what many regions would consider a significant amount of precipitation, 45.6 inches (115.7 cm) per year on average, it also has an ecology and economy that are dependent upon those average amounts. Climate change has the potential to change the quantity and quality of water (both ground and surface) available and increase the variability of each, which in turn can create both environmental and water supply stresses.

The extension of the growing season and extreme temperatures will put more stress on water supplies. At the same time, the state will experience peak water demands that last longer. Water quality changes are also likely to require additional drinking water treatment and monitoring and may lead to limits on the use of water for some industrial, agricultural, or recreational activities. Longer periods of low-flow conditions in streams, punctuated by more frequent and intense extreme precipitation events, will result in challenges to maintain water quality. Changes in temperature ranges, nutrient loads (nutrients inputs into the water), and reductions in dissolved oxygen levels will have the greatest effect on sensitive aquatic life. These changing conditions are likely to alter the species assemblages that reside in New Jersey (see Chapter 5.7 for more information).

5.2.1 Groundwater

5.2.1.1 Groundwater Supply

Groundwater is an important source of water in New Jersey (Figure 5.6). In addition to sustaining baseflow in streams, it supplies 30% of the total statewide water supply needs. In some regions, like the Atlantic Coastal water region, it accounts for over half of the total withdrawal. For smaller self-supplied users, groundwater is the only source of water available. This is especially true for the almost 400,000 private domestic wells spread across the state.

Groundwater resources are extracted from either unconfined or confined aquifers. Unconfined aquifers receive recharge from precipitation and direct infiltration. They may also gain water from or lose water to underlying aquifers. Confined aquifers are those where recharge is restricted by impermeable layers. Confined aquifers ultimately get their water from groundwater recharge, but the age of the water can be thousands of years old and travel times can be centuries for deeper units. Not all aquifers are created equal; some are barely productive enough to meet potable domestic well needs, while others can produce thousands of gallons per minute for large industrial, irrigation, or public water supply sources. Groundwater availability is a complex function of the timing and magnitude of recharge and the aquifer's hydrogeologic properties. Groundwater recharge is the mechanism that conveys precipitation to our aquifers. It is an even more complex function of the timing and magnitude of precipitation, surface water runoff, land cover, evapotranspiration, and the soil moisture (New Jersey Geological and Water Survey 1993).

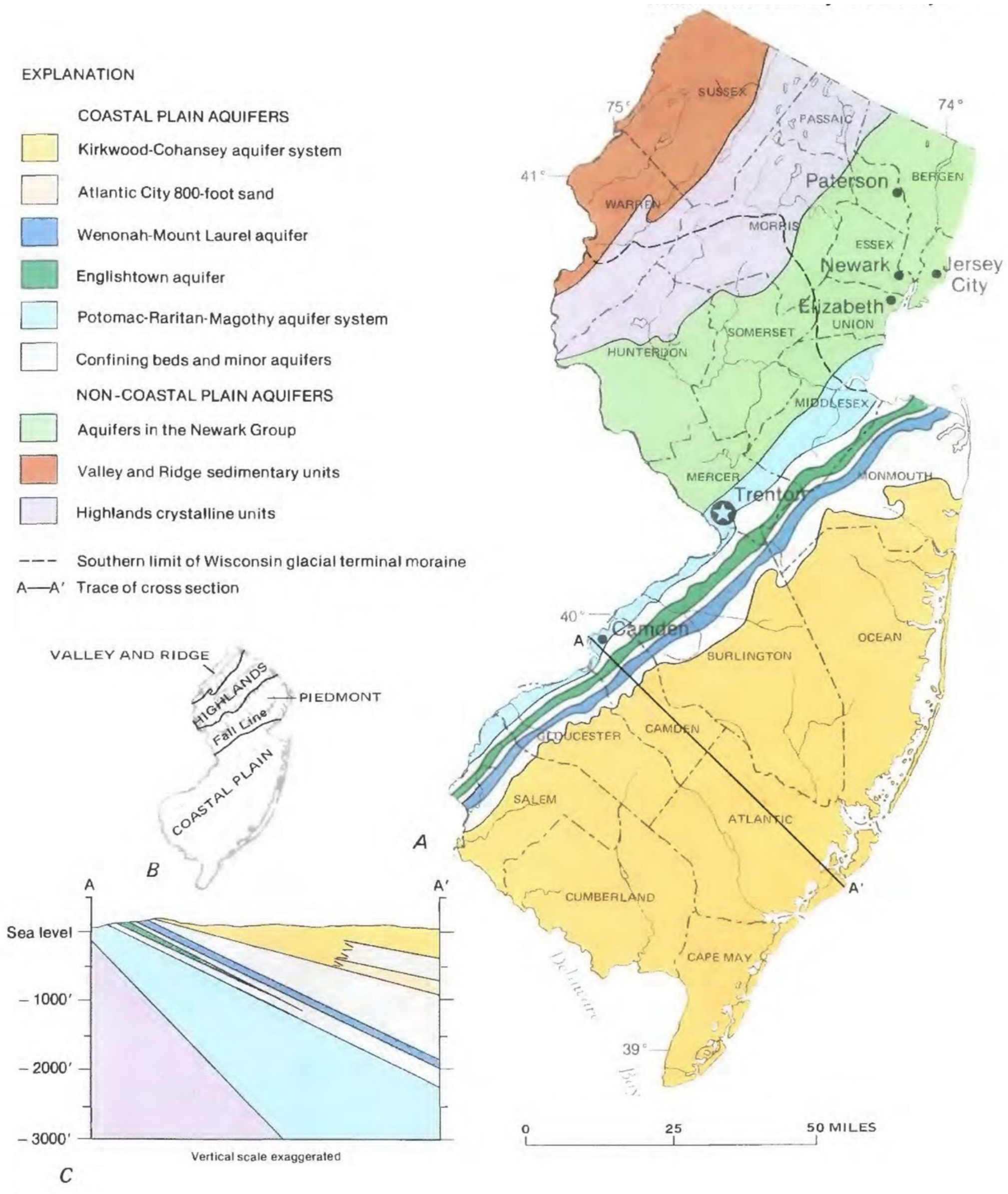


Figure 5.6. Principal Aquifers of New Jersey. Adapted from (Herman et al. 1998).

Due to concerns with over-pumping and depletion of aquifers during normal and drought conditions, New Jersey passed the Water Supply Management Act in 1981, giving the State the authority to respond to those concerns through a variety of regulatory, planning, and scientific actions. These include a robust water allocation and well permitting program, the declaration of two groundwater-supply critical areas, water supply master plans, numerous scientific reports on groundwater recharge, including water level assessments conducted within a relatively short period and under specific hydrologic conditions.

Climate change will likely impact groundwater resources differently from a quantity and quality perspective. Those impacts will vary over time throughout the state and may also vary due to date and time. Predicting where and when these impacts and influences will occur and what the differences will be is difficult, in part because there are limits to the present scientific understanding of the land phase of the hydrologic cycle (NJDEP 2011). This is an area of scientific research that New Jersey Geological & Water Survey is pursuing through the development and calibration of its Land Phase Hydrologic Model (NJDEP 2024a). This model is based on the logic of a soil water budget and simulates a variety of parameters, including precipitation, snow accumulation and melting, land use and land cover change, overland flow, evapotranspiration, soil water storage, groundwater recharge, and streamflow. Model computations use a daily timestep and a 300-meter grid encompassing the state.

The Land Phase Hydrologic Model has been used to investigate changes in groundwater recharge in response to climate change on a trailing (temporal) rolling average basis. Preliminary results indicate that, using (spatial) averages for both northern and southern New Jersey, precipitation has been increasing faster than potential evapotranspiration and that the amount of precipitation available for recharge has been increasing since 1950. The Land Phase Hydrologic Model has also been used to develop nine climate change forecast scenarios using combinations of low, medium, and high changes in temperature and precipitation through the year 2050. All nine scenarios forecast that more water will be available for groundwater recharge in 2050 than in the 1990s, as statewide averages. From 2020 to 2050, only two scenarios forecast a decrease, while five scenarios forecast increases and two forecast stable conditions (NJDEP 2024a). It should be noted that Land Phase Hydrologic Model runoff simulations do not yet account for increasing storm intensity, which may result in greater percentages of precipitation running off rather than recharging. Also, potential evapotranspiration for these efforts was estimated based on observed air temperature data and calculated daylight hours, but future efforts may also make use of other observed climate data such as windspeed and relative humidity.

Other studies have come to alternate conclusions. An Australian study predicts that with increased precipitation, evapotranspiration will increase due to more plant growth resulting in less recharge (Taylor et al. 2013). Under both a low emission and high emission scenario, a United States Geological Survey study of potential climate change impacts on a glacial unconfined aquifer system in New Hampshire (similar to those present in northern New Jersey), predicted that overall groundwater levels and baseflow in rivers will decrease, but that the changes will vary over the years (Bjerklie and Sturtevant 2018).

More work is needed to evaluate the range and spatiotemporal distribution of potential changes to groundwater recharge from climate change in New Jersey.

Taken as a statewide average over the long term, and as temperatures increase and the growing season lengthens, there will be greater water demand for irrigation use (e.g., crop, nursery, golf course, and outdoor residential). This will put more stress on ground and surface water supplies. Water demands peak in warm weather, and even more so during heat waves. These peaks often occur near the same time that unconfined aquifer storages are most limited and streamflow is low.

5.2.1.2 Groundwater Quality

Increasing temperatures, changing precipitation patterns, and sea-level rise are major phenomena likely to impact New Jersey's water resources as a direct result of climate change. These changes will alter groundwater temperature, recharge rate, water levels, and flow processes, leading to changes in groundwater quality. Climate change impacts on groundwater quality are expected to be gradual, with both long-term and seasonal variability. Quantifying these impacts remains challenging due to uncertainties in climate projections and complex hydrogeological responses. Changes in groundwater quality due to climate change are described in the report "Potential Impacts of Climate Change on Groundwater Quality in New Jersey" prepared by the DEP Division of Science and Research (Aziz 2023), and are briefly summarized below.

Rising air temperatures are projected to increase groundwater temperatures by 2.1 °C by 2100 under low to intermediate CO_2 emissions, particularly affecting shallow aquifers (Benz et al. 2024). This warming can accelerate biogeochemical processes, such as mineral weathering, chemical adsorption and desorption, and microbial activity, leading to increased concentrations of some major elements, heavy metals, redox-sensitive elements (e.g., arsenic [As], iron [Fe], and manganese [Mn]), and dissolved organic carbon (DOC).

Climate models predict increased annual precipitation with more intense events and longer dry spells, altering the recharge dynamics of aquifers. Enhanced recharge can dilute certain contaminants, potentially improving water quality, but it can also transport harmful chemical compounds stored in the unsaturated zone to the water table, posing risks to groundwater quality. Recharge events deliver electron donors, primarily DOC, and electron acceptors (EA), such as oxygen, nitrate, sulfate, and anthropogenic pollutants into aquifers, which can cause groundwater redox reactions (a type of chemical reaction that involves a transfer of electrons between two chemical species) and water quality changes. DOC and electron acceptors change redox conditions in aquifers and release geogenic contaminants such as Fe, As, and Mn into groundwater. The vertical migration of emerging contaminants, such as per- and polyfluoroalkyl substances (PFAS) and microplastics, depends on the intensity of precipitation and recharge (O'Connor et al. 2019, Guo et al. 2020, Zhang et al. 2022). Therefore, these conditions can make groundwater susceptible to contamination.

Flooding can dramatically affect groundwater recharge, introducing large amounts of DOC, EA, and pollutants into aquifers, causing changes in groundwater quality. Urban areas are particularly vulnerable to increased contamination from oil, solvents, and sewage during floods, posing immediate health risks through microbial contamination. Flooding can also alter redox conditions in soils, increasing metal solubility and mobilizing contaminants like As, Fe, Mn, and other metals. Droughts have the potential to significantly impact groundwater. Recent studies have observed post-drought increases in nitrate concentrations (Jutglar et al. 2021) and certain redox-sensitive ions (sulfate) and metals such as Fe and Mn (Aladejana et al. 2020). During drought conditions, lowered groundwater due to reduced recharge exposes arsenic-iron sulfide bearing minerals to oxygen introduced by diffusion through the unsaturated zone, causing oxidation of these sulfide minerals. These minerals are significant sources of high levels of geogenic arsenic in New Jersey's groundwater (NJGS 2004).

Rising sea levels may lead to saltwater intrusion and salinization of coastal aquifers (see Chapter 5.2.1), resulting in the loss of fresh groundwater and posing a particular threat to the Kirkwood-Cohansey Aquifer (Fiore et al., 2018). Increased salinity affects the mobility of metals such as As, cadmium, lead, vanadium (V), and radium due to cation exchange and other complex chemical interactions, potentially degrading water quality. Coastal areas relying on septic systems may face failures and contamination risks due to rising groundwater levels, further exacerbated by sea-level rise.

> ***"Changing precipitation patterns...coupled with increased temperatures will affect groundwater recharge and hence discharge."***

Long-term studies with dense observation networks are essential to refine predictions and guide effective management strategies. New Jersey has an extensive systematic monitoring network to evaluate chemical and physical parameters in groundwater. This network aids in assessing water quality as well as potential impacts on the water supplies.

5.2.1.3 Saltwater Intrusion

Increased rates of groundwater pumping are known to, and rising sea levels associated with climate change may lead to increased saltwater intrusion of coastal New Jersey aquifers and estuaries and inundation of coastal wells and other critical water infrastructure (NJDEP 2024a). The magnitude and extent of those impacts will vary depending on the hydraulic connection between the source of saltwater and the freshwater portion of the aquifer, the magnitude of sea-level rise, and the proximity to water supply wells. To date, most saltwater intrusion issues are associated with over-pumping of wells near either seawater or connate saline water (saltwater trapped in rock pores).

Not all aquifers used in New Jersey coastal areas are connected or proximate to saline water sources. For those that are, the distance to the salt front can vary, so the risk of saltwater intrusion is not solely a function of proximity to the ocean or bay but rather more dependent on groundwater pumping and withdrawals in these areas (McAuley et al. 2001, Lacombe and Carlton 2002). Areas that have already experienced saltwater problems due to overpumping include:

- Diversions in Cape May County south of the county airport from deeper wells and along the Delaware Bayside from shallower wells. These issues are due primarily to over-pumping of groundwater sources near saltwater.
- The Raritan Bay communities of Union Beach, Keyport, and Keansburg were over-pumping wells in the Potomac-Raritan-Magothy aquifer system (see Figure 5.6), so they moved to inland sources. These aquifers have water levels below sea level, and the aquifer appears to be connected to the bay.
- The Potomac-Raritan-Magothy aquifer system in the Camden-Gloucester County region is affected by increased salt concentration in some wells where over pumping has occurred in the areas of inland connate sources.
- Recharge of the Potomac-Raritan-Magothy aquifer system primarily occurs from the freshwater reaches of the Delaware River in much of the Camden-Gloucester County region. As sea-level rise moves the salt front further upstream in these recharge areas, saltwater intrusion may occur.

An increased use of water supplies will, and sea-level rise may, lead to saltwater intrusion problems in some parts of the state. Along the coast, aquifer withdrawal limits have been established to address increasing saltwater intrusion concerns (Millsaps 2016). Efforts to combat saltwater intrusion, like the construction of desalination plants, may be complicated if systems are vulnerable to coastal flooding and storm surges. Injecting water into aquifers has been shown to buffer saltwater from freshwater in California and Florida (USGS 2020).

Saltwater intrusion poses a potential risk to the New Jersey groundwater supply. Shallow, unconfined aquifers, including outcrop areas of confined aquifers, would be the first immediate threat to a direct rise in sea level and landward inundation. New Jersey Geological & Water Survey staff used the DEP Sea Level Rise Inundation Depth Grid (NJDEP 2021) for 2-foot and 5-foot sea-level rise to analyze the potential impacts to New Jersey's aquifers from the direct inundation of seawater for the year 2050 and 2100 sea-level rise conditions, respectively. The unconfined Kirkwood-Cohansey (K-C) aquifer system would suffer the greatest harm with an estimated 77,400 acres being directly inundated by 2-feet of sea level rise (NJDEP 2024a). Confined aquifers with outcrop areas, where a water-bearing layer nears the ground surface and can be recharged directly by precipitation, which extend to mapped inundated areas, are also at risk. The Magothy and Potomac Formations run parallel to the Delaware River and are the confined aquifers that currently exhibit some degree of hydraulic connection with the river and thus are most at risk. The 2-foot sea level rise would inundate approximately 9,000 acres of the outcrop area of the Magothy and 5,100 acres of the Potomac Formations (NJDEP 2024a).

Inundation of Coastal wells and other critical infrastructure is a related concern when considering the 2-foot and 5-foot sea level rise conditions. The immediate impact from a 2- or 5-foot sea level rise impact would be to unconfined wells with a direct connection to the surface. However, confined wells would also be prone to direct inundation of seawater from the wellhead, which could provide a pathway for vertical migration of salty water to deeper confined and non-salty water.

Table 5.1. Number of Wells Within the 2- and 5-foot Sea-level Rise Zones by Source of Water (NJDEP 2024a).

Source of Water	2-ft Sea-level Rise		5-ft Sea-level Rise	
	Well count	Volume (mgd)*	Well count	Volume (mgd)*
Confined	23	7	132	29
Unconfined	35	2	140	10
Surface	70	21	100	40
Unknown	0	0	1	0
Total	128	30	373	79

**Annual volumes (2016-2020) were averaged for each site then summed by use type (million gallons per day).*

Table 5.2. Number of Wells Within the 2- and 5-foot Sea-level Rise Zones by Use of Water (NJDEP 2024a).

Use of Water	2-ft Sea-level Rise		5-ft Sea-level Rise	
	Well count	Volume (mgd)*	Well count	Volume (mgd)*
Agriculture	70	2	100	3
Commercial	3	0	5	0
Industrial	27	19	70	32
Irrigation (non-ag)	10	0	33	0
Mining	0	0	5	6
Potable supply	18	9	158	38
Power generation	0	0	2	0
Total	128	30	373	79

**Annual volumes (2016-2020) were averaged for each site then summed by use type (million gallons per day).*

5.2.2 Surface Water

5.2.2.1 Surface Water Supply

Surface water withdrawals represent about 70% of New Jersey's total water use. This is especially true for more populated areas where demands exceed the available supply of groundwater, like the central and northeastern regions of New Jersey (NJDEP 2024a). Climate change has the potential to change the timing and magnitude of streamflow, as well as increase the variability of flows over multiple timescales. Warming air temperatures will increase water temperatures, which along with increased extreme precipitation events, will lead to water quality changes. Such changes, like increased turbidity and excess nutrient inputs and subsequent eutrophication to reservoirs and drinking water supplies may pose treatability issues. Some of those changes may stress the water treatment processes required by the Safe Drinking Water Act or limit use for other non-potable uses. Sea-level rise will push the saltwater-freshwater

> ***"Stormwater management will become a challenge for all communities as flooding will likely increase over time, requiring additional investment in mitigation solutions and stormwater infrastructure."***

interface (location where salt and freshwater meet in a waterbody or the saltwater front) further upriver and threaten intakes, aquifer recharge areas, and the aquatic ecology. Extreme dry periods or flash droughts may temporarily push the salt front even further upstream.

The advancement of the salt front is of particular concern because existing surface water intakes and treatment plants are not designed to treat elevated salt levels. Increased salinity can lead to corrosion within older lead drinking water service lines and may release lead if not properly controlled. Additionally, there are no primary drinking water standards for chloride and sodium, both components of saltwater, although secondary standards do exist.

In the Delaware estuary, there are large potable supply intakes in Delran, New Jersey and Philadelphia, Pennsylvania, as well as numerous industrial intakes. The current range of the salt front is typically between river mile 67 and 76, where river mile 0 is at the mouth of the Delaware Bay (where the bay meets the Atlantic Ocean) and the intersection of the line between Cape May Lighthouse in New Jersey and the tip of Cape Henlopen in Delaware. The distance the front moves can be countered with flow management strategies, like releasing water from reservoirs, in an effort to ensure salt does not interfere with drinking water and other operational needs. Flow management strategies introduced in the early 1980s have been able to keep the salt front from advancing past river mile 92.5, about 17.5 miles downstream of drinking water intakes (Chen et al. 2025). The Delaware River Basin Commission has modeled the extent that the salt front may advance upstream. The Delaware River Basin Commission models show that with 1.0 meter (3.3 feet) of sea-level rise the salt front moves to river mile 100, the point reached at the height of the drought in the 1960s, and with 1.6 meters (5.2 feet) it moves to river mile 104, about six miles from the drinking water intakes. A repeat of similar drought conditions and compounded by sea-level rise will move the salt front even further upriver, increasing the reliance on management strategies (Chen et al. 2025). There are similar concerns along smaller estuaries along the Atlantic Coast and Barnegat Bay where infrastructure could also be impacted. In the Hudson River waterfront and Newark Bay region of New Jersey, most water supplies are piped in from the New Jersey Highlands region. Although the source water in these areas may not face the same risks, the infrastructure that delivers the treated drinking water to its customers may.

5.2.2.2 Streamflow

The regional hydrologic systems in the Northeastern United States will be affected by the increase in precipitation events (Melillo et al. 2014) that are expected to result from the climate changes discussed so far in this report. However, when and how intense those events will be is uncertain. An increase in extreme precipitation events and annual precipitation has the likelihood of altering streamflow patterns and impact surface water supplies. Competing climatic forces complicate the ability to predict future annual streamflow. Increased precipitation alone would increase streamflow, especially following significant isolated heavy rains. In a warmer climate, evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) is expected to increase while soil moisture will decrease. Both evapotranspiration and soil moisture will collectively reduce and perhaps offset streamflow increases (DeWalle et al. 2000, Luber et al. 2014, Wasko and Sharma 2017). Although, a study by Milly and Dunne (2017) strongly suggests that drying conditions due to increased evapotranspiration are being "systematically and substantially" overestimated in streamflow analyses and thereby masking potential streamflow increases.

The hydrologic dynamics of waterways can also be greatly altered by the sediment load in streams and rivers that result from runoff and in-stream erosion (IPCC 2018b). While long-term increases of high streamflows have been reported in New Jersey, the trends do not appear to be directly related to increases in precipitation, especially in undeveloped watersheds (Watson et al. 2005). Some of the observed increases are likely due to increases in urbanization or associated increases from runoff (Melillo et al. 2014). The uncertainty between these forces complicates the ability to predict the magnitude and extent of future streamflow.

A projected increase in winter precipitation and temperature is expected to reduce snow accumulations and effectively shift the timing and extent of winter and spring flows in the Delaware River Basin (Williamson et al. 2016). Accordingly, winter flows will increase due to reduced snowpack and subsequent additional rainfall. Spring snow will melt earlier with less volume resulting in reduced spring flows. Additionally, short-duration streamflow spikes and three-day peak flows are projected to increase as a result of more intense precipitation events while low-flows, including the 7-day low-flows, are expected to decrease, exacerbating low-flow conditions (Demaria et al. 2016). The length of the low-flow season, defined as May through October, is projected to increase by up to five days on average by mid-century. Evapotranspiration is expected to increase in the Northeastern United States with greater rates during the summer and fall, leading to reduced soil moisture storage and ultimately altering runoff patterns and streamflow responses.

Temporal changes to regional groundwater levels also need to be considered when evaluating potential climate-induced changes to streamflow. Reductions to groundwater recharge, due to increased rates of evapotranspiration or drought conditions, can greatly influence surface water flows since a significant proportion of baseflow can come from groundwater discharging to the stream. In New Jersey, this is a particular concern especially in the Pinelands region where groundwater can constitute over 80% of annual flows (Rhodehamel 1998). While historic streamflow trends that evaluate average, high, and low flows are present for specific monitoring stations throughout New Jersey (Watson et al. 2005, McHugh et al. 2024), it is not appropriate to assume such changes are due solely to changes in precipitation or climate. While both are contributing factors, historic changes may be driven primarily by temporal changes in land-use, agriculture, and water withdrawals and diversion (McHugh et al. 2024). McHugh et al. evaluated long-term streamflow trends at New Jersey locations for the period between 1903 and 2017. Long-term trends in low flow were relatively mixed with a similar percentage of sites either expressing an increase or decrease in stream flow, while many showed no statistical change. However, a larger percentage of sites around the state showed long-term increases in high flows compared to those that indicated decreased high flows. Only about a quarter of the sites showed a significant change in flow variability. Decreased flows were more common in the southern part of the state.

Climate-driven simulations of projected streamflow and precipitation were evaluated in the Northeast United States. One particular study projected a slight increase in streamflow under an intermediate greenhouse gas emission scenario (RCP 4.5) and showed no statistical increase in streamflow under a very high long-term emissions scenario (RCP 8.5) despite a projected increase in precipitation (Demaria et al. 2016). The United States Geological Survey (USGS) used a Precipitation Runoff Modeling System (PRMS) in New Hampshire that estimated monthly projected changes to the state's streamflow (Bjerklie and Sturtevant 2018). The results showed that streams will see a larger range of high flows to lower flows as a result of climate change. Overall, the study shows that New Hampshire's rivers and streams will become more unpredictable due to localized changes in precipitation (Bjerklie and Sturtevant 2018). Similar unpredictability can be assumed for New Jersey.

In summary, climate change in New Jersey will likely intensify evapotranspiration and shift precipitation patterns. This will likely lead to heavier, more intense events. These trends are expected to reduce soil moisture and groundwater recharge, leading to lower baseflows and extended low-flow periods outside storm events. Conversely, extreme precipitation events may increase peak streamflows, heightening flood risk. The net effect is a more variable streamflow regime, with higher flood peaks and deeper, longer low-flow stretches. This outlook is supported by modeling from both local New Jersey studies and broader Northeast regional hydrologic analyses.

5.2.2.3 Reservoir Systems

Reservoir systems are designed to capture high flows and store that water for later use when the natural flows are not adequate to meet demands. In New Jersey, an extensive reservoir network has been established and management of this network dates back to the late 1800s (NJDEP 2024a). This intricate network of reservoirs is ideally suited to meet the increased streamflow variability likely under future climate change. There are limits to what those systems can store, treat, and deliver. It is quite possible that future variability and increased floods can overwhelm the capacity of each system. Systems that rely on water being pumped to the reservoir for storage are likely to be more at risk due to the nature of streamflow variability predicted under climate change. For example, reservoirs may be filled to higher than usual capacity following floods and lower low-flow conditions in streams may prohibit pumping to fill reservoirs for longer periods of time. Over the last decade, the DEP has developed computer models for the major surface water reservoir systems that can be used to evaluate the impact of hydrologic changes. Under current drought-of-record flows (varies according to system), the research and preliminary modeling conducted by the DEP Division of Water Supply & Geoscience shows that coordinated operations and the ability to move water between systems are key to maintaining adequate supplies and preventing unwanted shortages (NJDEP 2007). These drought responses are also likely to be valid under climate change, at least in the near term, where there is more variability, more variance between high and low flows and short, intense drought periods.

5.2.2.4 Surface Water Quality

There is strong potential for streams, rivers, and lakes in New Jersey to be affected by changing climate patterns. In areas where temperature increase has been the largest climate change driver, organic matter, nitrates, and phosphorus have affected water quality (IPCC 2018b). Increased variability in precipitation will also pose significant threats to the state's waters. Wetter winters and springs, for example, will lead to greater seasonal runoff, transport excess sediment and contaminants, and increase in-stream erosion. Changes in precipitation, especially increases, will increase the rate of streambank erosion. Changes would be more likely in alluvial (loose sediment) stream channels, while bedrock channels will be less sensitive to increased rates of erosion. Increased rates of erosion will ultimately lead to an increase in sediment delivery downstream and subsequent increases in total dissolved solids (TDS), conductivity, and turbidity (Goudie 2006). In turn, the increased sediment load can alter the stream discharge or volume of water passing a point per second. Collectively, increased water temperature along with increased nutrients and TDS amplifies the potential for reduced dissolved oxygen levels in waterways, especially in the summer (USGCRP 2017).

Increased precipitation and runoff will likely mobilize nutrients, which will cause an increase in surface water nutrient loading. Within these waters, this will lead to eutrophic conditions (the condition when excess nutrients in water from runoff causes excess plant growth, that leads to a lack of oxygen, and results in species death in the system) in watersheds of the Northeastern United States. The magnitude of nutrient mobilization and the increase in eutrophic conditions is uncertain (Sinha et al. 2017). This nutrient loading and warming of waters also poses the potential to stimulate rapid and excessive growth of harmful algal blooms (HABs); see Chapter 5.2.4 for more information (Sinha et al. 2017, Ho et al. 2019). Due to increased runoff, surface waters and water supplies in proximity to agriculture practices are at particular risk for nutrient loading because of the additional input of microbial pathogens and nutrients. In an effort to track changes in stream quality, New Jersey has an extensive systematic monitoring network to evaluate chemical and physical parameters in lakes, streams, estuaries, and the ocean. This will aid in assessing surface water quality and impacts on the state's water supplies, aquatic biology, and other designated uses of New Jersey waters.

Besides posing increased challenges and risks to drinking water operations, changes in water quality and quantity will also impact aquatic habitats. Aquatic habitat and populations are strongly guided by hydrogeomorphic variables and channel characteristics, including streamflow variability, substrate size, bedload sediment, and flooding frequency (Resh et al. 1988). Environmental factors, including water temperature and water chemistry also contribute to the maintenance of suitable habitat (Richter et al. 1996). Changes in any of these factors can lead to changes in species diversity and habitat availability (Beschta and Platts 1986, Poff et al. 1997, Bunn and Arthington 2002, Kennan and Ayers 2002) and may lead to community shifts (Vannote et al. 1980, Junk et al. 1989). Changes in the natural flow regime, primarily the magnitude and frequency of streamflow, may lead to alterations to the stream channel form (Wolman and Miller 1960) and structure (Leopold et al. 1964), which may also ultimately contribute to altered aquatic ecosystems (Poff et al. 1997, Postel 2000, Arthington et al. 2006, McKay and King 2006). This is shown specifically in the Pinelands area of New Jersey (Laidig et al. 2010, Procopio 2012, Laidig 2012).

Climate change in New Jersey and the broader Northeast is expected to alter stream water quality. Increased water temperature can lead to lower dissolved oxygen and increased ecosystem stress. Changes to nutrient cycling patterns and timing may occur, especially during winter and early spring. This can particularly impact seasonal HABs. Increased storms can intensify nutrient, sediment, and salt pulses. Salt contamination can be exacerbated by de-icing runoff from roads and coastal sea level rise. Lastly, a reduction in groundwater recharge and summer baseflow may amplify pollutant concentration during low-flow periods.

5.2.3 Stormwater and discharges to surface and groundwater

As a result of changing climatic conditions, surface water bodies may experience increased nutrient loads from groundwater and surface water sources, including stormwater runoff. As future precipitation events become more intense, historic data will no longer represent actual or current conditions. Based on recent and expected changes to precipitation patterns, updated precipitation depths associated with current storm probabilities were modeled to represent current and future conditions (DeGaetano 2021a, 2021b). See section 4.2 for more information. This will likely result in decreased efficiency of the design of current stormwater infrastructure (Wright et al. 2019). In addition, there will likely be a need for the size of stormwater management systems to be modified in order to minimize the risk to communities from increased nuisance flooding.

Stormwater management will become a challenge for all communities as flooding will likely increase over time, requiring additional investment in mitigation solutions and stormwater infrastructure. Increased precipitation will cause additional challenges for communities that have combined stormwater systems. Combined Sewer Overflows (CSOs) are discharges from combined sewer systems. Combined sewer systems are sewers that were designed many decades ago to collect rainwater and snowmelt runoff, domestic sewage, and industrial wastewater in the same pipe. As such, CSO communities may discharge combined effluent more frequently due to increased flooding, thereby increasing the load of nutrients and pollutants entering waterways. When additional flooding occurs or sea level rises at CSO outfall locations, they may become submerged and interfere with the effective discharge of combined stormwater, resulting in CSO flooding. Some communities have discharge points that are currently submerged which have effective strategies in place, such as tide gates and pump stations, to overcome this issue. However, some CSO communities may need to consider additional measures as sea levels rise.

In similar fashion, discharges from industrial sites in coastal areas or near other surface waters may be inundated more often, resulting in the direct discharge of unintended or contaminant materials. In areas where groundwater tables rise, including areas where rising sea levels influence the water table, septic systems may become ineffective, requiring more mounded systems or other treatment solutions. All such impacts will require a reevaluation of design standards and current best management practices.

Overall, changes in temperature, more intense precipitation events, and rising sea levels will impact New Jersey waters. The DEP, which oversees the Pollutant Discharge Elimination System permitting programs, anticipates several impacts to these programs due to climate change factors and recognizes that adaptive design specifications for collection systems and treatment units will need to be implemented in order to continue to protect the waters of New Jersey.

5.2.4 Harmful Algal Blooms

Harmful algal blooms (HABs) can occur in freshwater, brackish, and marine water bodies. Increased surface water temperatures and nutrient inputs drive cyanobacteria dominance and increase the likelihood for a bloom to form. Scientists have been reporting the observation of increased survival and sustained photosynthetic activity in cyanobacteria at both high and low temperatures in lab and field samples since the late 1970s (Konopka and Brock 1978). Recent studies continue to report a rise in intense toxic phytoplankton blooms worldwide and in the Northeast United States (Ho et al. 2019). In 2008, a landmark paper highlighted the notion that shifts in global climate trends can both spark and exacerbate conditions suitable for harmful bloom events to occur (Paerl and Huisman 2008). Generally, higher nutrient levels, particularly nitrogen and phosphorus, in aquatic systems promote the growth of cyanobacteria (Sinha et al. 2017, Ho et al. 2019) and they can survive significant temperature extremes. This is supported by the observation of cyanobacteria surviving in freezing conditions compared to other eukaryotic algae and zooplankton, which usually experience a “die off” during freezing conditions (Seckbach 2007). Additional catalysts for blooms can be anthropogenic activities (such as agricultural work or shifts in land use), or shifts in weather and climate-related variables, including precipitation, droughts, and extreme weather events (Antilla et al. 2015).

Observational and predictive modeling data from Europe indicate that cyanobacteria blooms are becoming more frequent and last longer (Joehnk et al. 2008). This is in part due to the increase in photosynthetic activity and the increased stability of the water column. This stability is known as thermal stratification and reduces the water’s ability to vertically mix, creating temperature zones in the water, which restricts the mobility of key competing species for cyanobacteria. Some species of cyanobacteria can regulate their buoyancy using structures called gas vesicles. These give them a direct competitive advantage, allowing the cyanobacteria to rise to the surface for photosynthesis during the day and fall back into cooler, nutrient-dense water at night. Field work showed that blooms increase the stability of the water column and enhance their growth compared to control areas where the water column was artificially mixed (Kumagai et al. 2000). Blooms have been observed to locally increase the surface temperature of affected water, creating a positive feedback loop that favors cyanobacteria over other plankton species.

The loss of diversity in the plankton community also has serious consequences for water quality, with modeling results showing that higher temperatures favor the dominance of cyanobacteria over other photosynthetic organisms (Elliott et al. 2006). This has significant effects because data indicate that warmer spring water temperatures lead to earlier nutrient uptake by plankton species. This early nutrient uptake can lead to nitrogen limitations and promote the growth of nitrogen-fixing cyanobacteria in late spring and summer (Elliott 2012). This appears to be the trend with New Jersey surface waters, with most blooms dominated by cyanobacteria capable of fixing atmospheric nitrogen (Kunz et al. 2024).

Nutrient loading and cycling in aquatic systems are influenced by changes in climate and precipitation (Sinha et al. 2017). As droughts and heavy rainfall events become more frequent, more biologically available nutrients may be introduced to an aquatic system, which may reduce species biodiversity (Isbell et al. 2013). Species biodiversity appears to be impacted, with cold-water organisms being negatively affected the most and warm/warm-tolerant organisms being positively affected (Heino et al. 2009). Patterns of intense rainfall and prolonged dry spells have been documented to cause massive cyanobacteria blooms in several water bodies (Paerl and Huisman 2008).

Conditions like those expected from a changing climate in New Jersey have been shown to affect several key aspects of aquatic systems, promoting the growth of cyanobacteria, either directly or indirectly. One such impact is on the production of toxins from cyanobacteria and cyanobacteria blooms. Climate change is predicted to amplify the risk of production of toxin from cyanobacteria when a bloom forms. Studies that have looked at breakpoints in anthropogenic activities have highlighted that human-led activities have induced higher cyanobacteria level and climate variables such as temperature or ice coverage induce these cyanobacteria to produce higher levels of toxin while a bloom is present (Erratt et al. 2023). This will lead to an expected increase burden on both recreational waters, but also to drinking water sources. Adverse effects of cyanotoxin exposure to humans are discussed in 6.3-2.2 Waterborne illnesses.

The likelihood of increased HAB in drinking water reservoirs is as high as in other water bodies and will require careful monitoring and maintenance to prevent serious impacts on the state's drinking water sources. Since implementing a HAB recreational response strategy in 2017, New Jersey has documented an increase in the detection of freshwater HAB events, with some of these events' duration (the length of time of the bloom) and frequency (how long between bloom events) increasing (Kunz et al. 2024).

An increasing number of cyanobacteria blooms in New Jersey do not fully resolve and instead remain active or in a semi-active state through the winter. The long-term impact this phenomenon may have on both the phytoplankton community and the larger lake ecology remains an area of investigation.

CHAPTER 5.3

UPLAND FORESTS

KEY FINDINGS

- **Upland forests in low-lying coastal areas are vulnerable to the impacts of sea-level rise, storm surge, and saltwater intrusion, which can cause a direct loss of forested land area.**
- **Pests opportunistic in warmer temperatures are expected to disperse and adversely affect forest resources. The persistence of the Southern pine beetle in New Jersey represents an early example of the destruction of invasive pests that can occur due to climate change impacts.**
- **Wildfire seasons are likely to be lengthened and occur outside typical seasons.**
- **The frequency of large fires may increase due to hotter and longer dry periods.**

5.3 Upland Forests

New Jersey's forest land includes both upland and wetland forests, collectively making up roughly 40% of the total land area in the state (NJDEP 2020c). See Chapter 5.4 for more information about coastal wetland forests. While much of New Jersey is covered in forests, including portions of urbanized areas, most of this forested land is located within the northwestern and southeastern portions of the state. New Jersey's forests are one of the state's most critical natural resources and are home to wildlife, clean the air and water, and provide recreational opportunities for residents and visitors, such as hiking, birdwatching, and camping.

Climate change is expected to bring stress and change to forests through changes in temperature and precipitation patterns, and increased pressure from insect pests and disease, as well as the risk of wildfire. These impacts will likely be amplified by the non-climate stressors such as development, forest density, and increased competition for limited resources. The result will be changes in the composition of New Jersey's upland forests. Differences between individual species and how they grow, survive, and reproduce will play key roles in how different species respond to a warming climate, changes to precipitation patterns, and more drought-like conditions, and will play a role in how climate change will impact New Jersey forests. For example, a species that can leaf-out early and extend its growing season may seem to be a better competitor with warmer springs, but sensitivity to late-season frost may make this behavior a liability compared to a more conservative or frost-hardy neighbor (Hufkens et al. 2012).

5.3.1 Changes in Temperature Zones

New Jersey has already experienced an increase in the average annual temperature by 4.1°F (2.3°C) (Office of the New Jersey State Climatologist 2025a) and temperatures are projected to continue to increase (see Chapter 4.1.3 and 4.1.4, respectively). This warming occurs at a greater rate during the winter season compared to other seasons (Broccoli et al. 2020, Climate Central 2023), which can affect plant hardiness (i.e., the ability of a plant to withstand cold temperatures) and the tree species that grow at a given latitude. Temperature zones have and continue to shift northward (Figure 5.7) (National Climate Assessment 2014). These zones help determine which species will thrive based on temperature. This means that tree species that are more adapted to cooler temperatures in the northern part of the state, such as those associated with northern hardwood forests, could be outcompeted by more southerly adapted species or generalist tree species that can thrive in a wide variety of conditions.

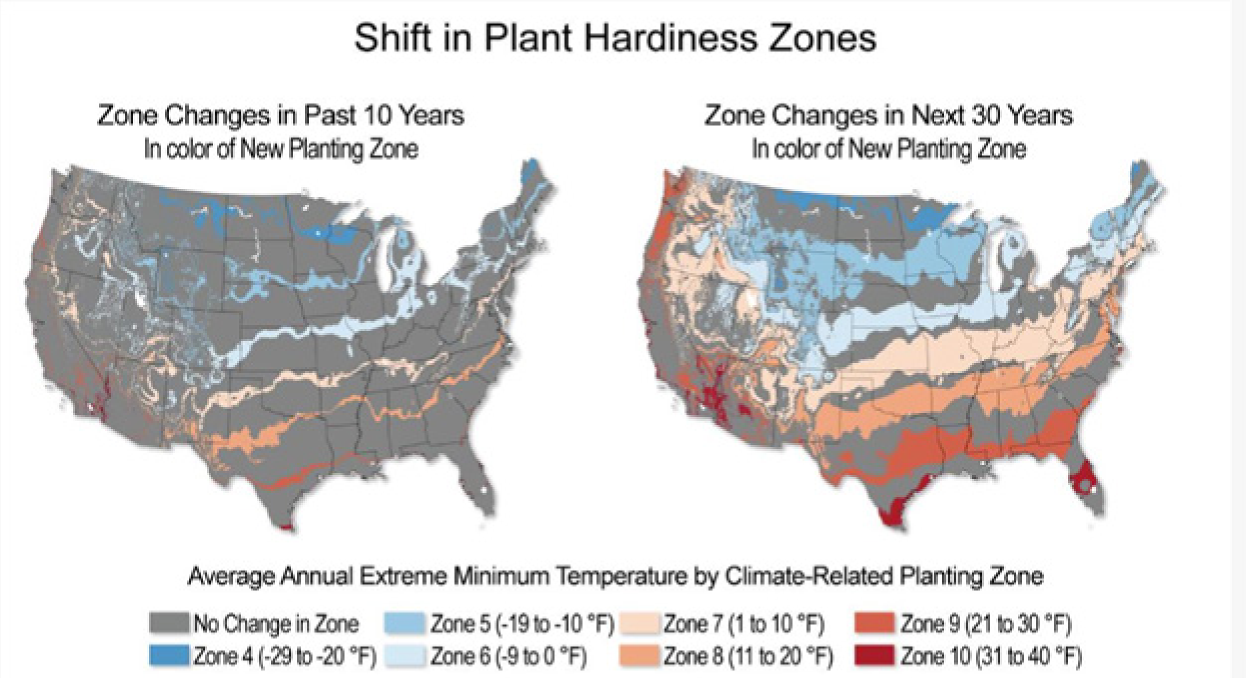


Figure 5.7 Shift in Plant Hardiness Zones. Shifts in plant hardiness zones across the United States in the last 10 years (left) and projected changes in the next 30 years (right) (National Climate Assessment 2014).

To help understand how forest composition will be altered over time and as the climate changes, it is necessary to consider all factors that influence forest conditions. The United States Forest Service, Climate Change Tree Atlas has attempted to provide species-level predictions for how suitable tree species habitat will be depending on different climate change scenarios (Prasad et al. 2007). Predictions from the Climate Change Tree Atlas describe a significant southern shift to New Jersey forests' composition, where sweetgum (*Liquidambar styraciflua*), pitch pine (*Pinus rigida)*, red maple (*Acer rubrum*), and white oak (*Quercus alba*) will still be some of the most abundant species. Loblolly pine (*Pinus taeda*) will become even more abundant than it currently is, with post oak (*Quercus stellata*), winged elm (*Ulmus alata*), water oak (*Quercus nigra*), black hickory (*Carya texana*), long leaf pine (*Pinus palustris*), shagbark hickory (*Carya ovata*), black gum (*Nyssa sylvatica*), and southern red oak (*Quercus falcata*) also becoming more abundant. Red maple, while still abundant, is expected to be less so in the future along with sugar maple (*Acer saccharum*) and northern red oak (*Quercus rubra*). Some relatively minor species currently in New Jersey are expected to become more abundant, like persimmon (*Diospyros virginiana*), shortleaf pine (*Pinus echinata*), and blackjack oak (*Quercus marilandica*), see Figure 5.8.

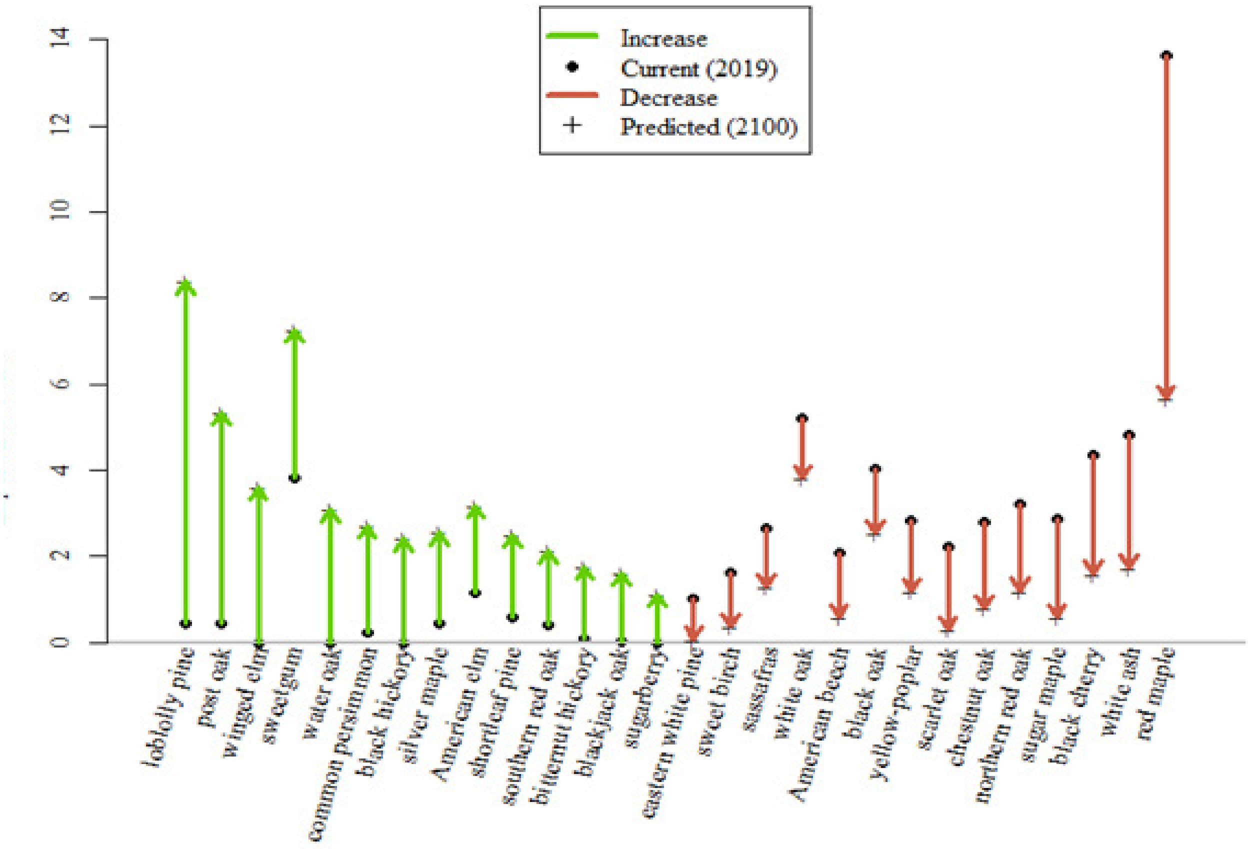


Figure 5.8. Changes in Abundance for Selected Tree Species in New Jersey. This figure shows the importance value assigned to each tree species in the United States Forest Service Climate Change Atlas. The importance value is based on both tree basal area and the number of tree stems. The species with higher importance values are more abundant in New Jersey and are expected to be more suited to climatic growing conditions in the years indicated. Data from (Prasad et al. 2007).

These predictions seem to provide a clear narrative: as New Jersey's climate becomes more similar to current southern conditions, forest composition will comparatively shift. For New Jersey's largest forest types, these predictions mean that the expected future climate is likely to favor oak- and pine-dominated systems as these species are thought to be more resilient to drought and compete better under physiologically drought-like conditions, like sandy soils that do not retain moisture.

Conversely, northern hardwood forests are more likely to be stressed by climate change due to rising temperatures, drier summers, increased disturbances of invasive insects and plants, and have variable regeneration success after a disturbance (Rogers et al. 2022, Stern et al. 2023). It is unclear whether fine-scale processes, such as the ability of individual trees to adapt to changing conditions, will be enough to mitigate possible mortality from drought or whether droughts in currently oak-dominated systems will be significant enough to cause more than minor compositional changes (Gustafson and Sturtevant 2013, Coble et al. 2017) due to the mortality of northern hardwoods.

The oak-hickory forests of northern New Jersey are moderately threatened by climate change. These forests are relatively drought-resistant, especially in the early growing season, but as future summers get hotter, the increasing frequency and intensity of periods of drought are likely to cause mortality

(Au and Maxwell 2022). Moreover, in oak-hickory forests experiencing fire exclusion and increased annual precipitation, mesophication can occur, and shade-tolerant mesic species can begin to outcompete and replace the disturbance-adapted oaks and hickories (Woodbridge et al. 2022). Mesophication is the process by which the forest environment becomes cooler, damper, and more shaded due to larger and older trees.

Loblolly-shortleaf forests, which include pitch pine, in the south New Jersey Pine Barrens should be fairly resilient as pine-dominated systems generally compete better under physiological drought-like conditions (NJDEP 2020c) and could therefore be better adapted for hotter and drier conditions. Additionally, the New Jersey Forest Service anticipates that the well-drained sandy soils in which this forest type is found should mitigate major precipitation events. Observations have shown that Pitch pine, the most abundant species in this area, has been able to regenerate in robust numbers after disturbances like frequent fires and Southern Pine Beetle (*Dendroctonus frontalis*) infestations.

The Climate Change Tree Atlas predictions indicate that the ranges of current moisture-tolerant understory and co-dominant species are most strongly affected by climate factors (Prasad et al. 2007). It is expected that these species will be negatively impacted by climate change relative to areas made up of oaks, hickories, and pines which can thrive in warm, dry soil conditions.

> ***“Southern pine beetle behavior…foreshadow massive mortality events covering tens of thousands of acres of New Jersey’s pine forests.”***

However, forests are not changing as rapidly as the climate (Woodall et al. 2018), and climate is not the only factor that has shaped, or will continue to shape, New Jersey forests (Foster and D’Amato 2015). Past and current decisions about how land is used is and will continue to be a dominant force in shaping forest composition. The land use choices made today will determine the forest composition and structure of future forests (Butler-Leopold et al. 2018). For example, silviculture practices, such as thinning, can both reduce tree mortality from drought and may also reduce the severity of drought, given that higher density forests consume more water through transportation (NJDEP 2020c). Climate change will similarly be an influential factor that drives future forest composition.

5.3.2 Changes in Soil Moisture

Both changes in precipitation and temperature impact the amount of moisture available to forests and the amount of moisture forests will require. The amount and frequency of precipitation seen in New Jersey varies over long periods of time and from season to season. While the average annual precipitation the state receives has already slightly increased (Robinson et al. 2022), and it is expected that the state will experience more intense rainfall events (DeGaetano 2021b), it is also anticipated that there will be longer periods of drier conditions (Sweet et al. 2017, DeGaetano 2021b) (see Chapter 4.2). Warmer temperatures can lead to drier soils, even under normal rainfall conditions. This can temporarily affect a tree’s ability to take in the water (Butler-Leopold et al. 2018) and can cause stress to the tree’s system by stunting growth rates and making it more susceptible to pest and disease issues.

Rising temperatures can also stress tree species that favor high moisture environments, like maples (Swanston et al. 2018). Species more tolerant of dry conditions, including oaks and pines, will be better suited to future climate conditions (Swanston et al. 2018).

5.3.3 The Role of Forests in the Water Cycle

Vegetation plays a key role in the water cycle. Water that reaches the ground is either used by plants, evaporates, or makes its way to groundwater and streams through infiltration and runoff. Transpiration by plants occurs when water travels from the ground through the plant and is released into the atmosphere as vapor through tiny leaf pores, called stomata. Transpiration through stomata keeps leaves cool, and by keeping stomata open, the leaves are also able to accept atmospheric CO_2. Under a warmer climate, forests are expected to increase their water use to maintain comfortable leaf temperatures (Lévesque et al. 2014). In southern New Jersey, evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) currently consumes about half of the water budget (Sloto and Buxton 2005, Walker et al. 2011). Evapotranspiration can be as high as 67-92 percent in the New Jersey Pinelands, with Atlantic white cedar swamps having the highest evapotranspiration and oak-pine upland forests having the lowest (Isaacson et al. 2023). For more information about Atlantic white cedar, see Chapter 5.4.3.

Global-scale models predict that increases in vegetative water demand will not surpass the amount of available water in New Jersey due to increased extreme precipitation (Mankin et al. 2018). However, local models show that under expected climate changes, a modest decrease in surface water for southern New Jersey results from the increased demand of vegetation (Sun et al. 2015).

Finer-scale processes are also likely to unbalance the water budget to the detriment of water resources. The trend to wetter forest conditions is causing a shift away from species that utilize relatively less water, such as oaks and hickories, and towards species that use relatively larger quantities of water, such as northern hardwoods like maple (Ford et al. 2011, Caldwell et al. 2016). More sudden loss of keystone species (i.e., species with a larger effect on the environment than expected relative to its abundance) to emergent pests, like the near-eradication of eastern hemlock (*Tsuga canadensis*) by hemlock woolly adelgid (*Adelges tsugae*), will cause permanent reductions in surface water yield because hemlocks, which utilize relatively smaller amounts of water, will be replaced by northern hardwoods, which utilize relatively larger amounts of water (Brantley et al. 2013, 2014).

Climate-induced declines in available groundwater could have profound effects on the composition of the New Jersey forested landscape. In New Jersey's Pinelands, plant community composition is strongly related to the depth of the water table (Laidig et al. 2010). Water table declines are expected to cause shifts in the patterns of plant communities in the Pinelands area, with wetland communities, which require a larger water budget, being disfavored (Lathrop et al. 2010). Even if subsurface recharge remains in balance under a changing climate, longer periods between rainstorms will still put stress on upland forest communities.

5.3.4 Changes in Insect and Disease Pests

Changes in temperature zones are also expected to impact insect pest and disease species. Some forest pest species native to North America are expected to take advantage of the warmer temperatures caused by climate change. As an insect's development is closely tied to the temperature, a warmer climate allows insect pests to mature faster, achieve more generations per year, and move into new habitats that no longer have a winter season cold enough to be lethal. The effect of warming on native insect species is expected to be even more dramatic as these species will disperse into forests that have not before experienced the pressure of these pests (Olatinwo et al. 2014).

Of particular concern for New Jersey's forests is the southern pine beetle (*Dendroctonus frontalis*). The southern pine beetle is native to the southern coastal plain pine forest and is one of the most important bark beetle pests in the United States, affecting southern yellow pines like pitch and shortleaf pine. In landscapes where southern pine beetles are native, populations are always present in low numbers and survive by killing isolated unhealthy trees. As populations build up, however, even healthy trees succumb to the mass attack of congregating beetles. This causes a positive feedback loop that creates population eruptions, where outbreaks of the insect kill tens of thousands of acres of forest (Coulson and Klepzig 2011).

Southern pine beetle behavior in New Jersey represents an early example of the current impacts of climate change. The southern pine beetle has long been present, but its role was insignificant. Starting in the early 2000s, New Jersey began to experience spot outbreaks of the beetle that have moved progressively northward, especially along the coast (Hassett et al. 2018). Rising winter minimum temperatures are thought to be responsible for this northward movement (Trần et al. 2007) since insects are killed when temperatures drop below 3.2°F (-16°C) (Ungerer et al. 1999). As that thermal control on southern pine beetle moves north, the range and population size of the beetles will likely increase (Kanaskie et al. 2023). These alarming developments foreshadow massive mortality events covering tens of thousands of acres of New Jersey's pine forests.

Other pests are likely to experience range shifts, increased vigor, or increased impacts as a result of a changing climate, making the future more challenging for New Jersey's forests. Invasive insects like the sirex woodwasp (*Sirex noctilio*) are expected to eventually reach New Jersey, as their range expands faster in warmer environments (Lantschner et al. 2014). Lethal diseases like annosus root disease (*Heterobasidion annosum*) and bacterial leaf scorch (*Xylella fastidiosa*), as well as less virulent ones like fusiform rust (*Cronartium quercuum f. sp. fusiforme*), may become more prevalent in New Jersey as temperatures warm and eventually match those to the south of New Jersey. Host species shifts may additionally increase prevalence of pests (Olatinwo et al. 2014). As a consequence, other invasive species may take hold in areas where the forest community has little evolutionary defense.

The United States Forest Service, Climate Change Tree Atlas provides valuable predictions about the suitability of specific tree species in different climate change conditions, but does not take into account other damage-causing agents, like insect pests and disease, which can weaken forests and put them at greater risk to climate change conditions like warmer conditions and changes in precipitation. As such, forests will be more stressed from the impacts of climate change, making it easier for insect pests and disease to interfere in their life processes and spread.

5.3.5 Forest Fires

The New Jersey Office of Emergency Management defines a wildland fire "as any non-structural fire that occurs in the wildland (State of New Jersey 2019)," and refers to fire in a landscape. A wildfire is an unplanned, unwanted fire burning in a natural area, such as a forest, grassland, or prairie (State of New Jersey 2024). Fires that occur naturally in New Jersey are rare due to the amount of precipitation New Jersey receives annually and its higher humidity, and are typically ignited by lightning strikes. Wildfires result in the destruction of forests, brush, grasslands, field crops, and private and public property. Alternatively, wildland fire can be used for management purposes, as in the case of prescribed burns, where fire managers use the appropriate timing, favorable fuels, and weather conditions to safely accomplish various resource management objectives.

New Jersey is at the highest risk from wildfires in spring (March through May) when vegetation is at its driest, but can also experience fires in the summer and fall or in any month of the year. Figure 5.9 depicts the wildfire hazard, or burn probability, throughout the state. Regionally, the Pine Barrens ecosystem of southern New Jersey is the most susceptible to forest fire and much of the area represents the greatest probability that a specific geographic location will experience a wildland fire during a specified time period. This region has a tremendous propensity toward burning (Forman and Boerner 1981, Buchholz and Zampella 1987) and that tendency to burn hot and often has shaped this unique landscape (Little 1998). As the Wildland Urban Interface, where rural land and developed area meet, continues its outward expansion into New Jersey's wildlands, the wildfire risk will likely continue to increase for improved property across the state. Figure 5.10 represents that risk as a Structure Exposure Score, which combines wildfire likelihood (burn probability) and consequence represented by the potential for damage assuming a home is present.

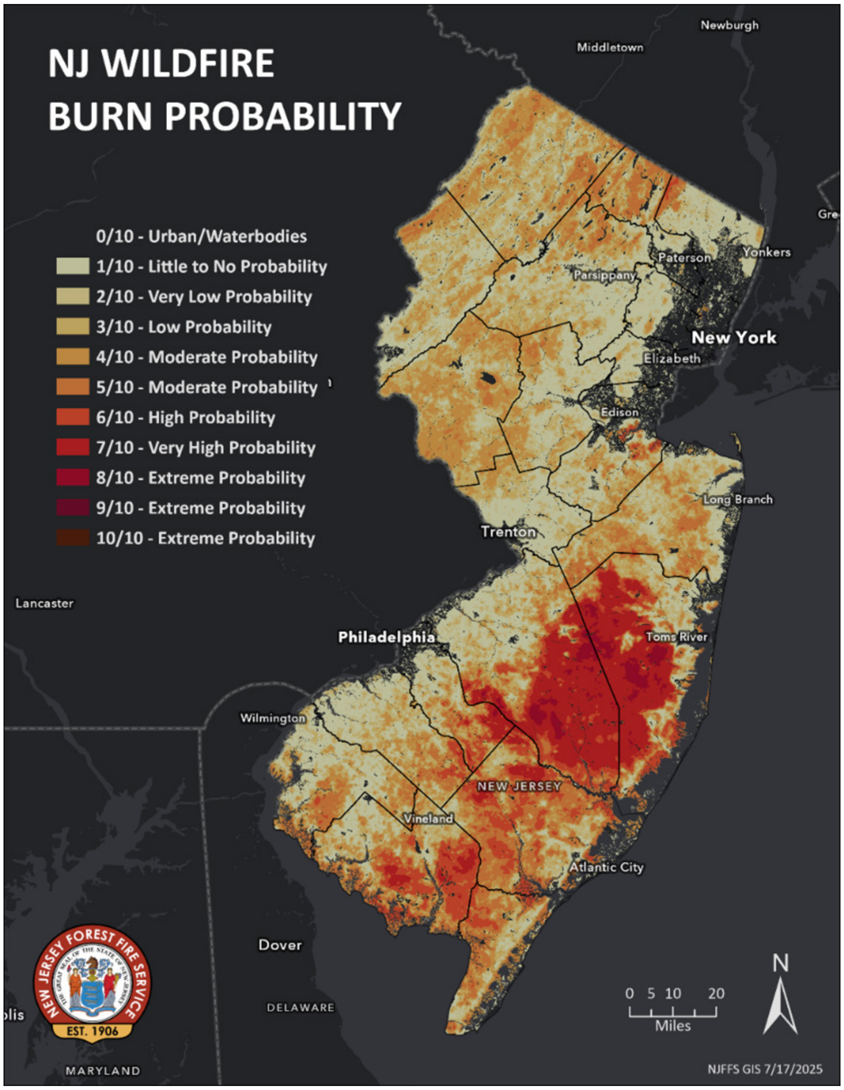


Figure 5.9. Wildfire Hazard in New Jersey – Burn Probability. This figure depicts annual burn probability across New Jersey (NJ Forest Fire Service 2025a). Burn probability is the likelihood that a specific geographic location will experience a wildland fire during a specified time period (1 year). Estimates of burn probability were generated with the large-wildfire simulation system, FSim.

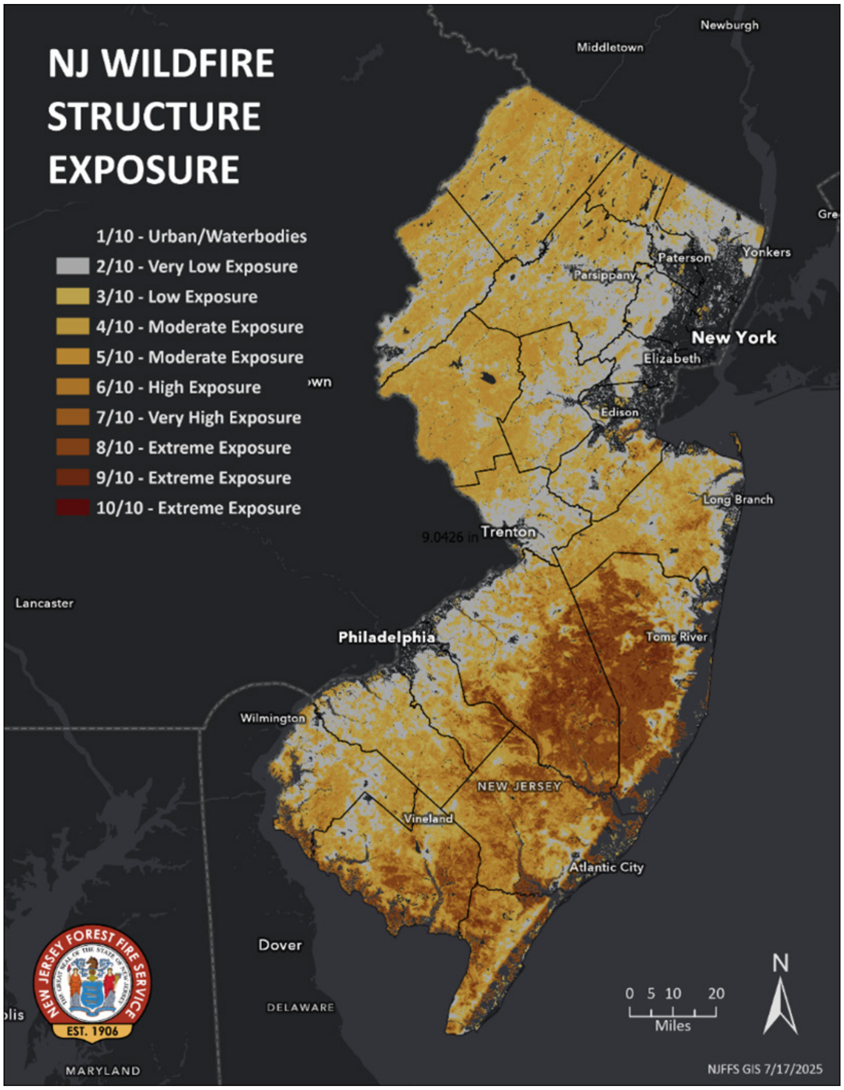


Figure 5.10. Wildfire Risk – Structure Exposure Score. Structure Exposure Score combines wildfire likelihood (burn probability) and consequence (represented by Damage Potential) assuming a home is present on every pixel. Each Structure Exposure Score class (1-10) is 1.5 times higher exposure to wildfire than the previous class (NJ Forest Fire Service 2025a).

The length of the fire season depends on local weather conditions, drought, and the amount and frequency of precipitation that occurs. Over the past several years, the average acres of state forest land damaged by wildfire has increased, as seen in Figure 5.11. Additionally, Figure 5.12 shows the number of wildfires that have occurred in the state since 2000.

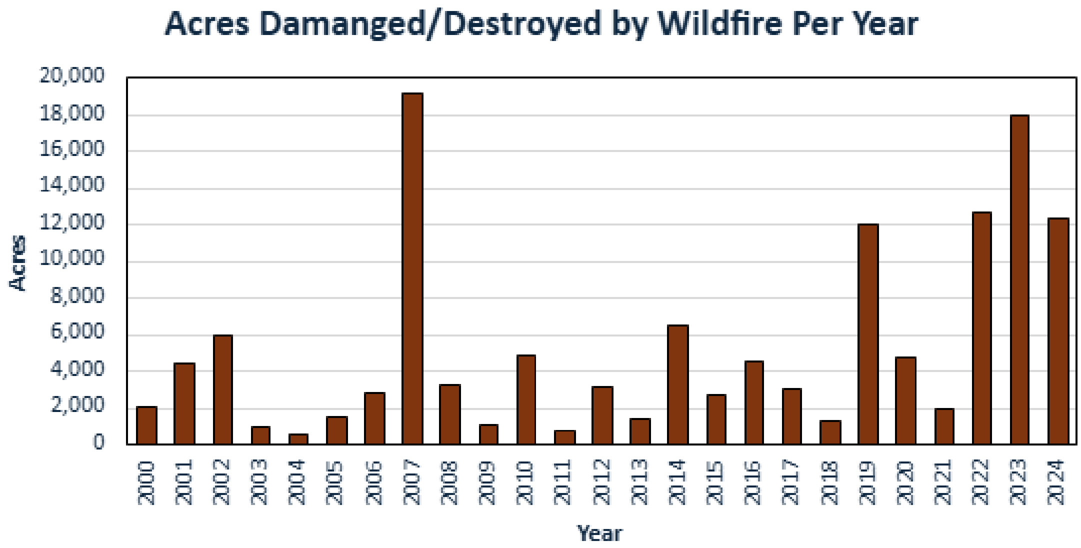


Figure 5.11. Acres Damaged or Destroyed by Wildfire in New Jersey. The figure shows the acres of state forest either damaged or destroyed by wildfire from 2000 through 2024 (NJ Forest Fire Service 2025b).

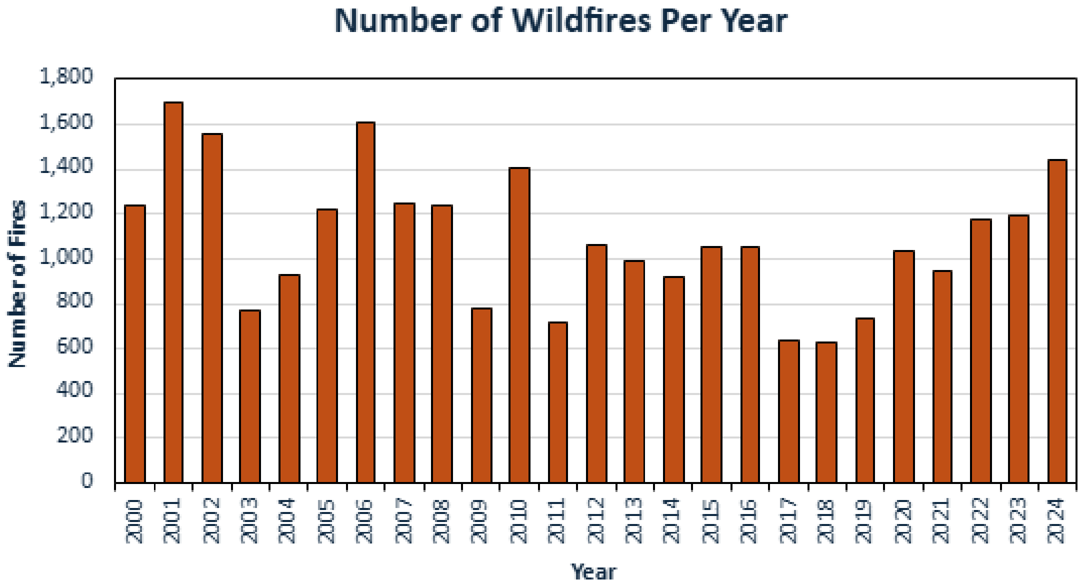


Figure 5.12. Number of Wildfires in New Jersey. The figure shows the number of wildfires that have occurred in the state from 2000 through 2024 (NJ Forest Fire Service 2025b).

How climate change will impact wildfires in New Jersey's forests is uncertain based on existing literature and models, of which there are few that focus on New Jersey specific conditions. Climate change is expected to cause increased temperatures (Chapter 4.1.4) and changes in precipitation events (Chapter 4.2.4) and drought (Chapter 4.2.5) that make it uncertain when a drought, or drought-like conditions may occur. Wildfire seasons could be lengthened or may occur in various seasons outside the norm, with the frequency of large fires increased from longer dry periods that are expected with climate change due to these conditions causing drier soils and vegetation (Nolte et al. 2018). Global- and national-scale assessments of fire risk for the Mid-Atlantic United States predict an increased occurrence of fire, but local-scale forecasts do not mirror this increase (Butler-Leopold et al. 2018). This is due to the fact that Mid-Atlantic coniferous forests are anticipated to experience increased precipitation during the fire season that will counteract increased chances of fire (Moritz et al. 2012). National level predictions of climate and forest disturbance patterns predict that New Jersey will see the establishment of southeastern mixed pine-oak, which will bring with it an increase in the chance of fire (Bachelet et al. 2001). Regionally, forests in the Northeast United States are predicted to see minor increases in the magnitude of fires (Scheller et al. 2012, Guyette et al. 2014).

Human-induced climate change has already led to a global increase in fire weather conditions, increasing the risk of wildfires (Jones et al. 2020). Namely, climate trends like warmer average temperatures and the increased frequency, intensity, and duration of regional droughts and heat waves all influence potential fire weather and wildfire risk (State of New Jersey 2019, Jones et al. 2019). Areas susceptible to burning, like the Pine Barrens, are very likely to increase if increases in summer precipitation do not occur. Additionally, climate change can act as a threat multiplier and increase the likelihood of tree mortality from insect outbreaks. Trees stressed from insect infestations provide an increased fuel source, which makes them easier to burn and is more likely to occur as insect populations expand in warmer temperatures (State of New Jersey 2024). Factors like current successional trends, patterns of land ownership and land use, forest fragmentation, and wildfire control activities all exert strong controls on fire behavior in the state, and are expected to continue (Clark et al. 2014). These factors are expected to maintain the existing wildfire regime, especially in the most fire-prone areas. Providing predictions on wildfires is challenging due to all the factors and conditions that contribute to when or where a fire may start (State of New Jersey 2024). However, given predictions about how climate change will impact New Jersey temperatures (Chapter 4.1.4), as well as precipitation and storms (Chapter 4.2), and that fire is determined by climate variability, some general statements can be made about how climate change will impact wildfires in New Jersey. Increases in temperature, and the hot, dry periods that result, may intensify the danger of wildfires by drying out vegetation and soil. With increases in the frequency and severity of storms, there is an increased potential for lightning to occur and ignite a fire. Also, any increase in winds, which could occur from weather changes due to climate change, would also increase the spread of fires. Due to the dry sandy soils and fire-prone nature of the New Jersey Pinelands, this area is susceptible to increased fire threats, especially along the wildland-urban interface (Scheller et al. 2011, Buchanan et al. 2018).

5.3.6 Sea-Level Rise Risks to Upland Forests

Upland forests in the coastal areas of New Jersey are especially vulnerable to the impacts of sea-level rise (see Chapter 4.3.4 for details on sea-level rise) and saltwater inundation caused by storm surge. Rising sea levels can result in the direct loss of land area in the barrier islands and other coastal locations. In addition, low-lying portions of the state can become much more vulnerable to flooding, amplified storm surge, and saltwater intrusion, ultimately causing impacts further inland (Haaf et al. 2021). Those impacts from saltwater intrusion, salinity increases in tidal water, and storm surges can create “ghost forests,” which are stands of dead trees. The impacts of storm surge and sea-level rise are important considerations for ensuring informed decision-making processes when assessing the potential for forest losses.

WILDFIRE DAMAGE IN THE PINE BARRENS

CHAPTER 5.4

WETLANDS

MEADOWLANDS, SECAUCUS, NEW JERSEY

KEY FINDINGS

- **Some freshwater wetlands may be lost due to inundation with saltwater.**
- **An estimated 61% of monitored tidal wetlands in New Jersey are not gaining elevation at a rate that is greater than or equal to recent rates of sea-level rise. Thus, some are expected to be lost to increasing rates of sea-level rise over time.**
- **Increased flooding and salinity are projected to lead to a loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100.**
- **Atlantic white cedar, a globally rare species, is expected to lose habitat in New Jersey because of rising sea levels.**

5.4 Wetlands

Globally, wetlands are critical to maintaining life, providing $3.8 trillion in benefits each year (Convention on Wetlands 2025). New Jersey supports a remarkable diversity of freshwater and tidal wetlands across the landscape. As the climate changes in New Jersey, potential changes to wetland habitats will include shifts in vegetation, carbon sequestration, evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration), fire frequency, and acidification. Sea-level rise is of particular concern for wetlands, as freshwater wetlands may be lost due to inundation with saltwater. Beyond the direct effects, climate change can also exacerbate other sources of stress and degradation in wetlands (Convention on Wetlands 2025).

5.4.1 Freshwater Wetlands

Freshwater wetlands are found at the interface between terrestrial upland and aquatic ecosystems, distinguished by the presence of freshwater at the surface and in the root zone, saturated soil conditions, and flood-tolerant vegetation adapted to seasonal or perennial wet conditions. In addition, seemingly isolated freshwater wetlands can be connected hydrologically to groundwater and therefore influenced by seasonally dynamic water level fluctuations. While most freshwater wetlands in New Jersey are located inland, freshwater tidal wetlands occur at the landward end of coastal estuaries and are influenced by both freshwater stream flow and coastal lunar tides that push the freshwater back and forth. The location of the fresh-saltwater boundary fluctuates with seasonal precipitation and river volume, as well as sea-level influence.

All freshwater wetlands are complex and productive ecosystems providing critical habitat for plants and animals that depend on water for breeding, foraging, and survival. Humans also benefit greatly from the ecosystem services and functions that freshwater wetlands provide, including flood attenuation, groundwater replenishment, sediment/nutrient retention and export, carbon sequestration, water purification, and habitat that supports a diverse community of species (e.g., plants, fish, shellfish, waterfowl, amphibians) and food chains.

New Jersey supports a remarkable diversity of inland and freshwater tidal wetlands across the landscape (e.g., Atlantic white cedar swamps, floodplain forests, pine barren riverside savannahs, etc.). More broadly, forested wetlands represent 83.5%, shrub wetlands 9.8%, inland herbaceous 5.8%, and freshwater tidal marsh 0.9% of natural freshwater wetlands mapped by the DEP (Anderson et al. 1976, NJDEP 2024c).

5.4.1.1 Climate Change Impacts on Freshwater Wetlands

Climate-influenced changes to hydrology can impact all of the critical functions and ecosystem services provided by freshwater wetlands. Two key indicators of a changing climate, temperature and precipitation, impact freshwater wetlands directly. Climate-driven changes in precipitation amount, periodicity, intensity, and timing of storm and drought events, rates of evapotranspiration, and vulnerability to fire directly impact wetland hydrology, soils, and vegetation (Mitsch 2016, Wardrop et al. 2019, Mitsch et al. 2023).

While freshwater wetland ecosystems are generally resilient, environmental and human stressors may reduce the natural capacity of wetlands to rebound. Threats to the integrity of freshwater wetlands in New Jersey include landscape fragmentation, alterations to hydrology, soil erosion, saltwater intrusion, deer browse, and invasive species (Walz and Faber-Langendoen 2019). The condition of wetlands and their landscape context affect the long-term viability, resilience, and adaptability of these systems in the face of a changing climate. Table 5.3 provides a look at climate change drivers, hazards, impacts, and the potential impact on freshwater wetland ecosystem services.

> ***"While freshwater wetland ecosystems are generally resilient, environmental and human stressors may reduce the natural capacity of wetlands to rebound."***

Table 5.3. Impacts of Climate Change on Freshwater Wetland Functions and Ecosystem Services. Primary climate change and natural hazards interactions and impacts to wetland functions and ecosystem services in New Jersey.

Climate Change Drivers	Climate Change and Natural Hazards Impacts	Freshwater Wetland Functions & Ecosystem Services Impacted by Climate Change
Increase in Greenhouse Gas Emissions (Carbon Cycle)	• Carbon Sequestration • Methane Emissions	Sediment and particulate retention and export; Nutrient transformation; Surface-water detention
Rising Temperatures	• Increased Evapotranspiration • Increased Fire Frequency and Intensity • Freezing Precipitation & Ice Damage • Lack of snowpack • Increase in groundwater temperature	Groundwater replenishment; Surface-water detention; Streamflow maintenance
Sea-level Rise	• Increase Salinity in Groundwater and Coastal Fringe • Landward Migration	Nutrient transformation; Shoreline stabilization
Changes in Timing and Amount of Precipitation	• Drought • Decreased rainfall during growing season • Increased intensity and duration of Storms • Increased rainfall during growing season • Flooding • Groundwater Recharge • Groundwater Discharge • Acidification (Acid Rain)	Flood control; Groundwater replenishment; Nutrient transformation; Sediment and particulate retention and export; Streamflow maintenance; Surface-water detention; Water purification
Extreme Weather	• Hurricanes & Tropical Storms • Severe Winter Storms & Nor'easters • Tornadoes • Extreme Precipitation • Strong Wind	Coastal storm surge detention (including freshwater tidal wetlands); Flood control; Shoreline stabilization; Surface-water detention
Ecological Linkages - Ecosystem Shifts	• Hydrological Cycle • Shifts in phenology • Pollinators • Invasive species • Pests and Diseases	Reservoirs of biodiversity; Provision of habitat for fish, shellfish, waterfowl, waterbirds, amphibians, and other wildlife

Plants that dominate tidal fresh and brackish marshes, as well as freshwater tidal swamps, tend to be intolerant of salinity increases. Based on mesocosm studies (i.e., outdoor experiments designed to examine the natural environment in a more controlled setting) and long-term studies done in the Mid-Atlantic regions, where the seedbank is available, more salt-tolerant species are likely to shift upriver with sea-level rise (Spalding and Hester 2007). Increased flooding and increased salinity have been projected to lead to the loss of 92% of brackish marshes, 32% of tidal swamps, and 6% of tidal fresh marshes in the Delaware Estuary by 2100 with 2.3 feet (0.7 meters) of sea-level rise (Glick et al. 2008). In addition to changes in plant communities, the loss of these habitats would have major impacts on the birds, fish, crabs, and mammals that use them. Brackish marshes are important feeding spots for bald eagles (*Haliaeetus leucocephalus*) and provide habitat for Atlantic menhaden (*Brevoortia tyrannus*) and several other fish species (e.g., herring, shad, and drum) (Strange et al. 2008). Tidal freshwater marshes support a diverse range of bird species, as well as frogs, turtles, and snakes that cannot tolerate saline or brackish conditions. The effect of increased salinity can already be seen in tidal swamps and non-tidal coastal forests of New Jersey. Saltwater intrusion, salinity increases in tidal water, and storm surges have created “ghost forests,” stands of dead trees surrounded by transitional marshes.

New Jersey supports a remarkable diversity of freshwater wetland types throughout the state, from glacial bogs on the Kittatinny Ridge to Atlantic white cedar swamps in the Pine Barrens. All freshwater wetlands provide critical functions in the landscape and ecosystem services to the public. Climate change will affect these functions and services in various ways, and the challenge will be to understand the vulnerability, resilience, and adaptive capacity of different wetland types in order to manage these systems effectively.

5.4.2 Saline Tidal Wetlands

Tidal wetlands exist along rivers, estuaries, and coasts where low-lying areas are influenced by the tide. The New Jersey Wetlands Act of 1970 defined the term "coastal wetlands" to include banks, marshes, swamps, meadows, flat or other low land subject to tidal waters whose surface is at or below an elevation of 1 foot above local extreme high water. In New Jersey, more than 184,000 acres of saline marsh form a characteristic green band of herbaceous vegetation spanning most of the Delaware River and Bay, the Atlantic Coast behind barrier islands, along the Raritan River, and up into the Meadowlands near New York City. Respectively, 82% and 3% of these are categorized as low and high saline marsh, while 15% are *Phragmites* dominated coastal marsh (NJDEP 2024c). New Jersey coastal wetlands belong to two main categories: (1) back-barrier wetlands, protected by island barriers and lagoons located mainly on the Atlantic coast, and (2) wetlands that are not protected by a barrier island and receive direct impact from the ocean force, located mainly on the northern shore of the Delaware River and Bay.

Tidal wetlands are among the most valuable habitats in New Jersey, providing more than $1.24 billion per year in ecosystem services (Purcell et al. 2020). Tidal wetlands buffer coastal communities from storms; filter nutrients and sediment out of the water, helping to make water fishable and swimmable; provide nursey habitat for commercially important fish; draw ecotourists interested in fishing, crabbing and birding; mitigate climate change by sequestering carbon in the soil; provide critical habitat for rare and endangered species; and beautify the coast (Woodward and Wui 2001, Costanza et al. 2006, Mitsch and Gosselink 2007, Liu et al. 2010, Barbier et al. 2011, Narayan et al. 2017, Sheng et al. 2021).

Located at the ocean-land interface, tidal wetlands are inherently highly dynamic and stressed habitats. They are often exposed to intense erosive forces from rivers, tides, storms, and boat wakes - making their shape and size naturally variable. Because of the stressful and dynamic nature of tidal wetlands, these habitats are surprisingly resilient to natural disturbances. However, current rates of climate change are sparking changes that are unprecedented in the ~4500-year history of New Jersey tidal wetlands (Walker et al. 2023). These changes are compounded by the expansive impacts of human activities, including dredging, shoreline hardening, and pollution, which have already decreased the resilience of tidal wetlands (Convention on Wetlands 2025). It is unknown how resilient tidal wetlands in New Jersey will be in response to the current and projected effects of climate change (Nikitina et al. 2025),

5.4.2.1 Sea-level Rise Impacts to Saline Wetlands

Sea-level rise is a contributor to the global loss of thousands of hectares of tidal wetlands each year, and it is projected that over the next couple of decades, wetlands will become increasingly less resilient over time (Hartig et al. 2002, Langley et al. 2009, Törnqvist et al. 2021). Tidal wetlands are resilient to moderate rates of sea-level rise; they gain elevation by trapping sediment brought in by the tide and building organic matter from plant roots and leaves (Nyman et al. 2006, Mitsch and Gosselink 2007, Cahoon and Guntenspergen 2010, Kirwan and Megonigal 2013). However, it is expected that there are tipping points after which habitats will begin to change.

The amount of sea-level rise that can be tolerated is thought to be influenced by salinity, shallow subsidence, tide range, accretion rates, and the amount of sediment in water (Partnership for the Delaware Estuary 2017). In New Jersey, tidal wetlands are more vulnerable to sea-level rise than they would be naturally due to historic and current land use practices, including manipulations for farming, waterfowl, and mosquito control. These practices left wetlands at lower elevations than the surrounding marshes. Sea-level rise and diking are blamed for the decreasing health of tidal wetlands in the Delaware Bay (Kearney et al. 2002, Smith et al. 2017, 2022a). When a tipping point is reached, the species composition of plant communities will shift from less flood-tolerant to more flood-tolerant species (Donnelly and Bertness 2001, Erickson et al. 2007, Cameron Engineering and Associates 2015). For example, high salt marsh habitats -- an infrequently flooded habitat dominated by saltmeadow cordgrass (*Spartina patens*) that is critical to the Black Rail (*Laterallus jamaicensis*), the American Black Duck (*Anas rubripes*), Saltmarsh Sparrow (*Ammodramus caudacutus*), and others -- are already giving way to the more regularly flooded middle and low marsh dominated by smooth cordgrass (*S. alterniflora*). Increased flooding from sea-level rise has been associated with stress on high marsh communities that are replaced by expanding low marsh communities (Donnelly and Bertness 2001). Smooth cordgrass dominated marsh appears to be more resilient to sea-level rise (Payne et al. 2019). When flooded for too long, even low marsh plants cannot persist, and the habitat will convert to mud flats and open water (Able 2021). The common reed, *Phragmites australis*, is a tall, dense grass that has been found to stabilize tidal marshes and reduce erosion associated with sea-level rise and violent storms (Theuerkauf et al. 2017).

> ***“Sea-level rise is a contributor to the global loss of thousands of hectares of tidal wetlands each year, and it is projected that over the next couple decades wetlands will become increasingly less resilient over time.“***

In light of tidal wetland vulnerability to increasing rates of sea-level rise, scientists and researchers are monitoring these ecosystems to evaluate their responses to current conditions and make predictions about future conditions of tidal wetlands. Long-term monitoring in the state is underway at ~250 sites by the New Jersey Tidal Wetlands Monitoring Network to better understand critical thresholds for habitat conversion and under what scenarios and timescales those thresholds will be reached. Answering these questions can help inform management decisions in New Jersey coastal zones.

There is evidence in New Jersey that tidal wetlands are already being negatively impacted by the rates of sea-level rise we are currently experiencing, although the effects are not uniform across all marshes (Weis et al. 2021, Smith et al. 2022a). The majority of salt marshes in the United States, and more specifically in New Jersey, are not gaining elevation at a rate that equals local relative sea-level rise (Cahoon 2015,

> ***"The majority of salt marshes in the United States, and more specifically in New Jersey, are not gaining elevation at a rate that equals local relative sea-level rise."***

US EPA 2019). In the New Jersey Tidal Wetland Monitoring Network, 61% of sites are not keeping pace with recent rates of sea level rise (NJTWMN 2025). A recent study in the Delaware Estuary and Barnegat Bay found that 94% of the thirty-two wetlands studied were not keeping pace with the rates of sea-level rise observed between 2000 and 2018. The accumulation deficit, the difference between the rate of elevation gain in the marsh and long-term sea-level rise trends, was as much as 0.16 in/yr (4 mm/year) in the Delaware Estuary Bay marshes and 0.26 in/yr (6.5 mm/yr) in Barnegat Bay marshes (Haaf et al. 2021). Similar studies conducted in the Meadowlands indicate that tidal wetlands are gaining elevation near current rates of sea-level rise, ranging between 0.16 in/yr and 0.23 in/yr (3.18 and 5.84 mm/year) (MERI 2015).

Recently, the DEP conducted sediment core investigations along the New Jersey coast exploring the environmental conditions over the last 500 to 2,000 years. These investigations revealed how much environmental conditions such as nutrients, salinity, and exposure to ocean tides naturally varied, as well as changes that were induced by the European settlers (NJDEP 2018). All examined sediment cores revealed that sea-level rise is negatively impacting the New Jersey coastal wetlands included in this study, with exposures to tides higher than during the previous centuries or millennia encompassed by the stratigraphic record.

Sea-level rise also affects several important hydrological factors. Tidal range (the difference in elevation between high and low tides) is projected to change in New Jersey, increasing in some areas and decreasing in others (Flick et al. 2003, Hall et al. 2013). Generally, it is considered that wetlands with a larger tide range are expected to be more resilient to sea-level rise, but there is little research on whether an increasing tidal range will be beneficial. In addition, mean high-water levels are rising at a faster rate than mean sea-level (Flick et al. 1999). Recent studies from New England have found that marshes situated below mean high water are experiencing greater losses than marshes sitting well above mean high water (Watson et al. 2017). Rates of increase in mean high water were several mm/year higher than rates of mean tidal levels in the Barnegat Bay and Delaware Estuary (Haaf et al. 2021). If mean high water is a critical threshold for tidal wetland resilience, then tidal wetlands in New Jersey are likely to face increased threats due to sea-level rise. This appears to already be happening in Barnegat Bay (Able 2021, Smith and Pellew 2021, Smith et al. 2022a).

As the sea level rises, the water depth increases, which allows for larger and stronger wave formation. Larger and stronger waves will increase erosion of tidal wetland shorelines. Wetlands in Delaware Bay are not as protected as the back-barrier wetlands along the Atlantic Coast of New Jersey and thus have higher rates of erosion. Average erosion of tidal wetland edges in the Delaware Bay between 1940 and 1978 was 0.13 in/yr (3.3 mm/year) (Phillips 1986); this number has likely increased as a result of sea-level rise. One recent study documented how coastal wetland edge erosion in the Delaware Bay can occur at rates up to 10 meters per year (Elsey-Quirk et al. 2019). In addition, creeks and ditches in tidal wetlands are also eroding, making these water conveyances wider (Smith et al. 2017). Changes in creek size, depth, and density alter the hydrology of the marsh and change the edge to interior marsh ratios, which is important for fish production (Cameron Engineering and Associates 2015).

As the sea level rises, new tidal wetlands can be established through marsh migration. Marsh migration (also referred to as marsh retreat) is the process by which new tidal wetlands form in upland areas as sea level rises. New Jersey's gently sloping coasts are ideal for marsh migration. While New Jersey may have ideal slopes for marsh migration under natural conditions, 29% of potential migration areas were found to be blocked by roads and other development in 2007 (Lathrop and Love 2007), and such infrastructure has a strong influence on the availability of accommodation space for marsh migration (Schuerch et al. 2018). The more developed regions of New Jersey coasts, like Raritan Bay, northern and central sections of the Barnegat Bay, the Meadowlands, and the wetlands associated with barrier islands have little room to move or build due to development (Lathrop and Love 2007, Artigas et al. 2021). In the less developed Delaware Bay, as much as 75% of tidal wetlands loss has been compensated by increases in new wetlands areas (Hardisky and Klemas 1983, Phillips 1986, Smith 2013, Watson 2019). However, these newly formed wetlands are largely dominated by the invasive *P. australis* and thus are not replacing the same high habitat that has been lost (Smith 2013, Cameron Engineering and Associates 2015, Dorset 2018). Studies in New Jersey and other neighboring states have shown how sea level rise has impacted and caused the restructuring of salt marsh habitat (Gonneea et al. 2019, Weis et al. 2021). In addition, the newly formed tidal wetlands often replace other important habitats, like non-tidal cedar swamps, further calling into question the quality of the new tidal habitats (Dupigny-Giroux et al. 2018).

Sea-level rise in New Jersey is projected to increase by 0.9 to 1.7 feet (274 to 518 mm) between 2005 and 2050 and, under an intermediate emission scenario, continue to rise an additional 1.3 to 2.1 feet between 2050 and 2100 in New Jersey (Kopp et al. 2025). When these estimates are converted into units that are more useful for tidal wetlands, the likely rate of change in sea-level from 2005 to 2050 is an increase of 0.02 to 0.04 ft/year (6 to 12 mm/year). From 2050 to 2100, the rate increases to 0.03 to 0.04 ft/year (8 to 13 mm/year). When potential rapid ice-sheet loss processes are included, sea-level rise is likely to reach up to 4.5 feet (1372 mm) above the 2005 baseline by 2100 at a rate of up to 0.05 ft/year (16 mm/yr) between 2050 and 2100 (Kopp et al. 2025). The majority of tidal wetlands studied in New Jersey are not keeping pace with recent rates of sea-level rise, which have a mean of 0.24 in/yr (6 mm/year) from 2000 to 2018 (Haaf et al. 2021). A rate of 0.39 in/yr (10mm/year) has been suggested as a potential tipping point that could result in a catastrophic loss of tidal wetlands (Orson et al. 1985).

Future projections of tidal wetland response to sea-level rise in New Jersey vary by region, salinity, sediment load, tide range, and accommodation space for landward migration. One of the main models used to predict tidal wetland vulnerability to sea-level rise is SLAMM (Sea-level Affecting Marsh Model, Warren Pinnacle Consulting, Inc., Waitsfield, VT). Although SLAMM is limited by data inputs, uncertainty associated with input factors, and general oversimplification of the system, the model can provide important insights into how the New Jersey coast may be impacted by sea-level rise. SLAMM has been run for portions of the New Jersey coast several times. Summaries of SLAMM projections for tidal wetlands in New Jersey are provided below.

SLAMM Projection Summaries

- In the Delaware River and Bay, many tidal wetlands were classified as high marsh (flooding one time or less per day). High marsh habitats are expected to be especially hard hit by rising sea levels, leading to a decrease in high marsh acres of 85-95% in the four watersheds studied. The rate of conversion is expected to increase rapidly after 2050. Under moderate rates of sea-level rise, current high marsh areas convert to low marsh (flooded twice daily), and new high marsh areas would be created in transition zones (marsh migration) with a net increase in total marsh area projected. Under high rates of sea-level rise (6.6 feet between 2000 and 2100), the current areas of high marsh largely convert to low marsh or open water, but new wetlands would be projected to form in transition areas resulting in little loss of total wetlands areas. Tidal swamps and tidal freshwater marshes are also projected to decline in acreage with moderate and high rates of sea-level rise, assumedly converting to salt marsh (US EPA 2019).
- Another recent SLAMM run for the entire coast of New Jersey predicted that tidal wetlands in New Jersey would be resilient to low rates of sea-level rise as of 2050 (1 foot between 2000 and 2050), potentially even increasing in area by more than 17,000 acres due to marsh migration. However, with moderate rates of sea-level rise (2 feet increase between 2000 and 2050), the picture changes. The Delaware and Raritan Bay wetlands generally seem resilient to a 2-foot increase, although the higher upstream the model traveled, the higher the likelihood of conversion from vegetated marsh to mudflat or open water. From Cape May north to Atlantic City is dominated by wetlands with a moderate likelihood of conversion by 2050. From Great Bay north to Toms River, many tidal wetlands would be projected to convert to mudflats with 2-feet of sea-level rise. In addition, there is far less room for tidal marshes to migrate on the Atlantic Coast of New Jersey (Rutgers University 2019).

5.4.2.2 Other Climate Change Impacts on Saline Wetlands

Saline wetlands are likely to be affected by several other aspects of climate change, including increased atmospheric carbon dioxide (CO_2), increased temperature, increased intensity and frequency of storms, changes in precipitation patterns, and coastal acidification (see Chapter 4.4.1 for more on ocean acidification). This section describes some of the observed and potential impacts of these effects.

The increasing concentration of atmospheric CO_2 is likely to facilitate a shift in the plant communities of New Jersey's tidal wetlands by stimulating growth in some plants, while having no effect on others. In turn, some of that increase in plant growth will become buried over time and stored in the soil, helping wetlands gain elevation at a more rapid rate (Cherry 2009, Langley et al. 2009, Lu et al. 2019). For example, in experiments conducted in the Chesapeake Bay with CO_2 elevated to levels projected for 2100, an increase in plant productivity was found to increase the rate of soil elevation gain in brackish marshes by 0.15 in/year (3.9 mm/year) (Langley et al. 2009). An increase of 0.15 in/year would nearly double current average accretion rates for tidal wetlands in New Jersey.

Certain plants are better able to take advantage of elevated levels of CO_2, increasing their ability to compete with other species. As CO_2 levels increase, the makeup of tidal wetland plant communities is likely to change, favoring sedges and grasses that use C3 pathways (a simpler process directly fixing CO_2 into a 3-carbon molecule) in photosynthesis, which are more limited by the amount of available CO_2, than plants that use C4 pathways (a specialized process fixing CO_2 into a 4-carbon molecule that concentrates CO_2 and allows the plant to use water and nitrogen more efficiently) for photosynthesis (Curtis et al. 1990, Rozema et al. 1991, Erickson et al. 2007). Studies on tidal wetland plants in the Mid-Atlantic and New England have found that biomass is increased in C3 plants when CO_2 is increased, but there is no effect on C4 plants when CO_2 is increased. However, this boon to C3 plants may be muted by C4 plants' adaptations during the growing season to the higher temperatures and drought conditions projected as a result of climate change. In New Jersey, the dominant native salt marsh plants are all C4 plants (*Spartina alterniflora, Spartina patens,* and *Distichlis spicata*), while the primary invasive species to tidal wetland systems, *Phragmites australis*, is a C3 plant. Increases in CO_2 and temperature have been found to increase the biomass of *P. australis,* especially with elevated levels of nitrogen (Mozdzer and Megonigal 2012, Eller et al. 2014). In addition, the combination of elevated CO_2 and increased temperature decreased *P. australis* sensitivity to salt, allowing it to encroach into more saline areas where it had been excluded from before (Eller et al. 2014).

The average annual temperatures in New Jersey have increased by 4.1°F (2.3°C) over the past century and are expected to continue to rise (Chapter 4.1). The effect of warmer weather on carbon sequestration in tidal wetlands is complex. Tidal wetlands excel at capturing carbon dioxide from the air and sequestering it in the soil. Increased plant productivity as a result of climate change would also increase the rate of carbon storage in the soil (Lu et al. 2019, Wang et al. 2021). However, the soil carbon density may actually decline as temperatures increase because rates of decay also increase at higher temperatures (Chmura et al. 2003). In addition, benefits to increased plant production from a longer growing season and warmer temperatures may be offset as the heat and summer droughts reduce the moisture content of the soils, consolidating salts and other chemicals (Kreeger et al. 2010). Changes in soil moisture can cause rapid shifts in soil chemistry, which is stressful for the plants and animals that live there. These extreme shifts in soil chemistry can contribute to marsh loss (Bason et al. 2007, Kreeger et al. 2010, Elmer et al. 2013).

Annual precipitation amounts in New Jersey are projected to increase by 5.9% to 7.3% by 2100 under an intermediate or high emission scenario, respectively (Wang et al. 2016, AdaptWest Project 2022), with projections indicating this may be driven by seasonal increases in the winter and spring (Runkle et al. 2022). Precipitation intensity is projected to increase throughout New Jersey (DeGaetano 2021b), and cyclone activity along the east coast that peaks in late summer and fall is also expected to intensify (Ting et al. 2019). These trends could lead to increased flooding in coastal areas with negative impacts to coastal wetland habitats (Partnership for the Delaware Estuary 2022). Uncertainty in the changes of storm characteristics, such as frequency and intensity is evident in many studies, but the direct impacts these storms can have on coastal systems will likely be exacerbated due to the rising sea levels. Recent studies have shown that sea-level rise will have a greater overall impact due to higher flood levels in higher latitude regions such as New Jersey (Kopp et al. 2025). Paired with increases in sea-level rise, low-intensity storms are projected to cause considerable damage to coastal communities due to the higher frequency of recurrent inundation (Rezaie et al. 2021).

Storm erosion events have been observed in wetland sediment sequences from Delaware Bay. On the northern shore of Delaware Bay, sediment cores collected from Sea Breeze and Fortescue in Cumberland County revealed that these wetlands have received blunt force impacts from prolonged periods of heavy storms over the past 2,000 years. Sediment cores collected from these sites indicated sharp changes in sediments from organic to inorganic, with layers void of vegetation corresponding to erosion events that eradicated the vegetated marsh (Nikitina et al. 2014). The sediment core record also revealed a marsh recovery time span of approximately 200 years, and in some cases longer, for re-vegetation of tidal flats with *S. alterniflora* and development of high marsh communities. See Figure 5.13 for an example of storm events in a sediment core from Fortescue. Other sediment cores collected from Barnegat and Cheesequake State Park (Raritan Bay) did not display erosion discordances and sediment layer successions associated with storm events; this is possibly due to the wetlands benefiting from natural protection by barrier islands or other forms of protection. These findings may imply that present-day wetland protection practices, such as living shorelines and the reuse of dredged materials to build back-Bay islands for example, may help preserve the wetlands from erosion impacts from storms and/or other ocean forces.

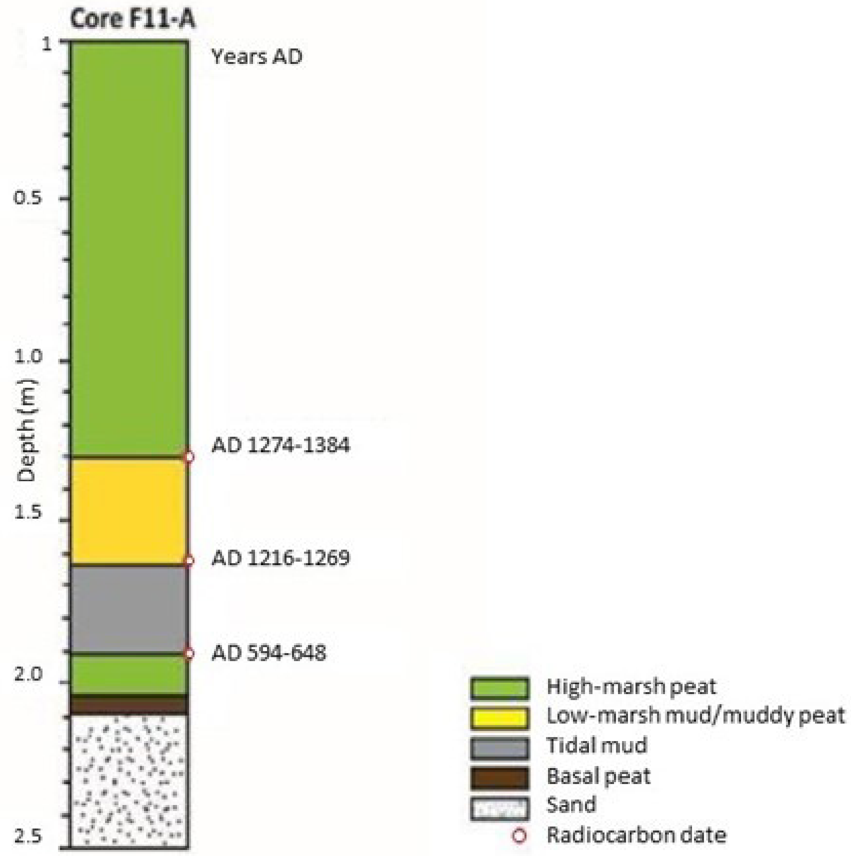


Figure 5.13. Example of a Sediment Core Lithology from Fortescue, Delaware Estuary Wetland Displaying a Storm Erosion Event Followed by Mud Flat Deposition. Radiocarbon ages were calibrated using data from (Stuiver and Reimer 1993, Reimer et al. 2009). Figure modified from (Nikitina et al. 2014).

Increased flooding during storms can have variable effects on tidal wetlands. In addition to erosional impacts described above, the increased turbidity and inundation times associated with storms can increase sedimentation on the marsh, facilitating increases in elevation that could reduce their vulnerability to sea-level rise. However, increased sedimentation from storms may be offset by the compaction resulting from the weight of flood waters during a storm. For example, one study of the elevational effects of Superstorm Sandy on tidal wetlands found variable wetland response depending on the localized storm characteristics (Cahoon et al. 2019). Some sites increased in elevation, indicating the added sediment compensated for any compaction effects of the storm surge. Other sites experienced a larger storm surge and lost elevation, indicating compaction of the marsh was greater than the accretion benefits of the storm surge (Cahoon et al. 2019).

Despite a trend toward more precipitation since 1970, the Northeast United States is also experiencing longer periods without rainfall during longer growing seasons. The result is a drier growing season, especially during the summer months, when temperatures and evapotranspiration are highest (Groisman and Knight 2008). Drought and heat can cause dieback in salt marshes and change the composition of plant communities in tidal wetlands (Salt et al. 2005, Rolando et al. 2023, Yang et al. 2025). Rapid marsh die-off has been found to be related to increased porewater salinity, which can occur when there is little freshwater input from rain and increased evapotranspiration during the growing season. It can take an extended period for a marsh to recover from rapid die off (Rolando et al. 2023).

5.4.3 Coastal Wetland Forests

The composition of coastal wetland forests will likely be altered under a changing climate, including increases in frequency and intensity of storms, flooding, salinity, and precipitation (White et al. 2022). Sea-level rise impacts to groundwater levels and salt water intrusion have been identified as the most important factors driving this change in the Northeast United States (Sacatelli et al. 2023), and one study along the Mid-Atlantic United States documented a decline in the ability of some trees to germinate as soil salinities exceeded 1.5-4.2 parts per thousand (ppt) (Langston et al. 2025). Additionally, multiple studies have shown that stress at the forest-marsh interface has resulted in forest die-back and transition to salt marsh habitat (Smith 2013, Kirwan and Gedan 2019, Sacatelli 2020, White et al. 2022).

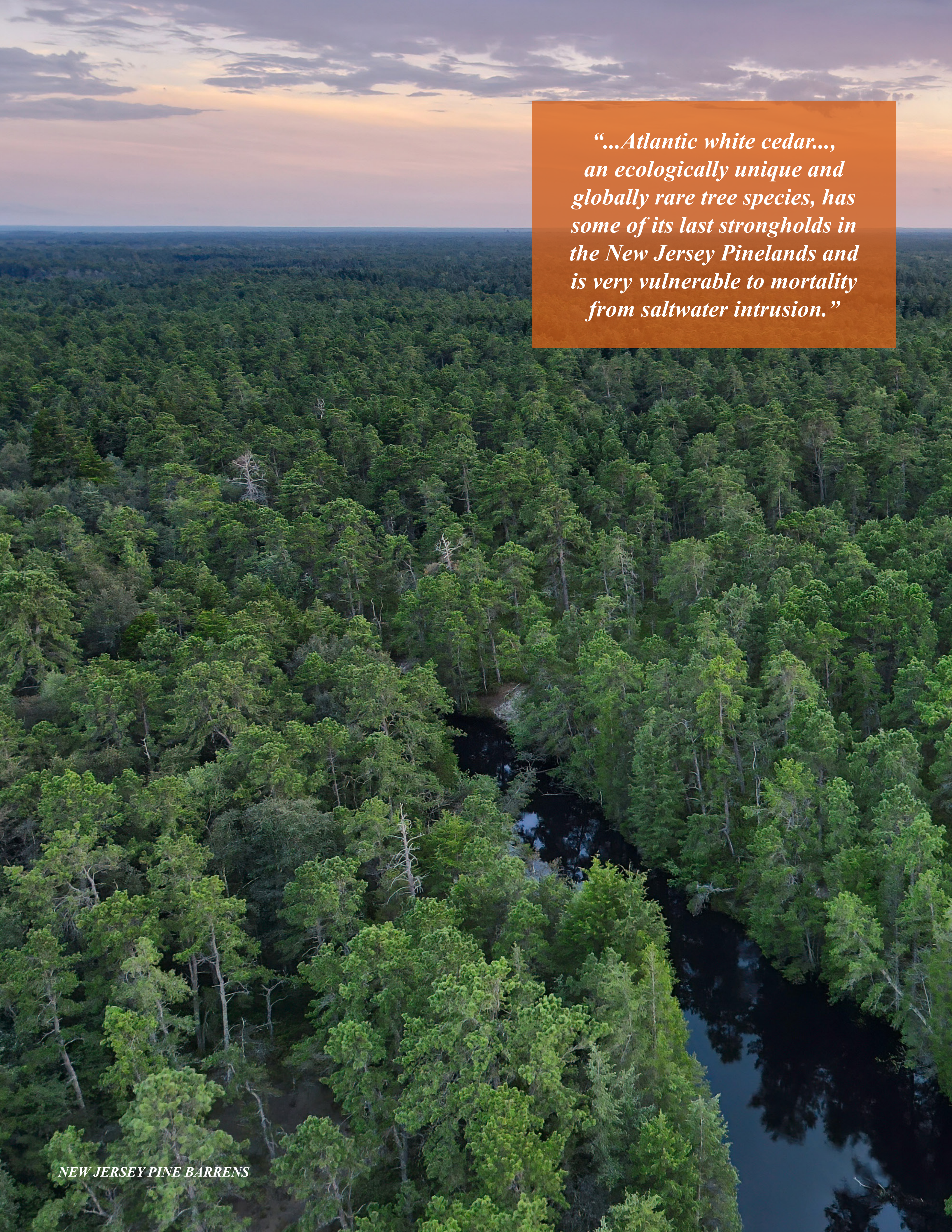
For instance, Atlantic white cedar (*Chamaecyparis thyoides*), an ecologically unique and globally rare tree species, has some of its last strongholds in the New Jersey Pinelands and is very vulnerable to mortality from saltwater intrusion (NJDEP 2020c). This species thrives within a narrow range of water table levels, where excessive flooding (from either freshwater or saline water) and extended dry periods can lead to losses or impairment. In addition to the threats associated with sea-level rise, changing precipitation patterns could affect the water table and negatively impact Atlantic white cedar stands (Mylecraine et al. 2005, Atkinson 2020). This high-value species will suffer disproportionately compared to other native New Jersey species due to rising seas. Atlantic white cedar typically occurs within one hundred miles of the Atlantic coast, from Maine to Mississippi. It competes well against other trees in wetlands, which are often the lowest-elevation features on the landscape. However, it is completely intolerant of saltwater inundation, although it does have a capacity to reestablish on salted sites if enough salt is leached from the soil (Little 1950). In New Jersey, it mainly grows in wetlands with muck soils on the outer coastal plain. This low-lying coastal distribution and utter intolerance of salt makes the species particularly susceptible to rising seas. Persistent inundation from direct sea-level rise is not needed to eliminate cedar from a site: periodic and unpredictable flooding from saltwater storm surges is all that is needed to kill a forest. Hence, loss of area and range of this globally rare species is expected with rising seas. In southern New Jersey, relative sea-level rise that is approximately double the global average has resulted in the emergence of "ghost forests," or standing dead forests mainly comprised of Atlantic white cedar, in portions of the Mullica River and its tributaries (Sacatelli et al. 2023).

Cedar swamps dying and being colonized by marsh species is not new; losses to saltwater have been noted for this species since the 1850s, attributed then to coastal subsidence (Cook and Kitchell 1857). The immense decay resistance of the species has left evidence of the longer-term impacts of rising seas by way of buried cedar stumps well into coastal marshes and shallow bays. These examples show that Atlantic white cedar forests have been retreating with rising seas since the last glacial period.

For cedar forests to maintain their presence on the landscape despite losses on the coast, the conditions that created the establishment of those forests must also be maintained. For cedar, that disturbance process was mainly driven by fire. Cedar can be an excellent competitor as a colonizer of sites left open by disturbance like fire, provided that the disturbances occur, and cedar can get to the openings.

Compared to historical levels, the current diminished extent of this species makes the threat from sea-level rise much more pressing, as cedar will likely find difficulty in establishing itself in new sites to replace those lost to salt. In forested wetlands that no longer have a cedar component, disturbance of those areas will not increase the chance for cedar to establish (Sheffield et al. 1998, Mylecraine and Zimmermann 2000). Hundreds of years of cutting of the species has reduced its abundance, reducing it to a minor canopy component in almost all of the forested wetlands outside the Pinelands National Reserve. Combined with changes to the behavior, frequency, and extent of fire on the landscape, it is not expected that cedar forests will have suitable habitat to retreat to in response to rising seas.

“...Atlantic white cedar..., an ecologically unique and globally rare tree species, has some of its last strongholds in the New Jersey Pinelands and is very vulnerable to mortality from saltwater intrusion.”



NEW JERSEY PINE BARRENS

CHAPTER 5.5

TERRESTRIAL CARBON SEQUESTRATION

RAMAPO MOUNTAIN STATE FOREST, NEW JERSEY

KEY FINDINGS

- **The loss of coastal wetland and forest habitats to climate change will result in carbon losses and increase New Jersey's net greenhouse gas emissions.**

5.5 Terrestrial Carbon Sequestration

New Jersey natural lands, including forests, woodlands, salt marshes and wetlands, seagrasses, and agricultural lands, are large carbon sinks and can provide important mitigation against greenhouse gas emissions. Carbon that is removed from the atmosphere is stored in live trees and plants, standing dead trees, understory and marsh vegetation, downed dead wood, forest floor litter, and soil organic carbon. It is estimated that in 2022, New Jersey's land sector of forests and associated land cover sequestered the equivalent of 8.1 million metric tons of carbon dioxide equivalent ($MtCO_2e$), resulting in net greenhouse gas emissions of 98.6 $MtCO_2e$ (NJDEP 2019a). It is important to note that this is an estimate, as there is limited New Jersey-specific data about the sequestration capabilities of the state's lands, and it is likely an underestimate because it does not include wetlands sequestration (NJDEP 2024d). As described further in Chapter 3.2, carbon dioxide equivalent is a term used to compare the emissions from various greenhouse gases based on their Global Warming Potential to the reference gas of carbon dioxide (CO_2), which has a Global Warming Potential of 1. Changes in land use can contribute to changes in how much carbon is stored in ecosystems, also known as carbon storage, and can cause the release of greenhouse gases.

The Intergovernmental Panel on Climate Change (IPCC) defines a 'sink' as any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol from the atmosphere (IPCC 2014). Terrestrial carbon sequestration is a process that involves the capture of CO_2 from the air by plants through photosynthesis, and storage of that carbon in woody biomass and in plant-derived soil organic carbon (United States Department of Energy and the National Energy Technology 2010). Terrestrial carbon sequestration occurs naturally, however, human actions can both enhance and impede the capacity of terrestrial environments to sequester carbon. New Jersey has large areas of permanently preserved lands, which already serve as carbon sinks (NJ Climate Adaptation Alliance 2014, Lathrop et al. 2016, Crocker et al. 2017, NJDEP 2024d) and include state parks, forests, wildlife management areas, and natural areas; preserved farmland; county and municipal parks; nongovernmental organization nature preserves; and federal wildlife refuges, parks, and military installations.

Forests and wetlands represent major components of New Jersey's landscape (NJDEP 2024c) and are important contributors in the state's capacity for removing carbon from the atmosphere through sequestration processes (NJDEP 2024d). Forests represent the largest terrestrial carbon sink on Earth (Oswalt et al. 2019) and are the largest natural land cover category in New Jersey, with only urban land representing a larger land cover category overall (NJDEP 2024c). Land use changes play a critical

> ***"New Jersey natural lands, including forests, woodlands, salt marshes and wetlands, seagrasses, and agricultural lands….can provide important mitigation against greenhouse gas emissions."***

role in carbon flux processes. For example, forested land can become net sources of carbon when they are converted to non-forested land uses (e.g., warehouses) or directly impacted by catastrophic fires or pest outbreaks that kill large percentages of trees. Healthy forests have some advantages, including long lifespans, large aboveground biomass, and extensive root systems, that allow for exceptional carbon sequestration benefits (NJDEP 2024d). In addition to the large carbon burial benefits of trees in forested settings, trees located in urban and community forest settings also contribute substantially to the sequestration of atmospheric carbon (NJDEP 2020c).

Some wetland ecosystems have the capacity to capture and store atmospheric carbon at rates up to 10 times greater than forests on a per-area basis (Pidgeon 2009), making them particularly important to the fight against climate change (Howard et al. 2014, Adame et al. 2024). In wetland habitats, most of the carbon storage occurs in wet soils, where it can remain locked up for centuries or more (Pidgeon 2009). The effects of climate change on carbon sequestration processes are complex. For example, longer growing seasons and increasing temperatures and CO_2 in the atmosphere may increase plant biomass production, which increases the carbon sequestration rate of wetlands (Lu et al. 2019, Wang et al. 2021) and forests (Talhelm et al. 2014, Wang et al. 2017). On the other hand, temperature directly affects evapotranspiration and groundwater levels, particularly in productive ecosystems like forested swamps, where increased temperatures and lower water levels allow for the oxidation of organic soils and subsequent release of carbon. Increased temperature and elevated CO_2 can also stimulate the decomposition of carbon stored in the soil, re-releasing carbon back into the atmosphere as greenhouse gases (Peng et al. 2022, Noyce et al. 2023). For some forests, research has indicated that under warming conditions, more carbon can escape from soils than what is added by plants (Liang et al. 2024).

Seasonal and annual fluctuations in the timing and intensity of precipitation complicate the response of ecosystems, creating the potential for forests and wetlands to serve both as carbon sources and sinks. With predictions for changes in precipitation, sea-level rise, rising temperatures, and extreme weather, the ecosystem responses to these changes will be complex and are not well understood. For example, carbon storage in forest soils can be impacted through both vegetation growth and decomposition processes due to temperature increases (D'Amore and Kane 2016). Projections also indicate potential for increased frequency of fire weather and risk of wildfires, which could lead to plant mortality and carbon emissions (NJDEP 2020c).

Recent studies on carbon sequestration in freshwater wetlands indicated that they have significant capacity for storing carbon over long time periods (Bernal and Mitsch 2012, Valach et al. 2021, Sapkota et al. 2025). Soil carbon data are currently on the US EPA's National Aquatic Resource Survey - National Wetland Condition Assessment website and are pending publication approval (Nahlik et al. 2023). In coastal wetland carbon systems, the high salinity limits production of methane, which is a potent greenhouse gas (Kroeger et al. 2017). This makes existing salt marshes carbon sequestration powerhouses. Changes in salinity and flooding as a result of sea-level rise are expected to net carbon sequestration in estuarine wetland systems (Mueller et al. 2020). Increased flooding and waterlogged organic soils increase the potential for sequestering carbon. However, under an intermediate emission scenario, 83% of existing salt marshes in the Mid-Atlantic are projected to be lost by the year 2104 due to sea level rise, resulting in erosion of stored soil carbon by waves and storms and re-releasing it into the atmosphere as greenhouse gases (Warnell et al. 2022). At the same time, new salt marshes will form as they replace freshwater tidal marshes and move into previously upland areas. The amount of vegetation in a wetland is critical for the rate of carbon sequestration. For more information on the effects of climate change on wetlands, see Chapter 5.4, and upland forest, see Chapter 5.3.

Terrestrial carbon sequestration in New Jersey has incrementally increased, with annual estimated rates up from 6 MTCO$_2$e in 2006 to 8.1 MTCO$_2$e in 2022, a rate increase of 2.1 MtCO$_2$e (NJDEP 2025a). Minor gains are attributed to carbon accumulation in biomass and soil due to the continued maturation of New Jersey forests and wetlands. However, despite this fact, between 1986 and 2020, New Jersey saw an increase of over 390,000 acres in developed (urban) land, and experienced decreases in upland forests, cropland, grassland, and wetlands (NJDEP 2024c). As seen in Figure 5.14, from 2015 to 2020 New Jersey lost over 4,300 acres of forest, 450 acres of wetland, and over 14,000 acres of crop/grassland (NJDEP 2024c). The rate of urban growth has slowed in more recent years, due in part to the Great Recession of 2008, changes in housing market preference, and New Jersey's strong land preservation policies (Lathrop and Hasse 2020). These historical land use decisions have reduced New Jersey's carbon pool and impacted the annual rate of sequestration.

The ability of land to sequester carbon is impacted by land use and changes in land use (United States Department of Energy and the National Energy Technology 2010). The conversion of land from a natural to a developed or disturbed condition is well documented as causing significant direct, as well as secondary and cumulative, environmental impacts. Environmental impacts associated with land conversion and alteration, beyond limiting carbon sequestration, include habitat loss (NJ DFW 2019), fragmentation (McGuire et al. 2016), the introduction of invasive species (Anderson et al. 2016), and changes to the energy budget like the urban heat island effect (Solecki et al. 2004). Urban/developed land includes both land with houses, buildings, pavement, and other areas; these are essentially impervious to infiltration of rainfall, reducing evaporative cooling, and reflect less solar energy while absorbing more than rural surfaces (US EPA 2008).

Looking forward to 2030 and 2050, DEP analysis under a very high emission scenario (RCP 8.5) depicts terrestrial carbon sequestration in New Jersey reaching 8.6 MtCO$_2$e by 2030 and 9.5 MtCO$_2$e by 2050 (NJDEP 2019b), as seen in Figure 5.15. Future analyses should include more likely scenarios, such as the intermediate emission scenario (SSP2-4.5). The high emission scenario used in this analysis (RCP 8.5) assumes no significant changes in recent land use data and

a decline in land clearing due to development being concentrated in already developed or built-up areas of the state. This projection does not take into account recent sea-level rise projections, which predict upwards of 1.7 feet (0.5 meters) of sea-level rise by 2050 (Kopp et al. 2025). The rising sea level could critically endanger coastal wetlands and forest habitats that currently serve as key carbon sinks (Lathrop 2014, Weis et al. 2021).

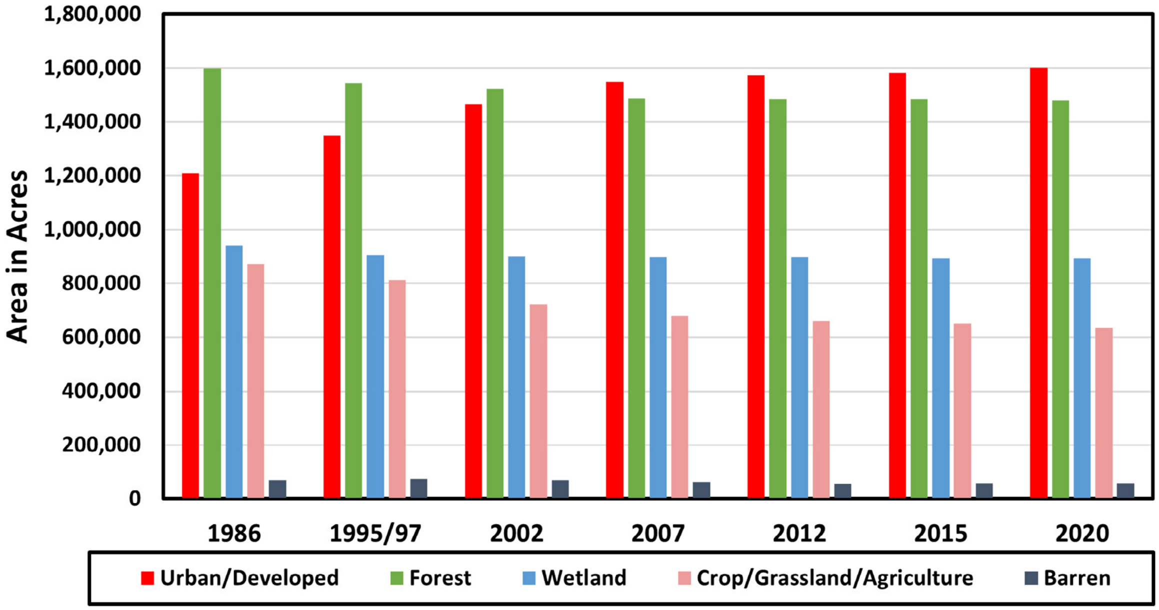


Figure 5.14. New Jersey Land-Use Trends, 1986-2020. This figure shows the acres (y-axis) of developed/urban land, forest land, wetlands agriculture, and barren lands in New Jersey between 1986 and 2020. Note the consistent increase in developed/urban land and decrease in crop/grassland/agriculture, wetlands, and forests (NJDEP 2024c).

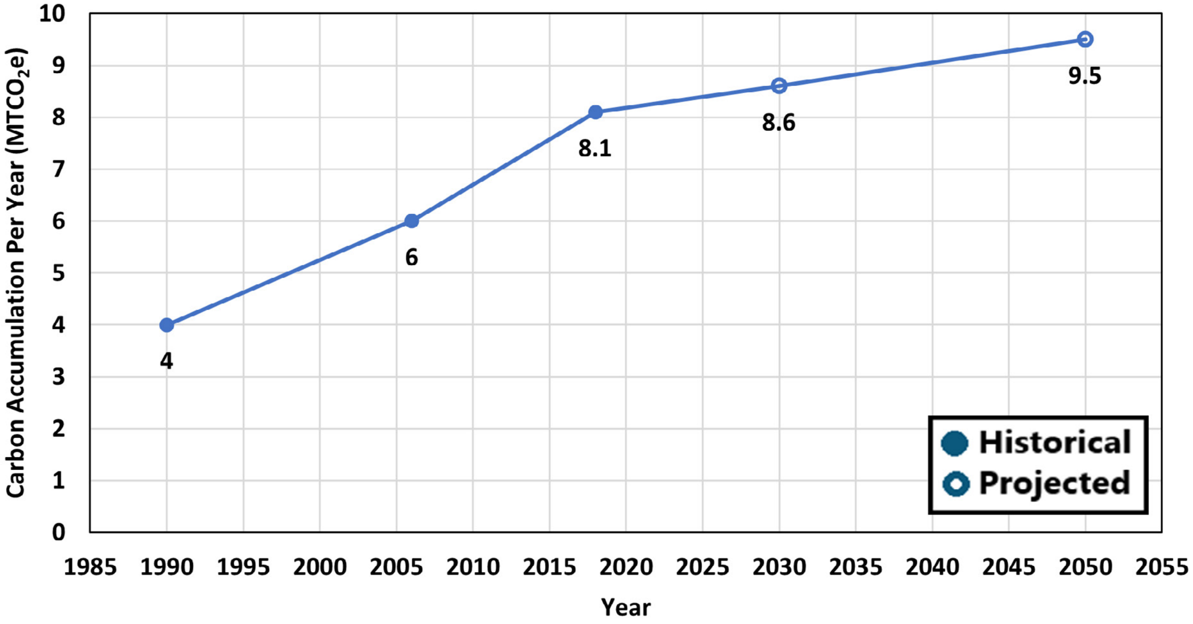


Figure 5.15. Trend of New Jersey Terrestrial Carbon Accumulation. This figure shows the historic and projected trend of carbon accumulation per year in MtCO$_2$e from 1990 through 2050 (NJDEP 2019b). The projections depicted for 2030 and 2050 were only analyzed under a very high emission scenario (RCP 8.5). However, future analyses should consider a range of emission scenarios, with an emphasis on more likely scenarios such as the intermediate SSP2-4.5.

Additionally, the sequestration ability of New Jersey forests and wetlands may be threatened not only by sea-level rise, but also from other climate change factors such as changes in winter weather patterns that can cause increases in the number of annual generations of the southern pine beetle (Trần et al. 2007), which can kill trees within several months during periods of insect outbreak (Coulson and Klepzig 2011). Forests killed by beetles can regrow and adapt in response to this disturbance, but regrowth and adaptation are long processes and the carbon losses from such an event can cause forests to become temporary net carbon emitters, similar to the damage and negative impacts seen in western pine-dominated forests from the mountain pine beetle (Kurz et al. 2008).

See Chapter 5.3 and Chapter 5.4 for more information on the effects of climate change on these carbon-capturing habitats.

CHAPTER 5.6

TERRESTRIAL SYSTEMS

AMERICAN GOLDFINCH — RAMAPO MOUNTAIN STATE FOREST, NEW JERSEY

KEY FINDINGS

- **Climate change is likely to further facilitate expansion of invasive plant species.**
- **29% of New Jersey's bird species are vulnerable to climate change, including the American Goldfinch which is the state bird of New Jersey.**
- **Saltmarsh Sparrows, a globally endangered species, may reach quasi-extinction population numbers by 2040 due to habitat loss from sea-level rise.**
- **Many insect species, including ones that are listed as Species of Greatest Conservation Need, will experience range shifts towards the poles as temperatures increase.**

5.6 Terrestrial Systems

The plants and animals that reside in terrestrial systems throughout New Jersey will be impacted by the effects of climate change. Rising sea-levels, changing precipitation regimes, and increased intensity and frequency of storms will affect terrestrial plant and animal species.

5.6.1 Terrestrial Plants

New Jersey occupies a unique place in both the Mid-Atlantic and Northeast regions of the United States. The five physiographic provinces in New Jersey (Ridge and Valley, Highlands, Piedmont, Inner Coastal Plain, and Outer Coastal Plain) give the state an astounding geographic and geological diversity, resulting in impressive biodiversity. These unique conditions mean that New Jersey is home to several globally rare communities such as sea-level fens and Atlantic white cedar swamps. There are over 2,000 native plant species in New Jersey; several of these species are found nowhere else in the world. This plant richness is comparable to states significantly larger, even though New Jersey is the most densely populated and fifth smallest state in the United States.

Climate change poses a significant threat to New Jersey plants and plant communities. Changes brought on by a warming climate, such as earlier arrival of warm temperatures in the spring, hotter summers, warmer winters, changing precipitation patterns, and rising carbon dioxide (CO_2) concentrations, will challenge the resilience of New Jersey's natural systems (Snyder and Kaufman 2004). Under the effects of climate change, New Jersey plants and plant communities will be subjected to a variety of stressors and changes, some gradual, others rapid. However, climate change will affect species differently; the effects might lead to greater or fewer limits to species' abundance, distribution, and fitness (Antão et al. 2022). The impacts of climate change are compounded by other existing pressures,

> ***"Changes brought on by a warming climate, such as earlier arrival of warm temperatures in the spring, hotter summers, warmer winters, changing precipitation patterns, and rising CO_2 concentrations, will challenge the resilience of New Jersey's natural systems."***

including natural climate variability, ecological factors, and human alterations like habitat fragmentation and removal.

5.6.1.1 Phenology

Trends of changing temperatures in the Mid-Atlantic and Northeastern states are clear: winters are becoming milder and springs are arriving earlier every year, with ever higher mean temperatures (Parmesan and Hanley 2015, Hoegh-Guldberg et al. 2018, Lipton et al. 2018). Between 1915 and 2003, the duration of the growing season in Northeast New Jersey expanded 0.7 days/decade, with a rapid acceleration to 2.5 days/decade between 1970 and 2000 (Frumhoff et al. 2007). Plants, in general, are disproportionately sensitive to changes in average temperature and thus, they are indispensable for monitoring the impacts of climate change (Cook et al. 2012). Specifically, changes in plant phenology are major indicators of a changing climate. Phenology is the study of cyclic events in the life stages of plants and animals. Phenological events like spring leaf emergence, spring flowering, and autumnal leaf colorations are often highly sensitive to temperature (Shen et al. 2022). One way that plant species adapt to the warming world is with a shift in phenology, with the general trend being that of phenophases (observable stages of development, e.g., flowering) occurring earlier in the season, although to what degree this occurs differs by species (Antala et al. 2022). An earlier onset of phenological events such as seed germination, leaf emergence, and flowering has been documented and tracks closely with temperature increases in temperate areas worldwide (Parmesan and Hanley 2015). Many researchers have found that mean temperatures from three months prior to the date of flowering had the strongest correlations with flowering phenology and greatest influence on flowering time when compared to mean temperatures for other timeframes in the preceding year (Park and Schwartz 2015, Jones and Daehler 2018).

> ***"With warming trends expected to continue and even accelerate, wild plants will be pushed into earlier first-flowering dates."***

Accelerated phenologies have been documented across much of the northern hemisphere in mid-latitudes in temperate and boreal ecosystems (Lamichhane 2021). Long-term datasets documenting plant phenology events and local temperature trends offer a wealth of information regarding the effects of climate change. One such dataset from Mohonk Lake, in Ulster County, New York (Cook et al. 2008) used local temperature records beginning in 1895, combined with first flowering dates of 19 native plant species beginning in 1920. They found that most spring-blooming herbaceous plants advanced their flowering by 1.9 days per decade and tracked with a roughly linear trend in mean temperature increase.

Similarly, a dataset from Washington D.C. containing 100 species, showed that between 1970 and 1999, 85% of species had advanced flowering dates by an average of 5.6 days (Abu-Asab et al. 2001). Many species had advanced first-flowering dates by more than 10 days, indicating that some species are more sensitive than others to rising spring temperatures.

In Massachusetts, record-breaking spring temperatures in 2010 and 2012 resulted in the earliest recorded flowering of 27 different species (Ellwood et al. 2013). Mean flowering time in 2010 was a full three weeks earlier than in 1852, and mean spring temperature (52°F; 11°C) in 2010 was higher than in 1852 (42°F; 5.5°C). Individual species show even greater change; for example, highbush blueberry (*Vaccinium corymbosum*) bloomed six weeks earlier in 2012 than it did in the 1850s.

Researchers are finding earlier phenophases of vascular plants in mid-latitude peatlands (Antala et al. 2022), on the Qinghai–Tibetan Plateau (Shen et al. 2022), in Siberia (Rosbakh et al. 2021), and in the Northeastern United States (Primack et al. 2004). With warming trends expected to continue and even accelerate, wild plants will be pushed into earlier first-flowering dates. Multiple studies have concluded that for every 1.8°F (1°C) increase in average temperatures, flowering time will advance by roughly four days (Primack et al. 2004, Ellwood et al. 2013). Leaf emergence (leaf-out) is advancing at a similar rate and shows strong associations with maximum daytime temperature in the late winter and spring (Piao et al. 2015).

Although phenological shifts associated with climate warming have been documented in many species, not all species shift their phenology or do so in the same direction or magnitude (Burdon and Zhan 2020). For boreal plants in Siberia, the species-specific phenological changes from 1976-2018 showed quite a bit of variation. While 34 species (51%) had earlier leaf-out, with a range of 1.6-6.7 days, three species (4%) delayed leaf-out; 17 species (26%) flowered earlier, but three species (5%) flowered later than in 1976 (Rosbakh et al. 2021). Early-flowering species shift their phenology more than later-flowering species; that is, species that flower later in the summer are less or not affected by changing spring climate (Inouye 2022). Variations in response to warming are also attributed to latitude, distance from northern range edge, and life form; warming advanced spring phenophases ever earlier as latitude increases (Dobson and Zarnetske 2025).

Many species require an accumulated amount of winter chilling as a cue to initiate physiological processes in spring. Warmer winters with fewer days at the necessary cool temperatures act to delay flowering (Jones and Daehler 2018) and leaf emergence (Iler et al. 2021) in these species. Patterns can be hard to untangle when flowering is both delayed by lack of chilling days, and at the same time, flowering is advanced by warmer spring temperatures. These are both important physiological cues to trigger flowering, working in opposition to each other. Species may differ in terms of which cue is primary, or the combination of cues that trigger initiating the physiological processes (Inouye 2022).

Fu et al. (2015) studied seven tree species at 1,245 sites in Europe from 1980-2013, finding that the expected early leaf-out due to climate warming decreased by 40%, from 4.0 ± 1.8 days per increase of degrees in Celsius, to 2.3 ± 1.6 days per increase of degrees in Celsius (Fu et al. 2015). Plants in New Jersey are likely to experience this phenomenon as winter temperatures have risen 5.6°F (3.1°C) from 1895 to 2024 (Office of the New Jersey State Climatologist 2025a), and significant future increases are expected (Chapter 4.1.3). The complexity of plant responses to climate change indicates that current estimates are likely to underestimate the magnitude of the effect climate change is having on wild plants.

In deciduous forests, many understory wildflowers leaf-out and/or flower in early spring to take advantage of high light conditions before being shaded by the tree canopy. However, in the Northeastern United States, the time between understory and overstory leaf-out is less than it was

ALDER BUCKTHORN

> ***"If a plant flowers well before or after its associated pollinators are active, it is likely that both plant and pollinator species will experience a drastic decline in reproductive success."***

a century ago. Heberling et al. (2019) found that since the 1850s, first leaf-out dates have shifted nearly two weeks earlier for trees (12.9 ± 0.7 days; average of 15 species), but less than a week for spring wildflowers (5.9 ± 2.2 days; average of 14 species. With fewer days before full canopy leaf-out, wildflowers have less time to manufacture carbon, potentially resulting in reduced seed production. When occurring along with other stressors, such as high herbivory and invasive species, population persistence is further at risk (Heberling et al. 2019).

Phenological shifts may have positive or negative effects on different species, depending on the demographic consequences of the change to the life-cycle event, and if survival and reproduction are negatively impacted (Iler et al. 2021). Species that alter their phenologies are sensing and responding appropriately to changing environmental cues and will potentially be able to remain within their climate niche (Iler et al. 2021). Positive effects could occur if the species gains more time for growth and reproduction, or if it is released from a negative interaction (Iler et al. 2021). However, temperature and precipitation are changing at different rates, resulting in novel climate conditions to which species are exposed and may not be able to adjust (Iler et al. 2021). Phenological shifts have negative consequences when important interactions are less likely to happen due to shortened time frames or less spatial interaction and could affect population persistence if there is a change in vital rate (e.g., birth and death rates) due to changes in reproductive traits (Iler et al. 2021).

Climate change is likely to increase the frequency of late spring frosts (Lamichhane 2021), which are caused by an unusually early warm spell that triggers early phenologies, followed by a frost event (Inouye 2022). Although climate change is causing fewer frost events over the course of the year, there are more frequent frost days during the early part of the growing season (Liu et al. 2018). Regions with the greatest increases in growing season length have the most increase in frost events in the spring (Liu et al. 2018). Late spring frosts are more likely to cause damage to plants with earlier phenologies, causing reduced plant growth and reproduction in plants that flower or leaf-out earliest in the season (Antala et al. 2022). Researchers project that in the future, spring frost damage will affect over ten percent of North American temperate forests (Lamichhane 2021).

There are potential complications and threats associated with phenological changes and the earlier arrival of spring. Changing plant phenologies affects interactions with herbivores, pollinators, and seed predators (Inouye 2022). If a plant flowers well before or after its associated pollinators are active, it is likely that both plant and pollinator species will experience a drastic decline in reproductive success (Memmott et al. 2007, Lipton et al. 2018). Simulated changes in the flowering dates of 429 species predicted that between 17 and 50% of pollinator species will experience a decline in food supply under a warming scenario. Moreover, the more dramatic the changes in flowering date, pollinator species were more likely to experience a lack of or inconsistency in food supply (Memmott et al. 2007). There is also evidence that an increase in average spring temperatures can reduce the overall springtime longevity of important pollinators such as butterflies (Lepidoptera) and bees (Hymenoptera) (Bosch et al. 2000, Karlsson and Wiklund 2005). However, controlled experiments and simulations do not always match *in situ* observations. The results of a study of 10 generalist bee species native to eastern North America indicate that long-term trends of spring bee emergence are nearly identical to those of plants, and that phenological mismatch has not yet occurred. A majority of the phenological advancements for both plants and bees took place between 1970 and 2010, suggesting that alterations in phenology are accelerating in response to worsening climate change. The authors still warned that future warming, particularly in more urbanized regions, could facilitate phenological mismatches detrimental to both plants and pollinators (Bartomeus et al. 2011). However, if pollinators are exhibiting parallel responses to spring-sensitive plant species, phenological mismatches may become an even larger issue for plants subject to delayed flowering due to insufficient winter chilling. While long-term generalizations cannot necessarily be made based on the long-term emergence trends of just 10 bee species, the conflicting results of these studies are a reminder that responses to climate change are difficult to forecast and are often more complex than expected.

5.6.1.2 Migration

One of the most common ways plants respond to climate change is through changes in species' geographic ranges (Manes et al. 2021). If new climate conditions are unfavorable, species may migrate to new areas with more favorable conditions (Zhang et al. 2023). Plant species' ranges can shift via the population expanding or contracting, or both simultaneously. At the expanding edge, dispersal and establishment of propagules determine range expansion. At the trailing edge, local extirpation determines range contraction (Alexander et al. 2018). Scientists have documented and expect to see more species' ranges shift towards higher latitudes (poleward) and upward in elevation (Burdon and Zhan 2020, Zhang et al. 2023) influenced primarily by the warming climate (Antão et al. 2022). When plant species are forced to migrate upslope due to climate warming, their range usually contracts (Zhang et al. 2023).

Although New Jersey-specific information is lacking, it stands to reason that certain plant species reaching their southern terminus in New Jersey will likely not be present in the future due to conditions brought on by climate change (Pitelka 1997, Ring et al. 2013). The rate and direction of migration are species-specific and can vary considerably based on species' ability to persist at their trailing range edge, and their ability to track climate change through effective dispersal and establishment (Alexander et al. 2018). Habitat loss, barriers, fragmentation, and landscape connectivity may prevent range shifts causing smaller ranges than predicted by climate alone (Alexander et al. 2018, Zhang et al. 2023). Riparian corridors may act as habitat refugia and potential migration corridors for species impacted by climate warming (Zhang et al. 2023).

Some species are more vulnerable to extirpation or extinction as they attempt to adjust to climate change with range shifts (Manes et al. 2021). Endemic species with more restricted geographic ranges are at higher risk of extinction from the effects of climate change, especially if they have a small population size, inadequate adaptive capacity, and limited dispersal abilities (Manes et al. 2021). A species that has a larger range will more likely be able to find refugia within parts of its range (Manes et al. 2021).

5.6.1.3 Physiology

Climate change will increase temperatures in all seasons, which can have dramatic effects on plant physiology. A review of stress mechanisms in plants found that a temperature increase of 7-9°F (4-5°C) above normal caused decreases in important physiological processes in vegetative and reproductive life stages, such as reductions in growth and decreases in chlorophyll content, although the degree of impact varied by species (Chaudhry and Sidhu 2022). Not all plants will respond in the same way, as species differ in their ability to adapt to climate change-related stressors. Physiological traits differ, such as sensitivity to or tolerance of heat stress, increasing CO_2, and ozone (Schleuning et al. 2020). Most information regarding the physiological effects of climate change comes from experiments with model and agricultural species, but the findings can still offer clues to the types of effects climate change will have on wild plants in New Jersey.

Under warming experiments, certain species of plants produce fewer or no flowers at all; plants that did flower, produce smaller flowers and shorter corollas (petals), which can affect pollinator attraction (Scaven and Rafferty 2013). Increased temperatures also negatively affect pollen production and viability in a variety of plants, which could hinder reproduction and gene flow among plant populations. Certain species exhibit 35-50% lower pollen production under experimental warming (Scaven and Rafferty 2013). Experimental warming was shown to cause changes in the nectar properties of flowers as well: changing overall volume, ratios of sugar molecules, and a decrease in compounds responsible for floral scent production. Changes in flower shape, size, and nectar availability could affect pollinator visitation (Scaven and Rafferty 2013). Graminoids had decreased flower lifespan with increased temperatures (Dobson and Zarnetske 2025).

Other species underwent mass flowering in response to warming (Scaven and Rafferty 2013); for example, a study of peatlands' response to climate change found that shrubs produced more flowers (Antala et al. 2022). Warming experiments tend to find that fruit weight increases in response to warming, especially for graminoid species (Dobson and Zarnetske 2025). At higher latitudes, the effect of warming on the number of fruits and fruit weight increases, and there is also a marginal increase in the effect of warming on the number of flowers (Dobson and Zarnetske 2025).

In response to warming, vascular plants tend to increase aboveground and belowground biomass, overall plant growth, and leaf growth (Antala et al. 2022, Dobson and Zarnetske 2025), with graminoids and forbs tending to show stronger responses than other life forms. Species closer to their northern range edge were more sensitive to warming in terms of increased plant growth and percent cover, as opposed to individuals of the same species in other parts of the species' range; this may be because they are undergoing selection for traits that enhance colonization (Dobson and Zarnetske 2025).

Bryophytes and lichens are not commonly measured plant types, but when investigated, the responses of nonvascular plants to warming move in the opposite direction to vascular plants. Bryophytes and lichens have reduced percent cover when exposed to warming climate (Dobson and Zarnetske 2025), and a study of peatlands' response to climate change found that sphagnum moss was in decline (Antala et al. 2022).

Higher temperatures may lead to lower foliar (i.e., leaf) nitrogen concentrations (Mason et al. 2022). Warming experiments show decreased foliar nitrogen content in response to warmer temperatures, with graminoids and forbs showing the strongest decreases in aboveground nitrogen (Dobson and Zarnetske 2025). Mutualistic interactions with mycorrhizal fungi may be negatively affected because of these decreases in foliar nitrogen content (Iler et al. 2021).

Warming experiments varied in approach, with some only testing effects of warming in the growing season, others testing year-round warming; year-round warming experiments may more accurately reflect real-world climate changes (Dobson and Zarnetske 2025), as warming is projected to be greatest in winter months and at night (Dusenge et al. 2019). Compared to longer-term experiments, experiments with shorter timeframes demonstrated stronger effects from warming; this may be because plants have an initial strong response to the new stress of warming, but over time, they may acclimate and dampen their trait response (Dobson and Zarnetske 2025). Specifically, as the number of years warming increased, the effect of experimental warming on flower lifespan, fruit number, and leaf growth became weaker; that is, the effect size became closer to zero as the number of years warmed increased (Dobson and Zarnetske 2025).

Carbon dioxide is the primary cause of the changes in plants associated with increased greenhouse gases (Cassia et al. 2018). Atmospheric CO_2 concentrations are currently the highest they have been in over 800,000 years (Lindsey 2019). Carbon dioxide directly affects plant metabolism (Dusenge et al. 2019); for example, poison ivy (*Toxicodendron radicans*) has responded to higher CO_2 concentrations by not only increasing its growth rate, but by synthesizing even greater amounts of urushiol, the compound responsible for the dermatitis experienced after contact (Ziska et al. 2007).

Elevated CO_2 concentrations are expected to increase photosynthetic rates (Dusenge et al. 2019). An increase in atmospheric CO_2 can enhance plant growth through a process known as CO_2 fertilization (Parmesan and Hanley 2015). Experiments conducted in controlled conditions such as greenhouses, laboratory controlled-environment chambers, and transparent field chambers suggested positive responses by plants to increased CO_2 because plants would increase their photosynthesis and stomatal conductance, resulting in faster growth and more biomass (Cassia et al. 2018). However, plant response to elevated CO_2 depends on species, environment, time frame (Cassia et al. 2018), leaf temperature, and water and nutrient availability (Dusenge et al. 2019). Augmented CO_2 could cause negative feedback of photosynthesis to take place, resulting in only short-term benefits to plants in natural ecosystems (Parmesan and Hanley 2015, Cassia et al. 2018).

Elevated atmospheric CO_2 fertilizes plants, causing them to grow faster, but plant nitrogen is diluted in the process, leading to a cascade of effects that lower the availability of nitrogen (Mason et al. 2022). Nitrogen availability has been declining in many ecosystems worldwide since 1980. Studies in the Northeastern United States forests have demonstrated a decades-long pattern of decreased soil nitrogen cycling despite elevated atmospheric nitrogen deposition. Elevated atmospheric CO_2 levels are likely a main driver of declines in nitrogen availability, often reducing foliar nitrogen concentrations as well as plant-available soil nitrogen (Parmesan and Hanley 2015, Mason et al. 2022).

5.6.1.4 Biodiversity loss

Climate change negatively impacts biodiversity and may lead to species extinctions through changes in temperature, soil nutrients, land use, changing hydrological cycles, and the increased frequency and magnitude of extreme weather events like hurricanes, floods, and droughts (Kariyawasam et al. 2021, Habibullah et al. 2022). Native plants are projected to face high extinction risk in areas of high biological diversity (Manes et al. 2021). Endemic species (having a limited geographical distribution) from biodiversity hotspots are more threatened by climate change than other native species (Manes et al. 2021). Terrestrial endemics were projected to be 2.7 times more impacted by climate change than non-endemic native species, and 10 times more impacted than introduced species (Manes et al. 2021).

A meta-analysis of 97 studies quantified expected changes to biodiversity under different climate change projections (Nunez et al. 2019). The fraction of locally occurring plant species is reduced by 18% under a scenario of a temperature increase of 1.8 to 3.6°F (1–2°C); higher temperature increases of 3.6 to 5.4°F(2-3°C) and 5.4 to 7.2°F (3-4°C) estimate the fraction of locally occurring plants species to be reduced by 20% and 27%, respectively. The suitable climate area for plant species is reduced by 34% under a scenario of a 1.8 to 3.6°F (1–2°C) temperature increase; under more extreme temperature increases, the suitable climate area is reduced by about 54% (Nunez et al. 2019).

Climate change will influence the genetic diversity of plant species. As species' distributions shift and migrate in response to climate change, and landscape fragmentation puts constraints on pathways for migration, genetic diversity is expected to be altered. The potential impacts of climate change on future genetic diversity of species is not a common focus of research, but it's expected that as species migrate due to climate change, their genetic diversity will be impacted through the processes of gene flow and genetic drift (Wróblewska and Mirski 2018). A study of three circumboreal plant species predicted that their genetic diversity will likely remain similar to or lower than the present level. Another study showed that *Phragmites australis*, a dominant species in coastal wetlands globally, had reduced genetic diversity after three years of elevated CO_2 and nitrogen levels (Mozdzer et al. 2022). More studies are needed to better understand how climate change will affect the processes of gene flow, genetic drift, and adaptation (Wróblewska and Mirski 2018).

Increasingly intense storms threaten more than just forest plant communities. Coastal plant communities such as beaches, dunes, maritime forests, and coastal plain forests are under increased risk as sea-levels rise in response to climate change (Frumhoff et al. 2007, Butler-Leopold et al. 2018). Maritime forests are a unique community found on the barrier islands of New Jersey and characterized by dense thickets of stunted trees, shrubs, and a sparse herbaceous layer (Anderson et al. 2013). Trees and shrubs such as black cherry (*Prunus serotina*), scarlet oak (*Quercus coccinea*), pitch pine (*Pinus rigida*), scrub oak (*Quercus ilicifolia*), and American holly (*Ilex opaca*) are common in this habitat. Relatively large and intact stretches of maritime forest can be found in areas like Gateway National Recreation Area, Island Beach State Park, and Cape May. In New Jersey, the endangered shrub Nantucket serviceberry (*Amelanchier nantucketensis*) is only found in the openings of these coastal forests, putting it at risk to the effects of climate change and sea-level rise (Anderson et al. 2013, NJNHP 2025). In the coastal plain region, maritime forests are the most vulnerable communities to sea-level rise, as frequent and prolonged saltwater inundation can increase tree mortality and spur shifts in species composition (Butler-Leopold et al. 2018). In New Jersey, maritime forest habitat is already fragmented and uncommon due to development along the coast; it is projected that erosion of barrier islands, rising sea-levels, and more frequent coastal flooding will contribute to further loss of this habitat. Beach habitat in New Jersey is expected to suffer from a dramatic increase in erosion and inundation (Frumhoff et al. 2007). New Jersey beaches are home to several rare plant species, including seabeach knotweed (*Polygonum glaucum*), seabeach sandwort (*Honckenya peploides* var. *robusta*), and seabeach amaranth (*Amaranthus pumilus*). All three species are critically imperiled in New Jersey and are rare globally (NJNHP 2025). The increase in erosion and flooding has the potential to destroy important beach habitats and negatively affect all three species.

Saltwater intrusion in coastal plant communities will increase as sea levels rise. Cape May is home to several rare plant communities and is expected to erode and flood heavily due to rising sea levels and more severe storms. Cape May is home to unique and rare plant communities like intermittent ponds and the Cape May lowland swamp, both of which are considered globally rare. A substantial number of rare plant species are found in these unique wetland communities. such as awned meadow beauty (*Rhexia aristosa*), short-beaked bald-rush (*Rhynchospora nitens*), wrinkled jointgrass (*Coelorachis rugosa*), swamp pink (*Helonias bullata*), and featherfoil (*Hottonia inflata*) (Heimerdinger 2011, Ring et al. 2013, NJNHP 2025). Sea-level rise and erosion associated with climate change are direct threats to these globally rare plant communities. Further, an increase in droughts will enable saltwater to intrude farther inland for longer periods of time as rivers draw down. More severe flooding caused by hurricanes and nor'easters will penetrate further inland, affecting freshwater swamps. Many coastal swamp communities can withstand raised salinity levels for short periods of time, but an increase in the frequency and duration of saltwater intrusion will likely lead to mortality among plant and tree species with lower tolerances to salinity. Inland plant communities that rarely experience changes in salinity can be severely affected by saltwater intrusion (Middleton 2016, Butler-Leopold et al. 2018). Following Superstorm Sandy, there was high mortality of freshwater swamp trees and shrubs such as red maple (*Acer rubrum*), sweet gum (*Liquidambar styraciflua*), and holly (*Ilex spp.*) due to an increase in salinity that remained in the soil for over two years (Middleton 2016).

In New Jersey, there are over 2,000 native species of plants, of which over 860 are rare or endangered (Breden et al. 2006, NJNHP 2025). The unique and varied geography and geology of New Jersey results in incredible plant diversity. Many species such as Hammond's yellow spring beauty (*Claytonia virginica* var. *hammondiae*) and bog asphodel (*Narthecium americanum*), are found nowhere else in the world. Climate change represents a substantial threat to many of these rare species. A study of 70 rare plant species in New Jersey found that 50 of the 70 species were vulnerable to climate change (Ring et al. 2013). Of these 50 species, 41 were ranked as moderately vulnerable, eight were ranked as highly vulnerable, and one was ranked as extremely vulnerable to climate change. Species were divided into two groups depending on the region they were found in: the Skylands of northern New Jersey or the Pinelands of southern New Jersey. Species were further subdivided into four specific habitat types found within those regions. These four habitats will be among the hardest affected by climate change in New Jersey. Habitat types included calcareous fens and calcareous sinkhole ponds in the Skylands and Pine Barrens Savannas and Coastal Plain Intermittent Ponds in the Pinelands. Vulnerability of many of the species stemmed from the anticipated drying of their wetland habitat, a risk factor consistently projected to increase under climate change scenarios. Another significant risk factor, particularly for species found in the northern New Jersey Skylands, was that of range shifts associated with climate change. Many of those species, such as rush aster (*Aster borealis*) and bog birch (*Betula pumila*), reach their southern range extent in New Jersey and will likely experience a poleward range shift in the future (Ring et al. 2013). Another significant risk consistently projected to increase for many of these species relates to dispersal ability. Rare plants often depend on specific habitat requirements and are, thus, scattered, fragmented, and found in small, precarious populations (Pitelka 1997). Southern species within savannas and intermittent ponds, often at the northern edges of their range, face sea-level rise as well as natural and anthropogenic barriers to dispersal (Ring et al. 2013). Due to the relatively low number of populations and specific habitat requirements, rare plants are severely limited in their ability to disperse or migrate in the face of climate change. It is likely that many of the vulnerable plant species in New Jersey will no longer be present or severely reduced by the effects of climate change.

One of the largest risk factors for the 34 vulnerable species found in the Skyland region was related to changes in the historical hydrological niche (Ring et al. 2013). While this specific study only examined 41 Skyland species with sufficient data, there are over 120 rare plant species in northern New Jersey that exist in similar habitat types (NJNHP 2025). These species will probably be vulnerable to the hydrological changes brought on by climate change as well. Furthermore, Eastern hemlock (*Tsuga canadensis*), already reduced in New Jersey due to the invasive woolly adelgid, is projected to fare even worse due to climate change (Rustad et al. 2012). Eastern hemlock is an important component in the swamps and forests of northern New Jersey and plays a vital role regulating microclimate and soil moisture. Compared to hardwood forests, stands of Eastern hemlock lose 50% less moisture to evaporation during the summer months and provide significantly more shade year-round. The combination of drier overall conditions, warmer summers, and the loss of many more Eastern hemlock stands will negatively affect rare plants that have specific thermal and hydrological requirements (Ring et al. 2013). Recent New Jersey projections indicate likely increases of up to 50% in

> ***"An increase in temperature, growing season length, and frequency of droughts will put a considerable amount of strain on New Jersey plants and plant communities."***

total rainfall depths for the top 1% of storm events in some northern counties (DeGaetano 2021b).

An increase in temperature, growing season length, and frequency of droughts will put a considerable amount of strain on New Jersey plants and plant communities. Changes in winter precipitation can have far-reaching impacts on the growing season as well. With earlier snowmelt and more winter precipitation in the form of rain, streams will reach maximum spring flow one to two weeks earlier than in the past. In addition to early stream flow peaks, summer rain events are becoming less frequent but more severe. As a result, periods of low summer stream flows are arriving earlier and lasting longer. The growing season is also expected to last longer in New Jersey. Warmer average temperatures can spur a dramatic increase in evapotranspiration (the release of moisture from open water and soils by evaporation and from plants by transpiration) from the leaves of plants and from the soil (Parmesan and Hanley 2015). This increase in average summer temperature, combined with a deficit of soil moisture, could have detrimental effects on seedling establishment and spur dramatic shifts in plant communities (Butler-Leopold et al. 2018). Drier forest soils will lead to declines in interior forest plants such as sweet cicily (*Osmorhiza spp*.), blue cohosh (*Caulophyllum thalictroides*), blue-bead lily (*Clintonia borealis*), and trilliums (*Trillium spp*.); blue-bead lily and two species of *Trillium* are listed as rare species in New Jersey, *Trillium grandiflorum* being state endangered (Rustad et al. 2012). Drought-resistant generalists and invasive species will likely expand and dominate under these conditions (Frumhoff et al. 2007, Parmesan and Hanley 2015).

> ***"It is highly likely that the effects of climate change will help facilitate the range infilling and expansion of invasive plant species."***

5.6.1.5 Invasive Plants

Introduced species are projected to respond positively to the effects of climate change, directly or indirectly (Frumhoff et al. 2007, Bradley et al. 2010, Rustad et al. 2012, Butler-Leopold et al. 2018, Hoegh-Guldberg et al. 2018, Manes et al. 2021). Invasive species are able to disperse over long distances, establish rapidly in disturbed systems, and often have tolerance to wide climatic conditions relative to native species (Finch et al. 2021). A recent analysis of 13,575 plant species and their potential ranges concluded that invasive plants, compared to natives, have not even begun to reach their hypothetical range limits within the continental United States (Bradley et al. 2015). It is highly likely that the effects of climate change will help facilitate the range infilling and expansion of invasive plant species (Pitelka 1997, Bradley et al. 2015, Hoegh-Guldberg et al. 2018). Wang et al. (2019) used species distribution modeling to predict suitable future habitats of invasive plants. Coastal and high latitude ecoregions, such as temperate forests and coastal rivers, saw intense encroachment by invasive species under climate change. New Jersey forests are among the terrestrial ecoregions with the highest potential for invasive plant expansion (Wang et al. 2019).

Changes to disturbance regimes such as fire, flood, and hurricanes generally increase physical disturbance and nutrient enrichment, to which invasive plants generally respond positively to the increased opportunities for colonization and reduced competition (Leishman and Gallagher 2015). Intense and severe ice storms, thunderstorms, hurricanes, and nor'easters will become more powerful and, in some cases, increase in frequency as climate change progresses (Rustad et al. 2012, Rustad and Campbell 2012, Butler-Leopold et al. 2018). New Jersey will be subject to more intense storms during both winter and summer months (Frumhoff et al. 2007, Butler-Leopold et al. 2018). These extreme climatic events increase the likelihood of the introduction of invasive species via propagule dispersal (Leishman and Gallagher 2015).

ASIAN BITTERSWEET

These storms have the potential to cause high-intensity disturbance to the forests of New Jersey, creating large canopy gaps and littering the ground with woody debris (Rustad and Campbell 2012, Butler-Leopold et al. 2018). Many forests in New Jersey are subject to unnaturally high deer densities and inundated with a large number of invasive plant species (Van Clef 2004, Rustad et al. 2012, Kelly 2019). Gaps created by intense storms will likely create opportunities for invasive plants to establish and crowd out any native regeneration, reducing the diversity of native herbaceous plants, shrubs, and trees (Rustad et al. 2012, Butler-Leopold et al. 2018). Older, more intact forest plant communities are not immune to this threat. For example, multiflora rose (*Rosa multiflora*), a prolific and aggressive invasive shrub, frequently utilizes gaps as "springboards" to invade intact interior forest (Dlugos et al. 2015). Another invasive shrub, alder buckthorn (*Frangula alnus*), is also known to rapidly occupy the forest floor directly beneath canopy gaps (Burnham and Lee 2010). Invasive plant species are a substantial problem, constituting one of the largest threats to native regeneration within canopy gaps (Massad et al. 2019).

Invasive plants also pose a substantial threat to the rare plant species of New Jersey (NJNHP 2025). There are over 1,000 non-native plant species established in New Jersey (Snyder and Kaufman 2004). Forest damage caused by more intense storms will only serve to facilitate the further spread of non-native and invasive plants in New Jersey. As the climate becomes less optimal for native species, and as extreme weather and disturbance events become more frequent and intense, natural communities are likely to have lowered biotic resistance and thus become more susceptible to invasive species (Finch et al. 2021). Current management tools to combat invasive plants may not be as effective; biocontrol species must adapt to the changing climate just as their host species do. Under elevated CO_2, the herbicide glyphosate was less effective on some invasive plants (Finch et al. 2021).

Wild plants and communities in New Jersey face a myriad of challenges associated with climate change. Rising sea levels, changing precipitation regimes, and more severe storms represent substantial threats. Shifts in phenologies and species' ranges affect interactions with other species and community composition. Climate change negatively impacts plant biodiversity through changes in temperature, precipitation, atmospheric CO_2 concentrations, and invasive species spread. Climate change may lead to plant species extinctions through impacts to biodiversity and ecosystem services (Kariyawasam et al. 2021).

5.6.2 Terrestrial Animals

In New Jersey and elsewhere, rising sea levels will inundate animal habitats, particularly in low-lying areas such as wetlands and beaches. This will lower the amount of habitat available for terrestrial animals, especially as coastal communities continue to armor coastlines and prevent systems from migrating naturally. After storm and erosion events, replenishment of ocean and estuarine beaches may also impact habitat availability and/or quality for species. Moreover, as temperatures and precipitation patterns shift, species compositions may also change, particularly at the edges of their current ranges. Two recent examples in New Jersey include Royal Terns (*Thalasseus maximus*) and White Ibis (*Eudocimus albus*), which are undergoing a range expansion from their more traditional southern nesting areas, presumably due to the warming climate in the state (Ramirez-Garofalo et al. 2025). They both began nesting in New Jersey in earnest in the early 2020s. They are both flourishing, but it remains to be seen if they will outcompete other species using the same habitat and food resources, including those that have a conservation status.

Many bird species will be affected by climate change worldwide. Population declines have occurred across much of the North American avifauna (birds) over the past 50 years (Rosenberg et al. 2019). This biodiversity loss is due to habitat loss and modification, agricultural intensification, coastal development, and direct anthropogenic mortality, all of which are exacerbated by climate change. The rapid climatic and habitat changes that are expected to occur because of climate change could lead to population declines, relocation of species, and local extinctions (Audubon 2019). Additionally, bird species are good indicators of ecological change and are early responders to climate changes. One recent study on the Edwin B. Forsythe National Wildlife Refuge estimated that the Saltmarsh Sparrow (*Ammospiza caudacuta*), a globally endangered species, population may reach a quasi-extinction threshold by 2040 due to habitat loss from sea-level rise and predation (Roberts et al. 2019). Similar results were found regarding Saltmarsh Sparrow population decline along the rest of coastal New Jersey, as far north as the Meadowlands (Correll et al. 2017). According to an Audubon study (Audubon 2019), 29% of New Jersey's 248 bird species are vulnerable to climate change, including the American Goldfinch (*Spinus tristis*), which is the State bird of New Jersey.

Of all avian species, shorebirds are particularly sensitive to the effects of climate change. Of 49 species that were evaluated in one study, 90% were predicted to experience an increased risk of extinction (Galbraith et al. 2014). Shorebirds are more highly vulnerable to climate change than other bird species for a few reasons. First, the majority of shorebird species migrate, breed, or winter in areas that will be severely affected by climate change such as low-lying, coastal breeding areas. For example, some ground-nesting birds are seeing declines in the number of nesting sites, which is at least partially attributed to a reduction in habitat suitability because of flooding. For example, the

SALTMARSH SPARROW

> ***"...the Saltmarsh Sparrow, a globally endangered species, population may reach a quasi-extinction threshold by 2040 due to habitat loss from sea-level rise and predation."***

state endangered Black Skimmer nested in upwards of 20 colonies in the 1970s and 1980s. In 2015 there were 10 colonies, and in 2024 there were just three (Davis and Heiser 2024). The overall number of adults has remained stable, but there is danger in having too few colonies, as this results in all colonies needing to perform well to keep the population stable or growing. Second, migration exposes shorebird species to high risks of changing weather patterns, including the increase in intensity of storms. Third, ecological synchronicities are necessary for many species, especially regarding the availability of food sources. For example, shifts in spatial and temporal overlap between horseshoe crabs and red knots could be problematic (Smith et al. 2011). Horseshoe crab spawning and shorebird stopover must match temporally in Delaware Bay for eggs to be available as food for red knots. However, onshore winds can result in reduced spawning activity by horseshoe crabs during shorebird stopover. Climate change-induced increases in severe storm frequency and changes in onshore winds could impact food availability (i.e., horseshoe crab eggs) for migratory shorebirds and reproductive success for breeding shorebirds, as eggs and chicks can be swept away by floods during peak breeding season.

Shorebirds and other migratory bird species must arrive and depart from their breeding grounds in synchronization with the peak food and nesting site availability. Shifting temperatures across seasons could alter the phenologies (life cycle events) of bird species so that they are no longer synchronized. This lack of synchronization could lead to lower reproductive rates for migrants (Carey 2009). Non-migratory birds will also be impacted by mismatches in food and nesting site availability due to changes in precipitation and/or temperature.

Although many of the effects of climate change will be negative for animal species, some effects can be positive. For instance, coastal storms can benefit species by creating new habitat (Maslo et al. 2019). Specifically, in New Jersey, Superstorm Sandy created nesting habitat for three of four avian species studied (American Oystercatcher, *Haematopus paliatus*; Least Tern, *Sternula antillarum*; and Piping Plover, *Charadrius melodus*). Black Skimmers (*Rynchops niger*) were the only species assessed where nesting habitat decreased as a result of the storm. Unfortunately, much of this newly formed nesting habitat was located outside of existing reserve boundaries and in areas that are inhabited by humans. In many of these non-protected areas, natural resources were not the main concern because infrastructure (e.g., roads, houses, access points, etc.) was damaged by the storm. Since most of the new nesting habitat created by the storm was in developed areas, these areas were rebuilt for human use instead of conserved for wildlife.

Many non-avian species will also be affected by climate change, including many insect species that are listed as Species of Greatest Conservation Need. The impacts of climate change are highly variable across the hundreds of different insect species that face negative impacts. Monarch butterflies (*Danaus plexippus*, State Special Concern) have declined in North America over the last two decades (Thogmartin et al. 2017). This decline in Monarch butterfly populations is in part attributed to climatic factors. In particular, breeding season temperature is an important determinant of annual variation in abundance for Monarch butterflies. An increase in extreme weather events and climate variability can have a significant impact on migrating Monarchs that are caught in sudden changes of weather conditions. The longer growing season in the fall leads to many late emerging adult Monarchs that face being trapped by the sudden onset of cooler weather. Bumblebee populations are also being negatively affected by climate change (Kerr et al. 2015). For many species, geographical ranges are expanding toward the poles in response to climate change. Unfortunately, bumblebees have been unable to expand their northern range limits to track the recent warming trends. Some insect species, like invasive spotted-wing drosophila (*Drosophila suzukii*), are having a range expansion due to warming conditions (Shope et al. 2023). *D. suzukii* first invaded New Jersey in 2011 and have since surpassed the native blueberry maggot fly (*Rhagoletis mendax*) as the primary target of insecticide treatment in blueberry crops. Larger population sizes and increased activity of *D. suzukii* were attributed to decreases in winter freezing days and increases in summer growing degree days. Trap sampling showed that the first capture of *D. suzukii* each year happened earlier over time. Since the arrival of *D. suzukii*, native *R. mendax* have been first captured later in the growing season; in 2021, *R. mendax* were captured 24-31 days later than the historic range. By 2050, climate projections indicate that *D. suzukii* are expected to arrive two weeks earlier due to warming temperatures. Invasive species often have a competitive advantage over native species, which may be exacerbated by opportunities for range expansion with changes in temperature and precipitation patterns.

Climate change-related sea-level rise may negatively impact many coastal species of insects that depend on beach and dune habitats or coastal marshes. Beach and dune areas are inhabited by listed and Species of Greatest Conservation Need, such as Northeastern Beach Tiger Beetle (*Habroscelimorpha dorsalis dorsalis*, Federally and State Endangered), that are threatened by inundation and erosion of their coastal beach and dune habitats (NJDEP 2022b). Loss and retreat of coastal saline and brackish marshes and saltwater intrusion to inland habitats are leading to decreases in suitable habitat for species such as the Aaron's Skipper (*Poanes aaroni*) and Rare Skipper (*Problema bulenta*, Special Concern) (NJ DFW 2018).

Climate change-related changes to temperature regimes are pushing many northern species of insects out of the southern edge of their range in New Jersey, particularly in the northern part of the state (NJ DFW 2018). New Jersey has recently lost several species of listed, Species of Greatest Conservation Need, and rare butterflies to the northern retreat of their range, including Harris' Checkerspot (*Chlosyne harrisii*), Myrina Fritillary (*Boloria myrina)*, and Arctic Skipper (*Carterocephalus palaemon*). Increasing temperatures render the habitat no longer suitable for these species.

Extreme weather events caused by climate change, including more frequent droughts and heat waves, decrease butterfly numbers overall (NJ DFW 2018). Drought conditions can lead to butterfly chrysalises desiccating and perishing. Heat waves cause additional stress on adult butterflies and present challenges for their survival and nectaring if a combination of heat waves and dry conditions reduce nectar resources. More frequent and severe rainfall events can cause direct mortality to butterflies. Changes to precipitation regimens that lead to increased rainy, cloudy, and cool conditions during flight windows for listed or rare species can decrease survival and reproduction because these insects are dependent on the sun and appropriate temperatures to be active.

In 2014, the spotted lanternfly was first found in the United States in Pennsylvania, and this invasive species has already spread to other surrounding states including New Jersey (NJDA 2022). Spotted lanternflies will likely extend their range throughout the Northeastern and Southeastern United States as temperatures continue to warm (Jung et al. 2017, Maino et al. 2022). One study even suggested that spotted lanternflies may spread to the west coast of the United States, specifically California, by 2033 (Jones et al. 2022). As the spotted lanternfly range extends, it will continue to negatively impact hardwood trees and agricultural crops including vineyards (Urban 2020).

The effects of climate change on animals will likely include loss of habitat, population declines, increased risk of extinction, decreased reproductive productivity, and shuffled species distribution. Although some effects of climate change may be positive (such as the increased habitat availability for avian species following Superstorm Sandy), conservation managers will need to allow for more fluidity as the spatial distribution of animal species changes.

MONARCH BUTTERFLY

CHAPTER 5.7

FRESHWATER SYSTEMS

KEY FINDINGS

- **Freshwater fish, like brook trout, that need cold-water habitats are expected to lose habitat as water temperatures increase due to climate change.**
- **As waters warm, New Jersey's waterways are becoming more hospitable to invasive fish species.**
- **As sea level rises, saltwater intrusion of coastal freshwater lakes can result in fish kills.**
- **Reptiles with temperature-dependent sex determination could experience changes in sex ratios as New Jersey temperatures increase.**
- **Many species of freshwater invertebrates will be affected by changes in the water cycle and decreasing habitat availability due to climate change.**

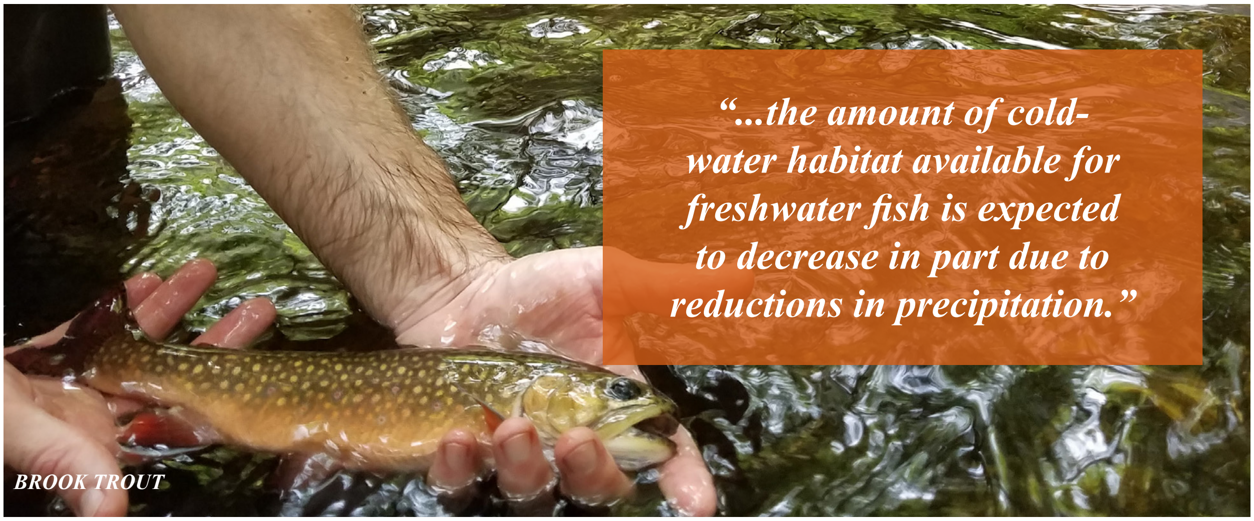
5.7 Freshwater Systems

In freshwater systems, fish, reptile, and amphibian species, as well as less charismatic species (e.g., invertebrates), will be negatively impacted by climate change. As temperature and precipitation patterns shift, the ecology of freshwater systems will also change, particularly in shallow streams where these changes will be the greatest. Habitat fragmentation problems will likely increase as some aquatic areas become too warm for cold-water species. Increased frequency and duration of droughts will also be problematic as the habitat availability of vernal ponds decreases. Adaptation strategies will need to focus on improving connectivity between habitats to decrease fragmentation.

5.7.1 Fish

In response to increasing temperatures and fluctuations in precipitation, the ecology of freshwater systems will change. Fluctuating extremes in precipitation are expected in New Jersey as a result of climate change (Chapter 4.2.3). More intense precipitation events will cause flooding and erosion in streams altering current habitat conditions (Chapter 5.2), and these issues may be exacerbated in areas already impacted by stormwater runoff. Moreover, flooding events can create connectivity and be a vector for the distribution of invasive species. Drought, in comparison, will likely promote crowding, increased competition, physiological stress, and mortality. In particular, seasonal weather patterns affect brook trout (*Salvelinus fontinalis*) population dynamics (Kanno et al. 2016). Young-of-the-year abundance is a key driver of brook trout population dynamics that is mediated by seasonal weather patterns. Increased winter precipitation will have negative impacts on young-of-the-year abundance and population dynamics of brook trout, whereas changes in other seasons may have positive or negligible effects. The timing of life history events, such as migration and spawning, will be altered as well. For instance, as water temperature has been shown to be the crucial trigger in initiating spawning for American Shad (*Alosa sapidissima*) in the Hudson River (Chang and Chen 2024), and populations in the Columbia River now begin Spring migration earlier in response to warmer springs and summers (Quinn and Adams 1996), we expect to see similar responses to warmer springs from American Shad, and other herring species, in the Delaware River.

Furthermore, the amount of cold-water habitat available for freshwater fish is expected to decrease in part due to reductions in precipitation (Jones et al. 2013). Changes in stream temperatures, flows, and spatial extent of suitable thermal habitats for freshwater fish have been modeled using a range of projected changes in temperature and precipitation caused by increased greenhouse gases. In general,



> ***"...the amount of cold-water habitat available for freshwater fish is expected to decrease in part due to reductions in precipitation."***

BROOK TROUT

the spatial distribution of cold-water fish species is projected to decrease and be replaced by warmer-water tolerant fish. Nonnative brown trout (*Salmo trutta*), established throughout New Jersey, are more tolerant of warmer temperatures than native brook trout. Besides displacement, stream warming may have other implications. Another native cold-water species, slimy sculpin (*Cottus cognatus*), has coexisted with brook trout (*Salvelinus fontinalis*), but brown trout populations have shown evidence of altering slimy sculpin population structure (Zimmerman and Vondracek 2006). The study suggests that native and nonnative trout do not fill the same niche, and the expansion of nonnatives facilitated through climate change will have additional community-level effects. Moreover, many of these warm-tolerant species are considered less desirable by recreational fisheries. Accounts of New Jersey trout streams showing cold-to warm-water tolerant species shifts because of direct or indirect thermal impacts have already been documented and will likely increase as temperatures rise. Under a very high emission scenario, cold-water fisheries are projected to decline by approximately 50% by 2100 and to be confined to mountainous areas in the western United States and the Appalachians. In New Jersey, the majority of current cold-water fisheries are projected to be warm-water fisheries by 2100 regardless of climate scenario (Zimmerman and Vondracek 2006).

Climate change will also lead to increases in average air temperatures in New Jersey (Chapter 4.1.4). Brook trout will experience growth and physiological stress responses if subjected to increased surface water temperatures (Chadwick and McCormick 2017). Although surface water temperatures are not expected to increase at the same rate as air temperature, a significant portion of stream water is derived from more temperature-moderated groundwater inputs (Kaandorp et al. 2019). When brook trout were subjected to chronically elevated or daily oscillating temperatures and then monitored for growth and physiological stress responses, growth rate decreased at temperatures above 60.8°F (16°C) (Chadwick and McCormick 2017). Plasma cortisol, a stress hormone, increased with temperature and was 12 to 18-fold higher at 71.6 to 75.2°F (22 and 24°C), respectively, than at 60.8°F (16°C). Elevated temperatures induced cellular and endocrine stress responses and provided a possible mechanism by which growth was limited at elevated temperatures.

As with many other species, warming temperatures can also alter the distribution and abundance of freshwater fish. Higher temperatures could further warm rivers and streams, making them less suitable for cold-water fish (Trumbo et al. 2014). However, freshwater fish species in some areas may be buffered from the immediate impacts of air temperature change due to the thermal inertia of water (Snyder et al. 2015, Culler et al. 2018). Air temperatures tend to increase at a greater rate than stream temperatures, especially in areas with groundwater inputs. However, even small increases in water temperature extended the duration of physiologically stressful conditions for fish. These changes in water temperature are likely to be highly site-specific, as additional key determinants appear to be shading from riparian vegetation, cold water input from springs, surrounding land use, and elevation (Trumbo et al. 2014). A follow-up study developed a framework to estimate the effects of groundwater seepage on stream temperature in unsampled locations (Johnson et al. 2017). Geomorphological (e.g., stream slope, elevation, network length, etc.) and precipitation predictors of groundwater influence varied in their importance between watersheds, suggesting differences in spatial and temporal controls of recharge dynamics and the depth of groundwater source.

New Jersey’s waterways are becoming more hospitable to invasive fish species (NJDEP 2025f). As waters warm and flow patterns become altered, species like the northern snakehead (*Channa Argus*) and flathead catfish (*Pylodictis olivaris*), already established and expanding their range in New Jersey, have a distinct advantage (Lynch et al. 2016). Both species are “thermophilic,” or warmth-loving, so as rivers and lakes warm, they will find more suitable habitats to thrive in. Expansion will put immense pressure on native fish, which may be less adaptable to these rising temperatures. More intense rainstorms and flooding can provide conduits for invasive fish into new waterways. Snakeheads are known for their ability to make short overland movements and can survive out of water for up to four days, which makes them incredibly effective at expanding their range. In contrast, drought conditions can concentrate fish in smaller, more stressful areas, increasing competition and making native species even more vulnerable.

Coastal freshwater lakes that were historically managed as popular recreational fisheries are being significantly impacted by saltwater intrusion. Hooks Creek Lake at Cheesequake State Park experienced major saltwater intrusion during Superstorm Sandy in 2012, that led to a massive fish kill (American Littoral Society 2012). Freshwater fish that were present, such as largemouth bass and bluegill sunfish, cannot tolerate high levels of salt in their environment, and the lake experienced a significant fish kill.

Overall, climate change poses a multifaceted threat to New Jersey's freshwater fish communities. From rising water temperatures and altered flow regimes that stress native species and favor invasive ones, to increased saltwater intrusion that can decimate entire fish populations, the state's aquatic ecosystems are facing a complex array of challenges. To address these threats, management strategies should focus on identifying and preserving cold water resilient habitats, aggressively controlling the spread of invasive species, and expanding and preserving natural areas, along with implementing green infrastructure, to mitigate the effects of intense rain events on critical fish habitats. Without such measures, New Jersey risks losing some of its most iconic native fish species and the recreational fisheries they support.

5.7.2 Reptiles and Amphibians

As with many other species, climate change will affect reptile and amphibian populations in multiple ways. Higher temperatures and altered precipitation patterns will warm freshwater and brackish water systems, leading to negative consequences for reptiles and amphibians in New Jersey. An increase in droughts throughout the state will decrease the availability and size of freshwater habitats. Lower water levels and depths in streams, for example, can increase the rates of predation by mammals on aquatic-dependent reptiles occupying those habitats with fewer sheltered areas to flee or hide (Kamm et al. 2024). Also, as the sea level continues to rise, shoreline erosion will increase, low-lying coastal areas will flood, and wave heights will be increased during storms. These impacts of sea-level rise will decrease habitat available for reptiles and amphibians, especially those species located close to the coast. Many reptiles and amphibians have limited dispersal abilities and are thus particularly vulnerable to rapid changes in habitat availability

> ***"...increased storms and extreme temperatures could contribute to unusual mass mortality and cold stunning events in diamondback terrapins."***

(Whitfield Gibbons et al. 2000, Butler 2019). The overall vulnerability of reptiles and amphibians to the effects of climate change has not been assessed in New Jersey; however, an assessment has been performed in a neighboring state.

Severe changes in weather, including an increased number and intensity of storms, as well as more extreme temperatures than typical, will impact many species. For example, increased storms and extreme temperatures could contribute to unusual mass mortality and cold-stunning events in diamondback terrapins, *Malaclemys terrapin* (Egger 2016). Wood turtles (*Glyptemys insculpta*) will be directly impacted by changes in temperature and precipitation by influencing their seasonal ecology (e.g., mating, emergence, nesting), reproductive success, overwintering physiology, and foraging efficiency (Jones et al. 2018). Increasing winter and summer temperatures and a changing precipitation regime will change habitat quality for wood turtles by elevating stream temperatures and reducing dissolved oxygen content of streams. Moreover, increased temperatures could lead to changes in sex ratios in reptiles with temperature-dependent sex determination (Schlesinger et al. 2011, Butler 2019, Roberts et al. 2023).

Many amphibian species depend on the availability of vernal pond habitat; however, vernal ponds may disappear for periods due to drought and altered precipitation patterns from climate change (Brooks 2009). Some vernal ponds may even disappear because of droughts (Cartwright et al. 2022). Not only may some ponds disappear, but the remaining ponds will become increasingly isolated and less likely to properly support amphibian metapopulations that depend on connectivity between ponds. On the other hand, in recent years, some vernal ponds in New Jersey have unexpectedly held water year-round, resulting in a reduction of suitable habitat for specialists like eastern tiger salamander (*Ambystoma tigrinum*) due to predatory fish colonizing the space (pers. comm. with DEP F&W; October 2025). Sea-level rise will also introduce saltwater into coastal freshwater systems, including vernal ponds. Some low-elevation freshwater wetlands may become brackish, particularly if groundwater withdrawal is high in the area (Werner and Simmons 2009). This increase in salt content of the water in vernal ponds may negatively affect amphibian species, many of which are already at risk of extinction. Coastal amphibian populations may be especially at risk because of the threat of more intense tropical cyclones (Kopp et al. 2025) to cause increased saltwater overwash into vernal ponds (Schlesinger et al. 2018).

Sea-level rise will decrease the amount of habitat available for some reptile and amphibian species. For example, diamondback terrapins, an estuarine species, depend on the availability of salt marsh areas for nesting (Egger 2016). As sea levels rise, the amount of habitat available on nesting beaches will likely decrease. Atlantic Coast leopard frogs (*Rana kauffeldi*) will also be susceptible to the impacts of sea-level rise because their preferred freshwater habitats tend to be located in close proximity to the coast (Schlesinger et al. 2018).

The vulnerability of reptiles, amphibians, and other at-risk species to climate change has been evaluated in New York (Schlesinger et al. 2011). This vulnerability assessment assumed that climate change vulnerability was the result of two factors: exposure and sensitivity. Exposure parameters included temperature, moisture, and sea-level rise, in addition to other factors, and sensitivity included genetic diversity, dispersal capability, past climate regime, phenology, and other factors. Overall, most reptile populations were rated as stable or likely to increase, with the exception of bog turtles (*Glyptemys muhlenbergii*) and mud turtles (*Kinosternon subrubrum*), which were listed as extremely vulnerable and highly vulnerable, respectively, to the effects of climate change. Likewise, two amphibian species were listed as extremely vulnerable (eastern tiger salamander, *Ambystoma tigrinum*; hellbender, *Cryptobranchus alleganiensis*) and three as highly vulnerable (marbled salamander, *Ambystoma opacum*; mink frog, *Rana septentrionalis*; and eastern spadefoot, *Scaphiopus bolbrooki*). Many of these vulnerable species also reside in New Jersey, with the exception of hellbenders and mink frogs.

In conclusion, some reptile and amphibian populations in New Jersey may experience shifts in distribution range, reproductive ecology, and habitat availability as the climate continues to change. The expected increases in temperatures, frequency and intensity of precipitation, droughts, and sea-level rise will all continue to decrease habitat availability for reptiles and amphibians. Not only will the overall amount of habitat available decrease, but there will be problems with connectivity between habitats (i.e., fragmentation). Climate change adaptation strategies will need to focus on creating a well-connected landscape to allow reptile and amphibian species to move to appropriate habitats (NJ DFW 2019).

5.7.3 Invertebrates

Freshwater aquatic invertebrates can be found throughout New Jersey's freshwater systems. While often overlooked, they provide several important benefits, including a critical link in aquatic food webs, accelerating nutrient cycling processes through the consumption of organic matter, and as bioindicators of water quality. Climate change effects are expected to affect countless species of freshwater invertebrates due to the projected impacts resulting from increased temperature, altered precipitation patterns, and rising sea level. One recent study in the Northeast generated species distribution models for 15 species of dragonflies using ensemble climate model projections through 2080 (Collins and Mcintyre 2017). This study determined that climate change would decrease habitat availability for all 15 species. Depending on the species, the results indicated that by 2080 climate change effects could reduce suitable habitat by 45 to 99%. In addition, much of the remaining habitat in 2080 was projected to become less suitable, which has implications for numerous other species as well.

Diverse and abundant invertebrate assemblages provide numerous benefits to aquatic environments, influencing nutrient cycling, decomposition rates, and food availability (Wallace and Webster 1996). These communities allow for efficient processing of organic matter (e.g., leaves), which is consumed and accumulated into their body tissues. When healthy invertebrate assemblages are present, they are the base of many food webs and are consumed by countless other larger organisms, including mammals, birds, fish, reptiles, and amphibians (Baxter et al. 2005). However, small changes in temperature (e.g., 2.7°F [1.5°C]) can result in species-specific responses, which could potentially shift the timing of insect emergences and disrupt relationships with predators that rely on them (Cheney et al. 2019). Responses to changing climactic cues (e.g., seasonal temperatures and precipitation patterns) are expected to vary by taxa due to behavioral and physiological differences (Rodenhouse et al. 2009, Cheney et al. 2019).

Hydrology is among the most important influences on freshwater ecological communities. Hydrological alterations, including changes in streamflow and availability of ephemeral habitat (seasonally available water sources that occur during wet conditions, such as winter and early spring in New Jersey), are anticipated to have negative impacts on invertebrate assemblages (Brooks 2009). One study found that in 67 rivers in the Northeastern United States, changes in hydrologic variables had significant impacts on invertebrate community assemblages, such as reductions in trophic structure, overall biodiversity, and species that are sensitive to water quality changes (Kennen et al. 2010). Increased temperature and changes in precipitation patterns are likely to alter hydrology to freshwater aquatic habitats. Localized changes in the timing and intensity of precipitation are already occurring (DeGaetano 2021a, Kim et al. 2022, Robinson et al. 2022) (Chapter 4.2.3) and are projected to continue in New Jersey (see Chapter 4.2.4), which is expected to drive increasingly variable streamflow, with a larger range of high and low flow conditions (Bjerklie and Sturtevant 2018). Increases in extreme precipitation events and annual precipitation totals implies increases in rates of streamflow. However, warmer temperatures and drier conditions will also intensify evapotranspiration rates, which could lead to lower stream baseflow conditions and extended low-flow periods between storm events (see Chapter 5.2).

The geomorphology of a stream (e.g., slope, geology, substrate) determines habitat quality and availability for the inhabiting species, and extreme precipitation can result in large-scale changes to stream geomorphology due to flooding and high streamflow conditions (Death et al. 2015). Streams can be impacted during extreme precipitation and flooding events from increases in runoff, streamflow, and in-stream erosion, introducing sediments, filling in interstitial spaces in stream substrates where many invertebrate species thrive, and washing organisms downstream of preferred habitat (Death et al. 2015). During flooding and high streamflow events, some invertebrates are resilient and able to find refuge to endure through the harsh conditions (Stamp et al. 2020). In the aftermath of high streamflow, recolonization often occurs if suitable habitat is still available. However, increased frequency and intensity of extreme precipitation and resulting high streamflow conditions are expected to cause more frequent disturbance and alteration to stream hydrology, resulting in deterioration of habitat quality and reductions in the abundance and diversity of invertebrate species (Stamp et al. 2020).

Climate change is also projected to increase the potential for more frequent and prolonged droughts (Trenberth 2011). Droughts and dry conditions reduce streamflow, raise water temperatures, and reduce oxygen levels, which can negatively impact many species (Boulton 2003). Previous research on hydrological changes indicates that changes in the timing and duration of inundation and streamflow, such as would be expected with increased frequency and intensity of droughts and dry conditions, would likely impact invertebrate species richness, productivity, and abundance (Brooks 2009). Hydrology is particularly critical to ephemeral waters. In New Jersey, ephemeral waters include vernal ponds and small streams that provide temporary habitat for a plethora of invertebrates. During drier periods, these habitats often dry up and can become less spatially available and less connected across the landscape (Cartwright et al. 2022), which can reduce opportunities for these communities to disperse and interact with one another.

The potential impacts of climate change on freshwater invertebrate communities is a research topic that is understudied. If climate change impacts result in the reduction of invertebrate abundances and diversity, as some studies have indicated, it could be expected to cause reductions in numerous invaluable ecosystem services and have devastating ripple effects on the local ecology by reducing the availability of food sources for numerous other species. Further investigation is warranted in order to better understand how invertebrates will respond to changing climactic cues, hydrologic intensification, and the compounding effects of climate change and habitat disturbance.

> ***“...small changes in temperature (e.g., 2.7°F [1.5°C]) can result in species-specific responses, which could potentially shift timing of insect emergences and disrupt relationships with predators that rely on them...“***

CHAPTER 5.8

MARINE ECOLOGICAL SYSTEMS

WESTERN ATLANTIC HARBOR SEAL — SANDY HOOK, NEW JERSEY

KEY FINDINGS

- **Current climate changes could result in more "dead zones" from hypoxic events, which are of particular concern for summer flounder which is commonly fished in New Jersey.**
- **Many commercially important shellfish species including mussels and oysters will develop thinner and frailer shells due to ocean acidification.**
- **As temperatures increase, environmental conditions in New Jersey estuaries may improve for invasive species like the clinging jellyfish.**
- **The effects of climate change will reduce available habitat for submerged aquatic vegetation.**

5.8 Marine Ecological Systems

Marine ecological resources are expected to be impacted in a variety of ways by climate change, particularly because of increases in temperature, intensity and frequency of storms, acidification, and hypoxia. This is of noteworthy concern due to the state's many commercially and recreationally important marine fisheries; however, other marine species, including mammals, invertebrates, and vegetation, may also be affected.

5.8.1 Mammals

Specialized diets, restricted ranges, or reliance on specific sites make many marine mammal populations particularly vulnerable to climate change (Silber et al. 2017). Marine mammal species play an important role in maintaining healthy habitats because any loss or change of habitat will not only affect these predatory species directly but will also ripple throughout various ecological systems (Askin et al. 2017). Despite their resilience, climate change has impacted marine mammals, particularly food sources and habitats. In particular, rising ocean water temperature will impact predator-prey relationships, which in turn will impact migration, range and distribution shifts, as well as breeding success, and susceptibility to disease (Learmonth et al. 2006). However, the direct and indirect stressors that could potentially have dire consequences for marine mammals are unknown, and only predictions exist due to a lack of data. Marine mammals are probably one of the best sentinel organisms (i.e., organisms utilized to detect potential risks to humans by providing early warnings) in aquatic and coastal environments because many species have long life spans, feed at a high trophic level (i.e., mammals are high up on the food chain), and have extensive fat stores that can serve as depots for anthropogenic (human-caused) toxic chemicals (Reddy et al. 2001). Direct observations have been made of several marine mammal populations that illustrate responses to climate change. Marine mammal populations have been, and are expected to continue to be, affected by changing climate conditions (Lettrich et al. 2019).

Humpback whales (*Megaptera novaeangliae*) are seasonal migrants that utilize primary breeding sites in the West Indies and primary feeding sites

> ***"...climate change has impacted marine mammals, particularly food sources and habitats."***

in the Gulf of Maine, eastern Canada, western Greenland, Iceland, and Norway (Brown et al. 2018). However, some humpback whales feed in less well-studied areas, including the New York-New Jersey Harbor Estuary. From 2011 to 2019, there were 787 humpback whale sightings in this area (Smith et al. 2022b). The number of humpback whale sightings increased over this time period; however, more effort was extended to locate whales as the study progressed and thus this trend is likely biased (Brown et al. 2018, Smith et al. 2022b). Humpback whales feed on Atlantic menhaden (*Brevoortia tyrannus*), and there have been documented increases in larval menhaden along the Atlantic coast from 2000 to 2013 which may help explain the increase in whale sightings (Simpson et al. 2016). Furthermore, environmental DNA has been used to co-detect humpback whales and their prey sources (including Atlantic menhaden) in the New York Bight (Alter et al. 2022). Climate change may lead to mismatches between the arrival times of migrants and their food source. However, in this case, this interpretation should be made with caution because of the changes in effort by researchers in sighting humpback whales over time (Brown et al. 2018, 2022a).

Common bottlenose dolphins (*Tursiops truncatus*) are found throughout the world in both coastal and offshore waters. The dolphins found along the coast of New Jersey are part of the Western North Atlantic Northern Migratory Coastal stock and are considered depleted under the Marine Mammal Protection Act. New Jersey has been the approximate northernmost range of the stock in the northwest Atlantic Ocean and the northernmost destination of these seasonal migrants (Toth et al. 2011, Waring et al. 2011), but the northernmost range has extended to Long Island, New York (Whitt et al. 2015). When assessing the effects of climate change on animals, it is essential to study the species at the extent of their range because the changes from climate change may first be detected in the expansion or reduction of this range. The expansion of the bottlenose dolphin range to the New York and New Jersey Bight (coastal area off New York and New Jersey) may be triggered at least in part by the abundance of prey (Atlantic menhaden) in the area (Trabue et al. 2025).

Although the direct effects of climate change on bottlenose dolphins were not directly assessed, photo-identification surveys were conducted in southern New Jersey to determine seasonal occurrence, distribution, and movement patterns. During aerial surveys from 2008 to 2009, a total of 319 sightings of bottlenose dolphins were recorded from the beginning of March through mid-October (Whitt et al. 2015). It is unlikely that the seasonal appearance of bottlenose dolphins in New Jersey is directly determined by water temperature because bottlenose dolphin populations occur in water temperatures as low as 41°F (5°C) (Ross and Cockcroft 1990, Sykes 2002, Whitt et al. 2015). Rather, water temperature more directly affects the movements and temperature tolerances of prey. Steep-sided valleys like the New York and New Jersey Bight drive warmer waters towards the coastline, and that may be drawing in both the dolphins and their prey (Trabue et al. 2025). The primary prey of bottlenose dolphins along the east coast of the United States is sciaenid fishes and noise-making fish such as drums, croakers, weakfish, mackerel, and mullet (Barros and Odell 1990, Gannon and Waples 2004, Trabue et al. 2022, 2025). These species occur along the New Jersey shoreline during the summer months, seasonally migrate to and from New Jersey during spring and fall, and overwinter south or offshore during winter months (Able and Fahay 1998). Future studies plan to determine how climate change will affect the distribution of prey, water temperatures, and high-quality dolphin habitat.

Western Atlantic harbor seals (*Phoca vitulina concolor*) will also be impacted by climate change. From 1996 to 2011, Western Atlantic Harbor Seals were monitored on their regional overwintering grounds in the Great Bay–Mullica River estuary in southern New Jersey (Toth et al. 2018). This overwintering ground is the southern limit of routing occupancy for Atlantic harbor seals in the Northeastern United States and thus is an important population to assess considering potential climate change impacts. Over the 15-year time frame, the maximum number of individuals counted at one time increased from 100 individuals in 1996 to 160 seals in 2011. Since 2011, additional counts have been conducted using a spotting scope at the Rutgers University Marine Field Station (pers. comm. with Roland Hagan; Feb. 2020). In February 2020, a record high of 230 harbor seals was observed at Fish Island in Great Bay, New Jersey. These results are valuable in monitoring future changes in habitat use, potentially resulting from climate change.

In conclusion, some of the effects of climate change on marine mammal populations will be direct, such as bottlenose dolphin skin lesions from low water temperature and salinity (Trabue et al. 2024). However, there will also be many indirect effects of climate change such as changes in prey availability, abundance, and migration patterns. In general, marine mammals tend to be tolerant of changes in water temperature. Therefore, the main concern for marine mammal populations in New Jersey is likely the potential shift in the distribution of prey sources because of ocean warming.

5.8.2 Finfish

Finfish are the most diverse group of vertebrates, and the effects that climate change-related stressors have on fish species are diverse and complex. All species have an optimum range of temperature, pH, salinity, and dissolved oxygen, in which conditions are ideal for growth, survival, and reproduction. As conditions depart from this optimum range, organisms experience increased physiological stress (Deutsch et al. 2015) and energy costs. Warming water, changing precipitation patterns, and altered water chemistry may result in changes in growth, survival, reproduction, migration patterns (Tamario et al. 2019), and distribution (Morley et al. 2018). When the ocean is warmer and more acidic, it is less productive.

> ***“Catch location for summer flounder has shifted latitudinally northward... rapid range shifts are linked to significantly reduced population sizes.”***

Range shifts have been observed in many targeted marine species (Pecl et al. 2017). Summer flounder, or fluke, is targeted commercially in New Jersey and is the most sought-after species by saltwater anglers. In 2018, the Atlantic Coastal Cooperative Statistics Program estimated that the New Jersey commercial summer flounder fishery landed over $4.5 million in fish. Catch location for summer flounder has shifted latitudinally northward from 1996 to 2014 (Dubik et al. 2019). Recent research suggests that rapid range shifts are linked to significantly reduced population sizes (Chaikin et al. 2024).

Phenology is the link between seasonal environmental patterns and life history events, like spawning in fishes. The environmental cues that trigger these activities are complex (Šmejkal et al. 2023) and include water temperature, day length, lunar phase, and freshwater inflow. If the timing of the cues changes, phenological mismatches can occur (Ferreira et al. 2023), e.g., when prey availability no longer coincides with reproduction and development, larvae may have reduced growth and survival. This effect may be amplified by higher metabolic needs of the predator and other changes in the prey population that are also caused by climate change (Stock et al. 2017). There is evidence, however, that range shifts in some fishes can mitigate climate change impacts associated with phenological mismatches (Asch et al. 2019).

Climate change is an existential threat to marine fisheries (Mid-Atlantic Fishery Management Council 2025, NOAA 2025g) and presents a significant challenge to fisheries management (Xu et al. 2024). New Jersey’s commercial and recreational marine fishing industries have social and economic value; the economic value alone exceeds $2 billion annually (National Marine Fisheries Service 2024). Movement of stocks will create significant obstacles to the industry due to increased distances fishermen must travel to reach productive fishing grounds, which results in raising fuel, food, and maintenance costs (Morley et al. 2018). Extreme weather events put vessels and shoreside support communities at risk (US EPA 2025b). It remains difficult to disentangle the effects of climate change from those of other human-generated influences. This is especially true of populations that may change in abundance or distribution in ways that could be attributed to either climate-induced and/or harvest-induced impacts. For instance, shifts in black sea bass and scup, two economically important species in the Mid-Atlantic and New Jersey, have been identified as climate-driven, while summer flounder distribution shifts have been attributed to a decrease in fishing pressure (Bell et al. 2015). These shifts have entered directly into ongoing policy debates about the appropriate management response for summer flounder. Preventing overfishing and developing management strategies that are robust to environmental change are essential to maintain and rebuild fisheries capacity and support livelihoods in a warming ocean.

5.8.2.1 Effects of Changing Temperature and Precipitation Regimes

Physical environmental changes, like temperature and precipitation, have direct and cascading effects on the marine ecosystem. These and other anthropogenic factors often interact in complex ways that may amplify overall environmental damage (Gill and Malamud 2017), adversely affect water quality, and degrade fish habitat (Brander 2007).

Our oceans have absorbed 90% of the heat generated by the greenhouse effect (NASA 2025c) and the surface layer, where oxygen is produced and most marine life is found, holds most of it. As surface waters warm, they become more buoyant and less likely to mix with deeper, nutrient-rich water. Long-term data sets indicate that it is very likely that stratification of surface waters has been increasing since 1970 (Bindoff et al. 2019). Prolonged stratification can result in nutrient depletion in surface waters and reduced oxygen in deeper waters. Conversely, more frequent and intense weather events as well as increased outflow promote mixing.

The Mid-Atlantic Bight (i.e., the coastal region from Massachusetts to North Carolina) Cold Pool is an ecologically important example of seasonal ocean stratification. Forming off the coast of New Jersey in the spring, this layer of cold water lies beneath warm surface water and functions as a thermal refuge for a variety of fish and their prey. The Cold Pool is warming and shrinking, and these changes will affect the productivity of the ecosystem and fish populations (Friedland et al. 2022).

Most fishes and all invertebrates are ectotherms, meaning their internal temperature is regulated by their environment. Biochemical reaction rates and enzyme function are directly related to temperature, and as body temperature rises within a species' zone of tolerance, so does metabolic rate (Kovacevic et al. 2019). Food and oxygen requirements increase. Fishes are particularly vulnerable to global warming (Alfonso et al. 2021), however, gradual, long-term changes in temperature may lead to acclimatization in fish, such as alterations in metabolic and digestive enzyme profiles (Volkoff and Rønnestad 2020).

Changes have been observed in the abundance and spatial distribution of commercially and recreationally targeted fish species in recent years. In a seminal study, trends over the time period from 1968 to 2007 were analyzed for average biomass, depth, temperature, and the area occupied by each of 36 fish stocks along the Northeastern United States continental shelf (Nye et al. 2009). Clear shifts in spatial distribution were demonstrated for most of the fish stocks examined, with 24 of the 36 stocks exhibiting statistically significant changes associated with large-scale warming. Projections of habitat shifts due to temperature changes (Morley et al. 2018) and climate vulnerability assessments (Hare et al. 2016) are critical to predicting the impacts of climate change on marine stocks. Of stocks assessed by the Northeast Climate Vulnerability Assessment, about half of the species were forecast to experience a negative effect due to climate change (Hare et al. 2016). Other studies noted that populations that may be projected to respond positively to warming are unlikely to

> ***"More frequent high-intensity events could lead to more widespread damage of coastal habitats that are a vital fish nursery habitat…"***

maintain productivity gains and will reach a peak where continued warming drives these populations past their optimum thermal range (Free et al. 2019).

Altered precipitation patterns described in Chapter 4.2 of this report will affect the timing, frequency, and volume of freshwater inflow and ocean mixing. High-intensity storms are likely to occur more often, which can have damaging effects on coastal environments. More frequent and heavier runoff from rain events or dry periods could change salinity profiles, leading to changes in stratification, altered community structure, and population dynamics. Runoff causes degradation of water quality and pollution as rainwater carries nutrients, metals, chemicals, and other debris into a waterbody (Center for Climate and Energy Solutions 2019). Finfish like striped bass have shown decreased survival correlated with rainfall and pollution stressors (Uphoff 1989).

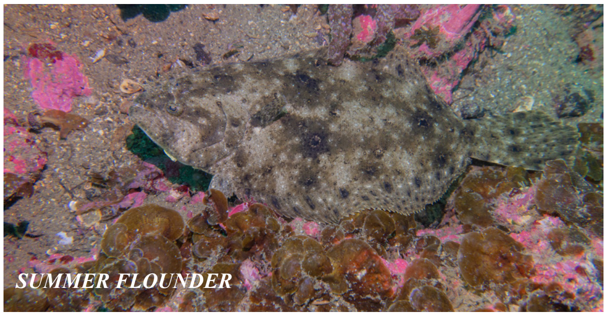
A range of other potential threats exists with the possibility of altered precipitation patterns in New Jersey. Heavy freshwater inputs to seawater can directly reduce the pH and increased rainfall in New Jersey has been linked to exacerbation of impacts of ocean acidification on important marine species (Pörtner et al. 2014). Increased storm activity or drought can cause physical damage or losses of fish spawning areas or wetlands. Physical and chemical water changes could alter fish spawning and juvenile survival. More frequent high-intensity events could lead to more widespread damage of coastal habitats that are vital fish nursery habitat (see Chapter 5.8.4 Submerged Aquatic Vegetation below), coastal flooding buffers, and natural pollutant filters.

Different fisheries may respond to changes in the precipitation regime in different ways. Some species have more successful survival after wet years, while others show better success during dry years in the same environment (Meynecke et al. 2006). Some species may benefit from higher flood lines, as habitat may be expanded to new areas of rivers or bays. The relationship between precipitation and diadromous fishes (species that migrate between salt and freshwater) varies with species, specific environmental conditions, and the extent of change. While some species might show resilience or even benefit from certain precipitation patterns, climate change and extreme weather events pose significant challenges to the health and sustainability of diadromous fish populations and their associated fisheries. It is largely unclear how our marine ecosystems will respond to climate-driven changes to rainfall.

Continued research is essential for the management of New Jersey's marine ecosystems in the face of climate change. Profitable fisheries may experience declines if water quality changes in our bays and estuaries. Some species may thrive in newly created habitats or more suitable aquatic environments. There remains considerable uncertainty about how climate change may drive temperature and precipitation patterns in New Jersey, and how it might affect marine resources.

5.8.2.2 Effects of Changing Water Chemistry

Climate change is affecting the chemical properties of water that fishes are particularly sensitive to, oxygen, pH, and carbon dioxide (CO_2). Water chemistry shifts directly and indirectly affect finfish populations. Direct effects include physiological stress, survival, and reduced fitness to individuals and populations; indirect effects include changes in prey community, disease, and competition from invasive species. Oxygen depletion, ocean acidification, and changes in nutrient supply have already altered the distribution and abundance of marine organisms in the ocean (Bindoff et al. 2019). Ocean acidification (see Chapter 4.4) not only threatens the health of the oceans, but also the economic value that people and industries depend on.



SUMMER FLOUNDER

Dissolved oxygen is vital for fish survival and overall water quality. Almost all marine organisms rely on oxygen for respiration, and some species are more sensitive to low dissolved oxygen than others. The warming of surface waters affects not only vertical mixing, but warmer water also holds less oxygen, increasing the risk of depletion of dissolved oxygen in bottom waters. Current climate change trends suggest the possibility of more frequent hypoxia events (i.e., dissolved oxygen concentration is too low to support aquatic organisms) in New Jersey's coastal waters, which could lead to a complicated range of changes to the state's marine resources and fisheries. The food supply will be affected if, as predicted, dissolved oxygen declines by 1.3 to 3.7% and primary productivity drops 4 to 11% by 2081-2100 (Bindoff et al. 2019).

Depleted dissolved oxygen causes unsuitable, stressful, and sometimes lethal conditions for aquatic life. Dissolved oxygen levels below 5 mg/liter cause stress to fish, below 3 mg/liter is considered hypoxic and lethal to fish, and below 1 mg/liter supports almost no life (US EPA 2025c). "Dead zones" and fish kills are commonly documented results of rapidly occurring hypoxia, but less dramatic responses still show impacts on individual fish and populations (Breitburg 2002). Species response to low dissolved oxygen varies, but acute effects include reduced respiration, reduced activity, reduced feeding, and reduced escape behavior to hide from predators. Longer-term impacts include slower growth, delayed egg hatching, and various developmental issues (Weis et al. 2017).

In the summer of 2023, Rutgers scientists recorded acidification and dissolved oxygen levels below 5 mg/liter in bottom waters between Sandy Hook and Tuckerton at depths between 15 and 60 meters; at the same time, mortalities in fish and shellfish were being reported (Rutgers 2023). The same research team reviewed DEP data from 1979-2005 and found that dissolved oxygen levels dropped below 5 mg/liter routinely in the summer with periodic, localized concentrations <2 mg/liter (Rutgers 2023).

Summer flounder are especially sensitive to low dissolved oxygen and exhibit slow recovery to other stressors in hypoxic conditions (Brady and Targett 2010). Black seabass have poor tolerance to hypoxic conditions, particularly in increased water temperatures (Slesinger et al. 2019). Anadromous species like striped bass, river herring, and the threatened Atlantic sturgeon may suffer reduced recruitment because of more frequent hypoxic events, especially in upstream spawning habitat.

The larger-scale impacts of hypoxia on fisheries are quite complicated and generally not well understood. Some research has shown the possibility of positive fishery responses because of the increased fish biomass. Increased nutrients and growth in a system (which ultimately causes hypoxia) can allow for high prey abundance, providing more food for fish on higher trophic levels, many of which might include commercially or recreationally important species (Breitburg 2002). Nevertheless, this theory is dependent on the survival of lower trophic-level species in hypoxic conditions, and the prey-predator interactions that follow. Other research suggests a possibility of higher fisheries catch because of high-density of target species on the fringes of a hypoxic zone (de Mutsert et al. 2016). However, this grouping behavior is unlikely in New Jersey's highly developed, shallow bay ecosystems, where there would be very little refuge area in the eventt of a large-scale hypoxic zone. Additionally, reduced feeding behaviors in fish could be expected to cause a reduction in recreational catch, particularly rod-and-reel, as fish would be less likely to feed on bait and lures.

It is predicted that future hypoxic events will increase in frequency and severity (Gilbert et al. 2010). The complexity of modeling the occurrence of hypoxia (Hinson et al. 2024) and the significance of ecological impacts (Saba 2019) is a global concern, and perhaps the most dire. A 2021 study found that hypoxic events had consistently detrimental effects on survival, abundance, development, metabolism, growth, and reproduction across taxonomic groups, developmental stages, and geographic locations (Sampaio et al. 2021).

While rising levels of CO_2 in the atmosphere and ocean are the root cause of each of the stressors described above, there are also direct effects on water quality and marine life. Elevated CO_2 acutely affects respiration, circulation, and metabolism in fishes (Ishimatsu et al. 2005), and requires fishes to expend more energy for ventilation and less on foraging, avoiding predation, and other essential survival behaviors, an effect compounded by ocean acidification (Ishimatsu et al. 2008), and less energy is available for growth and reproduction.

Because early life stages are the most vulnerable, there is concern that increased CO_2 levels will affect the survival and development of eggs and larvae and, therefore, the recruitment of individuals to a population. Increased CO_2 reduced the survival rate of summer flounder embryos (Ferguson et al. 2015) and larval clownfish (Munday et al. 2010). At 700 parts per million (ppm) CO_2, clownfish larvae became more active and less aware of potential threats as their ability to sense predators was impaired. As a result, predation mortality was five to nine times higher. Increased mortality rates of eggs and larvae of other species (such as the inland silverside) have been directly related to elevated CO_2 levels as well (Baumann et al. 2012). A study on the development of otoliths, inner ear bones that function in balance, movement, and hearing, found that larval cobia exposed to elevated CO_2 had significantly larger otolith size (49%), density (6%), and mass (58%), changes that may influence their dispersal, survival, and recruitment (Bignami et al. 2013).

Adult fish exposed to elevated CO_2 levels have also exhibited behavioral effects. Orange clownfish lost their natural fear of predators and their ability to distinguish between predators and non-predators when exposed to olfactory cues under simulated ocean conditions, such as pH 7.8 and 1,000 ppm CO_2 (Dixson et al. 2010). Brown dottyback avoided the smell of injured prey, increased activity levels, and decreased feeding activity when exposed to two different levels of CO_2 that are predicted to occur by 2100 (Cripps et al. 2011). Five-lined cardinalfish displayed impaired homing behavior in a displacement experiment in which the fish were released approximately 650 ft (200 m) from their respective home site after being exposed to elevated CO_2 levels for four days (Devine et al. 2012). These studies suggested behavioral changes in certain fishes in response to elevated CO_2 levels, however, there is some variation in response, as shown by Clark and others (Clark et al. 2020) who observed only a negligible behavioral effect in coral reef fishes.

As more CO_2 dissolves into the ocean (see Chapter 4.4), hydrogen ions are produced, and the water becomes more acidic. Enzymes govern every chemical reaction of life and are very sensitive to pH, so the effect of ocean acidification on marine life begins with metabolic and physiological stress to organisms. As pH drops, so does the availability of carbonate ions, which organisms use to build and maintain their skeletons. Summer flounder has been shown to be sensitive to drops in pH (Ferguson et al. 2015). When fluke embryos were exposed to a lowered pH of 7.5, mortality reached 52%. At an extremely low, 7.1 pH, fluke embryo mortality reached 84%. Although there are large data gaps, monitoring of pH in New Jersey estuaries and the ocean has occurred since the mid-1990s. Ocean acidification will directly impact recreational and commercial fisheries, jobs, and revenue associated with these fisheries, as well as tourism.

Reducing CO_2 emissions nationally and internationally is a critical component of climate change mitigation. Models predict significant differences in outcome related to temperature change, dissolved oxygen declines, and primary productivity when low CO_2 emission scenarios are compared to a continued increase (Bindoff et al. 2019).

> ***“One of the main factors driving the appearance of marine invasive species along the Atlantic coast is warming ocean temperatures...”***

5.8.2.3 Occurrence of Diseases

The potential for an increase in severity and incidence of marine diseases is another consequence of climate change that could rapidly impact New Jersey fisheries (Okon et al. 2024). As the environment changes, organisms under stress may become less resistant to disease and more likely to encounter new diseases as the natural ranges of the host, disease-causing organisms, and vectors change (Lafferty 2009). The opportunity for disease transference may increase as previously uninhabitable areas for parasites could become inhabitable (Lafferty 2009). An outbreak of a disease can occur rapidly once conditions are optimal for the disease to thrive and spread. Outbreaks can leave ecosystems and fisheries in critical condition, taking years to recover, if at all.

Changes to temperature, salinity, pH, and dissolved oxygen are all elements that directly impact the marine environment and the immune systems of organisms. Temperature is one of the key factors involved in whether an infection results in disease and mortality or immunity and recovery (Shortt et al. 2017). Moreover, these diseases or disease carriers also have ideal ranges. The chance of an outbreak is increased when an environment compromises the host's immune system but is optimal for a pathogen or parasite (Marcos-López et al. 2010).

The effects of parasitic, bacterial, and viral infections are more severe when their host’s health is compromised. In addition, these infections will be a bigger threat in an environment where these diseases are in their optimum range. Optimum conditions for diseases make for a situation where they can flourish, multiplying and infecting at higher rates (Marcos-López et al. 2010). Pathogenic organisms that rapidly reproduce will also have a high rate of mutation, which can enable pathogens to adapt and respond rapidly to novel opportunities created by climate change, such as establishment in new host species (Gale et al. 2009). Pathogen evolution lowers the species barrier, so new strains are more likely to affect a wider range of hosts (Kuiken et al. 2006). A novel mutation can allow parasites and pathogens to bypass the defenses of their hosts or become more transmissible, virulent, or lethal. A lethal outbreak in an exploited marine resource can affect human health, economics, and societies. New or more severe outbreaks of disease may occur if marine populations are not able to acclimate to climate change and bolster their defense against the occurrence of diseases.

5.8.2.4 Non-Native Species

As ranges of marine organisms shift, non-native species move into new areas and may thrive, particularly where native species have not evolved the ability to prey on, compete with, or avoid predation by the newcomers. Invasive species can also reduce populations of natives by altering habitats and introducing disease. This could have cascading effects on food webs and trophic structures.

One of the main factors driving the appearance of marine invasive species along the Atlantic coast is warming ocean temperatures, causing a latitudinal shift northward of aquatic species distributions as well as creating suitable habitat for introduced invasives that otherwise could not successfully overwinter off the coast of New Jersey. This problem may prove to be especially severe in the marine waters of New Jersey, as the latest modeling efforts as described by the National Oceanographic and Atmospheric Administration (NOAA), predict that the northwest Atlantic will be warming at nearly three times the global average (Saba et al. 2016). This predicted accelerated warming pattern will make it difficult for native species to adapt through evolution and natural selection, and may allow invasive species to get a foothold and outcompete native wildlife.

The state has already begun to see the effects of these warming temperatures as fish traditionally viewed as southern or tropical species are starting to be encountered with some regularity. The red lionfish, *Pterois volitans*, a species of venomous fish native to the coral reefs of the central and Indo-Pacific, has now been encountered in and around New Jersey's natural and artificial reefs (Albins and Hixon 2008). This species has established confirmed breeding populations as far north as North Carolina and spread throughout the Caribbean and Gulf of Mexico after first being encountered off Florida in the early 1990s. This Indo-Pacific resident was most likely introduced to the Atlantic both intentionally and unintentionally through the aquarium trade. It is a voracious predator that readily consumes other finfish, cephalopods, and crustaceans. One study has shown that the presence of lionfish on an experimental patch reef caused a significant decrease in recruitment of native species by 79% over five weeks (Albins and Hixon 2008). The problem may be compounded because the lionfish has no natural predators in the Atlantic, preventing any sort of natural population control. Given the rate of warming of the ocean waters off New Jersey and the species' pattern of expanding its range along the south Atlantic coast, there is a distinct possibility that a lionfish population may establish itself on New Jersey's natural and artificial reef structures and have deleterious effects on recreationally, commercially, and ecologically important species.

Other finfish species that are native to the South Atlantic coast are likely to appear more regularly in state waters. Sheepshead, cobia, and triggerfish, once only late summer visitors, are now being reported by fishermen earlier in the year and with increasing regularity. These reports mirror the predictive modeling projections that project northward shifts of many fish stocks as waters warm and suitable habitats change (Kleisner et al. 2017, Morley et al. 2018), and southern species may begin to displace the native species that have long since supported New Jersey's important commercial and recreational fisheries. Our commercial and recreational fishers must continue to adapt to a changing ocean, and natural resource managers must consider the social and economic impacts of climate change as well as the ecological impacts.

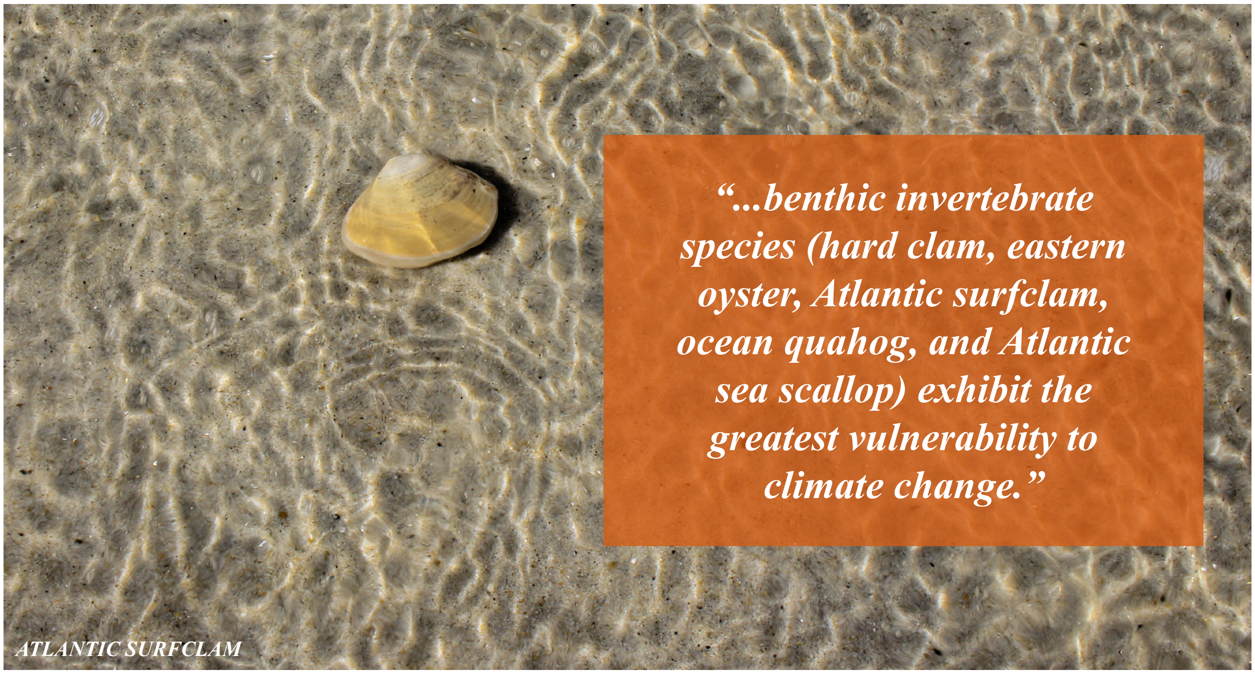
5.8.3 Invertebrates

In New Jersey, marine invertebrate species such as shellfish, crustaceans, gastropods, and jellyfish are susceptible to the impacts of climate change. Shifting temperature, precipitation, and water chemistry patterns will have a range of direct and indirect impacts on marine invertebrates. The occurrence of diseases may increase, and more invasive species may move into New Jersey waters.

5.8.3.1 Effects of Changing Temperature and Precipitation Regimes

The Northeast Climate Vulnerability Assessment found that in relation to overall climate vulnerability, benthic invertebrate species (hard clam, eastern oyster, Atlantic surf clam, ocean quahog, and Atlantic sea scallop) exhibit the greatest vulnerability to climate change. Thermal stress due to warmer waters is likely causing altered growth and development, mortality, and shifting stocks of Atlantic surfclams (*Spisula solidissima*), one of New Jersey's most valuable fisheries (Weinberg 2005, Czaja et al. 2023). New Jersey's surf clam population has shown dramatic declines since the mid-1990s, despite significant decreases in harvest over the past 15 years, and the stock remains historically low (Normant 2022). These climate change-driven impacts have had broad negative economic implications, particularly to ports and businesses relying on the surf clam resource.

Fluctuations in salinity associated with changes to rainfall and drought patterns may be another factor impacting marine life. High freshwater inputs from precipitation reduce the salinity of a waterbody; whereas lack of freshwater inputs caused by drought results in increased salinity (Habib et al. 2008). Species adapted to current salinity profiles may be unable to survive changes from altered precipitation patterns. The eastern oyster (Crassostrea virginica) is an example of a species that is sensitive and unable to survive significant changes in salinity due to precipitation (Levinton et al. 2011). Oyster aquaculture, an


ATLANTIC SURFCLAM

> ***"...benthic invertebrate species (hard clam, eastern oyster, Atlantic surfclam, ocean quahog, and Atlantic sea scallop) exhibit the greatest vulnerability to climate change."***

important industry for food and habitat restoration in New Jersey, could be threatened by changes in precipitation patterns. Naturally occurring oyster reefs, which provide valuable habitat and ecosystem services for waterbodies throughout the state, may also be impacted. Additionally, as precipitation patterns change, heavy rain events and subsequent increases in stormwater runoff may cause more frequent contamination of estuaries and shellfish resources (Leight and Hood 2018). Rainfall events are often tied to the detection of harmful bacteria in New Jersey bays, triggering shellfishery closures. Increased storm activity could thus lead to more frequent potential health risks and closures of the state's shellfisheries.

Shellfish and finfish populations will also be impacted by beach nourishment projects. As more frequent and intense weather events occur, communities may respond to the threat of flooding with beach nourishment projects where sand will be mined from offshore and placed on beaches. As a result, essential habitat for shellfish will be removed or changed. Sand lumps from where the sand is mined for New Jersey have a contoured bottom that houses key invertebrate species and attracts recreationally and commercially important species to these areas. This loss of habitat not only affects the ecology of the area but could also result in a loss of prime fishing grounds, adversely affecting the economic benefit New Jersey gains from its recreational and commercial fishing industries.

5.8.3.2 Effects of Changing Water Chemistry

Changes in marine water chemistry, such as increased CO_2 levels, are likely to impact marine invertebrates in direct and indirect ways. Calcium carbonate is critical for many shellfish species (and corals) as they need it to build their skeletons and shells. By reducing the availability of calcium carbonate, these organisms will then expend more energy on shell-building and less energy on basic survival tasks like foraging.

Many commercially important shellfish including hard clam, scallops, and oysters, rely on carbonate availability in seawater to form their shells. Increased CO_2 levels in seawater has been found to adversely affect shellfish growth and larval development of commercially important shellfish species (Gazeau et al. 2007). The calcification rates of two commercially important shellfish species (edible mussel, *Mytilus edulis*; Pacific oyster, *Crassostrea gigas*) were found to decline as a function of decreasing pH and increasing CO_2. Increased CO_2 levels were also found to impact shell development, leading to thinner and more frail shells when exposed to projected CO_2 levels (Talmage and Gobler 2010). Larval stages are especially vulnerable life stages, resulting in potentially malformed, pitted, or softened shells, which increase the likelihood of death by predation or failure to reach adulthood. This could pose a significant risk to the survival of juvenile shellfish and their ability to combat predation in the wild and ultimately affect the distribution and densities of shellfish resources and the state's vibrant shellfish industry.

Throughout the United States, wild shellfish harvest and shellfish aquaculture industries are valued at $3 billion dollars (NOAA 2024a). The value of these industries may be at risk with changing ocean chemistry. Among other combined threats. For example, a parasite known as Multinuclear Sphere X (MSX) was responsible for widespread mortality in Delaware Bay oysters in the 1950s, an area which historically and currently supports a major shellfishing industry. Significant mortality events caused by parasites and diseases make it difficult for the oyster resource to expand back to historical extents. While oysters are known to be resilient, the current rate of ocean acidification may result in a reduced ability to adapt to compounding threats.

5.8.3.3 Occurrence of Diseases

In addition to concerns regarding ocean acidification and decreased dissolved oxygen concentration, diseases may become more common for shellfish species in New Jersey. For example, diseases such as Multinuclear Sphere X (MSX) and Dermo (also known as Perkinsosis) have become prevalent in oysters, when previously they were only found in warmer waters south of New Jersey (Najjar et al. 2000). The MSX disease has been present in oyster populations in the Mid-Atlantic since the 1950s; however, MSX became more common further north along the east coast of the United States starting in the 1980s (Hofmann et al. 2001). Climate warming is a contributing factor towards this northward movement of MSX disease.

5.8.3.4 Non-Native Species

There are several species of shellfish and parasites that are non-native species or have the potential to be invasive in New Jersey. Invasive shellfish species in New Jersey include Chinese mitten crab, Asian shore crab, European periwinkle, Wedge rangia, and European green crab. The European green crab (*Carcinus maenas*) has exceptionally flexible thermal physiology. It is substantially more heat-tolerant than co-occurring native crustaceans. The European green crab was first introduced to the United States near the Long Island Sound, New York in approximately 1817. This initial population spread up and down the Atlantic Coast (Tepolt and Somero 2014). Since European green crabs are very adaptable to a range of temperatures, it is a threat to native populations. These crabs are good foragers and are very adept at opening bivalve shells. They are better at gathering food than other species of crab, and therefore may outcompete native species (MacDonald et al. 2007). Green crabs prey on clams, oysters, mussels, marine worms, and small crustaceans, which also makes them a competitor of the native bird species and finfish. Their diet is like that of shorebirds, making green crabs a direct threat.

Another possible invasive species, as the water warms, is the green porcelain crab, *Petrolisthes armatus* (Hollebone and Hay 2008). The green porcelain crab is a non-native filter feeder and scavenger currently invading oyster reefs in the South Atlantic Bight which is the coastal area from Florida to North Carolina. Green porcelain crabs have suppressed the growth of juvenile oysters, the recruitment of mud crabs, and the abundance of microalgae, in addition to promoting enhanced survivorship of oyster predators. As water temperatures rise, the current range of the green porcelain crab could expand. These crabs can move north and affect oyster communities in the Mid-Atlantic Bight, including Delaware Bay.

The veined rapa whelk (*Rapana venosa*) is another potential invasive species. This large predatory gastropod is located in the lower Chesapeake Bay and the James River, Virginia (Mann and Harding

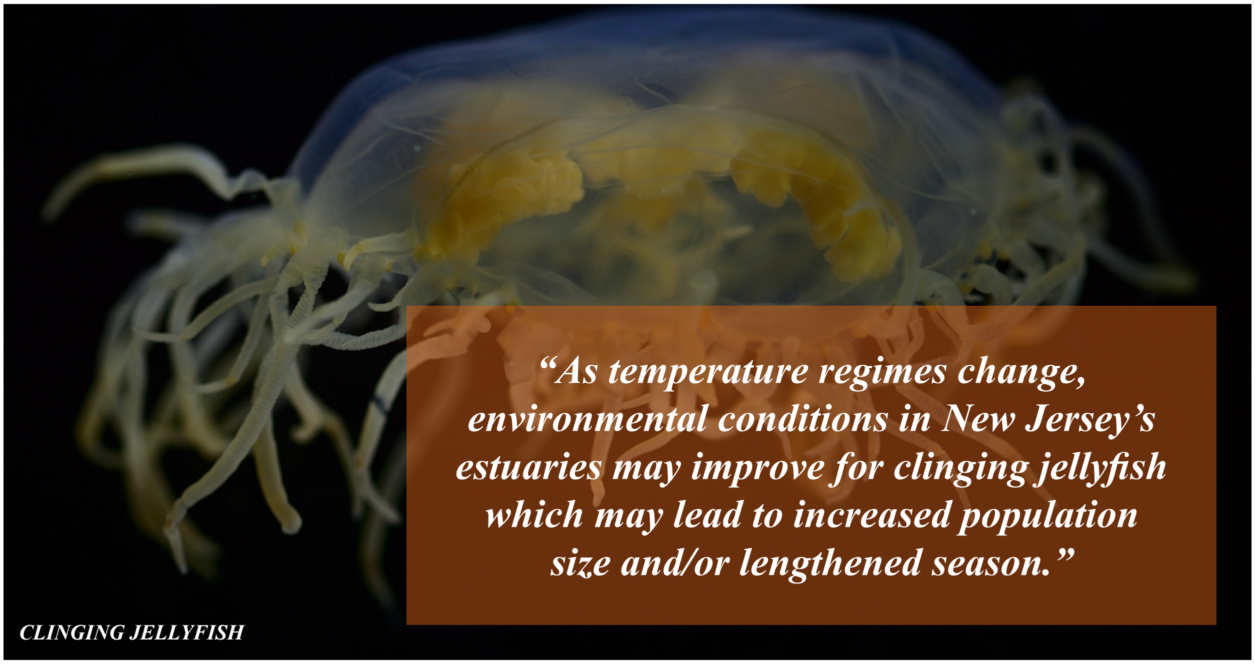
2000). From New York to Chesapeake Bay, water temperatures can support larval development. The veined rapa whelk has a broad dietary preference for bivalves. Lack of competition from other predatory gastropods and an abundance of prey species lead to this whelk's success. Expansion of the veined rapa whelk's current invasion is a cause for concern. This species produces viable pelagic larvae, consumes native species, and grows rapidly which all suggest its resilience. As waters around New Jersey become consistently warmer, this could lead to successful settlement of the veined rapa whelk.

Clinging jellyfish (*Gonionemus vertens*) are another example of a non-native species now inhabiting New Jersey waters. Although clinging jellyfish are native to the Pacific Ocean, they were initially introduced to the Atlantic coast around Woods Hole, Massachusetts in the 1890s, and now can be found in estuarine waters from Maine to New Jersey (Govindarajan and Carman 2016). Survey data suggest that clinging jellyfish are present in New Jersey waters starting in mid-May when water temperatures rise above 70°F (21.1°C) until mid-July when temperatures exceed 80°F (26.7°C) (NJDEP 2025g). Favorable conditions for clinging jellyfish include warm water temperatures, nutrients, and the presence of zooplankton (Govindarajan and Carman 2016). As temperature regimes change, environmental conditions in New Jersey's estuaries may improve for clinging jellyfish, which may lead to increased population size and/or lengthened season.

Non-native species invasion is affecting all aspects of local ecosystems. However, the rapid pace of invasions of non-native species threatens the function and maintenance of local marine communities and can fundamentally change these communities over large areas. Invasions can displace or completely disassemble native communities (Hollebone and Hay 2008). Natural resource managers will need to consider the impacts invasive species may have on native populations when changing, for dealing with and/or mitigating the effects of climate change in the future.

5.8.4 Submerged Aquatic Vegetation

Oceanic and estuarine habitats are an essential part of Earth's climate. These important habitats face many anthropogenic stressors along New Jersey's coastal margins because of climate change, including those associated with sea-level rise and warming temperatures. In New Jersey, sea level is projected to rise 0.8 feet by 2030 (Kopp et al. 2016).



"As temperature regimes change, environmental conditions in New Jersey's estuaries may improve for clinging jellyfish which may lead to increased population size and/or lengthened season."

CLINGING JELLYFISH

Sea-level rise can lead to several consequences on New Jersey's marine resources. Saltwater intrusion can alter upland habitats and modify salinity regimes that ultimately change estuarine habitats. Small increases in salinity within an estuary can have major impacts on shellfish populations by potentially increasing predation rates. The effects of climate change can also have major implications on other sensitive species, including rooted aquatic plants, known as submerged aquatic vegetation, by increasing metabolic stressors and altering distributions throughout the state.

Submerged aquatic vegetation is an integral part of New Jersey's estuarine ecosystem and is critical to protecting the coast against flooding and erosion. For instance, submerged aquatic vegetation meadows serve many purposes, including regulating water column dissolved oxygen, modifying the physical and chemical environment, and reducing suspended sediments, chlorophyll, and nutrients in the water column (Short and Neckles 1999). They are primary sources of food for waterfowl, serve as indicators of local water quality conditions, affect key sediment processes, and decrease the potential for shoreline erosion by dampening nearshore water flow and waves (Moore and Orth 2008). Submerged aquatic vegetation also serves as habitat for fish, crustaceans, and shellfish, which include commercially and recreationally important species such as blue crab, hard clam, and juvenile striped bass (Arnold et al. 2017).

There are certain environmental conditions that determine the distribution of submerged aquatic vegetation species: salinity, light, temperature, nutrient levels, sediment type, and physical setting (Moore and Orth 2008). Extensive submerged aquatic vegetation meadows provide valuable resources in shallow coastal waters, and due to increased temperature stress, the distribution of seagrasses will shift. Changes in sea level, salinity, temperature, atmospheric CO_2, and ultraviolet radiation can alter seagrass distribution, productivity, and community composition (Short and Neckles 1999).

> ***"The effects of climate change can…have major implications on…submerged aquatic vegetation…"***

Increasing water temperatures will have negative effects on submerged aquatic vegetation. Higher water temperatures can lead to an increase in algal growth on seagrasses, decreasing the amount of light available for photosynthesis; this can affect growth and decrease or eliminate meadows. Changes in temperature will also affect metabolism and carbon balance, which could lead to changes in the distribution and abundance of submerged aquatic vegetation (Short and Neckles 1999). Sea-level rise will also have negative effects on submerged aquatic vegetation. An increase in water depth due to sea-level rise will reduce the amount of light reaching existing submerged aquatic vegetation meadows, resulting in reduced productivity and will also move the salt front further inland and affect submerged aquatic vegetation distribution. Changes in the distribution of submerged aquatic vegetation meadows may have profound consequences for local and regional biota, nearshore geomorphology, and biogeochemical cycles.

Climate change will also lead to an increase in storm activity. Increased rainfall will increase sediment and nutrient input into estuaries, further decreasing light availability to the submerged aquatic vegetation meadows (Moore and Orth 2008). Submerged aquatic vegetation meadows have a high capacity to dissipate wave energy (Duarte et al. 2013) but the increased frequency and intensity of storms will lead to a decline of meadows, reducing their ability to mitigate storm surge and wave action (Moore and Orth 2008).

Submerged aquatic vegetation meadows also serve as a mechanism to capture and store CO_2, sequestering approximately 10% of oceanic organic carbon globally (Arnold et al. 2017). Climate change will cause submerged aquatic vegetation habitats to experience reduced distribution, decreased productivity, altered meadow structure, and reduced functional value (Short and Neckles 1999).

5.8.5 Vibrio

Pathogens of particular concern in New Jersey's marine systems are those associated with the bacterial genus *Vibrio*. *Vibrio* species are important microbial pathogens that are implicated in several transmitted freshwater and saline environmental illnesses. Notable examples of typical pathogenic *Vibrio* species are *Vibrio cholerae,* the causative agent of the disease cholera; *Vibrio parahaemolyticus,* which is found in brackish and saltwater and is a causative agent of foodborne illness when contaminated seafood is consumed; and *Vibrio vulnificus,* which can cause mild foodborne illness if consumed (like *V. parahaemolyticus*). *V. vulnificus* has been implicated in severe and often fatal cases of invasive wound infections known as necrotizing fasciitis. *V. vulnificus* is typically found in saline and saline-influenced environments.

Outside human exposure, discussed in Chapter 6.3.2 , *Vibrio* are known pathogens to other species such as fish, causing a disease known as vibriosis. In 2020 and 2021, New Jersey saw large mortality events of Atlantic menhaden (*Brevoortia tyrannus*) recently attributed to V. *anguillarum* (Lovy et al. 2024). Historically, *V. cholerae* has played an important role in human disease, and due in large part to increases in disinfection of potable water and advances in wastewater treatment technology, cases of *V. cholerae* have largely fallen around the globe (Safe Drinking Water Foundation 2017). While *Vibrio*-related drinking water illnesses have decreased, *Vibrio* species can often cause infections from the consumption of contaminated seafood (Newton et al. 2014) or bathing in waters with an open wound (Dechet et al. 2008).

Bathing-based events appear to be increasing, as both severe weather events and warming patterns seem to favor *Vibrio* species growth and habitat preference (Baker-Austin et al. 2024). Severe weather events such as hurricanes have resulted in increases in reports of fatal *Vibrio* cases (CDC 2005) and warming waters appear to increase the rate of *Vibrio* infections (Baker-Austin et al. 2013) Changes in climate patterns seem to be leading to an increase in the long-term detection range and season of *Vibrio*, which may lead to an increase of adverse *Vibrio*-based infection events (Martinez-Urtaza et al. 2010). Recent data suggest expansion of detection ranges for specific species of *Vibrio*, with the infection distribution range expected to increase northward for *V. vulnificus* towards New Jersey (Archer et al. 2023).

The DEP addresses *V. parahaemolyticus* and *V. vulnificus* through a detailed *Vibrio* Control Plan, which was developed to reduce incidences of food-borne illness from the consumption of contaminated oysters. The *Vibrio* Control Plan includes program coordination, response to potential outbreak, post-harvest time and temperature controls, hours of harvest for tidal and intertidal waters, and Hazard Analysis and Critical Control Points (HACCP) plan requirements, and recommends additional best management practices to be implemented to further minimize risk from these naturally occurring bacteria (Bryan 1992).

5.8.6 Phytoplankton

In 2025, the DEP released a report summarizing literature on the potential impacts of climate change on phytoplankton dynamics (Grubb and Procopio 2025). The authors reported that the thermal dynamics of New Jersey's coast are changing, which may impact phytoplankton communities. Assessing the effects of climate change on primary

> ***“Changes in climate patterns seem to be leading to an increase in the long-term detection range and season of Vibrio...”***

production and phytoplankton has been challenging due to inconsistent sampling and varied analysis methods. However, satellite remote sensing offers extensive data to address these issues. Recent studies indicated an increase in phytoplankton blooms as sea surface temperature rises, while chlorophyll-a concentrations have decreased since 2012 (Friedland et al. 2020, Dai et al. 2023).

In the coastal region from Massachusetts to North Carolina (i.e., the Mid-Atlantic Bight), long-term changes in phytoplankton communities have been observed. Satellite data from 1978-1986 and 1998-2006 show significant seasonal declines in chlorophyll-a during fall and winter (Schofield et al. 2008). These declines align with the Atlantic Multidecadal Oscillation's shift from a cold to warm phase, underscoring temperature's role in regulating stratification and phytoplankton dynamics.

Despite warming, seasonal temperature transitions in the Mid-Atlantic Bight have not significantly altered bloom timing. The spring transition occurs slightly earlier, while the fall transition is delayed by two weeks, yet neither change correlates with bloom timing shifts (Friedland et al. 2015, 2023). Recent analyses reveal reductions in mean annual chlorophyll-a concentrations, particularly in the southern Mid-Atlantic Bight, alongside shifts in phytoplankton community composition (Friedland et al. 2020). Smaller phytoplankton like pico- and nanoplankton have increased, while larger microplankton and diatoms have decreased.

Globally, climate change is expected to continue affecting marine phytoplankton populations and distributions. Ocean warming and increased stratification are likely to reduce nutrient concentrations and net primary productivity, favoring smaller phytoplankton (Fu et al. 2012, Henson et al. 2021). The North Atlantic, including the Mid-Atlantic Bight, is projected to experience longer, stronger stratification which will benefit small phytoplankton (Thomas et al. 2017, Zang et al. 2021). Models predict northward shifts for diatoms and dinoflagellates (Barton et al. 2016). These changes, driven by climate change, are expected to significantly impact the North Atlantic's seasonal phytoplankton community composition.

HARBOR SEAL

CHAPTER 6

HUMAN HEALTH, AGRICULTURE, AND COMMUNITY IMPACTS OF CLIMATE CHANGE

Since the middle of the twentieth century, the changes in weather patterns in combination with population growth have led to an increase in human exposure to more severe heat waves, forest fires, severe storms, increased flooding, droughts, and infectious disease vectors, with dire consequences to health, agriculture, and communities. New Jersey residents will face new and worsening challenges as climate change impacts our air, water, habitats, and food production. There will be higher risk of cardiovascular and respiratory dysfunction due to extreme weather. Flooding events may lead to more drownings and injuries, contaminated water, and damage to residential housing, which can displace people and reduce availability of safe housing. Additionally, the mental health toll climate change can have on individuals and communities is often overlooked. Our agriculture industry will also experience unfavorable conditions as the result of rising temperatures, changes in precipitation, and new pest species. Climate change is increasingly an environmental justice issue, as overburdened communities bear the brunt of the crisis. Altogether, the vulnerability of the human population to these changes is clear and only through concerted adaptation and thoughtful resilience planning will we be able to meet the challenges brought on by climate change.

Chapter 6 is divided into the following sections:

HUMAN HEALTH, AGRICULTURE, AND COMMUNITY IMPACTS OF CLIMATE CHANGE

KEY FINDINGS

- **The extreme weather events predicted for New Jersey, including heat waves and heavy precipitation, can lead to both immediate and long-term effects on cardiovascular, respiratory, and gastrointestinal systems, as well as on mental health and behavior.**
- **Climate change is anticipated to worsen air quality from both natural and human-made sources, which may lead to greater instances of cardiovascular disease, respiratory illnesses, and cancers in vulnerable populations.**
- **Climate impacts are threat multipliers, worsening the population's pre-existing and chronic health conditions such as asthma and cardiovascular diseases. Consequences of climate change in human health are not restricted to physical problems, such as respiratory and cardiovascular disease, but also have a tremendous impact on mental health, lives lost and individuals harmed, and housing and the built environment.**
- **Infectious diseases spread by arthropods, insects, and microbial contamination of food and water supplies are expected to become more prevalent as climate change increases the environmental conditions that are more favorable for pathogens and their hosts.**
- **The productivity of crops and livestock are expected to change due to climate-induced changes in temperature and precipitation patterns.**
- **New Jersey may become unsuitable for specialty crops like blueberries and cranberries in the future as higher temperatures reduce necessary winter chill periods.**
- **Population displacement because of sea-level rise, flooding events, and resource insecurity may add to the cumulative detrimental effects of climate change on mental health as individuals cope with the environmental and personal consequences of climate change.**
- **Climate change is increasingly an environmental justice issue, as overburdened communities bear the brunt of the crisis.**

CHAPTER 6.1

ADVERSE IMPACTS OF EXTREME WEATHER ON HUMAN HEALTH

6.1 Adverse Impacts of Extreme Weather on Human Health

Most extreme weather events associated with climate change are largely driven by increasing global temperatures, anomalous precipitation, and air pollution, all of which are intensified by human-driven emissions of carbon dioxide (CO_2) and other greenhouse gases. Together, increased heat and precipitation promote the occurrence of more intense and severe weather events (e.g., hurricanes and flash flooding). These disturbances to the natural climate cycle influence human health in a variety of ways, particularly in individuals with chronic illnesses, low-income households, children and older adults, and racially marginalized groups.

6.1.1 Extreme Heat

Climate change is fueling warmer and more frequent heat waves (see Chapter 4.1.3). The frequency of excessive heat events are increasing globally (Dahlman and Lindsey 2025) and, over the last 30 years, heat wave frequency has increased and diurnal temperature range has decreased in New Jersey (Wiley and Lester 2025). In New Jersey, out of the 20 warmest years since 1895, 15 have occurred since 2000, with 2024 the second hottest on record, following 2012 as the hottest on record (Davies et al. 2025). Globally, the ten warmest years on record have occurred since 2015 (NASA 2025b, WMO 2025). Extreme heat is a natural hazard, with a maximum level that can be tolerated by the human body. Under prolonged exposure, the body's innate mechanisms for thermoregulation or the process by which internal temperature is maintained are rendered ineffective, especially in patients with chronic health conditions. Excessive heat can lead to increased heat-related mortality and morbidity, including illnesses such as heat exhaustion, heat cramps, heat edema (swelling in the legs and hands), heat syncope (fainting), and heat stroke (USGCRP 2016, Cissé et al. 2022, CDC 2024a). Mortality due to heat related deaths in warmer seasons are increasing globally, with 37% attributable to anthropogenic climate change (Vicedo-Cabrera et al. 2021). It can be difficult to determine how much heat influences deaths when other underlying conditions are present, such as smoking and obesity, compared with deaths due to heat stroke, heat exhaustion, etc., which can be identified in the death certificate. In the United States, between the years of 1999 to 2023, 21,518 deaths were medically coded heat-related as the underlying or contributing cause of death (Howard et al. 2024). An analysis of cardiovascular deaths in adults from 2008-2019 in the contiguous United States linked extreme heat to an annual average of greater than 1,600 excess deaths per year, a value that is expected to increase by 160-230% by the middle of the 21st century under various greenhouse gas emission projections (Khatana et al. 2023).

The average number of heat-related emergency department visits in New Jersey during the warm season (May to September) between 2004 and 2023 was approximately 930 per year. In New Jersey, based on 2023 provisional data, there have been a total of 110 deaths due to exposure to excessive natural heat and sunlight as the primary cause of death between 2000 and 2023 (NJDOH 2025a). It is important to note that accurately measuring the impact of heat on mortality and morbidity is a difficult task. Increasing emphasis has been placed on identifying overt heat-related diseases, such as heatstroke, in the field and in emergency rooms. Heat as a cofactor in other diseases, in mental health, and in crime is only beginning to be recognized and studied. The true impact of heat on morbidity and mortality is debated. The only consensus among health officials and climatologists is that in the United States, heat-related fatalities and morbidity are grossly undercounted (Conrad 2023). During the summer months in climates with cyclical seasons, like New Jersey, consistent exposure to outdoor heat stress should lead to transient adaptation to higher temperatures. A 2022 systematic review looked at a number of studies that aimed to characterize how well the body adjusted to heat during the summer (Brown et al. 2022b). Overall, it was found that while people do adapt to higher temperatures, known as seasonal heat acclimatization, the

> ***"The average number of heat-related emergency department visits in New Jersey during the warm season (May to September) between 2004 and 2023 was approximately 930 per year."***

magnitude of that change is variable and influenced by environmental conditions, exposure duration and time of day, and the intensity and duration of outdoor physical activity. Seasonal heat acclimatization likely explains why emergency department reporting of heat-related illnesses in New Jersey is typically highest during the first heat event of the summer, when the population is not yet acclimated to increasing temperatures (NJDOH 2024a). Projected increases in the frequency and intensity of high temperatures and extended heat waves in New Jersey could lead to a significant increase in summer heat-related mortalities, potentially more than doubling in number between the mid-20th to mid-21st century (Kinney et al. 2004, Dupigny-Giroux et al. 2018).

6.1.1.1 Heat and Humidity

Humidity is an exacerbating factor contributing to the hazard of extreme heat, and global increases in heat and humidity can have deadly consequences (Raymond et al. 2020, Li et al. 2020). In a model evaluating climate variables to identify which were most likely to contribute to lethal heat conditions, daily surface air temperature and relative humidity were the most predictive pair (Mora et al. 2017). Above a certain combination of temperature and humidity, sweat will no longer evaporate from the surface of the skin, limiting the body's natural cooling mechanism. Prolonged exposure to such conditions can be fatal, and the higher the humidity, the lower the temperature at which heat stress can be fatal (Smith et al. 2014, Mora et al. 2017). While this is a greater threat to the equatorial regions of the globe, the Northeastern United States and New Jersey are prone to periods of high heat (Wiley and Lester 2025) and humidity and expected to have greater periods of such weather in the future (Dupigny-Giroux et al. 2018).

The combination of high heat with high humidity may compromise both outdoor occupational and recreational activities as humans reach thermal tolerance, meaning it will be uncomfortable and inadvisable to engage in heavy labor and other physically taxing outdoor activities. Studies estimate that heat stress has already led to a

10% reduction in labor capacity globally in peak months over the past few decades, and as mean global temperatures continue to rise towards 3.6°F (2°C), the upper limit of the 2015 Paris Climate Agreement, projections of heat-related labor loss could increase by 50%, particularly in the eastern mid-latitude region of the United States (Romanello et al. 2023). Temperatures above 85°F (29°C) led to a 5-7% increase in injuries, in both indoor and outdoor settings, compared with temperatures in the 60s°F (15-21°C), with injuries not necessarily strictly heat-related, including falling from heights, being struck by a moving vehicle, or mishandling dangerous machinery (Jisung Park et al. 2021). Workers in construction, agriculture, mining, and transportation, which tend to be lower income, experience greater instances of injury due to the nature of the jobs they perform (CDC 2013), and as a result, extreme heat will disproportionally affect lower- and middle-income workforce, particularly in those industries and other outdoor laborers (Gibb et al. 2025). The effects of climate change can be expected to exacerbate workplace disparity, not only through oppressive temperature conditions, but through other mechanisms discussed throughout this chapter. Heat is a well-studied stressor affecting both adults and children during outdoor athletic activity. Exertional heat stroke, the most severe manifestation of exertional heat illnesses, is the third leading cause of mortality in athletes during physical activity. Exertional heat stroke is characterized by central nervous system dysfunction in people with hyperthermia during physical activity and can be influenced by environmental factors such as heat waves, which extend the incidence of exertional heat stroke beyond athletics only (O'Connor and Degroot 2024).

6.1.1.2 Heat Vulnerability

People who are the most vulnerable to extreme temperatures include children, elderly, pregnant and post-partum individuals, homeless populations, and individuals in low-income communities and communities of color (Berko et al. 2014, Cissé et al. 2022, CDC 2024b, NJDEP 2024e). Urban communities are more susceptible to high temperatures, because the built environment (e.g., buildings, roads, and sidewalks) absorbs and re-emits the Sun's heat more readily than natural landscapes, a concept known as the urban heat-island effect (Chapter 4.1). In 2024, Climate Central analyzed how and where urban heat islands boost temperatures within 65 United States cities, including Newark, New Jersey; Philadelphia, Pennsylvania; and New York City, New York. An urban heat island index was calculated for every census block group within these cities to estimate how much hotter these areas are due to the characteristics of their built environment. The per capita average urban heat island index was 9.0°F for Newark, 8.5°F for Philadelphia, and 9.7°F for New York City. However, due to a differences in "cool pockets of shade and green infrastructure, 97% of Newark's population lives in census block groups with a urban heat island index of 8.0°F, compared to 83% in New York City and 52% in Philadelphia (Werbin et al. 2020). 'Grades of Heat', an analysis by The Brown Institute for Media Innovation at Columbia University, shows that the urban heat burden is unequally shared, with historically redlined districts experiencing hotter summers than non-redlined areas in 150 (84%) of 179 major United States cities (Michael Krisch 2025). In New York City, daily mortality spiked after a city-wide power failure in August 2003, due in part to increased exposure to heat (Anderson and Bell 2012). Further, in urbanized areas, the exposure to extreme heat is disproportionately experienced by people of color compared to non-Hispanic Whites, and by households below the poverty line relative to those at more than two times the poverty line (Hsu et al. 2021).

Extremes in temperature can worsen chronic health conditions, including cardiovascular and respiratory diseases, diabetes, and kidney disease (Cissé et al. 2022, Kazi et al. 2024). Hydration is key to maintaining normal physiological processes. Therefore, excessive perspiration and sweating without proper fluid intake can lead to a loss of electrolytes and plasma volume, in essence increasing the blood viscosity and straining the heart and kidneys, among other organs (Popkin et al. 2010). Heat exposure is a concern for agricultural laborers during the growing season who are exposed to the elements for long periods of time. The rise in chronic kidney disease in Central and South American farmers, generally associated with severe dehydration from laboring in extreme heat and humidity (Wesseling et al. 2013), serves as a cautionary tale for the Mid-Atlantic region of the United States as it prepares to experience more frequent and intense heat waves. The Rutgers New Jersey Agricultural Experimental Station provides a fact sheet with information related to best management practices in mitigating heat stress in agricultural workers (Rutgers NJAES 2024). Among the strategies for preventing heat stress are to (1) limit exposure time, (2) minimize heat exposure, (3) encourage rest breaks, (4) wear appropriate clothing, and (5) employ a buddy system to spot early signs of heat stress.

6.1.1.3 Extreme Heat Impacts on Behavior

The impact of extreme heat on sleep quality has more recently been discussed as an indirect consequence of climate change. Over the last 30 years, New Jersey heat wave frequency has increased, but the temperature ranges during those heat waves, or the differences between high and low daily temperatures, have decreased, indicating the tendency for temperatures to stay warmer longer (Wiley and Lester 2025). Warmer temperatures have been associated with insufficient sleep, which can lead to altered cognitive performance, compromised cardiovascular and immune health, and increased adverse mental health outcomes, even in children (Lopes 2024). As climate continues to increase the magnitude and frequency of elevated nighttime temperatures, sleep duration will decrease incrementally, which may disproportionately impact lower income communities, which may lack access to cooling amenities (e.g., air conditioning) (Minor et al. 2022). During periods of prolonged, extreme heat, sleep loss may be a contributing stressor for mental health and substance use conditions and can impair attention span and memory, as well as the ability to process new information.

There is also a demonstrated causal relationship between heat and interpersonal aggression—as the temperature goes up, people's behavior becomes more aggressive toward others (Otrachshenko et al. 2021, Zhu et al. 2023). A 1.8°F (1°C) increase in average annual temperature was connected to a rise of more than 6.3% in incidents of physical and sexual domestic violence across three South Asian countries (Zhu et al. 2023). Heat has a negative effect on cognitive functioning, which may reduce the ability to resolve a conflict without violence. The effects of heat can impair attention span and memory, as well as the ability to process new information. As the ability to perceive situational information degrades, the potential for reactive/impulsive decision-making increases, which is associated with aggression and violence. In hot weather, people are more likely to misread neutral signals as signs of hostility and less likely to avoid or condemn violence.

Broader climate change impacts on behavior and mental health are discussed in Chapter 6.5.4.

6.1.1.4 Temperature and Air Quality

High temperatures also increase the likely formation of ground-level ozone in the air and increased particulate pollution, the health consequences of which will be discussed in Chapter 6.2. Individuals with chronic health conditions are also more vulnerable to heat-related illness, and should take extra care to stay hydrated, avoid strenuous activity, and keep cool (e.g., have access to air conditioning) during extreme heat events (CDC 2024b). As the climate continues to change, more frequent and intense waves (Wiley and Lester 2025) with rising temperatures can be expected to increase heat-related illness, resulting in surges of hospitalizations and deaths.

6.1.2 Precipitation Anomalies

The more frequent and intense rainfall events projected for New Jersey (Chapter 4.2.4) will likely lead to an increase in precipitation amounts (DeGaetano 2021a). This can result in flooding, erosion, damage to infrastructure, and compromised human health. Of the greater than 10,600 deaths

> ***“Drinking water sources contaminated by heavy storm runoff have been associated with increased hospitalization in New Jersey for gastrointestinal effects, specifically from increased microbiological contaminants in raw water.”***

in the United States attributable to weather-related events from 2006-2010, over 6% were due to flooding, storms, or lightning, as a direct or associated cause of death (Berko et al. 2014). Flooding events are a hazard for drowning, injury, and hypothermia, and can compromise sanitation infrastructure, creating conditions that facilitate the spread of communicable and infectious diseases as local wastewater treatment facilities can become overwhelmed (Cissé et al. 2022). The Centers for Disease Control and Prevention (CDC) estimates that floods account for, on average, nearly 100 deaths annually in the United States (CDC 2024c). Males were twice as likely to die than females from such conditions, either directly from drowning during a flood or because of exacerbated preexisting medical conditions (e.g., cardiovascular disease). Acute and chronic health effects secondary to a flooding event, such as respiratory illnesses from mold exposure and transmission of infectious diseases resulting from the contamination of clean water by harmful microorganisms, are discussed in Chapter 6.2.2 and Chapter 6.3.2, respectively.

Increased soil erosion and agricultural runoff may result in contaminated surface and groundwater sources posing a public health concern, as the increased manure, fertilizers, and pesticides enter local waterways (USGCRP 2016). In a controlled field study, anthropogenic waste products containing household and industrial products were distributed as biosolids along an agricultural field, and contaminants were detected in surface waters and terrestrial sites far from the original point of application throughout the duration of the experiment (Gray et al. 2017). These waste streams contain many unidentified or bioactive substances further highlighting the need for further investigation into the potential adverse impacts on human health. Loss of soil and nutrients is only one of a myriad of negative effects heavy rainfall has on agriculture, discussed later in Chapter 6.4.

Contaminants from urban environments can also be transported distantly by heavy rain events. Environmental assessments indicate that anticipated increases in precipitation may mobilize legacy soil contaminants, such as heavy metals, dioxins, and PCBs, further elevating risks to food and water safety (Boxall et al. 2009, Tran et al. 2019). This is especially true for areas near Superfund sites. New Jersey has more federal Superfund sites than any other state in the United States, with 115 currently listed on the National Priorities List (US EPA 2023) and thousands of additional state-managed contaminated sites (NJDEP 2024f). Many of these federally-designated sites are in or near overburdened communities, increasing the risk of exposure to mobile chemical contaminants. Combined with New Jersey’s high population density, this raises serious concerns for public health and environmental safety, especially in urban areas vulnerable to flooding. Following the flooding that occurred with Superstorm Sandy, contaminated soils from Superfund sites around the New York-New Jersey region were found inland from the sites of origin (Marcantonio et al. 2019). Drinking water sources contaminated by heavy storm runoff have been associated with increased hospitalization in New Jersey for gastrointestinal effects, specifically from increased microbiological contaminants in raw water (Gleason and Fagliano 2017). In addition, human exposure to pollutants would increase during recreational activities (e.g., swimming in lakes) in areas where nutrients from run-off of agricultural fields or Combined Sewer Overflows (CSO) enter waterways. In New Jersey,

> *"Droughts and extended dry periods may affect water-storage, land-use and irrigation practices, and human population distribution."*

there are 212 CSOs located in 21 municipalities, many of which are overburdened communities (NJDEP 2024a).

The absence of precipitation can lead to its own range of human health complications. Droughts and extended dry periods may affect water-storage, land-use and irrigation practices, and human population distribution (see Chapter 4.2.5). Drought conditions intensify extreme heat events, leave the environment more prone to flash floods, promote dust storm conditions, and strain water supplies (CDC 2024b). The combination of reduced precipitation and increased evaporation of surface waters (from extreme heat) may lead to unreplenished groundwater supplies, resulting in regional water-insecurities (Stanke et al. 2013, CDC 2024b). In areas that rely on surface water for drinking, evaporation can reduce water volume, leading to higher concentrations of chemical pollutants—such as pharmaceuticals, endocrine-disrupting compounds, and nitrates—and ultimately lowering overall water quality. An example of this was observed in Lake Mead, the major drinking water source for southern Nevada, following several years of drought (Benotti et al. 2010). The increased concentrations of contaminants in ground and surface waters can increase human exposure to pollutants through drinking water and recreational activities (e.g., swimming).

Another health hazard from drought conditions is the increased likelihood of wildfires (see Chapter 5.3.5). Smoke inhalation is considered the leading cause of wildfire-related mortality and morbidity, accounting for a significant percentage of fire deaths (Gould et al. 2024). Wildfires also directly contribute to burn-related morbidity among affected populations, including civilians and responders, particularly in rural areas (Lakhlani and Sheckter 2025). The CDC reports that over 400 firefighters died in the United States from heat (e.g., collisions from low visibility) and sudden cardiac events while fighting wildfires from 2000-2019 (CDC 2023a). The general public can also be impacted in the aftermath of a wildfire event, experiencing eye irritation and corneal abrasions, heart attacks, asthma attacks, bronchitis, chronic obstructive pulmonary diseases (COPD), and premature death (Cascio 2018, Xu et al. 2020). A recent study shows that wildfire smoke notably increased levels of particulate matter and ground-level ozone across the United States from 2018-2023 (Lee and Jaffe 2024). The impact of particulate matter, ground-level ozone, and other toxic substances from wildfires and biomass combustion on air quality is discussed in Chapter 6.2. As droughts are predicted to occur more frequently in New Jersey and throughout North America due to changes in precipitation patterns, a greater portion of the population may

> *"New Jersey's coastal infrastructure and ecosystems are sensitive to the changing environmental conditions brought on by the more intense and frequent hurricanes, precipitation, and storm surges that are predicted for the region."*

be subjected to stress from increased exposure to smoke and particulate matter from wildfires or through decreased food and water security. The loss of life, homes, valuables, and neighbors leads to stress and depression.

6.1.3 Storm Intensity

Globally, weather-related natural hazards (e.g., storms and flooding) have risen since the mid-twentieth century, with tropical storms and hurricanes being major weather-related threats to the Mid-Atlantic coast (Marquardt Collow et al. 2016, Broccoli et al. 2020). New Jersey's coastal infrastructure and ecosystems are sensitive to the changing environmental conditions brought on by the more intense and frequent hurricanes, precipitation, and storm surges that are predicted for the region (Chapter 4.2). In the United States, the 2020 hurricane season was one of the worst on record, with 14 designated 'hurricanes' and seven as 'major hurricanes', 11 of which made landfall, and was the fifth consecutive year with above-normal Atlantic hurricanes. The trend continues as 2024 Atlantic hurricane season showcased above-average activity, with a record-breaking ramp up following a peak-season lull (NOAA 2024b). The Atlantic basin saw 18 named storms in 2024, 11 of which were hurricanes and five intensified to major hurricanes. Five of those hurricanes made landfall in the United States, with two making landfall as major hurricanes. Further, hurricanes are getting stronger, as evidence suggests that climate change is increasing the chance of storms reaching Category 3 or higher (Kossin et al. 2020). Damage to the coastline directly impacts commercial and residential areas, and the communities therein, especially as storm surges coupled with sea-level rise increases the chance of severe flooding events (USGCRP 2016, Cissé et al. 2022). In many regions, the increased sea levels will also lead to increased risk of population displacement (Cissé et al. 2022) (Cissé et al. 2022). Tropical storms are also associated with short-term excess mortality, particularly in vulnerable communities (Parks et al. 2023).

Powerful storms with heavy precipitation and hurricanes will cause roadway blockages (Burger et al. 2017), increases in drowning and other flood related injuries (Wu et al. 2024), exposure to contaminated drinking water and sewage disposal, and a host of additional public health concerns, including gastrointestinal illnesses, mental health impacts, cardiovascular diseases, infectious and parasitic diseases, and injuries and respiratory diseases (Lynch et al. 2025). Infrastructure failure following devastating weather events may cause health care system failures, including a loss of access to essential medical equipment or devices and medicine for patients (Burger et al. 2017), resulting in increased mortality that otherwise could have been avoided, particularly for the elderly and those of low-socioeconomic status (Moran et al. 2017, Bates 2019). Such was the case in New Jersey after Superstorm Sandy in 2012, where there was an increase in calls to emergency services, visits to hospital emergency departments, and hospital admissions (Moran et al. 2017).

Beyond the immediate emergencies following dangerous storms are the long-lasting drastic effects from infrastructure recovery (e.g., poor management of diseases and mental health stress), particularly to health care services, and the community consequences from possible population displacement (Bates 2019). The adverse health outcomes caused by storms and floods will likely increase over the century, particularly in coastal populations, unless mitigating measures are enacted (Cissé et al. 2022). The immediate and long-lasting consequences of extreme weather are more problematic for overburdened communities, which already suffer the cumulative effects of environmental stressors, poor infrastructure, and reduced health outcomes.

6.1.4 Compounding Effects on Health

Extreme weather events, be they excessive heat and humidity, heavy rainfall, drought, or natural weather-related disasters, lead to both immediate and long-term effects on human health. Factors such as medical conditions (e.g., chronic diseases), age, race, and economic status as well as community and social support systems all play a role in individual resilience to environmental threats. Power outages from extreme weather events, through increased demand or direct impacts on the infrastructure, for example, can lead to a range of public health crises, including the negative outcomes related to a taxed health care system, food and drinking water safety concerns, and secondary impacts, such as carbon monoxide poisoning and electrical shock (CDC 2024d). Infrastructure failure following devastating weather events may cause health care system failures, including a loss of access to essential medical equipment or devices and medicine for patients (Burger and Gochfeld 2017), resulting in increased mortality that otherwise could have been avoided, particularly for the elderly and those of low-socioeconomic status (Moran et al. 2017, Bates 2019). Furthermore, these threats are often not isolated events, as we observe throughout the country instances of extreme heat waves, droughts, wildfires, and even hurricanes impacting a region simultaneously. The effects of extreme weather influence and compound the health effects discussed in the subsequent sections.

> ***"Extreme weather events, be they excessive heat and humidity, heavy rainfall, drought, or increasingly intense storms, lead to both immediate and long-term effects on human health."***

CHAPTER 6.2

DIMINISHED AIR QUALITY

6.2 Diminished Air Quality

Climate change and air quality are in a destructive feedback loop. Air pollution not only contributes to climate change but is also exacerbated by it. New Jersey's air quality will be impacted by climate change, leading to increased human exposure to pollutants (e.g., ground-level ozone and particulate matter, particularly in densely populated urban areas. Exposure to such air pollutants has been associated with symptoms ranging from eye irritation to severe respiratory distress, reduced lung function, chronic obstructive pulmonary disease (commonly referred to as COPD), and increased mortality from lung cancer and heart disease. Additionally, increasing global temperatures and frequent flooding events will increase the production of allergenic air pollutants including mold (in houses and agricultural areas) and pollen due to a longer pollen season and more pollen production.

6.2.1 Exacerbated Air Pollution

Air pollution has both anthropogenic and natural sources, and the relationship between climate change and air pollution is discussed in Chapter 5.1. Human-caused sources of air pollution include burning fossil fuels (e.g., gasoline and diesel emissions, coal and natural gas, electricity production including higher energy demand on hotter summer days) and agricultural emissions from livestock (methane and ammonia), while natural sources include smoke from wildfires, dust from dry conditions, and pollen. As is the case with excessive heat, increased air pollution can aggravate chronic conditions, such as asthma, chronic obstructive pulmonary disease, and cardiovascular diseases, and increase the incidence of lung cancer (USGCRP 2016, CDC 2024b). Ambient air pollutants have been shown to increase cerebrovascular events, such as stroke, for both short and long-term exposures (Lee et al. 2018, Kulick et al. 2022, Gabet and Puy 2024). Asthma is a condition of chronic airway inflammation, which characteristically leads to wheezing, shortness of breath, chest tightness, and coughing in symptomatic patients that afflicts roughly 51 million Americans (8.6% of adults and 6.5% of children) and accounts for over 3,600 deaths each year (CDC 2025a). There are more than 600,000 adults and 167,000 children with asthma in New Jersey, with almost 40% of the 50,000 annual emergency department visits for asthma-related symptoms for children (NJDHSS 2013, NJDOH 2022). In 2021 alone, approximately 8.1 million deaths globally were attributed to air pollution attributable to ambient particulate matter pollution (e.g., $PM_{2.5}$; 58%), household air pollution from cooking fuel (e.g., wood, charcoal, coal; 38%), and ground-level ozone pollution (6%) (Health Effects Institute 2024). Children are generally more vulnerable to air pollutants because they inhale a higher volume of air per body weight than adults and have immature defense mechanisms (Salvi 2007). Ozone, particulate matter, and pollen were associated with increased pediatric asthma emergency department visits in New Jersey (Gleason et al. 2014). Warmer temperatures increase the concentration of air pollutants, further emphasizing that global climate change is a multifactorial problem (Cissé et al. 2022).

The United States Environmental Protection Agency (US EPA) requires states to monitor key air pollutants regularly under the Clean Air Act in order to attain and maintain nation-wide air quality standards designed to meet health-based guidelines for common air pollutants (US EPA 2025d). As discussed in Chapter 5.1, significant outdoor air pollutants include carbon monoxide (CO), airborne lead, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter, and ground-level ozone pollution. Due to the motor vehicle emission standards and the removal of lead from gasoline, both carbon monoxide and lead levels meet air quality standards nationwide. While particulate matter and ground-level ozone have decreased over recent years in part due to the regulation and controls implemented to reduce levels to achieve the National Ambient Air Quality Standards, they remain a concern in many areas of the country as they result from a myriad of different sources (Lioy and Georgopoulos 2011, US EPA 2025d). These air pollutants, among others, can cause serious health problems, particularly in populations that already have higher rates of heart and lung conditions. In New Jersey, for example, from 2011-2018, Black populations had higher prevalence of COPD on average compared to White, Hispanic, and Asian populations (NJDOH 2019a). In general, pollution in urban environments disproportionally harms low-income neighborhoods. Statistical analysis of daily nitrogen dioxide (NO_2) values in New York City, New York and Newark, New Jersey, between May 2018 and September 2021, demonstrated the inequalities of urban pollution associated with race, ethnicity, and or/household income (Dressel et al. 2022). Therefore, constant monitoring of the air quality is imperative to determining the effectiveness of federal and state efforts in maintaining healthy and clean air in the country.

Even healthy individuals, who may be less susceptible to the aggravated respiratory and cardiovascular effects of chronic disease, may experience a disruption of normal work and recreational outdoor activities when air quality diminishes due to increased levels of pollutants. Table 6.1 outlines the outdoor recreation recommendations for air pollutants based on the US EPA's Air Quality Index (US EPA 2012). The Air Quality Index (AQI) is an average measure of the pollutants in the air (e.g., carbon monoxide [CO], sulfur dioxide [SO_2], nitrogen dioxide [NO_2], particulate matter, and ground-level ozone) in a 24-hour period relative to their National Ambient Air Quality Standards. The AQI ranges from 0-500, where values below 50 are considered good air quality and healthy for all persons to be outdoors, whereas values greater than 300 describe hazardous conditions where everyone is likely to be affected (US EPA 2012). An AQI of 51-100 is considered moderate, but still acceptable to be outside for all activities, with the exception of individuals who are "unusually sensitive" to air pollution. During instances of higher than acceptable AQI levels, individuals with asthma may experience coughing, wheezing, difficulty breathing, and chest tightness. In extreme conditions (>150 AQI), even individuals who do not have asthma may experience these symptoms. Such guidance values are generally applied to protect school-aged children who are more sensitive to air pollution than adults. Air Quality Index values may also be used to investigate air quality trends within a certain area over time. As climate change affects air quality and vice versa, tracking AQI helps us understand how air quality changes over time and how these changes relate to impacts of climate change.

Table 6.1. Daily Air Quality Index (AQI) Values and Outdoor Activity Guidance. Table was modified from www.airnow.gov/aqi/aqi-basics/ with information from (US EPA 2012).

AQI Color	Levels of Concern	Breakpoints (µg/m3, 24-hr avg)	Index Value	Description of Air Quality and Outdoor Activity Guidance
Green	Good	0.0 to 12.0	0 to 50	Air quality is satisfactory. No health impacts are expected.
Yellow	Moderate	12.1 to 35.4	51 to 100	Air quality is acceptable. Individuals who are unusually sensitive to air pollution may be at risk for affects.
Orange	Unhealthy for Sensitive Groups	35.5 to 55.4	101 to 150	Members of sensitive groups may experience health effects and should limit outdoor exposure. The general public is less likely to be affected.
Red	Unhealthy	55.5 to 150.4	151 to 200	Members of sensitive groups may experience more serious health effects and should avoid outdoor exertion. Some members of the general public may experience health effects.
Purple	Very Unhealthy	150.5 to 250.4	201 to 300	Health alert: The risk of health effects is increased for everyone. Outdoor exertion should be limited or avoided.
Maroon	Hazardous	250.5 to 500	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected. Outdoor exertion should be avoided.

6.2.1.1 Ozone Pollution

Ground-level ozone, a major component of smog, is formed by a natural chemical reaction between nitrogen oxides (NO_x) and volatile organic carbons (VOCs) in the presence of heat and sunlight, but human activities like automobile emissions speed up this process (Chapter 5.1.1.1). High concentrations of ground-level ozone have been found to have a varying degree of impact on human health, ranging from eye irritation to severe respiratory distress and can lead to chronic illness or premature death (NJDEP 2024b). More specifically, ground-level ozone is associated with reduced lung function, and increased severity of asthma attacks requiring emergency department visits and admissions (USGCRP 2016, Nuvolone et al. 2018). Modeling of ozone-related premature deaths from 2000 to 2030 showed that the Northeastern United States had the second highest projected change of six geographic regions of the country, second only to the midwestern United States (USGCRP 2016). Children, elderly, and people with asthma, bronchitis, or emphysema are most at risk, but healthy adults with outdoor occupations may also be affected by ozone air pollution (Nuvolone et al. 2018, CDC 2024b). Each year, an estimated tens to thousands of ozone-related illnesses and deaths occur yearly, with a projected economic burden ranging from hundreds of millions to tens of billions of U.S. dollars (Fann et al. 2015). By 2030 in the United States, it is expected that the human health impacts attributed to increases in ozone due to climate change will lead to a significant increase in premature deaths, hospital admissions, and cases of acute respiratory illnesses per year.

Exposure to ozone occurs by way of inhalation where it is mostly absorbed by the upper respiratory tract. Absorption rates vary with age, gender, and overall physical health. Vigorous physical activity generally leads to higher penetration of ozone into the lung. Ozone will react with components of the natural fluid lining in the lung, leading to oxidative stress, cell injury, and inflammation. Symptoms of ozone exposure are similar with other air pollutants, including lung and throat irritation, coughing, wheezing, and difficulty breathing during exercise or outdoor activities (Nuvolone et al. 2018, CDC 2024b).

Ozone concentrations are generally highest in the warmer months in the Northern Hemisphere (USGCRP 2016, Dupigny-Giroux et al. 2018). Temperature is a key factor in the formation reaction, with higher temperatures increasing the reaction rate, generating more ground-level ozone. This phenomenon is known as the "climate penalty." While states have seen significant ozone emission reductions over time because of Federal and state laws and regulations, and technological advances that reduce the emissions that create ground-level ozone, there is evidence of the "climate penalty" with recent spikes in ground-level ozone emissions in the United States and Europe during particularly hot periods. With climate scientists predicting that extreme heat events or heat waves will increase in frequency and duration as the planet warms, there will be parallel increase in the formation of ground-level ozone that could counteract government efforts to reduce the pollutant (Boyle 2024). In addition, recent research shows that as the planet warms, ground-level ozone will become less sensitive to reductions in NO_2 emissions, meaning that greater NO_2 emission reductions will be needed to get the same air quality results (Le Roy et al. 2025).

With the rate of atmospheric warming expected to increase, particularly in New Jersey, several models have attempted to estimate the deaths in the United States attributable to ozone-related illnesses for the years 2000 to 2050, with the largest increase in deaths predicted for the Northeastern United States (Post et al. 2012). Climate change is threatening to offset the recent progress that the Northeast has made in improvements to air quality, due in part to the increases of ground-level ozone concentration, particularly in urban environments (Fann et al. 2015, Dupigny-Giroux et al. 2018). A recently published model predicted ozone concentrations to worsen across much of the contiguous United States by 2051 (Ren et al. 2022). In New Jersey, the daily ozone concentrations during the warm season (May to September) in 2051 are predicted to exceed the daily ozone concentrations measured in 2011 (Figure 6.1; pers. comm. with Panos Georgopoulos; April 2022).

Numerous epidemiology studies have found that the risk of adverse health impacts is linked to a population historically being exposed to air pollutants (Fann et al. 2016), as is often the case in overburdened communities. Specifically, there is a greater risk of suffering from aggravated asthma, visiting an emergency department or being admitted to the hospital for respiratory issues or other health impacts, and dying prematurely in populations that are exposed to elevated levels of ozone air pollution. There is also emerging scientific evidence that the human physiological response to air pollution can be more severe when individuals are also subject to climate-related stressors such as elevated temperature (Fann et al. 2016, Nolte et al. 2018). For example, exposure to a heat wave may increase the risk of dying from exposure to elevated ozone levels (Fann et al. 2016). In urban areas, such as many areas in New Jersey, the hottest days are also often associated with high concentrations of local and transported air pollutants including ground-level ozone (Fann et al. 2016, Nolte et al. 2018). Vulnerable groups that include young children, elderly, socially or linguistically isolated, economically disadvantaged, and those with preexisting health conditions will be more at risk to health impacts from the combination of heat stress and poor urban air quality (Dupigny-Giroux et al. 2018).

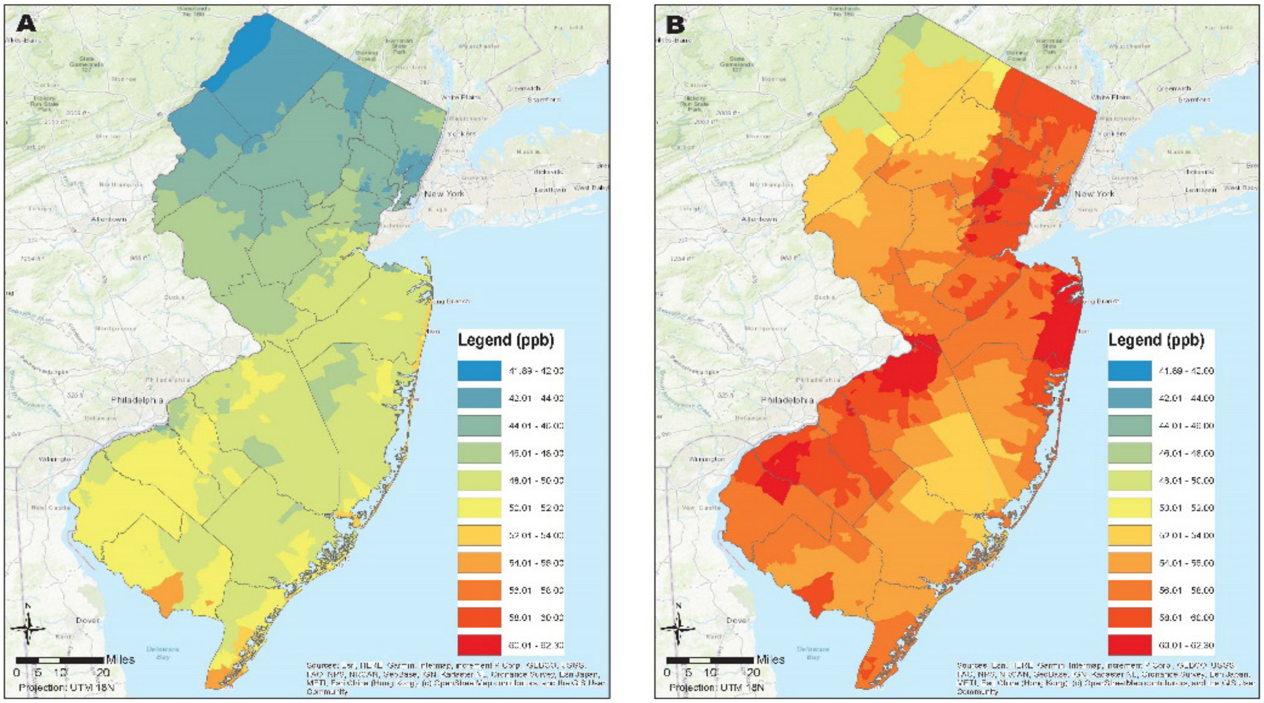


Figure 6.1. Maps of 2011 and Model Estimates for 2051 Levels of Ozone Across New Jersey. The maps show means of Daily Maximum 8-Hour Running Average values of ozone concentrations during the warm season (May to September) in 2011 (A) and predicted for 2051 (B). The 2051 estimates have been calculated for the RCP 8.5 ("worst case") scenario, using the method (combining CMAQ and Machine Learning) described in (Ren et al. 2022).

6.2.1.2 Particulate Matter Pollution

Particulate matter (PM) consists of particles and liquid droplets that are formed from gaseous precursor emissions of NO_2, sulfur oxides, ammonia, and other airborne compounds. Particulate matter can also be emitted directly, as in the case of black carbon (Chapter 5.1) (Dedoussi et al. 2020). While wildfires may pollute the air in acute episodes, by producing various PM, such as PM_{10} (particles with diameters <10 µm), $PM_{2.5}$ (<2.5 µm), and ultrafine particles (<0.1 µm, $PM_{0.1}$), there are other more chronic sources including power plants, gasoline- and diesel-fueled vehicle exhaust, and some household cooking. Short-term particle exposure (hours or days) can cause eye, nose, throat and lung irritation, coughing, sneezing, runny nose, shortness of breath, asthma attacks, acute bronchitis, and increased susceptibility to respiratory infections. Long-term exposure (years) has been associated with reduced lung function, chronic bronchitis, and increased mortality from lung cancer and heart disease (US EPA 2003). Particulate matter vary in composition, containing sulfate, nitrate, ammonium, carbon, metal fragments, liquid, sea salt, or dust, and their toxicity is inversely related to their size (USGCRP 2016). The smaller the particle size, the larger the relative surface area of individual particles, which in turn means a greater surface area on which to absorb materials (e.g., toxic chemicals). Smaller particles are also capable of penetrating deeper into the respiratory tract than larger particles and may carry along pollutants adhered to them. $PM_{2.5}$ are known to cause pulmonary inflammation to a greater extent than PM_{10}, whereas $PM_{0.1}$ have the potential to cause greater damage due to their ability to enter circulation by way of the lung vasculature (Schraufnagel 2020). Ultra fine PM are also capable of reaching the central nervous system directly via the olfactory nerve (a nose-to-brain route), in a size dependent manner. Exposure to airborne particles in general has been associated with neurotoxicity for some metals, such as manganese, however, the effects of other pollutants (in the form of particulate matter for instance) are still emerging (Lucchini et al. 2012). The health effects of $PM_{2.5}$ and $PM_{0.1}$ are thought to be driven by oxidative stress, an imbalance between cellular free radicals and antioxidants, and the triggered immune response in target tissues (e.g., lung, blood vessels, heart). Furthermore, PM air pollution is a leading cause of cardiovascular morbidity and mortality, particularly in elderly patients (Rao et al. 2018).

The overlap of heat waves with air quality is another area of concern, particularly for vulnerable individuals. A study conducted in Elizabeth, New Jersey, monitored indoor air quality in senior apartments during the summer of 2017 and showed a significant increase in $PM_{2.5}$ levels during days associated with a heat wave (He et al. 2023). The increase was consistent, regardless of smoking habits or air conditioning use, demonstrating a connection between high ambient temperatures and indoor air quality. While short-term exposure to either extreme heat or air pollution can independently increase mortality, the adverse effects from a combination of exposures has been shown to be greater than just the sum of their individual impacts (Rahman et al. 2022).

6.2.1.3 Air Pollution from Biomass Combustion

Prescribed burning is commonly utilized as a tool to reduce wildfire hazards in some areas of New Jersey, and there are also many ecological benefits to forest fires including wildlife habitat management, ecological plant and animal management, forest disease and pest control, nutrient recycling and positively influence soil chemistry, and others (NJDEP 2020d). However, combustion of products from wildland fires (wild and controlled forest, grass, and peat fires) pollutes the air, soil, and waterways of the surrounding area. In addition to producing greenhouse gases and climate pollutants (Chapter 3) , including carbon dioxide, methane, black carbon, and nitrous oxide, fires also produce ozone precursors (e.g., nonmethane VOCs, NO_2 and PM, both $PM_{2.5}$ and PM_{10}) (Urbanski et al. 2008). Primary pollutants from burning biomass, such as carbon monoxide (CO), remain a local burden, restricted to the immediate region, while $PM_{2.5}$ and ozone will be more broadly dispersed (Tao et al. 2020). The atmospheric transport of combustion products from wildland fire can reach far beyond the immediate location of the burn depending on meteorological conditions, plume dynamics (movement of the column of smoke and all that it contains through the air), the amount and chemical composition of the emissions, and the atmosphere into which the emissions are dispersed (Urbanski et al. 2008, Smith et al. 2014). As a result, particulate matter and ozone produced by combustion events have become the predominant pollutants for quantifying air quality. These pollutants form mainly through atmospheric chemical reactions following the release of precursor emissions (Dedoussi et al. 2020). The unusually high organic carbon content recorded at an air quality monitoring site located in Brigantine, New Jersey on July 7, 2002 was known to be attributable to a large wildfire in Quebec, Canada in that week (GFMC 2002). As more than 250,000 acres of forests burned, much of the Northeastern United States was covered in smoke and haze that reached as far south as Washington, D.C., and air traffic was affected as far south as New York State (GFMC 2002). Similar occurrences following eastern Canadian wildfires took place in 2015, where air quality was impacted by smoke moving into the United States and south to Baltimore, Maryland and in 2016, where multiple New Jersey air-quality monitors noted exceedances of health-based ozone standards (NJDEP 2017, Dupigny-Giroux et al. 2018). The record-breaking 2020 wildfire season with widespread the fires were across the western United States led to a co-occurrence of significantly elevated $PM_{2.5}$, ozone, and extreme temperatures over eastern North America during large, multiday pollution episodes, similar to what has been seen in previous years (Schnell and Prather 2017, Kalashnikov et al. 2022).

Exposure to fire emission pollutants is a growing global public health concern, as observed with increases in the incidence of acute cardiovascular events and the potential of such emissions to trigger

> ***"As the frequency and severity of wildfires are expected to increase in the western United States and Canada, the air quality in New Jersey could be negatively impacted..."***

respiratory conditions, such as asthmatic episodes and acute bronchitis; prolonged exposure to air pollutants could cause asthma and chronic bronchitis and further result in COPD (Cascio 2018, Anenberg et al. 2020). As a result, the risk of premature death due to exposure to fire emissions is also increased. Globally, fire emissions are estimated to be responsible for 339,000 to 675,000 deaths annually (Johnston et al. 2012, Roberts and Wooster 2021). A recent study modeling the global concentration and associated premature deaths of $PM_{2.5}$ over the past two decades found that the upward trend in $PM_{2.5}$ concentrations globally contributed to 156,000 to 241,000 premature deaths between 2000 and 2021, alongside population growth and aging. Further regression analysis indicated that climate change played a critical role in these trends, accounting for 56% of the net changes in $PM_{2.5}$-related premature deaths, with warming and drought emerging as key drivers of climate-induced health risks (Zhong et al. 2025). Individuals with respiratory and cardiovascular diseases, older adults, children, those who are pregnant, and fetuses are more sensitive to the adverse health effects of smoke exposure (USGCRP 2016). Excess hospitalizations were observed in areas downwind of wildfires, in a pattern following the distribution of smoke plumes (Deflorio-Barker et al. 2019). More specifically, increased exposure to elevated PM_{10} levels was associated with a higher incidence (Zhong et al. 2025) of acute coronary syndrome and hospitalization of elderly patients for several days following fire-related air quality exceedances (Kollanus et al. 2016, Kuźma et al. 2020). Admissions of both pediatric and adult asthma patients also increased with exposure to primary fire emissions $PM_{2.5}$, PM_{10}, or ozone, individually or in combination (Pope et al. 2017, Baek et al. 2020). Pre-term birth has been associated with exposure to CO and $PM_{2.5}$ early in pregnancy (Padula et al. 2019). The risk of hospitalization and pre-term birth is greater to vulnerable communities in areas prone to seasonal droughts, such as the western United States and Northeast (Dupigny-Giroux et al. 2018, Cascio 2018, Anenberg et al. 2020).

As the frequency and severity of wildfires are expected to increase in the western United States and Canada, the air quality in New Jersey could be negatively impacted and the incidences of respiratory illness, reduced visibility, and disruption of outdoor activities will likely increase (Chapter 5.1). For example, during the devastating 2020 wildfire season in the western United States, several populated cities, including Seattle, Washington, Portland, Oregon, and Sacramento, California, sustained "Unhealthy" and "Very Unhealthy" Air Quality Index values for several days. Many areas in the region experienced instances of "Hazardous" Air Quality Index conditions, including Portland, which recorded eight days above 200, and a maximum Air Quality Index of 509 that year. Cities of neighboring states Idaho and Nevada also experienced several "Unhealthy" and "Very Unhealthy" days with Air Quality Index in the 200s. In comparison, New

Jersey, which experienced less of an impact from the fires, never experienced state-wide Air Quality Indexes that were above “Unhealthy” in 2020, with the maximum Air Quality Index recorded as 143 for the Philadelphia-Camden-Wilmington, in the Pennsylvania-New Jersey-Delaware-Maryland region (US EPA 2025e). The severity of 2021 wildfire season led to multiple days of hazy skies and a characteristic red sun across the country and all the way to eastern cities, including the New York/New Jersey metropolitan area, due directly to a convergence of smoke plumes from several fires in the western United States and Canada (Popovich and Katz 2021). The resulting diminished air quality in the region led state officials to encourage vulnerable individuals to avoid outdoor activities to minimize exposure to air pollution (primarily $PM_{2.5}$), a call that may become more common as western wildfires continue to rage in the drought stricken west coast. The fine particulate ($PM_{2.5}$) levels in the Mid-Atlantic and New England states increased to “Unhealthy” because of wildfire smoke from the western United States and Canada on July 20 and 21, 2021. Again, in June of 2023, air quality in New Jersey was impacted from extensive wildfires in Eastern Canada with AQI across the state reaching “unhealthy” and “very unhealthy”. According to a study completed by the New Jersey Department of Health comparing asthma emergency department visits before and after the wildfire event, the number of asthma related visits were statistically significantly higher in the three-day period during the wildfire air quality impacts compared to the two weeks before – culminating in a 112% increase in the number of visits compared to the average daily visits of the two-week period prior (NJDOH 2025b). Although emissions from cars, trucks, and industry contribute to $PM_{2.5}$ air quality, the elevated levels of $PM_{2.5}$ on these days were caused by the wildfire smoke from upwind regions and resulted in concentrations exceeding the 24-hour average National Ambient Air Quality Standard for $PM_{2.5}$ throughout the Northeast.

An average of 1,500 wildfires damage or destroy 7,000 acres of New Jersey's forests each year. While the scale of wildfires in New Jersey does not compare to regions in the western United States, a significant portion of its homes are adjacent to forested areas, making even the small fires a concern for human health and property (Hurdle 2022, NJDEP 2025h).

Burning waste products, either by individuals or more broadly by a municipality, is another contributor to air pollution that can drive climate change. The combustion of refuse produces not only the normal pollutants (e.g., CO, SO_2, NO_2, PM, etc.) but can also release an abundance of toxic chemicals including but not limited to polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and polychlorinated biphenyls (PCBs) (Ferronato and Torretta 2019) as well as metals. In addition to the toxic emissions from burning refuse, disposing of the ashes from such activity can result in high concentrations of heavy metals and other chemicals in soils of dumping areas (USGCRP 2016). Byproducts of waste burning can then be redistributed by wind in drought conditions or by heavy precipitation, expanding the contamination area and increasing exposures to a larger population. New Jersey residents are prohibited from open burning of rubbish, garbage, trade waste, fallen leaves, or any kind of plant material (N.J.A.C. 7:27-2.3), and New Jersey's Air Quality Permitting Program regulates air toxic output from municipal and industrial incineration through a combination of state-of-the-art control technology requirements and risk assessments. However, neighboring state regulations may differ from New Jersey.

6.2.2 Increased Aeroallergens

Climate change-driven increases in carbon dioxide (CO_2), temperature and humidity, and precipitation have secondary consequences beyond those discussed previously. For example, CO_2 increases plant growth, which, in combination with the predicted lengthier warmer weather periods, may lead to longer growing seasons that in turn is likely to increase pollen counts and therefore exposure to pollen, increasing the prevalence of allergy and asthma symptoms in a population. Indoor environments are similarly adversely impacted from secondary effects of severe storms and flooding, including the growth of mildew and mold, increasing the likelihood of respiratory illnesses following exposure to spores. Additionally, the severity and prevalence of asthma and other allergic diseases, as well as respiratory infections, worsens due to prolonged and widely distributed over-production of "natural" threats (e.g., pollen) which alter the immune system response to the allergens (USGCRP 2016).

Allergies or allergic diseases develop in response to complex interactions, including genetic and non-genetic factors, environmental exposures, and socioeconomic and demographic factors (Fann et al. 2016, Nolte et al. 2018). The scientific literature indicates a high likelihood that the concentration, allergenicity, season length, and spatial distribution of various aeroallergens will increase with climate change (Nolte et al. 2018), posing serious health risks with respect to asthma, hay fever, sinusitis, conjunctivitis, hives, and anaphylaxis (Fann et al. 2016, Nolte et al. 2018).

6.2.2.1 Pollen

Climate change is expected to impart regionally specific effects on the start, duration, and intensity of the pollen season (Ziska and Beggs 2012, Anderegg et al. 2021). In the Northeastern United States, shorter, milder winters will likely lead to a longer and more intense pollen season (Dupigny-Giroux et al. 2018). The quantity of pollen produced, the amount that becomes airborne, and the sources of pollen (e.g., from changes in plant distribution), are all variables that contribute to human sensitivity to aeroallergen. The increase in pollen has led to a greater prevalence of allergic airway diseases (Seth and Bielory 2021). Aeroallergen exposures trigger respiratory effects such as asthmatic episodes, allergic rhinitis or hay fever, and sinusitis, but may also contribute to the occurrence of conjunctivitis (i.e., pink eye), hives, atopic dermatitis or eczema, and life-threatening anaphylaxis (USGCRP 2016). Seasonal allergic rhinitis may range in severity depending on individual susceptibility and concentration of allergen exposure. Pollen allergens trigger inflammatory cells to release histamine and other immune-stimulating molecules in the body. Together, asthma and allergic rhinitis are two manifestations of the common allergic respiratory syndrome (Xie et al. 2019). While the most significant changes in temporal pollen increases have been observed in Texas and the Midwest (Anderegg et al. 2021), pollen season for birch and oak was observed to start earlier and last longer in Newark, New Jersey in 2011 compared to 1994, an observation attributed to regional warming (Zhang et al. 2013). The longer frost-free seasons, changes in precipitation, and higher levels of atmospheric CO_2 are expected to result in increased exposure to pollen allergens in New Jersey and elsewhere (Fann et al. 2016).

Allergy symptoms can be exacerbated by the changes in local weather patterns, such as rainfall and changes to minimum and maximum temperatures (Fann et al. 2016). According to the United States CDC, in 2022 over 26 million people were diagnosed with asthma (CDC 2024e) and as of 2021, about one-third of the population is affected by an allergic illness (CDC 2023b). The prevalence of aeroallergenic responses has increased in the United States from 1970 to 2000, with hay fever increasing from 10% to 30% of the population and asthma rates raising from 55 per 1,000 persons to up to 90 per 1,000 persons (USGCRP 2016). Asthma rates have also increased from about 8 to 55 cases per 1,000 people to about 55 to 90 cases per 1,000 people during the same time period. In New Jersey, over 600,000 adults (9.0% of the populations) and 167,000 children (8.7% of the population) are estimated to have asthma. Asthma and hay fever are expected to worsen due to the effects of climate change, which will increase airborne allergen exposures (Nolte et al. 2018).

Increases in sales of allergy medicine, emergency medical service calls, and hospital visits for asthma and rhinitis symptoms have occurred with increasing pollen counts (Gleason et al. 2014, Dupigny-Giroux et al. 2018, Cissé et al. 2022). A study of children in Philadelphia, Pennsylvania were more likely to experience an asthmatic event if they exhibited an allergy sensitivity to early-season tree pollen, oak tree pollen, early-season weed pollen, and late-

> ***"Indoor dampness and mold growth have been associated with up to 20% of common respiratory infections in the United States alone and are linked to millions of cases of worsened asthma as well as with increased risk of developing asthma in young children."***

season molds compared with children who weren't sensitive to those typical outdoor aeroallergens (De Roos et al. 2024). While plant pollen is the most abundant aeroallergen, respiratory allergies are more prevalent among urban residents than rural residents, perhaps due to the interaction between chemical air pollutants and pollen grains, especially particulate matter (Sedghy et al. 2018). Storms can bring on an outbreak of asthma, as the meteorological event is thought to induce the release of pollen *en masse* (Xie et al. 2019). Storms can also lead to damp conditions, ideal for the release of fungi allergens (e.g., spores), as discussed in the next section.

There is also evidence to suggest that pollen may suppress the body's innate defense against respiratory viruses, making outdoor activities more hazardous to at-risk populations, including children and the elderly (Gilles et al. 2020).

Children, African American, Hispanic, and urban residents are most likely to be affected by asthma. Health risks may increase for individuals who are exposed simultaneously to both aeroallergens and air pollution, especially particulate matter (Nolte et al. 2018). Related symptoms can cause individuals to miss work or school (NJDOH 2019b). Serious asthma attacks may result in hospitalization, though most are successfully managed without it. Many people with asthma prevent serious attacks by avoiding known triggers, but that could become more difficult due to climate change.

6.2.2.2 Fungi/Mold

In addition to the immediate health hazards associated with extreme precipitation events, other hazards follow in the wake of storms and flooding events. Damp conditions, particularly in indoor environments, can create the ideal climate for mold and other fungi to propagate, at the detriment of human health (USGCRP 2016, Dupigny-Giroux et al. 2018). Reactions to fungal toxins induce symptoms akin to other aeroallergens (e.g., nasal congestion, sneezing, coughing) and may aggravate asthma symptoms. In fact, populations living in damp indoor environments, such as buildings damaged by hurricanes, experience increased prevalence of asthma and other upper respiratory tract symptoms, as well as infections in the lower respiratory tract, including pneumonia, respiratory syncytial virus (RSV), and RSV pneumonia (CDC 2024b). Indoor dampness and mold growth have been associated with up to 20% of common respiratory infections in the United States alone and are linked to millions of cases of worsened asthma as well as with increased risk of developing asthma in young children (USGCRP 2016, Baxi et al. 2016). For this reason, school and home environments with chronic or consistent water damage should be considered sources of exposure (Baxi et al. 2013, 2016). Fungi allergens are also associated with other respiratory illnesses, including allergic bronchopulmonary mycoses, allergic fungal sinusitis, and hypersensitivity pneumonitis (WHO 2009).

Mold and other fungal colonies can start to grow on damp surfaces within 48 hours of deposition from spores that circulate through the air and are an even greater concern when power outages compound the ability to dry out damp areas. In indoor air, humans may be exposed to a variety of fungal spores, metabolites, and other compounds (e.g., mycotoxins) produced by this diverse class of organisms (WHO 2009). Visible mold may indicate higher mold spore counts in a particular microenvironment, suggesting that if the mold is visible then exposure to fungal products is likely (Baxi et al. 2013). The human respiratory system, including the lungs, is a primary target organ for fungal products, and multiple mechanisms of immuno-activation can be triggered by the complex mixtures released by fungi, resulting in respiratory illnesses (WHO 2009, Baxi et al. 2016).

The prediction of more frequent and severe storms for New Jersey and the Northeastern United States, as well as the high temperatures and humidity, suggests that mold- and fungal-induced respiratory illnesses will likely be on the rise in the coming decades (Moran et al. 2017, Dupigny-Giroux et al. 2018).

6.2.3 Feedback Between Extreme Weather and Air Pollution

Climate change will likely worsen air pollution from a myriad of sources, both natural and anthropogenic. This may lead to greater instances of respiratory illnesses particularly in vulnerable populations, including people of color, people experiencing poverty, children, elderly, and communities located near sources of pollution (e.g., power plants, factories, traffic corridors and densely populated areas), wildfire vulnerable woodlands, and areas prone to heavy storms and flooding (American Lung Association 2025). Further consideration should be made for how climate change-driven warmer weather affects human adaptive behaviors (e.g., increased demand for air conditioning to cool buildings in the summer), which could in turn exacerbate air pollution (USGCRP 2016). Much of our energy currently comes from burning fossil fuels, meaning the prevalence and use of air conditioning undoubtedly increases emissions of air pollutants from power plants, further diminishing air quality and worsening human health impacts. One study estimated that approximately 9% of air-pollution-related mortality could be attributed to increases in emissions from power plants in an attempt to sustain the demand on electricity (Abel et al. 2018). Overall, though the US EPA and DEP have made strides in meeting health-based national standards of air quality since the 1970s, climate change factors pose an increasing threat to dampening of that progress.

CHAPTER 6.3

INCREASES IN INFECTIOUS DISEASE TRANSMISSION PATTERNS

6.3 Increases in Infectious Disease Transmission Patterns

In addition to the likely increase in acute and chronic cardiovascular and respiratory illnesses caused by extreme weather and diminished air quality conditions, the human health impacts of climate change also include challenges from other diseases, such as those brought on by vector-borne diseases, microorganism contamination (food and waterborne diseases), and other related consequences, which including increased exposure to pesticides used in vector control and novel pathogens. Associations between climate, infectious agents, and disease spread are apparent; however, the ability to accurately predict the distribution and prevalence of the myriad of vectors and pathogens is subject to a high degree of uncertainty (USGCRP 2016).

6.3.1 Vector-borne Diseases

Illnesses transmitted by arthropod and insect vectors, which include ticks, mosquitoes, and fleas, have historically afflicted humans throughout their existence. However, because weather and climate have direct impacts on the habitat and food sources of these arthropod and insect vectors, climate change is expected to influence many aspects of vector biology and behavior, and in doing so, alter the exposure paradigms for humans. Temperature (Chapter 4.1), precipitation (Chapter 4.2), and seasonal shifts can all play a role in altering geographic distribution, habitat availability and population dynamics of these species, and therefore may lead to spatial and temporal changes in the exposure window or to new human populations being exposed (USGCRP 2016, Ogden 2017, Dupigny-Giroux et al. 2018). Not all changes in vector-borne disease dynamics can be attributable to climate change. Anthropogenic influences, such as land use (e.g., habitat fragmentation caused by urbanization and suburban sprawl), agricultural practices, and pest-mitigation efforts, may also impact disease transmission (Dantas-Torres 2015, Ogden and Lindsay 2016, Jordan et al. 2022). However, this section will focus on ways climate change is affecting vector transmitted disease spread.

Vector-borne diseases are a growing public health concern globally, with tropical and subtropical countries bearing the greatest burden of cases (WHO 2003, Rocklöv and Dubrow 2020). In the United States, over 1 million cases of vector-borne diseases have been reported by states to the CDC between 2001 and 2023, with at least 17 different vector-borne diseases reported annually. Since 2004, the CDC reports a significant increase in vector-borne diseases, with over 1 million cases reported between 2001 and 2023 (CDC 2024f). The New Jersey Department of Health (NJDOH) works with local health departments to investigate, monitor, and evaluate trends of vector-borne diseases reported in the state. The data tracking and trends from 2010 onward are available to view on the Vector-borne Disease Data Dashboard (NJDOH 2025c). In New Jersey, infections transmitted by ticks surpass those submitted by mosquitos. From 2010-2024, annual case counts of mosquito borne diseases ranged from roughly 125-400 (excluding 2020, with an anomalous 35 cases, as it is likely the COVID-19 pandemic influenced reporting), compared to between 3,000 and 8,500 cases of tickborne diseases.

6.3.1.1 Tickborne diseases

Ticks are obligate parasitic arachnids (meaning they require a host to complete their life cycle) that can carry bacteria, viruses, or protozoa, which when transmitted to humans through a bite, cause a number of diseases. Tickborne diseases have been reported in every county of New Jersey in the last decade, with the greatest number of cases reported in Hunterdon, Monmouth, and Morris counties (Figure 6.2A). The most common tickborne disease, Lyme disease, is caused predominantly by the bacterium *Borrelia burgdorferi,* and afflicts an estimated 476,000 people in the United States annually (CDC 2025b). In 2023 alone, New Jersey reported over 7,000 Lyme disease cases (Figure 6.2B). Typically, symptoms of infection include fever, headache, fatigue, and a characteristic skin rash at the site of the bite wound. However, an untreated infection may spread to the joints, the heart, and the nervous system (NJDOH 2024b). In New Jersey, in addition to Lyme disease, other tickborne diseases are less frequently diagnosed such as Anaplasmosis, Babesiosis, Ehrlichiosis, Powassan, and Spotted Fever Group Rickettsioses (Table 6.2). As the anticipated changes to our regional climate take place, including increasing temperatures, precipitation, and humidity, tick activity is expected to start earlier, last longer, and perhaps more concerningly, expand in geographical range (USGCRP 2016, Dupigny-Giroux et al. 2018). The result of this change in activity is a likely increase in the chance of human exposure to the pathogens carried by the arthropods.

Ticks survive inclement weather by remaining in the protective soil layer of temperate woodland surfaces, and they rely primarily on humidity to rehydrate and survive from one life stage to the next (Ogden and Lindsay 2016). Warmer winters and more humid summers will promote tick survival, while prolonged heavy rains and persistent flooding will have a negative impact on tick mortality (Ogden and Lindsay 2016). Multiple studies have shown the northward migration of certain tick species, attributed mostly to the milder winters and extended growing seasons (Dantas-Torres 2015). Conversely, high temperatures in lower latitudes, particularly under dry conditions, may adversely affect tick survival (Sonenshine 2018). Soil and plant type are also very integral determinants for tick populations (Burtis et al. 2019, Mathisson et al. 2021).

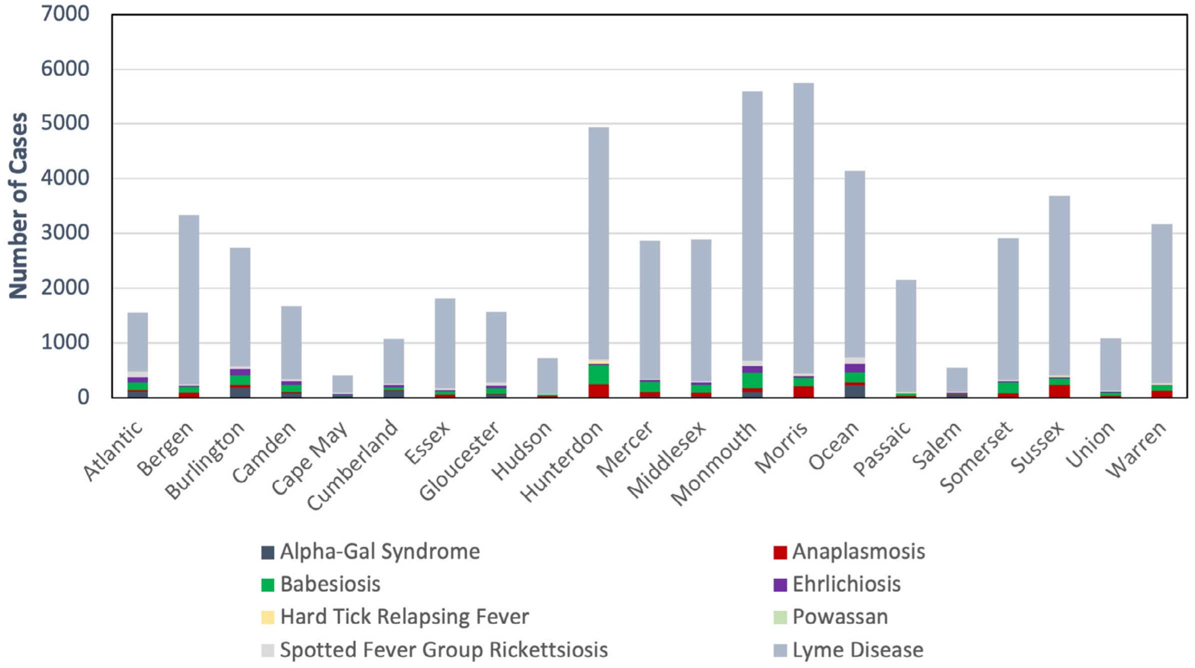
Different life stages of the various tick species are not equally sensitive to climate conditions, leading to further variations in the activity of these insects. Typically, ticks go through four life stages: egg, six-legged larva, eight-legged nymph, and adult. This life cycle lasts months to years (Ogden and Lindsay 2016). Ticks require a blood meal upon hatching to survive to each successive stage, and may feed on mammals, birds, reptiles, or amphibians. Their ability to find a host is dependent on proximity to a host, as ticks are only capable of moving a few meters on their own. While a tick is feeding, which can last for several days, small amounts of tick saliva may enter the host, thereby transmitting the pathogen (if the tick is infected). If their host carries the pathogen, the tick will ingest the pathogen and then it will be able to pass it along to a new host in the subsequent life stage (CDC 2024f). Humans are “dead-end” hosts because while they may be infected by the pathogen, they do not transmit the pathogen to others (Baum 2008).

Tick reproduction rate is dependent on both host density and habitat, which varies by tick species (Ogden et al. 2013). The likelihood of a tick surviving to the subsequent stage is also related to their ability to find a blood host. Therefore, climate has both direct and indirect effects on tickborne disease transmission; specifically, increased temperatures and humidity accelerate development and reduce mortality, while increased rainfall and flooding inhibit survival and activity (Ogden and Lindsay 2016) (Ogden and Lindsay 2016). Seasonally dependent activities of hosts are weather dependent and will alter accessibility, thereby indirectly impacting tick survival. While the transmission of tickborne diseases is expected to continue to rise in the Mid-Atlantic region, particularly in New Jersey (USGCRP 2016, Dupigny-Giroux et al. 2018), multiple factors determine the prevalence and are likely regionally specific.

Changes in climate patterns may raise the risk of human interaction with ticks and thus cause more tick bites. Shifting climate patterns leading to warmer winters and longer, hotter summers have already been implicated in the expanded domain of where Lyme disease carrying ticks have been previously reported (Beard et al. 2016). Specifically, a warming climate changes environmental characteristics like vegetation and temperature to be more suited for ticks in all life stages, raising the prevalence of tickborne diseases (Leighton et al. 2012).

> ***“ Changes in climate patterns may raise the risk of human interaction with ticks and thus cause more tick bites.”***

A. Geographic Distribution, by County, of Tickborne Disease Cases in New Jersey from 2015-2024



B. Lyme Disease Cases in New Jersey from 2015 to 2024

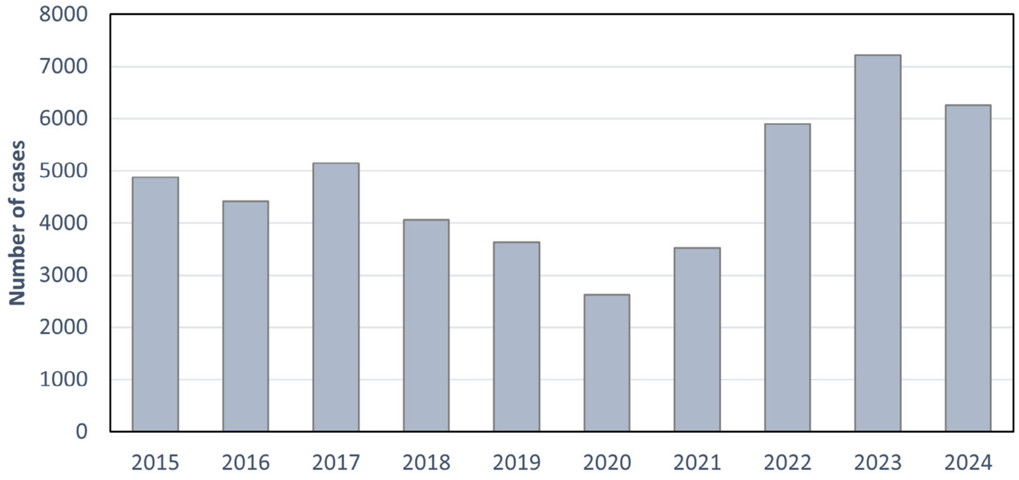


Figure 6.2. New Jersey tickborne diseases recorded by NJDOH from 2015-2024. A) Graphical distribution of all tickborne diseases in each county and B) Total cases of Lyme disease reported in New Jersey over the last decade. (Source: *Vector-borne Diseases in New Jersey Dashboard* (*www.nj.gov/health/cd/statistics/arboviral-stats/index.shtml*))

Table 6.2. Human Cases of Tickborne Pathogens and Diseases Detected in New Jersey. The NJDOH monitors for vector-borne diseases through their Communicable Disease Service program. For more information regarding county, age, and sex distribution of the human cases, visit the Vector-Borne Diseases in New Jersey Dashboard (www.nj.gov/health/cd/statistics/arboviral-stats/index.shtml).

Pathogen	Disease	2020	2021	2022	2023	2024
Anaplasma phagocytophilum	Anaplasmosis	116	203	122	194	173
Babesia species.	Babesiosis	237	258	293	409	276
Borrelia miyamotoi	Hard Tick Relapsing Fever	9	17	6	18	13
Borrelia burgdorferi	Lyme disease	2630	3523	5895[a]	7226	6258
Ehrlichia species	Ehrlichiosis	82	77	115	109	78
Powassan virus (Flavivirus)	Powassan	1	0	2	0	2
Rickettsia species	Spotted Fever Group Rickettsiosis	35	40	35	24	27

[a] *In 2022, the national surveillance case definition for Lyme disease was updated, which resulted in an expected higher number of annual cases.*

6.3.1.2 Mosquito-Borne Diseases

Mosquitoes are insects that can infect humans and animals with the viruses and parasites they harbor through a bite. Unlike ticks, the only parasitic life-stage of a mosquito is the adult female; other life stages (eggs, multiple larval stages, and pupae) do not require a blood host (Ogden and Lindsay 2016). Like ticks, climate change is predicted to have a direct impact on mosquito-borne disease dynamics (USGCRP 2016).

The life cycle of mosquitoes is such that eggs are laid in water, the sides of artificial containers, or on soil, and once they hatch, it takes approximately 7-10 days for larvae to develop into adults. Although mosquito eggs require water to survive, eggs from certain mosquito species, such as *Aedes aegypti* (yellow fever mosquito), can withstand dry periods for up to 8 months (Schraufnagel 2020). The preferred feeding source (e.g., human, animal), habitat (e.g., indoors, outdoors), and their ability to fly distances are all species dependent characteristics (CDC 2020d). However, water is crucial to the life cycle of a mosquito, and therefore these insects are vulnerable to changes in climate that will increase or decrease water availability.

There are at least 16 different diseases caused by the viruses and parasites carried by mosquitoes. In the United States, West Nile Virus (WNV) is the most common mosquito-borne disease, with a total of 2,628 cases reported in 2023 (CDC 2025c). Most (80%) individuals infected with WNV are asymptomatic; those who do develop symptoms (20%) can exhibit fever, headaches, body aches, joint pain, vomiting, diarrhea, rash, and fatigue. Less than 1% of infected individuals develop serious neuro-invasive symptoms, including encephalitis, meningitis, acute flaccid paralysis, or other acute signs of central or peripheral neurologic dysfunction that may require hospitalization (CDC 2025c). The virus itself requires a bird host, and it is spread between birds and mosquitoes readily (Baum 2008). The first case of WNV in humans was reported in 1999 in New York State (Queens, New York) (Baum 2008), and the CDC has recorded an average of 2,010 cases of WNV in the United States from 2013 to 2023 (CDC 2025c). The incidence of WNV in the Northeastern United States has declined in recent years. It is unclear, however, whether this decline is due to mitigation efforts with applications of insecticides, or due to the prevalence of antibodies in hosts (Baum 2008a). New Jersey monitors cases of WNV in humans, birds, animals, and mosquitoes annually, with the largest number of human cases, 61, reported in 2018 (Table 6.3) (NJDOH 2025c).

Table 6.3. Positive Cases of West Nile Virus in New Jersey. The number of human, avian, and mosquito pools tested from 2015 to 2014. The bracketed numbers represent the fatalities from reported infections in a given year. Data are from the NJDOH vector-borne disease www.nj.gov/health/cd/statistics/arboviral-stats/index.shtml.

Year	Human	Avian	Mosquito (Pools)
2015	26 [3]	28	904
2016	11 [2]	0	447
2017	8 [2]	0	861
2018	61 [3]	13	1331
2019	8	0	365
2020	3	1	241
2021	36 [5]	15	995
2022	20 [4]	7	609
2023	14 [1]	0	847
2024	41 [8]	5	995

Other important domestic mosquito-borne diseases and pathogens reported in the United States include, but are not limited to, Eastern equine encephalitis, Jamestown Canyon, La Crosse encephalitis, and St. Louis encephalitis viruses (CDC 2024f). Eastern equine encephalitis is detected annually in mosquito populations in New Jersey, with sporadic human cases reported as well. Eastern equine encephalitis is the most severe domestic arbovirus, resulting in death in approximately 30% of persons infected. Important travel-associated mosquito-borne diseases reported in the United States include malaria, dengue, chikungunya, and Zika. With the exception of malaria which is caused by a parasite, all of the previously mentioned mosquito borne-diseases monitored by NJDOH are caused by viruses. Human malaria, chikungunya, dengue, and Zika cases are generally associated with travelers or immigrants returning from countries with known high transmission rates. Routine disease surveillance of mosquito populations in New Jersey have not indicated any state specific reservoirs of these diseases (NJDOH 2025c). There are approximately 2,000 cases of malaria in the United States each year, largely from immigrants or travelers from Central and South America, the Caribbean, sub-Saharan Africa, India, Southeast Asia, the Middle East, and South Pacific (NJDOH 2024c). In New Jersey, malaria cases generally account for the greatest number of mosquito-borne diseases reported in the state, although in the last two years, dengue has surged (Table 6.4). There is currently no evidence that dengue transmission has occurred from a local carrying population of mosquitoes (NJDOH 2024d). In contrast with ticks, mosquitoes are highly dependent on their habitat for reproduction, and therefore directly vulnerable to extreme weather (Ogden and Lindsay 2016). Viral transmission of the respective pathogens will also be sensitive to extremes in weather as a consequence of altered habitats and activities of their hosts (de Souza and Weaver 2024). Warmer winters will likely permit more adult mosquitoes to survive through the cold months, and wetter summers present more optimal conditions for the water dependent-mosquito life stages (Ogden and Lindsay 2016). Bird host availability may also be affected as migration patterns are climate-driven behaviors, but the extent to which this availability impacts the transmission rates or geographic locations of mosquito-borne diseases is unknown (USGCRP 2016). The projected changes to the regional temperature, precipitation rates, and humidity are expected to influence the distribution and abundance of mosquitoes and, as a result, increase the potential for human exposure and the overall prevalence of mosquito-borne diseases (USGCRP 2016, Dupigny-Giroux et al. 2018).

Table 6.4. Human Cases of Other Mosquito-borne Diseases in New Jersey. The number of cases of mosquito-borne disease other than West Nile Virus reported to the NJDOH from 2015-2024. For more information regarding county, age, and sex distribution of the human cases, as well as mosquito pool testing data, visit the Vector-borne Diseases in New Jersey Dashboard (www.nj.gov/health/cd/statistics/arboviral-stats/index.shtml).

Disease	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Chikungunya	31	12	12	16	15	3	4	2	13	17
Dengue	61	50	25	20	73	2	12	35	98	127
Eastern Equine Encephalitis	0	1	0	0	4	0	0	0	0	2
Jamestown Canyon virus	1	0	0	0	0	0	2	0	1	1
Malaria	86	84	125	94	102	24	72	85	101	107
Zika	2	237	37	10	12	3	0	0	0	0

6.3.2 Food and Waterborne Diseases

Illnesses that result from food spoilage or contaminated water are yet another category of diseases that may increase as circumstances associated with climate change worsen. Generally, these include acute gastrointestinal illnesses caused by pathogens that thrive in warmer, wetter climates. Moreover, some pathogens that are predicted to flourish under projected climate conditions may inflict wound infections, neurotoxic effects, or organ damage, leading to more severe and sometimes fatal outcomes. The risk for increased infectious disease spread following a catastrophic weather event is great, as diarrheal illnesses contribute up to 40% of deaths following a flooding event (Liang and Messenger 2018). However, many gastrointestinal illnesses, particularly mild cases, go unreported thereby making it more difficult to uncover a pattern between climate change and the extent to which food and waterborne illnesses are related.

6.3.2.1 Foodborne Illnesses

Foodborne illnesses are caused by viruses, bacteria, and parasites (Scallan et al. 2011, Scallan Walter et al. 2025). Climate can alter key drivers of pathogen survival thereby influencing food quality. For example, higher temperatures favor bacterial population growth on food and heavy precipitation may lead to contamination of water supplies used for irrigation for crops. In the instance of prepared (e.g., sliced) vegetables, temperature and relative humidity were shown to increase growth rates of various of pathogenic *Salmonella* species (Alves et al. 2024). Additionally, rising ocean temperatures can increase the risk of pathogen exposure from ingestion of contaminated seafood as warmer temperatures lead to optimal conditions for pathogen survival (USGCRP 2023, Grubb and Procopio 2025). Because not all instances of illnesses caused by pathogens in food are officially recorded, the CDC estimates how many cases occur in a given year (CDC 2025d). From an analysis of foodborne illness-related surveillance data from 2010-2019, the CDC estimated that there are 9.9 million episodes of foodborne illness in the United States, with 53,300 cases requiring hospitalization and 931 cases leading to deaths (Scallan Walter et al. 2025). Of the 31 major pathogens identified annually, over 50% of cases tend to be norovirus, with *Campylobacter* species (spp.) and nontyphoidal *Salmonella* spp., accounting for much of the remaining cases, (Scallan et al. 2011, Scallan Walter et al. 2025).

Concerns have been raised over the potential for increased cases of norovirus, a highly contagious virus that induces symptoms such as diarrhea, abdominal cramping, nausea, vomiting, and low-grade fever. This virus is acquired by consuming contaminated food or water, inadequate handwashing after touching contaminated surfaces, and person to person contact (e.g., aerosols) (CDC 2021, NJDOH 2025d). Norovirus favors colder, dryer conditions, but benefits from extreme weather events, such as heavy precipitation and flooding (Rohayem 2009, USGCRP 2016). The aerosol transmission potential of norovirus from person-to-person contact can be influenced by local humidity and temperature conditions, which also facilitate the persistence and virulence of the virus (Rohayem 2009). Norovirus transmission is greatest during periods of inclement weather and winter, underscoring a seasonality to this virus and therefore its sensitivity to climate change dynamics (Rohayem 2009).

Salmonella spp. and *Campylobacter* spp., which also induce diarrhea, cramping, nausea, and fever as symptoms, are both susceptible to changes in the timing or length of seasons, precipitation and flooding, and extreme weather events (USGCRP 2016, Niedermeyer et al. 2020, Cissé et al. 2022). Unlike norovirus, *Salmonella* infections are observed to increase at higher temperatures (Akil et al. 2014). Salmonella outbreaks in the United States are linked to contaminated food products (e.g., poultry, alfalfa sprouts, pre-cut melon), with chicken as the major source of infections. The United States CDC estimates that only 1 in every 30 *Salmonella* infections are diagnosed out of the roughly 1.35 million infections it estimates occur each year (CDC 2024g). As temperatures rise, salmonella outbreaks are expected to become more frequent. *Campylobacter* outbreaks, reported in poultry, raw milk, and untreated water, are also expected to rise with increasing temperatures and number of heavy precipitation events, particularly in the summer months (Kuhn et al. 2020).

The CDC monitors the incidence of some enteric (intestinal) pathogens via FoodNet, a population-based surveillance network for laboratory-diagnosed infections caused by *Campylobacter, Cyclospora, Listeria, Salmonella,* Shiga toxin-producing *Escherichia coli* (STEC), *Shigella, Vibrio,* and *Yersinia.* Preliminary data from 2019 indicate that the incidence of infections caused by pathogens transmitted commonly through food either increased (for *Campylobacter*, *Cyclospora*, STEC, *Vibrio*, *Yersinia*) or remained unchanged (for *Listeria, Salmonella, Shigella*) compared to the previous three years, with the majority of cases being acquired domestically (Tack et al. 2020). As extreme weather events, such as hurricanes, challenge local infrastructure and cause power outages, food spoilage will likely be of increased concern (Dupigny-Giroux et al. 2018, Liang and Messenger 2018). An example of this followed the 2003 New York City black out that affected millions of people in the Northeast United States, where increased reports of diarrheal illnesses occurred due to the consumption of spoiled food (Dupigny-Giroux et al. 2018). Another example occurred when outbreaks of norovirus were reported in shelters following hurricane Katrina in 2005 and to a lesser extent in New York City shelters following Superstorm Sandy in 2012 (Liang and Messenger 2018).

Other non-microorganism driven foodborne illnesses may be caused by chemical contamination of food products in processing or packaging (e.g., overuse of pesticides, other agricultural products, heavy metals) (USGCRP 2016).

> ***"As extreme weather events, such as hurricanes, challenge local infrastructure and cause power outages, food spoilage will likely be of increased concern."***

6.3.2.2 Waterborne Illnesses

Water contamination by pathogens, either through drinking water sources or recreational surface waters, is likely to increase with rising surface water temperatures and with greater frequency and intensity of precipitation. These climate change related factors will affect the growth, spread, and virulence of waterborne pathogens, and increase the risk of human exposure to them (USGCRP 2016). Individuals are exposed to waterborne pathogens via ingestion of water from contaminated sources, accidental ingestion during a recreational activity, or from eating contaminated fish or shellfish (Table 6.5).

As briefly mentioned in Chapter 6.1.2 Precipitation Anomalies , one of the secondary effects of flooding is the potential for microorganism contamination of clean water from sewers and wastewater treatment plant overflows, as well as from agricultural and storm water runoff (Tran et al. 2019, Cissé et al. 2022). Infrastructure failures of water treatment plants following extreme weather events and storm surges are likely to increase, either from damage or capacity exceedances, as conditions of climate change worsen over time (USGCRP 2016). As such, the risk of human exposure to waterborne pathogens will increase. For example, norovirus and other enteric pathogens, which enter sewage as a result of human exposure to contaminated food (e.g., shellfish), can spread quickly in populated areas if sewage treatment plants experience flooding from heavy precipitation events (USGCRP 2016). In New Jersey, contamination of drinking water sources by storm runoff has previously been associated with an increase in hospitalization for gastrointestinal effects (Gleason and Fagliano 2017). Moderate flooding events projected to become more frequent in the Northeast United States will likely increase the risks of Combined Sewer Overflows and storm-related power outages, which escalate the risk of both food and waterborne illness (Dupigny-Giroux et al., 2018). Furthermore, recreational activities, such as fishing and shellfish harvesting, will likely become less favorable, as the organisms become contaminated with waterborne pathogens.

Enteric pathogens (viruses, bacteria, and parasites) are among the most common causes of diarrhea from contaminated water or food and are a major factor in morbidity and mortality worldwide (Smith et al. 2014). Children are especially vulnerable to diarrheal diseases, with almost 500,000 deaths annually for children 5 years of age and younger, largely in developing countries (Troeger et al. 2018). Immunocompromised individuals and people who endure less sanitary living conditions are also more likely to be exposed to diarrheal causing pathogens (Troeger et al. 2018). Enteric pathogens are naturally present in aquatic environments but are more commonly introduced to waterways through leaking sewage and septic systems, urban runoff, agricultural runoff, sewage outfall, and wastewater discharge (Fong and Lipp 2005). While disease transmission for these organisms displays some seasonality, the exact climate factors contributing to pathogen survival are species dependent (USGCRP 2016). Diarrheal diseases are largely preventable, and maintaining proper hygiene and sanitation go a long way to mitigate the transmission of many of the pathogens.

Table 6.5. Agents of Waterborne Illnesses and Their Climate-Sensitive Drivers. Summary of common pathogens and their respective health outcomes following oral exposure via drinking water or recreational activities.

(Adapted from USGCRP, 2016 and NJDEP, 2020a)

Pathogen or Toxin Producer	Exposure Pathway	Symptoms & Health Outcomes	Major Climate Driver
Algae: Toxigenic marine species of *Alexandrium, Pseudo-nitzschia, Dinophysis, Gambierdiscus* spp., *Karenia brevis*	Shellfish, Fish Recreational water Aerosolized toxins	Shellfish and Fish poisoning: • Gastrointestinal illness • Neurological illness Aerosolized toxins may cause: • Asthma exacerbations • Eye irritations	• Temperature (increased water temperature) • Ocean surface currents and acidification • Hurricanes
Bacteria: Cyanobacteria (multiple freshwater species and their toxins)	Drinking water Recreational water Fish	• Gastroenteritis • Liver and kidney damage • Neurological disorders • Respiratory arrest • Irritation (dermal, eyes, respiratory)	• Temperature • Precipitation patterns • Nutrient runoff
Enteric bacteria and protozoan parasites: *Salmonella enterica; Campylobacter* spp.*;* Toxigenic *Escherichia coli; Cryptosporidium; Giardia*	Drinking water Recreational water Shellfish	• Enteric pathogens generally cause gastroenteritis • Severe cases may be associated with long-term and recurring effects	• Temperature (air and water; both increase and decrease) • Heavy precipitation • Flooding
Enteric viruses: Enteroviruses; Rotaviruses; Noroviruses; Hepatitis A and E	Drinking water Recreational water Shellfish	• Gastrointestinal illness • Severe cases may include paralysis and infection of the heart or other organs	• Temperature (air and water; both increase and decrease) • Heavy precipitation • Flooding
Bacteria: *Leptospira* and *Leptonema*	Recreational water	• Mild to severe flu-like illness • Severe cases may induce meningitis, kidney, and liver failure	• Temperature (increased water temperature) • Heavy precipitation • Flooding
Bacteria: *Vibrio* spp.	Recreational water Shellfish	Varies by species: • Gastroenteritis (*V. cholerae and V. parahaemolyticus*) • Septicemia through ingestion or wounds (*V. vulnificus*) • Infections of the skin, eye, or ear (*V. alginolyticus)*	• Temperature (increased water temperature) • Sea-level rise • Precipitation patterns (as it affects coastal salinity)

> ***"Harmful Algal Blooms (HABs) are a global problem that can affect nearly all surface waters on the planet and are directly related to changes in climate."***

Harmful Algal Blooms (HABs) are a global problem that can affect nearly all surface waters on the planet and are directly related to changes in climate (Chapter 5.2.4). Due to projected climate change factors, waters are becoming more conducive and hospitable to photosynthetic microbial growth (USGCRP 2016, Cissé et al. 2022). Large scale events in marine environments caused by the over proliferation of noxious organisms (e.g., Brown Tide, Red Tide) are well documented and increasing in frequency (USGCRP 2016). Bloom events on our inland rivers, lakes, and streams are increasing in frequency too; due in large part to shifting climate patterns and anthropogenic activities (NJDEP 2020e). These events have been marked by both true algae species, which can cause issues with delivery of potable drinking water, and cyanobacteria, which can cause both short- and long-term negative health effects to human and animal health upon exposure. Exposure to cyanobacteria can cause health effects directly related to the cells or toxins they produce, known as cyanotoxins. These toxins can harm the nervous system, liver, and skin. Human exposure occurs during recreational activities through accidental swallowing, skin contact, breathing aerosols, and from ingesting groundwater from a private well near an affected water body due to surface water influence. Local and systemic toxic effects can result in a range of adverse reactions, from a mild skin rash to serious illness. Adverse reactions may occur in response to components of the cyanobacterial cells, regardless of whether the cells are producing cyanotoxins, and generally producing allergic-like irritation of the skin, eyes, respiratory tract, or gastrointestinal tract. Exposure to the primary cyanotoxins: microcystins, cylindrospermopsin, anatoxin-a group, and saxitoxin, can lead to severe health conditions, including gastroenteritis, liver inflammation, kidney damage, or muscular and respiratory paralysis (NJDEP 2020e). HAB events are expected to increase as changes to New Jersey's climate becomes more favorable to the growth and survival of these organisms.

Leptospira spp. are zoonotic pathogens causing the disease Leptospirosis, transmitted primarily via the urine-oral route from animals infected with the bacterium. Leptospirosis can cause a wide range of symptoms or none at all, but if left without treatment, can lead to kidney damage, meningitis, liver failure, respiratory distress, and death (CDC 2025e). Humans are exposed to *Leptospira* spp. through water or food contaminated with animal urine, or from their household pets infected by contaminated water or food, and exposure is expected to increase with the projected frequency of heavy precipitation and flooding (Brown and Prescott 2008, Lau et al. 2010).

Vibrio spp. are the source of a number of freshwater and marine environment waterborne illnesses and are of a particular concern for New Jersey (Chapter 5.8.5). *Vibrio cholerae* is the pathogenic source of the acute diarrheal infection cholera, which is characterized by profuse watery diarrhea, vomiting, thirst, leg cramps, and, in severe cases, death due in part to dehydration (CDC 2025f). Cholera has historically plagued human populations with poor sanitation; but increases in disinfection practices of potable water as well as advances in wastewater treatment technology has led to a decrease in infection rates globally. However, while *Vibrio*-derived drinking water illnesses have decreased, exposure to *Vibrio* spp. through other routes, such as consumption of contaminated seafood or recreational swimming (e.g., accidental oral ingestion or through open wounds) continues or is on the rise (Dechet et al. 2008, Newton et al. 2014). In fact, climate change projections for the Northeast, such as increased warming patterns or severe weather events, are favorable for *Vibrio* survival and infection potential, indicating that a greater incidence of infection rates from *Vibrio* spp. will occur (Martinez-Urtaza et al. 2010, Baker-Austin et al. 2013).

Together, food and waterborne infections are a major public health issue, particularly in developing countries where infrastructure is often suboptimal, but also in the United States, where our aged infrastructure (e.g., Combined Sewer Overflows) remains a persistent concern due to its vulnerability to extreme and severe weather events (USGCRP 2016, Dupigny-Giroux et al. 2018)

6.3.3 Other Concerns Related to Infectious Disease Transmission

The continued progression of climate change dynamics brings with it the concern for emerging, novel types of pathogens with a greater frequency and endemic potential (Ogden and Lindsay 2016). Pathogens will encounter new hosts as loss of habitat leads to population migration of traditional hosts. These new encounters are predicted to be more frequent for mammals and are more likely to occur in areas that are projected to be human settled or agricultural lands (Carlson et al. 2022). Extreme conditions may increase the potential for increased and novel contact between humans and other animals. For example, droughts followed by heavy rainfalls are associated with increased rodent population activity, which could lead to increased exposure to rodent-borne diseases and allergens (USGCRP 2016). Indirectly, human exposures to pesticides may increase, as mitigation efforts to combat pathogen containing vectors arise, but also contaminate the food supply (Dupigny-Giroux et al. 2018).

Fungal pathogens are increasing in range, detection, and virulence. The WHO estimated that over 300 million people suffer from serious fungal infections annually, but most go unreported (WHO 2022). Understanding how impacts of climate change such as rising temperatures and extreme weather events impact fungal communities are important to helping clinicians diagnose and treat infections (Mazi et al. 2023, Konkel Neabore 2024).

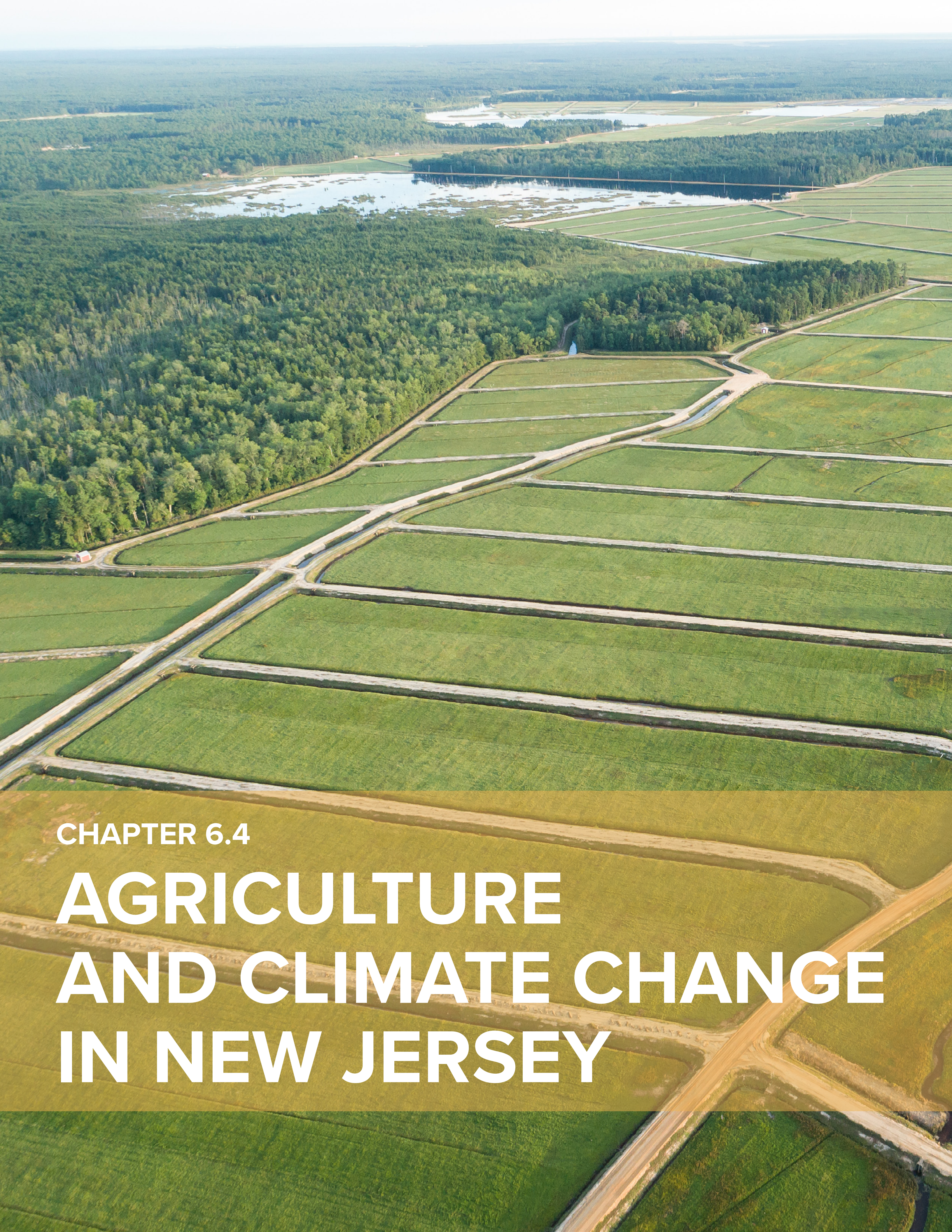
Legionella, the causative agent of legionellosis (including, Legionnaires' disease, Pontiac fever, and extrapulmonary disease), are gram-negative bacteria naturally found in various freshwater bodies and soil that benefit from some of the climate change conditions predicted for New Jersey. Specifically, precipitation, elevated temperatures, higher relative humidity, and flooding have all been associated with increases in the incidence of legionellosis cases (Hicks et al. 2007, Gleason et al. 2016, Moffa et al. 2023, Heilmann et al. 2024). Once introduced into human-engineered water systems (i.e., plumbing systems, hot tubs, cooling towers, etc.), legionella bacteria can proliferate

> ***"Fungal pathogens are increasing in range, detection, and virulence."***

under warm temperatures (68°-120°F), water stagnation, low disinfectant levels, and buildup of biofilm or sediment. Legionella spreads through aerosolized water from devices like showerheads, faucets, hot tubs, decorative fountains, and cooling towers and people can become infected by inhaling or aspirating contaminated water. Research in New Jersey found higher Legionnaires' disease rates during the weeks and month preceding periods of wet, humid, and warm weather (Gleason et al. 2016). Although the exact drivers are not fully understood, possible mechanisms include increased bacterial proliferation in natural and human-engineered reservoirs, increased use of cooling towers (Heilmann et al. 2024, Hammes et al. 2025), and increases in the time the bacteria remain in the air. Another concern is that maintaining disinfectant residuals in drinking water distribution systems becomes more difficult as water temperatures rise (Furst et al. 2024). These climatic shifts may result in short-term spikes or sustained increases in legionellosis cases (Dupke et al. 2023).

6.3.4 Challenges to Linking Infectious Disease Outbreaks to Climate Change

Large uncertainties remain as to the direct effects of climate change factors on the future of pathogen transmission and impacts on human health. One of the challenges in linking the spread of infectious disease to climate change is the incomplete reporting of infections. Mild cases of some illnesses may go unnoticed, misattributed, or unreported to the proper health authorities. With regards to vector-borne diseases, mitigation efforts to combat tick and mosquito populations, for example, come with additional challenges of how to protect the human population from excessive exposure to pesticides. Furthermore, climate change factors may act synergistically on non-human hosts, vectors, pathogens, and humans, making it difficult to predict and mitigate the effects of climate change on infectious disease spread. One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems, recognizing that the health of humans, domestic and wild animals, plants, and the wider environment, including ecosystems, are closely linked and interdependent (Mettenleiter et al. 2023). Applying an integrated One Health approach to addressing climate change health issues could significantly contribute to food security with emphasis on animal source foods, extensive livestock systems, environmental sanitation, and steps toward regional and global integrated syndromic surveillance and response systems. For example, the cost of outbreaks of emerging vector-borne zoonotic pathogens may be lower if detected earlier in the vector or in livestock rather than later in humans (Zinsstag et al. 2018). Recognizing that six out of every 10 infectious diseases in humans are spread from animals; animals can sometimes serve as early warning signs of potential illness in people; and public health preparedness depends on agriculture in a variety of ways, New Jersey was the first state in the Nation to legislatively mandate a One Health Task Force, established in P. L. 2021, Chapter 117, to strengthen One Health coordination and collaboration throughout the state. The Task Force has representation from DEP, DOH, and NJDA, as well as physicians, veterinarians, and researchers.



CHAPTER 6.4

AGRICULTURE AND CLIMATE CHANGE IN NEW JERSEY

6.4 Agriculture and Climate Change in New Jersey

New Jersey, aptly known as the Garden State, cultivates approximately 712,000 acres of farmland and supports almost 10,000 farms, according to the United States Department of Agriculture (USDA) 2022 Census of Agriculture (USDA 2024). Despite its small geographic footprint, the state's agricultural landscape is highly diverse. Distinct regions such as the Northern Highlands, Central Sourlands, and Southern Coastal Plain each exhibit unique combinations of soils, topography, hydrology, and microclimates. This environmental diversity allows commercial production of a wide variety of crops that supports a broad spectrum of agricultural operations.

New Jersey also has a long agricultural history marked by continuous adaptation. The state has undergone shifts in market trends, sweeping regulatory changes, stints of economic volatility, and environmental pressures. Farmers across the state have consistently demonstrated their ability to evolve. However, changing weather patterns, driven by broader climactic trends, are having an increasing influence towards the viability and management of agricultural systems across the region. These shifts are expected to disrupt planting schedules, reduce crop yields, complicate pest and disease management, and place added stress on livestock production (New Jersey Climate Change Resource Center 2020). Increasingly warmer winter temperatures pose a challenge for fruit crop performance, by disrupting winter dormancy periods and flowering cycles. Warmer winter temperatures create more favorable conditions for overwintering pests and diseases. Additionally, wetter springs may delay planting and hinder early crop development, while hotter, drier summers are likely to increase reliance on irrigation to maintain crop and pasture productivity (New Jersey Climate Change Resource Center 2020).

Climate projections for New Jersey point to substantial changes in seasonal weather patterns, including longer growing seasons, temperature fluctuations, and an increase in the frequency and intensity of extreme weather events. These conditions will have direct and indirect impacts on the state's crops, soils, livestock, and pests.

6.4.1 Changes to the Growing Season

The growing season, also known as the "frost-free" season, is measured from the date of the last spring frost to the first fall frost. This is the period of time when the soil temperature and moisture conditions are right for plants to grow (Zommers and Alverson 2018). Between 1915 and 2003, the duration of the growing season in the Northeast expanded 0.7 days/decade. However, when looking at a smaller timeframe, there was a rapid acceleration of growing season length to 2.5 days/decade between 1970 and 2000 (Frumhoff et al. 2007).

All plants, microbes (pathogenic and beneficial bacteria, fungi, etc.), and insects (beneficial and

> *"...changing weather patterns, driven by broader climactic trends, are having an increasing influence towards the viability and management of agricultural systems across the region."*

pest) depend on specific temperatures for their growth and development. As temperatures increase due to climate change (Chapter 4.1), the number of days that provide the ideal growing conditions for agricultural plants (and pests) will change. In the agriculture industry these days are referred to as Growing Degree Days (GDD) and are calculated by averaging daily high and low temperatures, subtracting a baseline threshold (commonly 50°F or 10°C in this region), and accumulating those values across the season (Staudinger et al. 2015, Harvey et al. 2023, Abduljaleel et al. 2025). This metric enables producers to make more informed decisions about planting dates. Between 1970 and 2021, approximately 97% of weather stations across the continental United States reported increases in GDD (Climate Central 2022). The eastern United States, including New Jersey, has witnessed a cumulative increase of roughly 525 GDD units over that period. This corresponds to longer growing seasons as well as an expanded windows for pest activity (Climate Central 2022).

6.4.2 Crop Productivity

Globally, climate change is expected to threaten food production and certain aspects of food quality. With the combined effects of rising temperatures, rainfall variability, and loss of essential nutrients, such as nitrogen, many crop yields are expected to decline (Luber et al. 2014, Cho 2022). Without initiating effective mitigation approaches, crop yield decline may occur through a variety of mechanisms, including saltwater intrusion in soil and groundwater, higher temperatures in summer, changes in frequency and intensity of droughts, flooding during extreme wet conditions, and expanding seasonal and regional distribution of insects (Ray et al. 2019). Livestock and fish production are vulnerable to similar factors (Brown et al., 2015).

Crops that do well in warmer conditions and those that need a longer growing season will benefit, while crops that don't do well in warmer conditions may not fare as well. Increased temperatures during critical periods of growth and reproductive states can result in plant stress, reduced productivity, and loss (Bita and Gerats 2013). The period of plant development that appears most sensitive to warmer temperatures is the reproductive stage (Hatfield and Prueger 2015). Controlled studies with maize demonstrated that grain yield can be significantly reduced under warmer temperature paradigms compared to normal ranges (Hatfield and Prueger 2015).

Quantity is not the only risk, but a loss of crop quality may also suffer (Godde et al. 2021). The nutritional value of staple foods such as wheat, rice, and soy may show signs of decline because of climate pressures. This change in nutritional value impacts not only plants for human consumption, but also plant-based feed for livestock, potentially reducing the quality and sustainability of livestock production (Godde et al. 2021).

For agricultural communities, decreased crop yields and widespread failures under drought conditions are increasingly well-documented. A 2024 study revealed that during the 2022–2023 growing season, spring droughts led to severe loss of winter wheat, with a staggering 37% decrease in production across the United States winter wheat belt (Zhang et al. 2024). These figures are comparable to the Dust Bowl era production numbers. Beyond losses in yield, researchers estimate that under a 1.8°F (1°C) warming scenario, without any adaptive measures, approximately 3.2 million additional acres of cropland across the United States could fail. This projection increases to 11 million acres (nearly a 3% loss) under a 5.4°F (3°C) warming scenario (Kamel et al. 2023). These disruptions not only generate economic stress for farmers but also place strain on regional and national food supply chains (Chapter 6.5.2).

6.4.3 Perennial Crops and Winter Chill Requirements

Warmer winters pose a threat to fruit crops traditionally associated with New Jersey. Mid-winter warm spells can cause premature blooming, making plants vulnerable to frost damage when temperatures drop again (Frumhoff et al. 2007). Perennial fruit crops, particularly

“Warmer winters pose a threat to fruit crops traditionally associated with New Jersey. “

Vaccinium corymbosum (blueberries), *Vaccinium macrocarpon* (cranberries), and various *Prunus* and *Malus* species (tree fruits), are highly dependent on the accumulation of ‘winter chill hours’ to achieve optimal development (Wolfe et al. 2018, Parker and Abatzoglou 2019). These species require a defined number of ‘chilling hours,’ typically between 32°F and 45°F (0°C to 7°C), to effectively transition from winter dormancy into the growing season. Interruption of this chilling period, with temperatures >45°F (7.2°C) can lead to ‘chill hour negation’, essentially restarting the number of chilling hours and potentially delaying or disrupting flowering. Climate projections indicating warmer average winter temperatures across the region suggest a decline in cumulative chill hour availability (Wolfe et al. 2018). This may jeopardize bud break synchrony (coordinated timing of bud opening among plants), reduce fruit set uniformity (the consistency and evenness of the developing fruit across a crop), and diminish yield potentials. Over time, these shifts could impair crop viability and profitability, necessitating adaptation strategies such as switching plant varieties or using treatments to encourage growth.

6.4.4 Weed and Pest Pressures

Elevated atmospheric CO_2 concentrations are expected to increase photosynthetic rates and enhance plant growth in general. However, combined with rising temperatures, the elevated CO_2 is also expected to increase weed competition, particularly from aggressive, heat-adapted species with C4 photosynthetic pathways (Jugulam et al. 2018, Jeena 2020). C4 photosynthesis is an efficient pathway used by certain plants to capture CO_2 for photosynthesis in hot, dry environments. It is more efficient than the C3 pathway used by other plants and allows for higher rates of photosynthesis and more efficient water usage under stressful (e.g., hot and dry) conditions. C4 plants are more efficient under high light and temperature conditions. While this area of research is still developing, studies suggest that warming may favor certain weedy species, leading to increased management costs and more complex herbicide strategies (Matzrafi 2019).

A change to the growing season could allow for an increase in pest and disease pressures, as warmer winters and higher seasonal temperatures will allow many insect pests and pathogens to complete additional generations per season and expand their ranges northward (Harvey et al. 2023). This is likely to elevate pest pressure across multiple commodities and may also require adjustments in integrated pest management (IPM) approaches (Matzrafi 2019, Harvey et al. 2023, Abduljaleel et al. 2025). A recent systematic review of agricultural productivity and climate change (2015–2024) underscores how changing precipitation and pest pressures are driving increased dependency on crop protection measures as part of broader climate adaptation strategies (Farah et al. 2025).

The increase in GDD units observed in the eastern United States over the last few decades corresponds to expanded windows for pest activity (Climate Central 2022). GDD thresholds are now commonly used in northeastern extension services in pest scouting (i.e., systematic monitoring of pests to detect infestations) and pesticide application timing (University of Massachusetts Amherst 2017, University of New Hampshire 2023). For example, gypsy moth egg hatch in the region typically occurs between 90–100 GDD (base 50°F), a key period for timely pest management, including control measures like insecticide applications or deployment of biological controls (i.e., natural organisms to manage pest populations that do not harm the crop), right before or at the onset of hatching when larvae are most vulnerable (University of Massachusetts Amherst 2017).

In parallel, a recent USDA National Institute of Food and Agriculture (NIFA)-funded project led by the University of Connecticut has analyzed GDD trends across the Northeast to model how climate-driven heat accumulation may alter the number and timing of insect pest generations (USDA NIFA, 2024). Findings from this research are helping to develop forecasting tools for growers to anticipate rising pressures from pests and adapt management strategies accordingly.

Another consequential pressure of climate change is the potential for greater pesticide use by farmers (and homeowners) to combat increased pest growth. Higher frequency of intensive rainfall has been correlated with increased herbicide use. This could be attributed to chemical wash-off and reapplication needs (Rhodes and McCarl 2020). Likewise, analysis of pesticide efficacy under erratic weather conditions emphasizes how hot, cold, or rainy extremes disrupt chemical performance in corn and soy, requiring more complex management responses (Matzrafi 2019). Climatic extremes play a significant role in pesticide expenditures (e.g., financial cost associated with pesticide usage) and can result in increased exposure of agricultural workers and local communities to potentially harmful chemicals.

6.4.5 Livestock Concerns

Livestock operations are also vulnerable to impacts of rising temperatures and increased precipitation, with effects on productivity and overall health of the animals. When summer temperatures exceed 75°F (23.9°C), dairy cows experience heat stress, which reduces feed intake and milk production. Rutgers Cooperative Extension estimates that heat

“A change to the growing season could allow for an increase and pest and disease pressures…”

stress during hot summers results in over $3 million in annual losses to New Jersey's dairy industry (Rutgers Cooperative Extension 2025).

Increased annual average precipitation and intensity of precipitation events (described in Chapter 4.2.3 and 4.2.4 , respectively), could result in extended wet periods. Overly wet soil is not only a concern for root disease, but also a challenge for livestock. Farmers may have to limit animal access to pastures to avoid hoof-related problems or damage to the land (Hristov et al. 2018). Like humans, farm animals subjected to cramped, damp environments may be exposed to waterborne and vector-borne diseases (see Chapter 6.3 for impacts to humans). Drought-like conditions pose other concerns for farmers, due to low forage quality in pastures and limitation on water resources (Brown et al. 2015).

Collectively, heat-stress and other climate change impacts on livestock translate into economic hardships not only for farmers, but also consumers. On a national scale, the meat and dairy sectors have already experienced spikes in consumer prices due to heat-induced stress on livestock and transportation delays during severe weather events (Diffenbaugh et al., 2012). Together with potential declines in crop productivity, resource insecurity may become a growing concern (Chapter 6.5.2).

6.4.6 Water Resource Concerns

Water availability (detailed in Chapter 5.2) presents an additional challenge when confronted with changes in precipitation, including prolonged periods of drought-like conditions that could coincide with higher temperatures and longer growing seasons. Scarcity of clean water threatens not only drinking water sources for humans but also agricultural supplies to maintain plants and livestock (Brown et al., 2015). While agriculture accounts for approximately 9% of statewide water use, this figure is expected to increase under warmer, drier conditions. Under drought conditions, decreased crop yields or overall crop failures are exacerbated leading to both economic stress for farmers and resource strain for the food supply chain regionally and nationally. As irrigation demand grows, particularly during peak growing months, competition for limited water resources may intensify—necessitating forward-thinking water planning (NJDEP 2024a).

While increased precipitation may help reservoir replenishment, intensified soil erosion and runoff can transport manure, fertilizers, pesticides, and industrial byproducts into local water sources. The risk of contaminated runoff from extreme rain events is especially a concern where biosolids or other areas where waste-based materials are used to improve soil quality and promote plant growth, as discussed in Chapter 6.1.2. Collectively, these insights suggest that agricultural systems will confront heightened challenges from pests, chemical use, and contaminant transport amplifying the need for resilient management strategies.

"Collectively, heat-stress and other climate change impacts on livestock translate into economic hardships not only for farmers, but also consumers."

CHAPTER 6.5

CLIMATE CHANGE-DRIVEN COMMUNITY IMPACTS

6.5 Climate Change-Driven Community Impacts

Rising temperatures, anomalous precipitation, diminished air quality from pollution and natural allergens, and greater exposure to vector-, food-, or waterborne pathogens, are all climate change effects expected to adversely impact human health. The collective impacts of climate change on the health of communities are more nebulous to catalog and predict, particularly because these impacts will not be distributed uniformly among populations. Human health impacts are often felt most strongly by high-risk or vulnerable communities that are located in areas where the impacts of extreme conditions occur most often and have insufficient access to risk reduction strategies, such as funding, updated early warning systems, and resilient infrastructure (Cissé et al. 2022). Resource insecurity (e.g., energy usage, food production, interrupted supply chains), the economic and logistical challenges to population displacement, and the negative effects that the compounding changes may have on mental health, are disproportionately experienced across New Jersey's overburdened communities.

In New Jersey, overburdened communities are defined as areas where (1) at least 35 percent of the households qualify as low-income households; (2) at least 40 percent of the residents identify as minority or as members of a state recognized tribal community; or (3) at least 40 percent of the households have limited English proficiency.

6.5.1 Human Adaptation to a Changing Climate

Climate change is likely to alter many human behaviors and activities as we learn to live under new environmental conditions. Hotter weather generally causes an increased reliance on air conditioning to off-set the heat, which in turn requires greater electricity consumption to meet the energy demands (Lundgren-Kownacki et al. 2018). Hotter weather may also drive people to shower more often and launder their clothes more frequently, utilizing greater volumes of water and increasing usage of detergents, which may increase surface water pollution and distort nutrient loads, consequently favoring algal bloom conditions (Liu et al. 2012). Applications of personal care products (e.g., deodorants, sunscreens) and over-the-counter medicines to mitigate mild symptoms from environmental exposure to sun, pollen, and pests (e.g., analgesics, cortisone creams, and antihistamines) will likely see greater use. Pharmaceuticals used in the treatment of more chronic cardiovascular and respiratory diseases are also likely to increase, as may the use of antibiotics for treatment to combat certain vector-, food-, and waterborne infections. However, the ecological impacts and the economic implications of these indirect climate change effects in usage are unclear (Redshaw et al. 2013). Individually, these actions may not amount to much change; however, a more significant impact may be observed on a community-wide level.

6.5.2 Resource Insecurity on the Rise

Boosting crop production to satisfy the growing demands of an increasing population amidst the threats posed by climate change is a difficult task. For information about how crop production will be impacted by climate change, see Chapter 6.4. Climate change may cause more frequent disruptions in any part of the food supply chain, including production, quality, transportation, trade, storage, processing and packaging, wholesale, retail, consumption, and disposal of food. Consequently, food prices may increase, directly impacting New Jersey residents, especially traditionally marginalized communities. This could make accessing essential resources more challenging, leading to increased food insecurity. Food insecurity occurs in situations where food is unavailable, inaccessible, or unusable to individuals or a group, and can happen in urban or rural populations, and in wealthy and poor nations alike (Brown et al. 2015). Despite the fact that food insecurity in New Jersey is below the national estimate of 13.5% across all ages, as of 2022, greater than 10% of New Jerseyans (over

994,000 people) are estimated to live with food insecurity (NJDOH 2025e). For the 18 years and under demographic, that estimate rises to 13.2% (over 262,000 children), which is an increase of 4% since 2020, and the highest percentage estimated from 2018 and 2022 (NJDOH 2025e).

In 2022, food insecurity in Black and Hispanic communities are more than double that of White communities (NJDOH 2025e) and as a result will be more likely to experience the impacts of climate change driven food insecurity sooner. In general, low-income communities are less likely to be in close proximity to grocery stores that provide access to healthy and affordable food options (Dutko et al. 2012). Climate change, indirectly, may lead to an increase in Food Deserts Communities, as food accessibility and security decrease though impacts on agriculture, supply chain disruptions, and overall economic stress. Food Desert Communities are characterized by low income, limited access to healthy food, transportation barriers, and other region-specific factors, as outlined by the New Jersey Economic Development Authority, which works to identify and address food deserts in the state (NJEDA 2022). In such situations, people turn to calorie-rich, nutrient-poor, and often cheaper foods (e.g., highly processed, packaged food), the consequences of which range from malnutrition to obesity (Luber et al. 2014, Cooksey-Stowers et al. 2017, Tonumaipe'a et al. 2021). Children are particularly vulnerable to the malnutrition that results from a poor diet due to their continued cognitive and physical development, the results of which may manifest as negative lifelong health and economic outcomes (Brown et al. 2015). In adults, food insecurity in the US is increasingly linked to obesity (Myers et al. 2020). The nutritional value of some foods (e.g., wheat, rice, soy) is also projected to decline due to climate change (Chapter 6.4) .

Water sustainability may also be challenged as future climate change projections become a reality. Scarcity of clean water threatens drinking water sources for humans and agricultural supplies to maintain plants and livestock (Brown et al., 2015). Storm surges and flooding brought about by extreme weather and sea-level rise can contaminate water supplies through run-off, sewage treatment failures, microbial pathogens, and saltwater contamination of groundwater (Brown et al., 2015; Cissé et al., 2022). Furthermore, the concentrations of contaminants in ground and surface waters may increase in responses to droughts (Benotti et al. 2010). The combined effects of compromised sanitation, poor hygiene, and crowded living situations are enhanced as supplies of clean water are limited, risking the spread of pathogens. Enteric pathogens, such as norovirus, are more likely to propagate in areas of dense human population (Rohayem 2009). This is a particular concern for the Northeast, where much of the sewage infrastructure is dated and more vulnerable to extreme weather events (Dupigny-Giroux et al. 2018).

Food and water are not the only community-important resources that will be impacted by climate change. Extreme weather events not only pose an immediate threat from the flooding caused by a storm but are also a concern for short- and long-term resilience of available resources. For example, after Superstorm Sandy made landfall in October 2012, flooding and medical care were the immediate concern for coastal communities, followed by safe food and water (Moran et al. 2017). However, for inland residents, the predominant concern was resource availability. The storm shut down utilities, restricting access to electricity and running water, and many people, especially those without cars or with mobility issues, could not easily access food stores, public transit, community or social services, or personal support networks. There were also widespread gasoline shortages, further exacerbating the conditions. Storms such as Superstorm Sandy may disrupt transportation, delaying first responders and access to medical treatment (USGCRP 2016). As the incidence of extreme weather events increases, sustainable and reliable access to resources in the long-term becomes a pressing concern. Prolonged extreme heat events also place strains on the health care and emergency department systems, particularly in areas that are not used to these types of events. In June of 2021, the Pacific Northwest experienced an unprecedented weeks-long heat dome where record-setting temperatures reached 120°F (48.9°C) in some parts of Washington State. A heat dome is a phenomenon where hot air is trapped by a strong area of high pressure over a certain area, causing extreme heat (American Meteorological Society 2024). Across British Columbia, Washington, and Oregon, the event's combined death toll was in the high hundreds, with was increased emergency department volumes, returned visits, prolonged length-of-stay, and work index scores (a metric used to measure emergency department crowding). The resulting impacts not only on patient volumes but on emergency department throughput and function during these events highlighted how implementation of extreme heat event response activities are essential to maintaining continuity of service, especially under co-stressor conditions such as the co-presence of the COVID-19 pandemic, limited staff capacity, resource acquisition challenges (e.g., beds, equipment and medical devices, medications), and inadequate regional collaboration and familiarity with extreme heat events (Wettstein et al. 2024, Korfmacher et al. 2025).

6.5.3 Population Displacement, Migration, and the Negative Implications on Tourism

Many of the climate change factors described in this addendum focus on the health effects individuals may experience, such as cardiovascular and respiratory distress conditions or infection from various vector-, food-, or waterborne pathogens. An indirect effect of climate change that affects a society more broadly is the damage to residential housing leading to displaced populations (CoreLogic 2022). Population displacement occurs when a catastrophic event (e.g., hurricane, wildfire, flooding, etc.) forces people to move away from their homes either for the short- or long-term (USGCRP 2016, Cissé et al. 2022). In 2017 alone, more than 18 million people worldwide were displaced as a result of weather-related disasters (Semenza and Ebi 2019). Devastating flooding events are already an ongoing threat to New Jersey homeowners. Since 1995, New Jersey's Blue Acres program has assisted more than 1,200 families in relocating after major flood events as well as those plagued by chronic flooding. The state then repurposes the acquired properties to expand natural floodplains, create parks, and provide open space for communities.

> *"If climate change effects on recreational areas become endemic, they will have a serious impact on the tourist economy in New Jersey."*

One immediate concern to population displacement is the spread of illness among displaced individuals residing in cramped conditions in emergency shelters. In the aftermath of Superstorm Sandy, around 1,200 people from Long Beach Island had to stay in shelters until roads were cleared and it was determined safe to return to their homes (Waxman 2012). Temporary shelters to house the displaced following severe weather events can become a breeding ground for infectious diseases, such that as much as 40% of deaths from natural disasters may be attributed to diarrheal illnesses (Chapter 6.3.2) (Liang and Messenger 2018). Further, population displacement strains food and other resources, which may lead to conflicts from competition over limited supplies amplified by internal strife and overcrowding.

Deteriorating infrastructure is another consequence of climate change that can lead to population displacement. In the Lower Manhattan Climate Resilience Study, a rise in the groundwater table was shown to have an adverse effect on Lower Manhattan's current infrastructure. In coastal areas, groundwater table rise, an impact of climate change, has the potential to destabilize building foundations, increase pressure and infiltrate underground utilities with saltwater, and uplift and unsettle buildings and underground utilities (New York City 2019). Coastal cities in New Jersey like

> ***"A reduction in land productivity and habitability are other indirect climate change-related factors that may result in population displacement, as people are driven away from regions heavily impacted by increasing ambient temperature, precipitation anomalies, frequent and intense extreme weather, and sea-level rise."***

Jersey City, Atlantic City, and Newark may face similar threats, and as the climate situation worsens, destabilized buildings will necessitate community displacement. Deteriorating infrastructure may be of particular concern in overburdened communities where resources may be unavailable to rebuild.

A reduction in land productivity and habitability are other indirect climate change-related factors that may result in population displacement, as people are driven away from regions heavily impacted by increasing ambient temperature, precipitation anomalies, frequent and intense extreme weather, and sea-level rise. Combined with economic and social factors, climate change is expected to give rise to increased migration (Semenza and Ebi 2019). The risk of disease may be higher for migrants because of conditions in their country of origin, conditions in their destination country, or conditions that they encounter during migration (Semenza and Ebi 2019).

Similarly, areas dependent upon tourism may struggle as travel destinations change due to climate variability (USGCRP 2016, Semenza and Ebi 2019). Increased extreme weather or wildfires can threaten travel or properties in affected regions. Wastewater treatment facilities overwhelmed by heavy precipitation can lead to bacterial contamination of bathing waters leading to beach closures. Warm winters lead to less natural snow and less ability to create snow at New Jersey ski resorts. If climate changes effects on recreational areas become endemic, they will have a serious impact on the tourist economy of the state. Changes in migration or tourism can add to the strain on resources and challenge public health efforts designed to provide adequate living conditions, screening and vaccination programs, and other medical intervention practices (Semenza and Ebi 2019).

6.5.4 Mental Health Consequences of Climate Events

The mental health consequences of climate change can range from minimal stress responses to serious clinical disorders (USGCRP 2016). For example, property loss, displacement, and the related traumatic experience of living through a catastrophic climate event increase the potential for mental illnesses such as post-traumatic stress disorder and depression. Population displacement that results in the loss or destruction of communities as people are dispersed can have detrimental effects on mental health. Alternatively, individuals living in low-income communities with fewer resources or means by which to evacuate may be forced to survive under inhospitable living conditions. Mental health problems increase following disasters among both individuals with no history of mental illness and individuals with pre-existing mental health conditions (Luber et al. 2014). Children, pregnant and post-partum individuals, the elderly, individuals in traditionally marginalized communities, and first responders are especially prone to suffering mental health issues following exposure to climate change-related disasters (USGCRP 2016). For example, studies have shown that exposure to wildfires in childhood was associated with decreased academic performance and with an increased likelihood of mental illness in adulthood (Xu et al. 2020). High levels of general anxiety and post-traumatic stress disorder have been identified among people affected by hurricanes, floods, and heat waves (Luber et al. 2014).

Extreme heat has been demonstrated to increase the prevalence of psychiatric emergencies. A study by researchers at Boston University found that days of extreme heat were associated with higher rates of behavioral health-related emergency department visits (Nori-Sarma et al. 2022). The number of behavioral health emergencies was highest on the day of extreme heat events, and there was some evidence that the rates remained high for two to four days after. The types of emergencies that increased during heat emergencies included anxiety, stress-related disorders, somatoform disorders, mood disorders, schizophrenia, schizotypal, and delusional disorders, substance use disorders, and self-harm. Some medications used to treat mental illnesses (e.g., schizophrenia) are known to interfere with the body's ability to self-regulate temperature and may leave patients more susceptible to heat (USGCRP 2016).

Psychosocial stress arising from the destabilization of social, environmental, economic, and geopolitical support systems, among others, can increase substance-use vulnerability. People with substance use disorders are at a higher risk of heat-related illnesses or death from extreme temperatures (Chang et al. 2023). The use of alcohol and other substances can place people at more risk of harm. Extreme weather events resulting from climate change can also increase gender-based violence (Zhu et al. 2023).

Climate change-specific mental health disorders is an emerging concern described with novel terminology, including: ecoanxiety, ecoguilt, ecopsychology, ecological grief, solastalgia (distress caused by environmental change), and biospheric concern (Cianconi et al. 2020, Comtesse et al. 2021). In particular, the mental and emotional strain on survivors and emergency responders experiencing extreme events, both throughout and following an event, is of significant concern. Even individuals who may not yet be directly affected by climate change may develop anxiety over the climate crisis (Ingle and Mikulewicz 2020). In a recent Surgeon General's report, climate anxiety was proposed as one of the reasons why feelings of sadness and hopelessness have increased by 40% over the last decade in United States high school students (US HSS 2021). Moreover, recently ecological grief and anxiety have been noted in relation to the experienced or anticipated loss of species, ecosystems, and meaningful landscapes (e.g., forests, coastal wetlands) due to projected environmental changes (Cunsolo and Ellis 2018). The beneficial effects of engaging or interacting with nature are well known to provide a benefit to mental health; therefore, the loss or impending loss of ecological features can understandably impact the mental health of some individuals (Dillman-Hasso 2021).

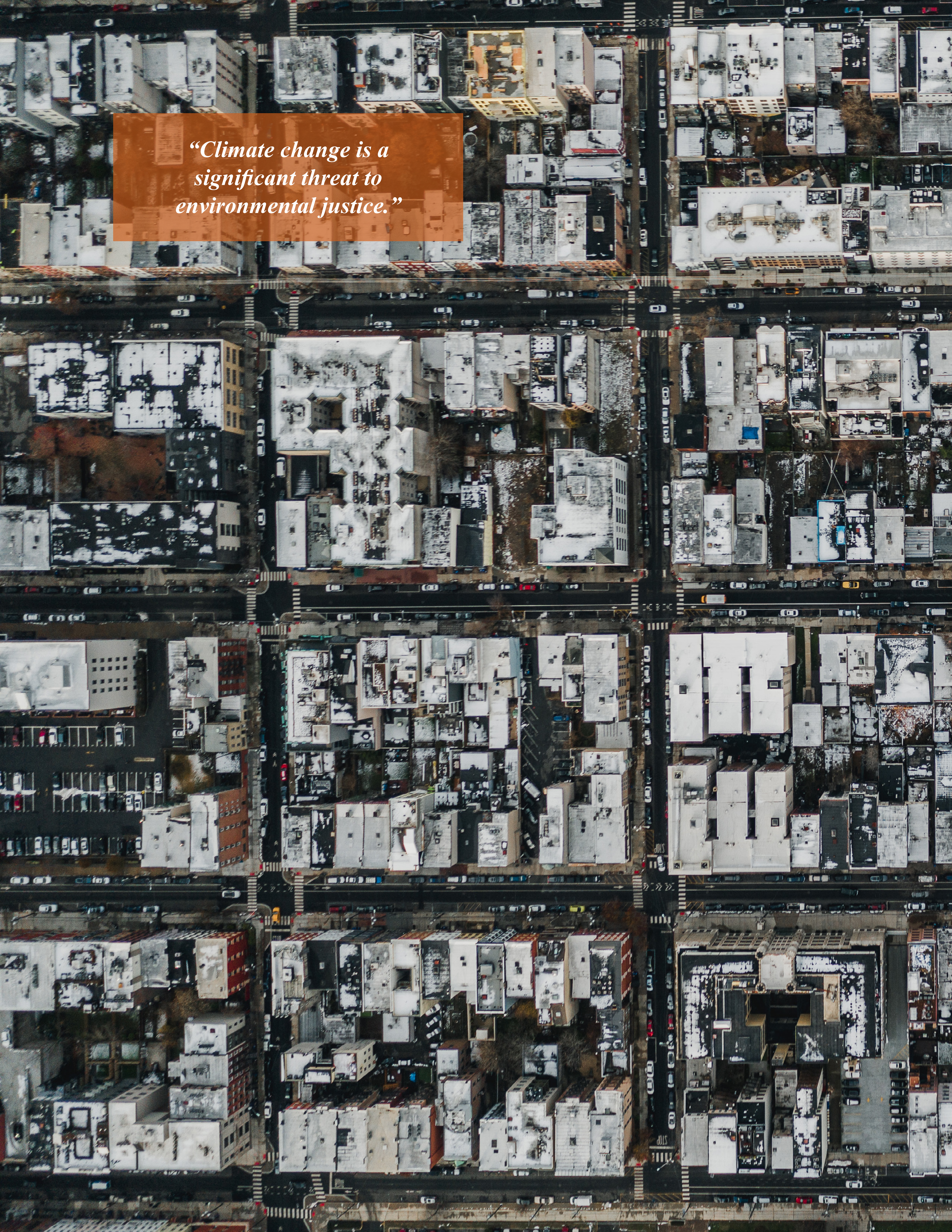
6.5.5 Disproportionate Effects of Climate Change

While climate change is a threat to everyone's physical and mental health, socially and economically disadvantaged individuals are particularly vulnerable to the greatest impacts of climate change. A lack of physical mobility and resilience capacity due to structural or systems-level inequities puts vulnerable populations, such as the chronically ill and elderly, communities of color, urban and rural poor, and non-English speaking communities at greater risk from storms, floods, heat waves, and other extreme weather events. Further, individuals with pre-existing conditions are further at risk if crises lead to stressed healthcare systems.

Climate change is a significant threat to environmental justice. Environmental justice is defined as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies," (NJDEP 2025i). Traditionally marginalized communities are disproportionately subjected to a greater number of environmental and public health stressors, and as a result, these communities experience asthma, cancer, elevated blood lead levels, cardiovascular disease, and other adverse health effects at higher rates than richer and whiter communities (Kazi et al. 2024, NJDEP 2025i).

The largest burden of climate change will likely be felt by the impoverished and communities of color because of inadequate infrastructure, health, income, and limited access to resources (Cissé et al. 2022). Some root causes of these climate injustices include structural racism, lack of power and political representation, and language barriers (Newell et al. 2021). Living in poverty and congested cities puts a significant population at risk from exposure to environmental conditions, including urban heat island effects, poor air quality, the prevalence of chronic illnesses, including asthma and obesity, a reliance on lower-paying jobs, and decreased access to healthy food options (e.g., food deserts). It is a further challenge for communities and people for whom English is not their native language. Environmental and public health stressors such as urban flooding, lack of tree cover, impervious cover, and lack of open spaces are all indicators related to climate impacts (heat and flooding specifically) that are included in New Jersey's evaluations to determine if overburdened communities are already adversely impacted by environmental burdens. The impact that socioeconomic status and racial disparities have on a population's vulnerability to climate change makes policies that strive to relieve overburdened communities from environmental and public health stressors, such as New Jersey's Environmental Justice Law (N.J.S.A. 13:1D-157), even more critical, especially as future climate change projections become a reality. New Jersey continues to make resources available to invest in clean energy, clean transportation, and equity programs via the Regional Greenhouse Gas Initiative (RGGI) that are aligned with objectives defined in the Global Warming Solutions Fund Act, one of which is to "be directly responsive to the negative effects on human health and the environment in communities that disproportionality impacted by the effects of environmental degradation and climate change."

In combination, the anticipated climate change effects (e.g., heat stress, poor air quality, flooding) will pose a greater threat to vulnerable groups, including young children, elderly, socially or linguistically isolated, traditionally marginalized communities, and those with preexisting health conditions—because these groups are less likely to have the resources necessary to recover quickly (USGCRP 2016, Cissé et al. 2022). Individual vulnerability is likely to increase as infrastructure failures become more common, especially in the northeastern United States, where infrastructure is generally older than in other areas of the country (Dupigny-Giroux et al. 2018). The urbanization of large portions of New Jersey makes the state's residents particularly vulnerable to the impacts of increased temperatures, which are made worse by heat island effects. The large expanses of asphalt and concrete associated with urban and suburban sprawl and the consequential loss of green spaces combined with traffic congestion, results in warmer temperatures in urban centers, particularly in the summer months (Carnahan and Larson 1990, Mohajerani et al. 2017).



“Climate change is a significant threat to environmental justice.”

CHAPTER 6.6

HUMAN HEALTH CHALLENGES FOR THE FUTURE

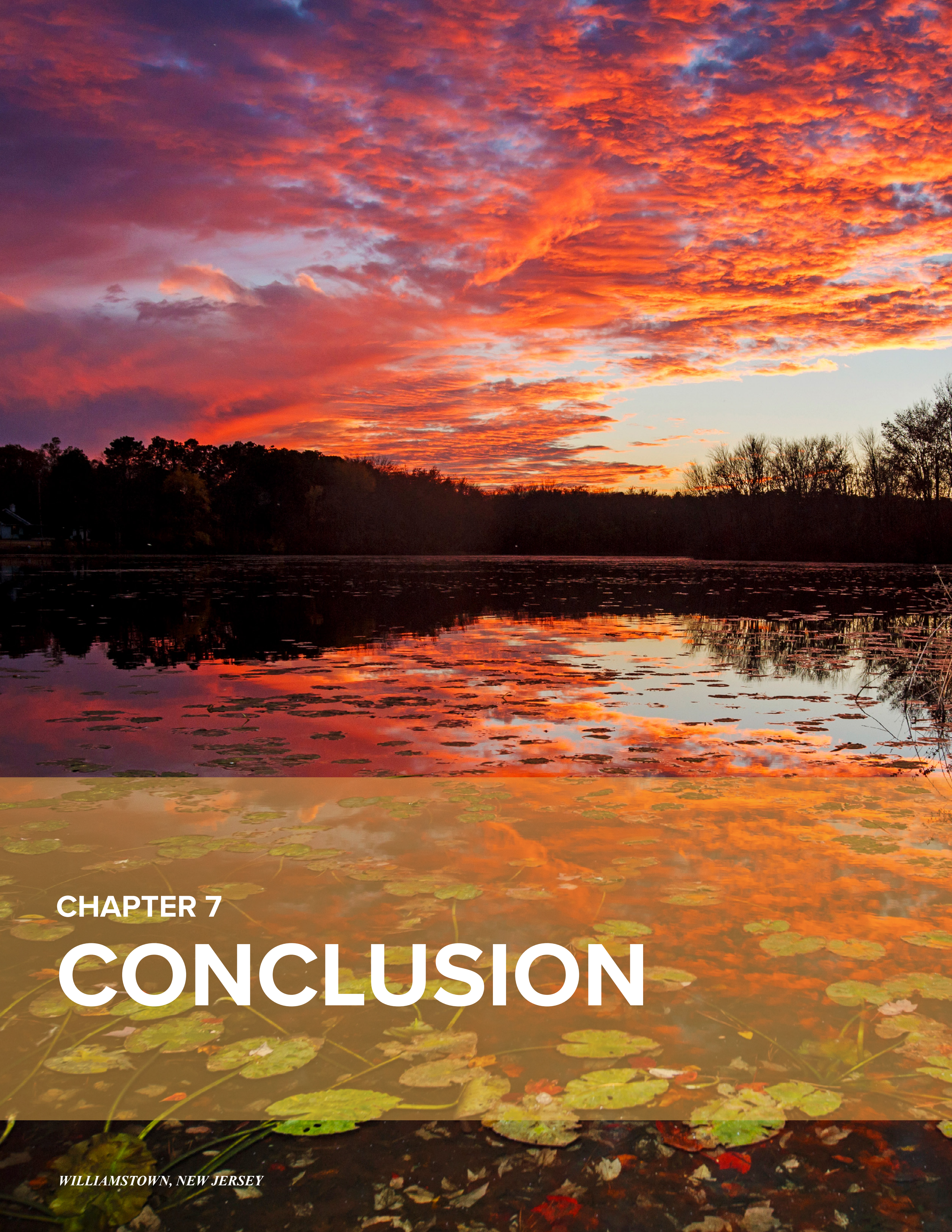
OCEAN CITY, NEW JERSEY

6.6 Human Health Challenges for the Future

The challenges humans may experience as the climate continues to change are not equitable nor are they easily quantified. Multiple public health organizations and agencies have begun to outline potential surveillance opportunities surrounding climate change and human health (USGCRP 2016, CSTE 2017). New Jersey Department of Health (NJDOH) tracks selected climate change-related health indicators, including heat-related hospitalization and emergency department visits; asthma, COPD, and heart attack hospitalization and emergency department visits; CO deaths, hospitalizations, and emergency department visits; CO detectors in the home; and ownership of portable generators (NJDOH 2025f).

In addition to the tragedy of lives lost, the economic disruption of climate change from losses in homes and/or businesses, from medical bills accrued, and from the destruction of structures and land is a growing concern for humans and their communities (NJDEP 2025b). New Jersey's agricultural producers, while accustomed to managing complex weather-related, economic, or regulatory variables, are set to face unprecedented climate change-related uncertainty. With accurate data and advances in technical assistance, New Jersey farmers will have to continue adapting, as will all New Jersey residents.

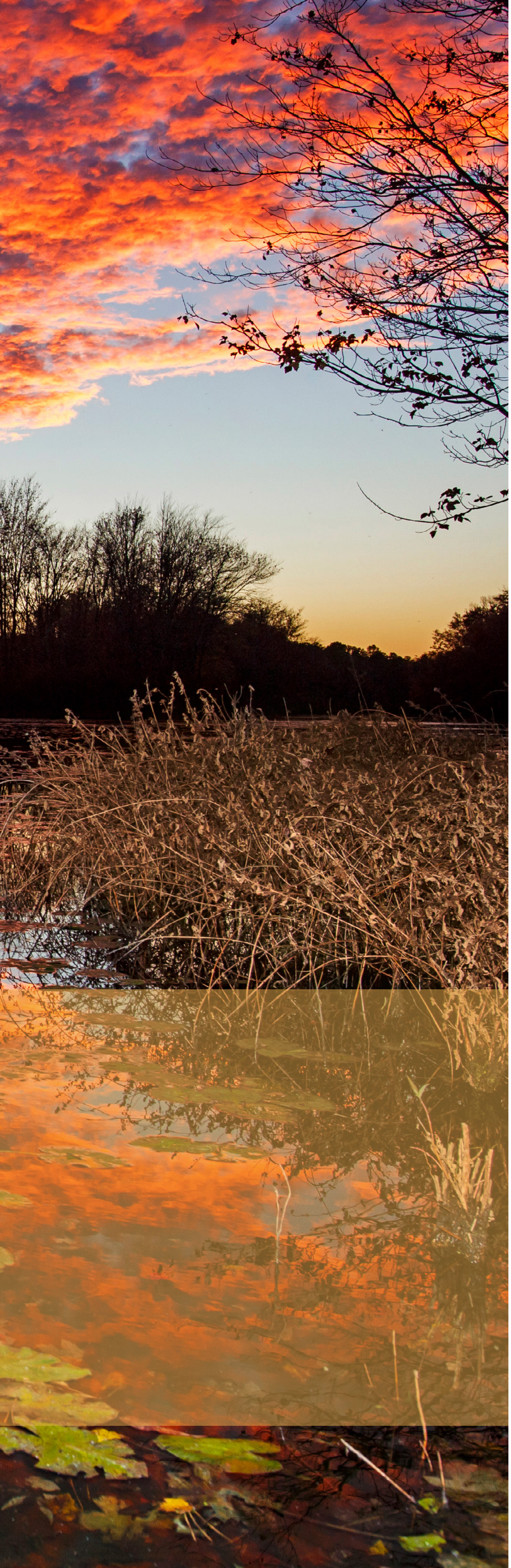
Overall, understanding how these challenges posed by climate change threaten human health, agriculture, and communities is essential to establishing strategies and environmental and public health policies that can effectively and equitably protect and improve health outcomes.



CHAPTER 7

CONCLUSION

WILLIAMSTOWN, NEW JERSEY



This report summarizes the advancements that have occurred in the scientific understanding of climate change as well as some of the current and anticipated impacts it will have on New Jersey's environment, natural resources, infrastructure, and communities. The research summarized throughout this report is a vitally important component of New Jersey's work to understand and address the impacts the state will face due to climate change. An equally important component is identifying the information needed to inform the policies, guidance, and recommendations that will be made by the state to address the existing and future impacts of climate change. As such, the DEP maintains a list of where further climate change research is needed and/or where data gaps exist:

https://dep.nj.gov/climatechange/science/research-gaps/

Click Here for Climate Change Research Gaps

The interconnection and interdependency of Earth's systems become apparent when looking at the growing evidence of climate change - increasing global temperatures, driven by increases in the atmospheric concentration of greenhouse gases, leading to more water vapor in the atmosphere, with adverse effects felt at all biological levels. Feedback mechanisms in the hydrological cycle can lead to an increase in precipitation as well as more intense weather patterns, and these weather patterns not only bring on extreme precipitation events, but also conditions that cause droughts and settings favorable for wildfires. Higher temperatures will also increase the melting of land and sea ice, which can amplify rising sea levels. Collectively, these changes affect resources like air quality, the amount and quality of available water, the ability of the agricultural industry to provide food, and ecological resources like forests, wetlands, plants, and animals. These resources are vital to New Jersey and the anticipated impact from climate change will affect all aspects of life, including health impacts to human populations.

CONCLUSION

The report has shown how anthropogenic (human-caused) greenhouse gases are primarily driving the changes in temperature, precipitation, sea-level rise, and ocean acidification that are altering the way life on Earth interacts and exists. The report also establishes that the impacts from climate change are already occurring, and those impacts will not only continue but worsen in the years ahead. The severity of impacts that New Jersey, and the world, experience will vary depending on global emissions and the ability of societies around the world to take action to reduce greenhouse emissions. Continuing to reduce the emissions of greenhouse gases and other climate pollutants is critical in mitigating the effects of climate change and reducing the risks of climate hazards.

The impacts of climate change on the environment and humans will be significant. The natural range of ecosystems; migrations of species; impacts on society from severe storms and extreme weather events; the sensitivity of agricultural production; changes in the intensity and frequency of heat waves, wildfires, floods, and drought; and many other indicators make it clear that both the environment and humanity are dependent on the state of the climate.

New Jersey is committed to pursuing a comprehensive and forward-thinking response by all levels of government, economic sectors, communities, and populations to address the impacts of climate change. As such, this report will be reviewed and updated in order to keep pace as the science behind climate change evolves.

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