Delaware 2025 Climate Change Projections Report

A Technical Report prepared for the Delaware Department of Natural Resources and Environment Control, Division of Climate, Coastal, and Energy

University of Delaware (UD) Center of Environmental Monitoring and Analysis (CEMA)

October 2025

Delaware 2025 Climate Change Projections Report

October 2025

Authors

Christina L. Callahan
John A. Callahan
Daniel Leathers
Matt Shatley
Kevin Brinson
Chris Hughes
Emmanuel Olamiriki

Acknowledgments
Funding for this study was provided by the Delaware Department of Natural Resources and Environmental Control (DNREC) Division of Climate, Coastal and Energy.

Thank you to all members of the Delaware Technical Climate Advisors committee and DNREC staff for their participation and thoughtful feedback during this process.

Cover photo by Diego Romeo on Unsplash.

Recommended Citation
Callahan, Christina L., John A. Callahan, Daniel Leathers, Matt Shatley, Kevin Brinson, Chris Hughes, and Emmanuel Olamiriki, 2025. Delaware 2025 Climate Change Projections Report, prepared for Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs. 166 pp.

Delaware Technical Climate Advisors

Tricia Arndt
Assistant Director, DelDOT Division of Transportation Resilience and Sustainability

Dr. Kevin Brinson
Assistant Research Professor, State Climatologist and Director of CEMA
University of Delaware
Department of Geography and Spatial Science

Dr. John Callahan
Affiliated Researcher (CEMA) and Affiliated Assistant Professor
University of Delaware
Department of Geography and Spatial Science

Christina Callahan
Assistant State Climatologist and Associate Director of CEMA
University of Delaware
Department of Geography and Spatial Science

Jesse Hayden
Administrator, Delaware Coastal Programs
DNREC Division of Climate, Coastal and Energy

Dr. Jerry Kauffman
Associate Professor and Director UD Water Resources Center
University of Delaware
Biden School of Public Policy & Administration

Dr. Daniel Leathers
Professor Emeritus and State Climatologist Emeritus
University of Delaware
Department of Geography and Spatial Science

Susan Love
Administrator, Climate and Sustainability
DNREC Division of Climate, Coastal and Energy

Dr. Holly Michael
Professor and Director of DENIN
University of Delaware
Department of Earth Science

Dr. Ashley Norton
Program Manager, Delaware Coastal Management Program
DNREC Division of Climate, Coastal and Energy

Dr. Gulnihal Ozbay
Professor and Associate Dean of Cooperative Extension & Applied Research
Delaware State University
Department of Agriculture and Natural Resources

Dave Perrego
Planner IV, Emergency Medical Services and Preparedness
DHSS Division of Public Health

Dr. Bob Scarborough
Environmental Scientist V
DNREC Division of Water

Danielle Swallow
Coastal Hazards Specialist
University of Delaware
Delaware Sea Grant

Dr. Dana Veron
Professor and Co-Director of the Climate Hub
University of Delaware
Department of Geography and Spatial Science

Dr. Jennifer Volk
Associate Director
University of Delaware
Cooperative Extension

Dr. David Wunsch
Director and State Geologist
Delaware Geological Survey

Dr. Mollie Yacano
Research Coordinator, Delaware National Estuarine Research Reserve
DNREC Division of Climate, Coastal and Energy

Table of Contents

Acronyms

AEP	Annual Exceedance Probability
AIS	Antarctic ice sheet
AMOC	Atlantic Meridional Overturning Circulation
AR5, AR6	Fifth, Sixth Assessment Report (IPCC)
CDD	Cooling Degree Days
CEMA	Center for Environmental Monitoring & Analysis
CMIP5, CMIP6, CMIP7	Coupled Model Intercomparison Projection (Phases 5, 6, and 7)
CO-OPS	Center for Operational Oceanographic Products and Services (NOAA)
CONUS	Contiguous United States (US mainland, the lower 48 states)
COOP	Cooperative Observer Program (NWS)
DBOFS	Delaware Bay Operational Forecast System (NOAA)
DCO	Delaware Climate Office
DNREC	Department of Natural Resources and Environmental Control
ENSO	El Niño-Southern Oscillation
FACTS	Framework for Assessing Changes To Sea-level
GCM	Global Climate Model
GDD	Growing Degree Days
GIA	Glacial isostatic adjustment
GIS	Greenland ice sheet
GMSL/GMSLR	Global mean sea level/global mean sea level rise
GRD	Gravitational, rotational and deformational
GW	Global warming
HDD	Heating Degree Days
HTF	High tide flooding
IPCC	Intergovernmental Panel on Climate Change
ITF	Interagency Task Force
KDE	Kernel Density Estimation
LOCA2	Localized Constructed Analogs Version 2
LWS	Land water storage

MHHW	Mean higher high water
MLLW	Mean lower low water
MSL	Mean sea level
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCA, NCA5	National Climate Assessment, Fifth National Climate Assessment
NCEI	NOAA National Centers for Environmental Information
NOAA	National Ocean and Atmospheric Administration
NOS	National Ocean Service (NOAA)
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network (NOAA)
NWS	National Weather Service (NOAA)
RCP	Representative Concentration Pathways
RL	Return level
SLR	Sea level rise
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate
SSP	Shared Socioeconomic Pathways
STAR-ESDM	Seasonal Trends and Analysis of Residuals Empirical Statistical Downscaling Model
TCA	Technical Climate Advisors (Delaware)
USACE	US Army Corps of Engineers
VLM	Vertical land motion
WCRP	World Climate Research Programme
WFO	Weather Forecast Office (NOAA NWS)

Executive Summary

This report presents a comprehensive assessment of climate change scenarios for Delaware using the most recent modeling results from the Coupled Model Intercomparison Project Phase 6 (CMIP6), the best available projections of future climate, and information from the most recent international and national climate assessments. Recent trends in Delaware indicate a rapid increase in mean annual and seasonal temperatures and associated temperature indicators, a gradual rise in annual precipitation, and an acceleration of mean sea levels and coastal flooding. These changes are already impacting ecosystems, infrastructure, public health, and the State's economy. The scenarios summarized in this report aim to inform policymakers, planners, and stakeholders by conveying the potential ranges and trajectories of climate changes through the mid- and late 21st century under a range of greenhouse gas concentrations and "shared socio-economic pathways" (SSPs). These SSPs represent potential futures of human activity and choices, such as population growth, development, and energy usage, that impact and drive future projection of greenhouse gas emissions. Understanding and preparing for these potential futures is essential to provide a strong scientific foundation for the development of the state's mitigation and adaptation planning and strategies.

Climate change projections for Delaware were developed through the collaborative efforts of the Delaware Department of Natural Resources and Environmental Control (DNREC), the University of Delaware Center for Environmental Monitoring and Analysis (CEMA), the Delaware Climate Office (DCO), and the Delaware Technical Climate Advisors Committee (TCA), a community of scientists and practitioners from Delaware's state agencies and universities. CEMA was responsible for all collection, analysis, and interpretation of the observational and modeled data and development of this report.

For temperature and precipitation, high resolution statistically downscaled model projections were obtained for Delaware and the surrounding region from the Seasonal Trends and Analysis of Residuals empirical statistical downscaling model (STAR-ESDM), and from the Localized Constructed Analogs statistical downscaling model (LOCA2). STAR-ESDM and LOCA2 were used to downscale 13 global climate models to produce Delaware-specific gridded climate projections for three different SSPs with representation greenhouse gas forcing: SSP2-4.5, SSP3-7.0, SSP5-8.5. Projections were developed through 2100 with an overlap of historical data that were hindcast to 1950 to determine how the models align during the observational record. In addition, historical temperature and precipitation data for Delaware as a whole and for specific stations were analyzed to provide an historical context for the projection scenarios.

For sea level, five sea level rise (SLR) planning scenarios were produced at the national level in support of the U.S. Fifth National Climate Assessment (NCA5), derived from CMIP6 and other modelling efforts and spanned the range of global mean sea level rise from 0.3 meters to 2.0 meters. For each of these planning scenarios, projections were downscaled to two NOAA long-term water level monitoring stations in Delaware: Reedy Point, located in northern Delaware, and Lewes, located in southern Delaware. Historical monthly and daily data at both locations were used to develop historical trends and state-wide future projections to 2100.

Major Findings

TEMPERATURE

Delaware has experienced a consistent warming trend of about 0.3°F per decade since 1895, amounting to over 3°F of total warming.

Future Projection

Mean annual temperatures in Delaware are projected to increase by 3-4°F by mid-century and by 5–9°F by end of century, relative to the current 30-year normal, with winter temperatures showing the strongest seasonal increases.

Historical Trends:

- Delaware annual and seasonal mean **temperatures** have *increased* by approximately 3˚F since 1895 when data for Delaware became available.

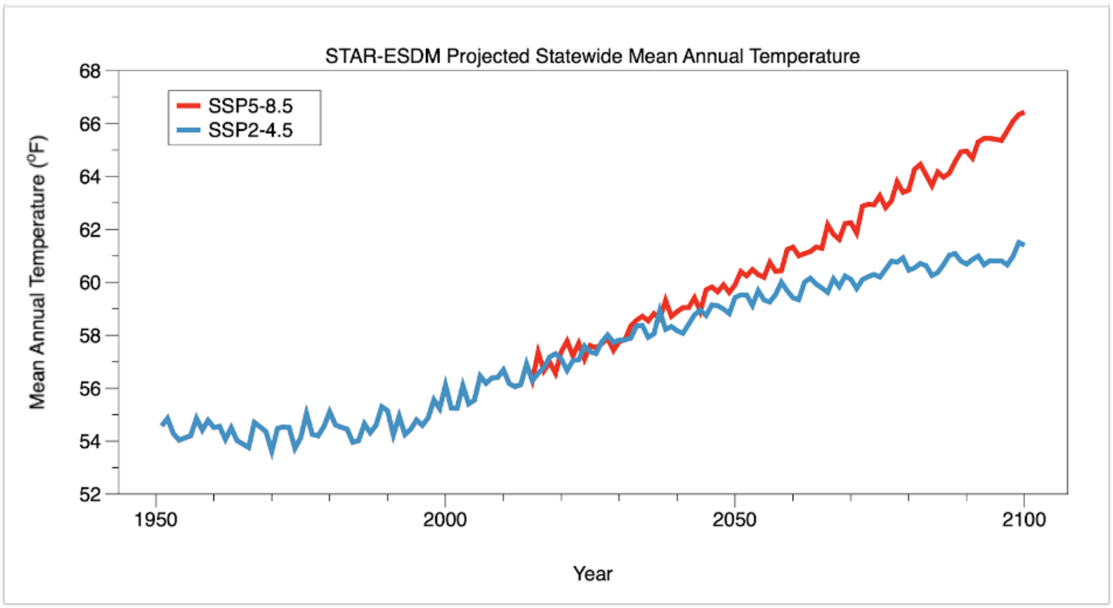
- Statewide mean annual and seasonal **temperatures** from 1895 to 2024 show a significant warming (*increasing*) trend, with temperatures *increasing* by approximately 0.20°F to 0.35°F per decade.

- Three National Weather Service Cooperative Weather Stations across Delaware (Wilmington Airport, Dover, and Lewes) were analyzed for significant trends in temperature indicators and temperature extremes for their individual periods of record. Each station showed significant upward (*increasing*) trends in the length of the **growing season** and the number of **warm nights** (days with minimum temperatures greater than or equal to 75°F). Significant downward (*decreasing*) trends were found for the number of **coldest nights** (days with minimum temperatures less than or equal to 32°F), and no significant trends were found in the number of **hottest days** (days with maximum temperatures greater than or equal to 90º F).

- **Heating degree days** showed a significant downward (*decreasing*) trend annually, while **cooling degree days** and **growing degree days** showed significant upward (*increasing*) trends annually, mirroring the temperature increases.

Future Projections:

- By the century's end (2081-2100), **mean annual temperatures** are projected to *increase* by 5º- 6°F for the SSP2-4.5 scenario and by 8°- 9°F for the SSP5-8.5 scenario, relative to the current 30-year normal (1991-2020). These *increases* are found annually and for all seasons.



STAR-ESDM downscaled ensemble mean annual temperature projections through the end of the century for SSP2-4.5 (blue) and SSP5-8.5 (red).

- By the mid-century (2041-2060), **mean annual temperatures** are projected to *increase* by approximately 3°F under SSP2-4.5 and about 4°F under SSP5-8.5, relative to the current 30-year normal (1991-2020). These *increases* are found annually and for all seasons.

- Large *increases* in the annual number of **cooling degree days** and **growing degree days**, as well as large *decreases* in **heating degree days** are projected by mid-century and continue through the end of the century.

- By the final twenty years of the century (2081–2100), the **growing season** is projected to lengthen (*increase*) significantly by about 30 days for the SSP2–4.5 scenario and roughly 60 days for the SSP5–8.5 scenario, compared to the 30-year normal (1991-2020).

- The number of **freezing days** (days with minimum temperatures less than or equal to 32ºF), *decreases* in the final twenty years of the century (2081-2100) by approximately 25 days per year under SSP2–4.5 and by approximately 50 days per year under SSP5–8.5, compared to the 1991-2020 normal.

- The number of **hottest nights** (days with minimum temperatures greater than or equal to 75ºF), *increases* in the final twenty years of the century (2081-2100) by approximately 10 days per year under SSP2–4.5 and by nearly 50 days per year under SSP5-8.5, compared to the 1991-2020 normal.

- The number of **hottest days** (days with high temperatures greater than or equal to 90ºF) *increases* in the final twenty years of the century (2081-2100) by approximately 35 days per year under SSP2–4.5 and by approximately 75 days per year under SSP5-8.5, compared to the 1991-2020 normal.

PRECIPITATION

Since 1895, Delaware's precipitation has increased by about 3 inches (0.23" per decade) and has shown large year to year variability.

Future Projection

Delaware's annual precipitation is projected to increase by 2–4 inches by mid-century with little additional increase through 2100. Winter season shows the strongest seasonal increase.

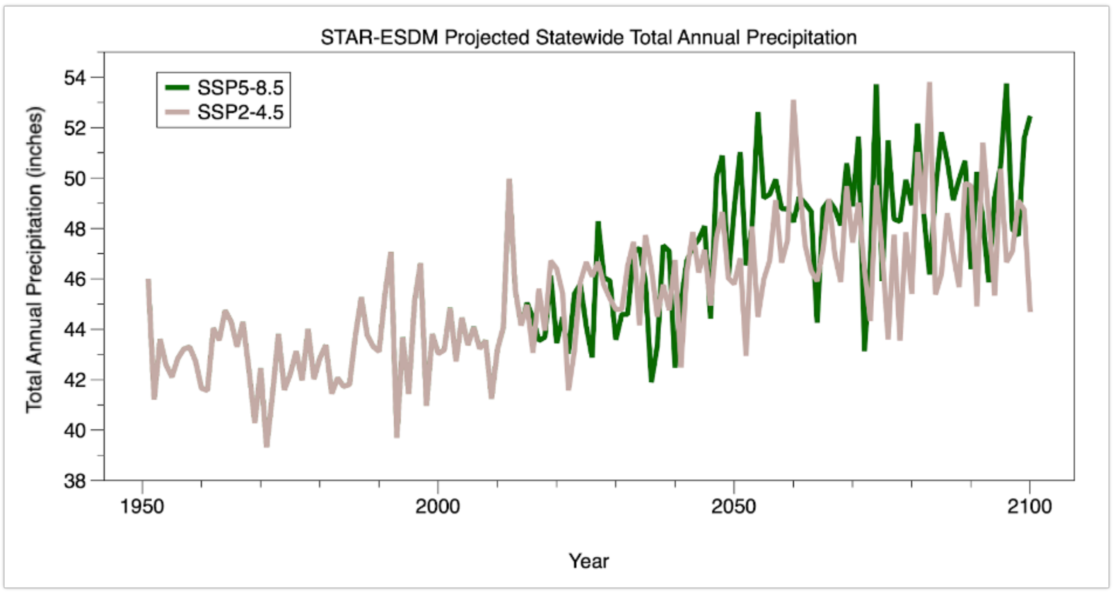
Historical Trends:

- **Precipitation** across Delaware averages approximately 44 inches annually (for the period 1895-2024), distributed relatively evenly throughout the year. However, Delaware's precipitation is subject to large interannual and intra-annual variability, with statewide annual totals varying from as low as 27.37 inches in 1930 to as high as 60.05 inches in 1948.

- No significant trends were identified in statewide **precipitation** from 1895 to 2024, either annually or during the winter, spring, or summer seasons. Only **autumn precipitation** showed a statistically significant *increasing* trend.

Future Projections:

- The **total annual precipitation** projections indicate an upward trend (*increase*) in precipitation for the State as a whole in the coming decades. The *increase* in precipitation between the current normal (1991-2020) and the end of century (2081-2100) is between 2" and 2.5" for the SSP2–4.5 scenario (a 5% increase) and approximately 4" for SSP5–8.5 (a 9% increase). Seasonally, **winter precipitation** generally has the strongest upward trend (*increase*) of all the seasons.



STAR-ESDM downscaled ensemble mean total annual precipitation projections through the end of the century for SSP2-4.5 (blue) and SSP5-8.5 (red).

- By the end of the century (2100), the number of **days with precipitation greater than or equal to 0.5"** is projected to *increase* about 12%, and **days with greater than or equal to 1.0"** *increase* around 25% under SSP5–8.5. **Days with greater than or equal to 2.0"** *increase* by just one day, with smaller changes at higher thresholds. It is important to note that these projections represent statewide averages and therefore may not reflect extreme precipitation trends at the local scale.

SEA LEVEL

Mean sea levels have increased about 10 inches since 1956 at Reedy Point and 15 inches since 1919 at Lewes, with acceleration occurring in recent decades.

Future Projection

Mean sea levels are projected to rise 1.2-1.5 feet by 2050, and between 2-3 feet under the Intermediate-Low and 4-6 feet under the Intermediate-High planning scenario by 2100, relative to 2000 mean sea level.

Historical Trends:

- Mean sea level trends were computed at the NOAA National Ocean Service tide gauges at Reedy Point (located in New Castle County in northern Delaware) and Lewes (located in Sussex County in southern Delaware). **Linear trend rates** over each gauge's entire period of record are 3.91 and 3.71 mm/yr at Reedy Point and Lewes, respectively. This equates to a **mean sea level change** of 10.3 inches since 1956 at Reedy Point and 15.2 inches since 1919 at Lewes.

- **Acceleration of mean sea levels** have been observed at both gauges. Over the last 40 years, linear trend rates are 4.41 and 5.52 mm/yr at Reedy Point and Lewes, respectively, with increasingly higher rates over the last 30 and 20 year time periods.

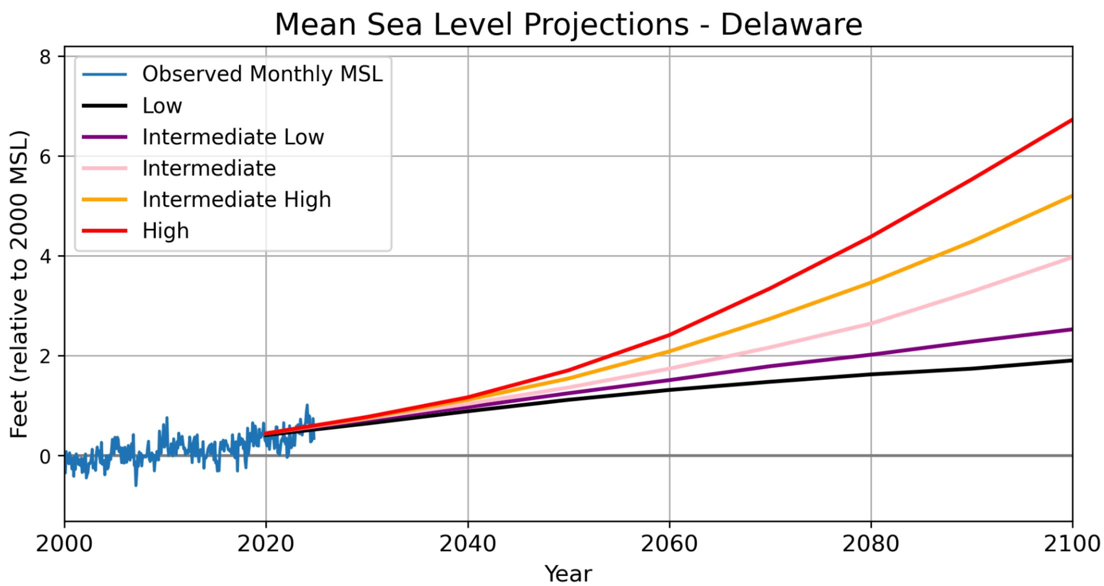
- **Coastal flood frequency** (annual count of daily floods above the NWS minor flood impact threshold) has *increased* exponentially at both locations. At Reedy Point, average annual flood frequency increased from 1.9 days/year over 1980-1989 to 22.8 days/year over 2020-2024. At Lewes, average annual flood frequency increased from 5.7 to 40.8 days/year over those same time periods.

- **Average seasonal cycle of mean sea level** at each gauge has nearly identical patterns. Mean sea levels are typically highest during the late summer/early fall (Aug-Oct) with secondary peak in May-June, and typically lowest in winter (Dec-Feb). Coastal flood frequency is also typically highest in Sep-Oct with a secondary peak in May but remains relatively high and with a higher likelihood of extremes over the winter months at Lewes.

Future Projections:

- **Observation-based trajectories** were developed using monthly observations from 1970 - 2023 and extrapolated to 2050. The mean sea level trajectory for Delaware is non-linear (i.e., demonstrates acceleration) and serves as an independent estimate of near-future sea levels from modeled projections. Following this trajectory, mean sea levels have *increased* 6.25 inches over the last 30 years, and are expected to *increase* by another 10.8 inches over the same amount of time into the future.

- **Mean sea levels** are projected to *increase* by 2.53 ft (2.07-3.08 ft likely range) under the Intermediate-Low scenario to 5.20 ft (3.95-6.15 ft likely range) under the Intermediate-High scenario by 2100, relative to 2000 mean sea level. Low and High scenarios extend those ranges and although unlikely to occur, may be appropriate to use in some cases.



Projections of mean sea level for Delaware under the five SLR planning scenarios. Historical monthly observations are plotted in blue. Data relative to 2000 mean sea level.

- The **observation-based trajectory tracks between the Intermediate-Low and Intermediate scenarios** and is increasing at a faster rate. Between present time and 2050, there is *little difference* among the scenarios and trajectory, with median projections ranging from 1.25 ft to 1.54 ft by 2050.

- Under the Intermediate scenario, the **leading process components** contributing to sea level rise in Delaware by 2050 are due to thermal expansion and changing ocean patterns (47%), vertical land motion (25%), and ice loss from land-based mountain glaciers (13%). By 2100, thermal expansion and changing ocean patterns is still the largest component (38%), however, ice loss from the Antarctic ice sheet plays a more influential role (26%), with continued contributions from vertical land motion (16%) and mountain glaciers (11%). Greenland and Antarctic ice sheets contribute increasingly larger amounts under higher warming futures and longer time frames.

- **Coastal flood frequency** days above the NWS minor flood threshold are expected to *exponentially increase* under all SLR scenarios. By 2050, the average flood frequency ranges from 136 to 190 days/year under the Intermediate-Low to Intermediate-High scenarios, i.e., nearly every other day. By the end of the century (2100), flood frequency days are approximately 330 days/year or more in all but the Low scenario.

- Under all scenarios and in accordance with mean sea level rise, the likelihood of **extreme water levels** also *increases*. Under the Intermediate scenario at the Lewes tide gauge, the 1-in-10-year event level (approx 4 ft above MHHW) in 2020 is expected to occur every year by 2060. Similarly, the 1-in-100-year event level (approx 6 ft above MHHW) is expected to occur every year by 2100.

This report presents a summary of historical local climate observations, reviews recent national and international scientific assessments, and provides projections of Delaware's climate through 2100. These projections—focused on temperature, precipitation, and sea level—are based on multiple future scenarios. The information is intended to support Delaware's Climate Action Plan as well as decision makers and stakeholders in planning for long-term resilience, mitigation, and adaptation.

1. Introduction

Changes in climate have been affecting Delaware for decades and will continue to do so into the future. In Delaware, the most prominent changes to our local climate are increased temperatures (including longer growing seasons and warmer minimum temperatures), changes in precipitation patterns (including more heavy rain events), and increased sea levels (including more frequent and more severe coastal flooding) (DNREC, 2021; Whitehead et al., 2023). These changes are increasing the risk of damage and degradation to Delaware's natural ecosystems, human-made infrastructure, and public safety. Essentially, the impacts of climate change multiply the threats we already experience due to weather and climate hazards, putting more stress on an increasingly taxed system.

Delaware Department of Natural Resources and Environmental Control (DNREC) and other agencies within the State of Delaware have continuously monitored and studied our local weather and climate as well as their impacts across many physical, social, and economic sectors affecting the state. Several climate-related resilience initiatives, research studies, and planning reports have resulted from the state's efforts, the most recent of which is the development and release of the 2025 Delaware Climate Action Plan, an update to the 2021 Delaware Climate Action Plan. Accordingly, this report also serves as an update to the last climate projections reports for Delaware issued in 2013 for temperature and precipitation and in 2017 for sea level rise. This report also summarizes historical local observations, reviews the latest national and international scientific assessments of global climate, and develops projections of Delaware's climate from present to the year 2100. Projections are provided under several possible future scenarios for the primary indicators of climate change impacting Delaware: temperature, precipitation, and sea level. This information will better inform Delaware decision makers and stakeholders to guide long-term resilience, mitigation, and adaptation planning.

1.1. Delaware's Climate

As a mid-Atlantic, coastal state, Delaware sits in a transition zone between humid subtropical climate conditions to the south and humid continental conditions to the north. The moderating effects of surrounding water bodies, including the Chesapeake Bay to the west and the Atlantic Ocean and Delaware Bay to the east, lessen temperature extremes compared to nearby locations not impacted by large water bodies (**Figure 1.1**). The state experiences cold winter temperatures, hot summers, and ample but highly variable precipitation throughout the year with annual temperature ranges of 55 to 58 degrees Fahrenheit and annual precipitation ranges between 40 to 50 inches (**Figure 1.2**).

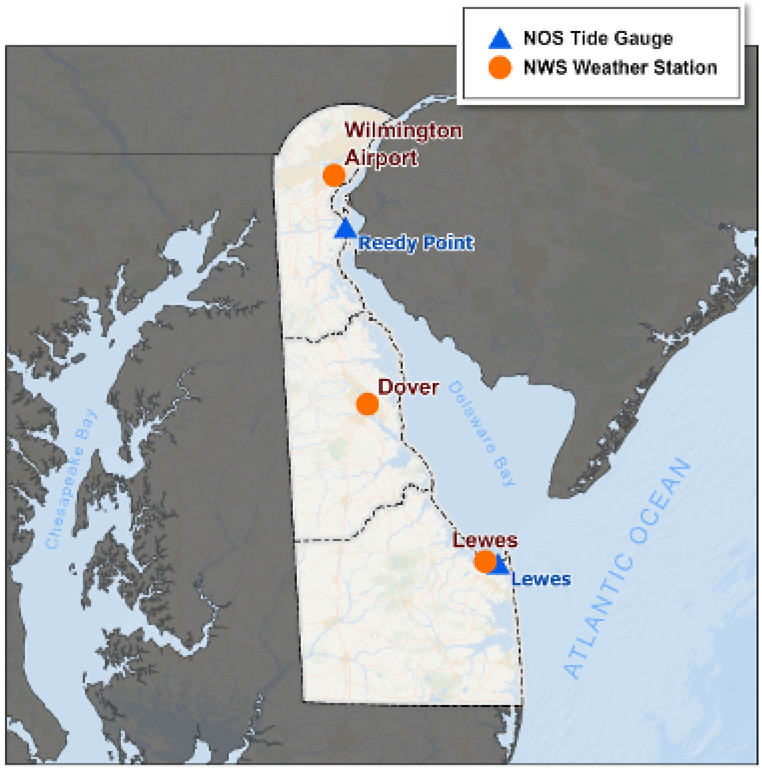
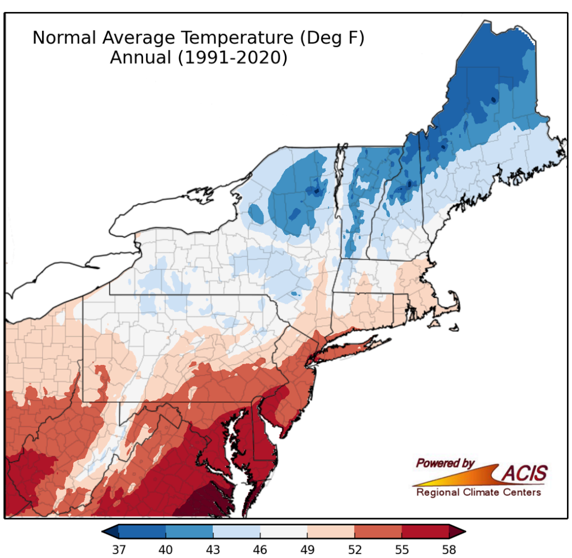


Figure 1.1. Delaware's three counties (from north to south: New Castle, Kent, and Sussex), and the location of the observation data points used for this report. (Orange circles represent NWS Cooperative Observer locations; Blue triangles represent NOAA CO-OPS stations.)



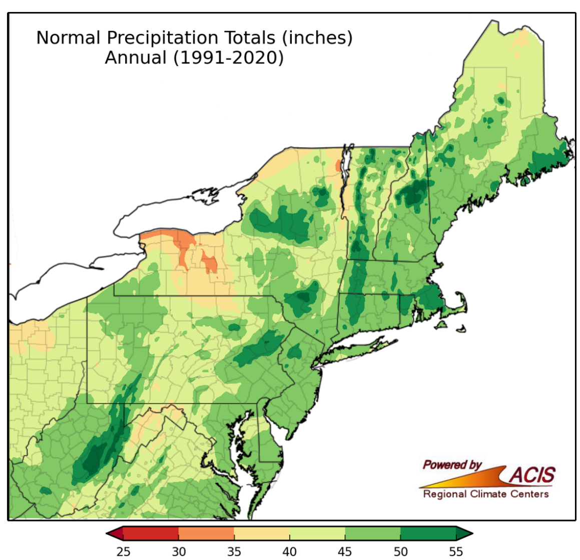


Figure 1.2. Maps showing 1991-2020 normal average annual temperature (left) and normal annual precipitation totals (right) for the Northeast United States. Delaware is located in the southern portion of these maps. Source: Regional Climate Centers ACIS.

Delaware has three counties: New Castle, Kent, and Sussex. New Castle County, the northernmost county, contains nearly 46% developed land surface with the remainder of the county made up of cropland (22.5%), wetland (16.3%), and forest, shrub, grassland (13.7%) and sits along the Atlantic Seaboard Fall Line with a major portion of the county in the Atlantic Coastal Plain. New Castle County is home to more than 50% of the state's population (US Census Bureau 2024 Estimates), and comprises the entirety of the Delaware Climate Division 1. Major weather-related concerns within New Castle County are centered on pluvial flooding, heat and humidity associated with urban heat effects, and drought affecting both water quality and water availability. The southern two counties, Kent and Sussex, comprise Delaware Climate Division 2 and are predominantly composed of cropland (42.8% and 39.8%, respectively) and wetlands (30.9% and 23.6%, respectively). Both of these counties fall squarely within the Atlantic Coastal Plain and their primary weather-related concerns include coastal flooding, storm surge, and drought. Delaware's agricultural industry is particularly vulnerable to weather and climate impacts. Delaware's agriculture centers on chicken broilers, corn, wheat, soybeans, and fruits (Delaware Agricultural Statistics Bulletin, 2023), and as such, extended heat waves and droughts as well as changes to the growing season length are a concern statewide. These strains can be exacerbated by impacts from sea level rise and storm intensification leading to flooding and saltwater intrusion toward the interior portions of Delaware. In addition to the effect on crop yield, this can lead to negative impacts on water quality, soil health, and habitats.

As a predominantly coastal state, Delaware is frequently impacted by the hazards caused by coastal flooding. Short-term processes (weather timescales from minutes to days) that cause coastal flooding in Delaware include astronomical tides, storm surge, strong winds, waves, and precipitation runoff and streamflow. Long-term processes (climate time scales from weeks to decades) can amplify these impacts and include monthly tide cycles (tides are higher during new/full moons), natural seasonal changes (sea levels are higher in the late summer), and changing atmospheric and ocean current patterns caused by large scale climate cycles such as from El Niño. Coastal flooding occurs throughout the year in Delaware. Most significant coastal flooding occurs in the colder months of October through May, due to the nearby ocean currents and strong gradients in sea surface temperatures enabling development and strengthening of off-shore storms, and in the late summer and fall due to Atlantic tropical cyclones (hurricanes) (Callahan et al., 2022).

A large part of Delaware's economy, infrastructure, and natural resources are located along the Delaware River, Delaware Bay, and Atlantic Ocean shores (DNREC, 2012; Callahan et al., 2017). Its flat topography and low-lying land makes many of its coastal communities and natural lands particularly susceptible to the impacts of coastal flooding. Coastal storms also include multiple hazards, such as heavy precipitation and strong winds and waves, known as compound flood events, amplifying the impacts from increased flood levels alone. **Figure 1.3** highlights areas along the Delaware coasts that are susceptible to both minor (land elevations that are below the minor flood impact threshold derived by the National Ocean Service) and major (potentially inundated areas from a Category 2 hurricane using the National Hurricane Center's surge model) flooding.

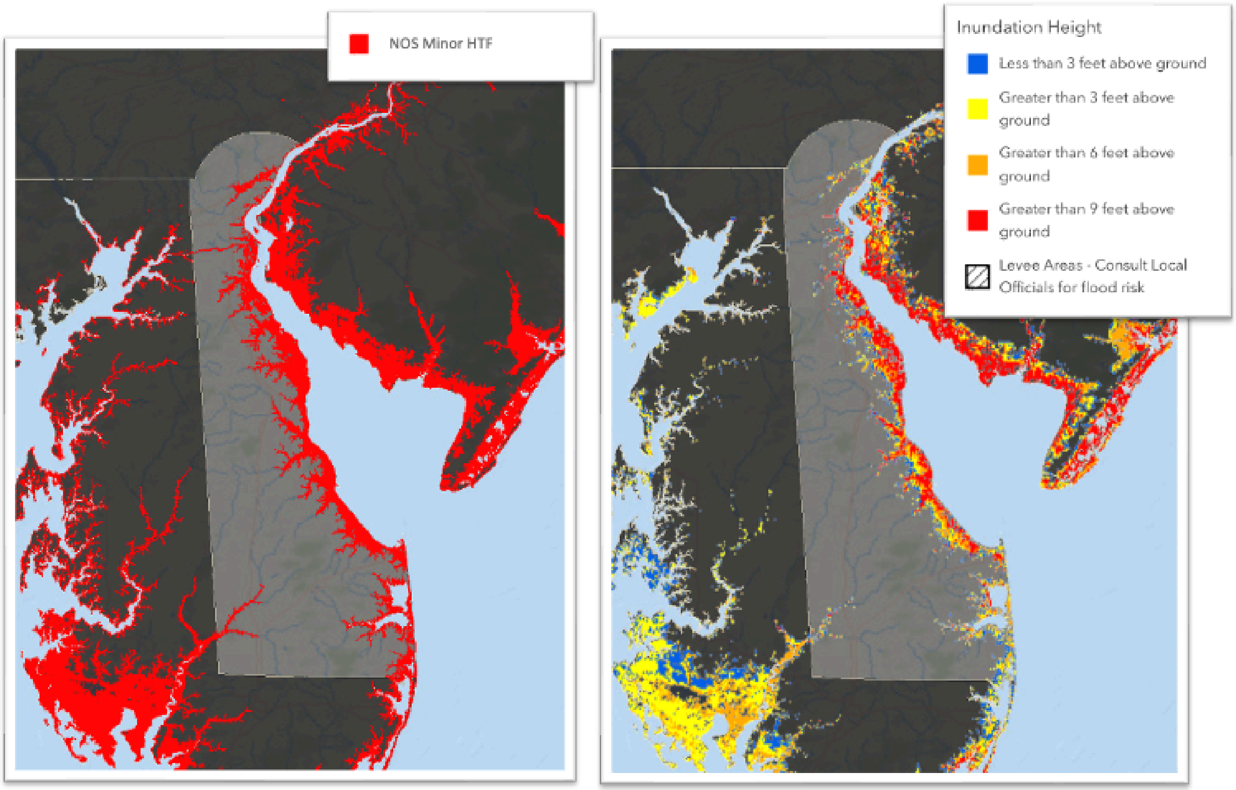


Figure 1.3. Coastal flooding hazard areas that are susceptible to high tide flooding based on the NWS Minor flood advisory threshold (left) and inundation by a Category 2 hurricane based on NHC's surge model (right). Nearly all of Delaware's coastline is vulnerable to minor and major coastal flooding. Source: NOAA National Ocean Service Coastal Flood Exposure Mapper[1].

As noted in previous Delaware SLR reports (DNREC, 2012; Callahan et al., 2017), sea levels have been rising along Delaware's coasts for at least the past 100 years, increasing the likelihood and severity of coastal flooding. Minor coastal flooding events, also called sunny day flooding or high tide flooding (HTF), most often occur around the time of highest tides each day and are largely driven by amplified tidal ranges during the new moon/full moon cycle (spring tides) as well as by temporary increases to the mean sea level from ocean currents, temperatures, or local wind and precipitation patterns (Sweet et al., 2018, 2022). HTF events in coastal communities recently have been occurring without significant contributions from the weather. Major flooding events from storms impact larger areas with higher mean sea levels.

Impacts on Delaware due to rising mean sea levels can be categorized based on time frame. *Episodic impacts* of higher average sea levels occur on short-term timescales (hours to days) include damage to private property and public infrastructure from storm surge; rapid erosion of beaches, dunes, and berms; saltwater mixing into freshwater systems due to overtopping protection embankments; and increased risk to public safety. *Gradual impacts* on longer timescales (months to years) include inundation of coastal marshes; loss of coastal wetlands and forests; changes to habitats for marine and tidal zone species; damage to infrastructure due

[1] https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html

to repeated contact with saltwater; and saltwater intrusion into the groundwater system. SLR and increased coastal flooding will continue to impact numerous industry sectors and residential coastal communities in all areas of the state (DNREC, 2012; Callahan et al., 2017).

In summary, Delaware has seen an increase in observed temperatures across all seasons, with a greater increase in minimum temperatures as opposed to maximum temperatures, leading to greater demands on energy for cooling and increased stresses on agriculture and health. Delaware precipitation remains variable with a slight increasing trend to precipitation totals. Sea levels have shown a marked increase in Delaware with impacts to infrastructure, natural resources, and public safety. For these reasons, it is imperative to continue monitoring these variables and prepare for projected changes to Delaware's overall environment.

1.2. Global and National Climate Trends

In the last decade (2011-2020), average global surface temperatures measured 2°F (1.1°C) warmer than the 1850-1900 baseline temperature and have increased faster in the most recent 50 years than in any other 50-year period over the last 2000 years (IPCC, 2023). Generally, land surface temperatures have warmed faster than ocean temperatures and, as a result, are noticeably (and negatively) affecting ecosystems, human health, agriculture, and contributing to shifts in global weather patterns and meteorological phenomena. Extremes in temperatures are being felt worldwide, with a vast majority of the extremes coming from warmer extreme events, while cooler extremes are becoming less common and less severe (Seneviratne et al., 2021). Examples of these warm extreme events are seen as increases in the number of warm and hot nights as well as in the length of heat waves. Because warmer air holds more moisture, there is a likelihood that heavy precipitation will become more frequent and most notably higher for the rarer events such as the 10-year (10% chance of being equaled or exceeded in any given year) and 50 year events (2% chance of occurring in any given year). Consequently, strong storms such as tropical cyclones will have increases in the average and maximum rain rates, while their location of maximum peak winds and tracks will shift poleward (Seneviratne et al., 2021).

The contiguous US (CONUS) has actually experienced a greater increase in temperatures than that of the global average temperatures. Since 1970, the US temperatures have risen by 2.5°F (1.4°C) as compared to the global rise in temperature of 1.7°F (0.9°C). Across the US, cities have shown a doubling of the average number of heat waves since 1980 and most notably, the number of warm nights (nights with temperatures never reaching below 70°F) is increasing in most locations, except for the Southeast (Marvel, et al., 2023). Winters are warming faster in the higher latitude states than in the south (Marvel, et al., 2023), and precipitation changes have become more pronounced with the eastern US increasing precipitation amounts by 5-15% while parts of the southwestern US are experiencing marked decreases in precipitation of about 10-15% (Fox-Kemper, et al., 2021; **Figure 1.4**).

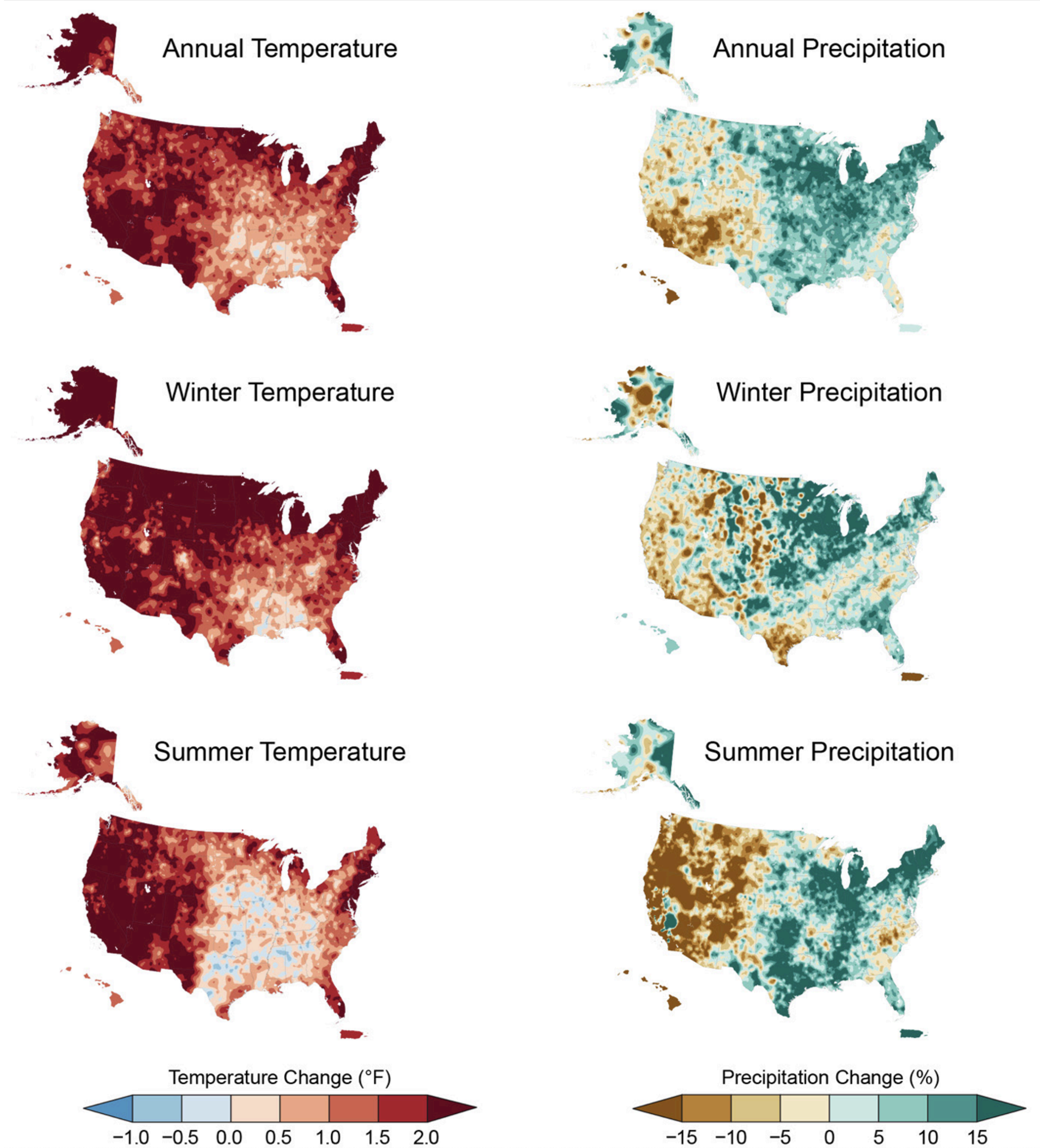


Figure 1.4. Changes shown are the difference between the annual average or seasonal temperatures (left column) and precipitation totals (right column) for the present day (2002–2021) compared to the average for the first half of the last century (1901–1960) for the contiguous United States (CONUS), Hawai'i, and Puerto Rico. Source: NCA5, Chapter 2, NOAA NCEI and CISESS NC.

With warming temperatures across the globe, sea levels have also risen (**Figure 1.5)**. Although its effects are felt locally, the drivers of sea level rise are a combination of global, regional, and local processes. Drivers of global mean sea level (GMSL) rise, i.e., the change in mean sea level averaged over all the global oceans, is directly related to changes in the global ocean's volume, which can be separated into two primary components: 1) thermal expansion due to warming, and 2) increase in ocean mass due to the additional meltwater from land-based mountain glaciers and ice sheets, most notably the Greenland (GIS) and Antarctic ice sheet (AIS). The second GMSL driver can be further divided into separate processes for modeling purposes. Both the GIS and AIS accumulate mass through snowfall on its surface and lose mass through ablation (i.e., water vapor evaporation from its ice surface), direct melting from at and below the water surface, and fracturing ice cliffs that break off into the ocean, resulting in a significant transfer of water mass from land to the ocean. Currently, about two-thirds of GMSL change comes from melting of land ice and one-third from thermal expansion (NASA, 2025; US Sea Level Change website[2]). Interannual variations of GMSL can be traced to the amount of land water storage (LWS) in surface lakes, rivers/streams, reservoirs (behind dams and impoundments), and groundwater aquifers. Larger amounts of LWS in any particular year leaves less available in the oceans.

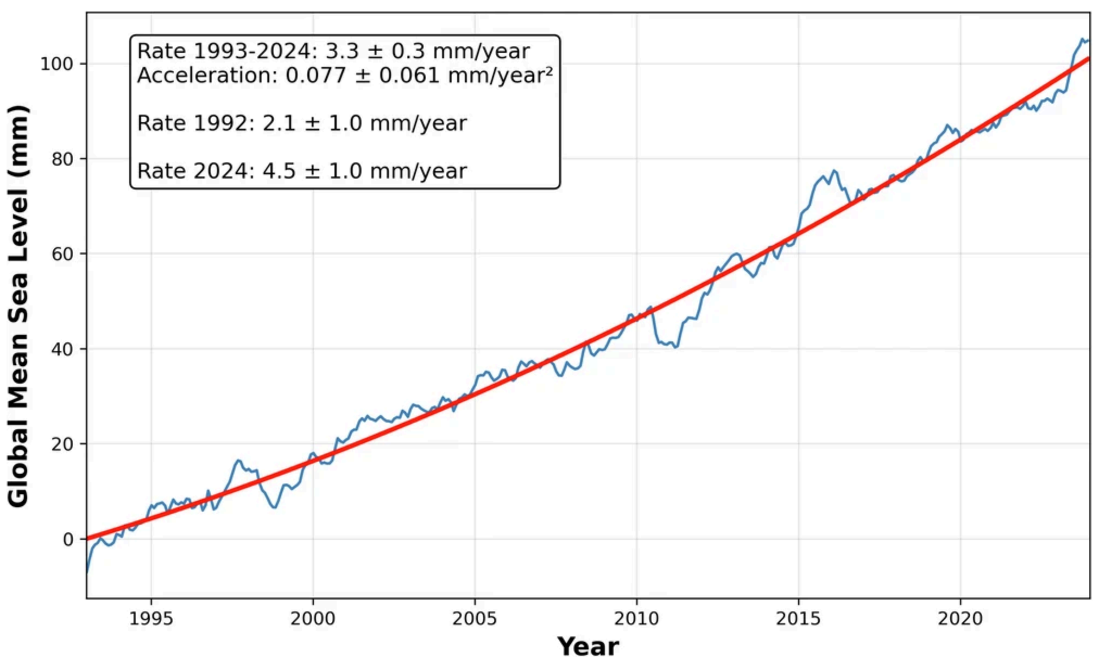


Figure 1.5. Global mean sea level from satellite altimetry over the time period from 1993 through 2023. The solid red line is the quadratic fit to the observations relative to 1993. Source:Hamlington, et al. (2024).

For at least the past 4,000 years, the Earth has experienced a relatively stable climate, resulting in only modest changes in global mean sea level (< 2 mm/yr) (Engelhart et al., 2009; Lambeck et al., 2014; Kopp et al, 2016). In the first half of the 20th Century, thermal expansion was the largest component of GMSL rise (Arias et al., 2021), whereas in recent years this trend has reversed (NASA, 2025a). Since the mid to late 20th century, much higher rates have been observed at most locations throughout the world with acceleration beginning around 1970 (Dangendorf et al., 2019; Frederikse et al., 2020, Sweet et al., 2022). Latest estimates show the

[2] https://earth.gov/sealevel/us/sea-level-101/global-sea-level-rise/the-basics/

rate of GMSL rise between 1993 and present day is approximately 3.4 mm/yr, doubling over that period increasing from 2.1 mm/yr in 1993 to 4.5 mm/yr in 2023 (**Figure 1.5**, Hamlington et al., 2024; WMO 2025). The quadratic fit to the observations in **Figure 1.5** is indicative of acceleration. Interannual variations are associated with climate patterns, most prominently strong ENSO events in 1997-1998 and 2015-2016 that translate water between the ocean and land and displaces local ocean heat content.

Regional drivers of SLR can further enhance or inhibit the GMSL increase, resulting in an uneven distribution in sea level changes throughout the world (**Figure 1.6**). Regional drivers of ocean sea surface heights can be broken into two primary components: 1) changes that arise from variability in the ocean's circulation patterns due to changes in density (temperature, saltiness) or other atmospheric forcing (Sweet et al., 2022; NASA, 2025b), and 2) changes that are due to ice sheet mass loss that are not directly attributable to the increase in ocean water volume, collectively termed gravitational, rotational and deformational (GRD) effects. Due to their huge masses, GRD effects from Greenland and Antarctica mass loss are distributed around the world and are most felt at locations far away from each ice sheet, whereas changes to ocean circulation patterns mostly influence nearby regions. Both of these regional drivers increase sea levels along the US Mid-Atlantic coast (Sweet et al., 2022).

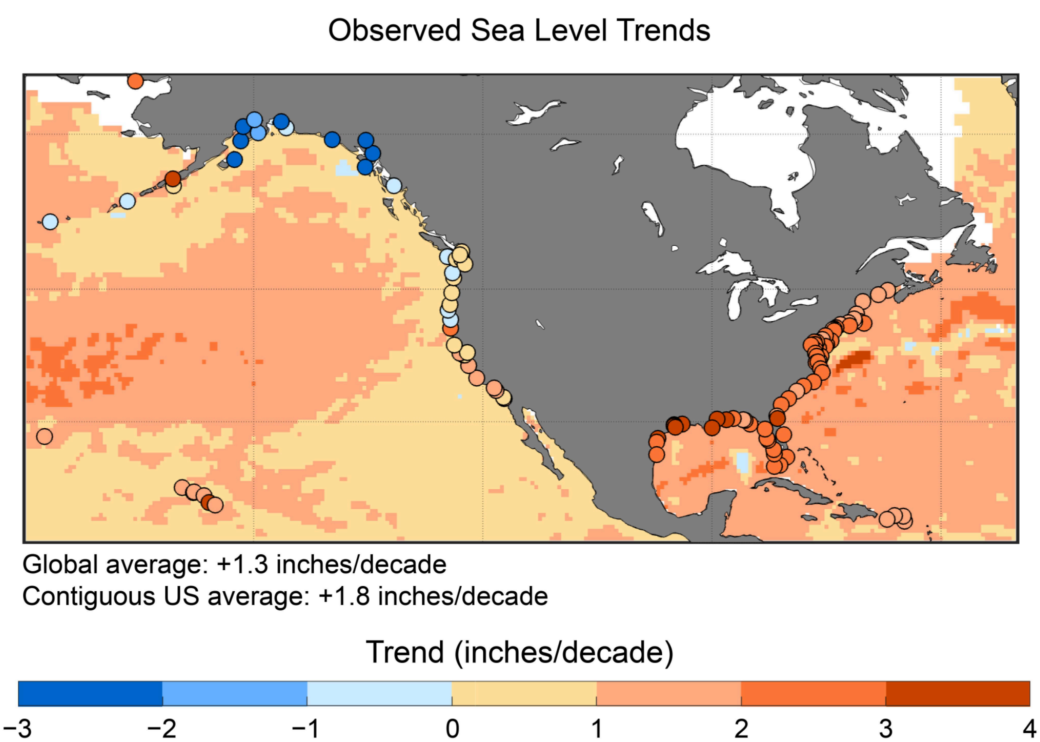


Figure 1.6. Satellite and tide gauge data showing the regional variation of sea level change trends during 1993–2020. The US East and Gulf Coasts have experienced high rates of sea level rise during this time period. Differences in rates between ocean and land-based observations can be largely attributed to local vertical land motion (VLM). Source Fig 2.5 in NCA5 Chapter 2: Climate Trends.

Lastly, local drivers can further enhance or inhibit the sea level changes measured at a location that are initially driven by global and regional processes. The most dominant of these local drivers along US coasts is vertical land motion (VLM). If the land is uplifting, for example due to tectonic activity along the US Northwest and Alaska coasts, VLM will compete against global and regional drivers and cause sea levels to fall, relative to the land surface. Similarly, if land is sinking, VLM will further increase relative sea level rise. Along the US Mid-Atlantic, land has been subsiding due to glacial isostatic adjustment (GIA), occurring gradually since the last ice age. VLM also occurs from consolidation of coastal plain sediments due to natural gas extraction or groundwater withdrawal (i.e., pumping) from lower aquifers, natural sediment compaction, and background non-climatic factors. Tide gauges, installed on land, measure the height of the sea surface relative to the land surface. VLM is therefore inherent in all tide gauge measurements, hence the difference between sea level rise recorded at tide gauges and open ocean locations, as in **Figure 1.6,** can generally be attributed to VLM processes.

Averaged over all tide gauges along US coasts, the US has experienced about 7 inches of relative sea level rise from 1970 to present and about 11 inches over the last 100 years (May et al., 2023). Regions that have experienced the highest rates of SLR are the central Gulf Coast, primary due to extremely high rates of VLM from subsurface groundwater and fossil fuel withdrawal (Kolker et al., 2011; Sweet et al., 2022), the Southeast, mostly due to recent ocean processes (Dangendorf et al., 2023), and the Mid-Atlantic, due to a combination of ocean and VLM processes (Sallenger 2012; Kopp, 2013; Boon et al., 2018).

Recent research provides perspective on the amount of uncertainty that still resides in our current state of knowledge to predict future global and regional sea level conditions. There is still significant uncertainty regarding the dynamic response of ice sheets, particularly rapid ice sheet loss/collapse in Antarctica under high emissions scenarios. Although the amount of water transferred from the land to the ocean is a dominant contributor to future GMSL rise, GCMs that include rapid ice sheet loss/collapse constitute a separate set of low confidence runs. Another large factor in projections of regional sea levels, storm tracks, and precipitation patterns in the North Atlantic Ocean is the strength of the Atlantic Meridional Overturning Circulation (AMOC), of which the nearby Gulf Stream is a segment of. It is currently unknown if the AMOC slowdown observed over the past 20 years will continue, potentially reaching a tipping point and settle into a new state/pattern, or if it’s only a temporary condition (Caesar et al., 2018; Marvel et al., 2023; Rahmstorf, 2024). However, nearly all recent climate models and past long-term reconstructions indicate that AMOC strength is at a low point and the slowdown is projected to continue (Fox-Kemper et al., 2021). Additionally, extreme coastal flooding events in the Mid-Atlantic are driven by both tropical cyclones/hurricanes and extratropical storms/nor'easters, and although these systems are projected to become more intense, there is a high amount of uncertainty in future frequency and location of tracks of these storms under projected climate change conditions (Pringle et al., 2021; Arias et al., 2021; Marvel et al., 2023; Lee et al., 2023). As well, sea surface temperatures (Terhaar et al., 2025) and global mean sea level (Hamlington et al., 2025) in 2023-2024 were both higher than expected predictions. Each of these components of our climate system pose significant risks of coastal flooding in the Mid-Atlantic region and research on their predictability and range of plausibility should be monitored closely.

Nonetheless, as with surface air temperature, the latest suite of GCMs and expert assessments indicate there is high confidence that sea level rise will continue throughout the 21st century. Sea levels also are expected to accelerate in many locations along US coasts, including the Mid-Atlantic, as well as the national and global means (Fox-Kemper et al., 2021; May et al., 2023). Land-based ice sheet loss is expected to become a larger factor in the latter half of the 21st century with VLM being a constant or minor contributor over the long term (in most areas outside of Alaska and central Gulf coasts). However, unlike air temperature, sea level rise will continue regardless of the greenhouse gas emission scenario, due to continued thermal expansion and land ice loss from already absorbed ocean heat content, and continued local VLM processes, with warmer futures associated with higher mean sea levels (Fox-Kemper et al., 2021; Sweet et al., 2022).

1.3. Past Delaware Climate Projection Reports

Delaware's coastal status plays a large role in Delaware's economy, management of natural resources and man-made infrastructure, and public safety, as well as many other aspects of Delawareans' culture and way of life. As such, Delaware government agencies have been concerned about rising sea levels for several decades. Two concentrated efforts previous to this current study that focused specifically on providing sea level rise projections for the state of Delaware took place in 2008-2013 and 2016-2017.

In 2008, the Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs (DCP) instituted the Delaware Sea-Level Rise Initiative, a comprehensive, multi-year partnership-based effort designed to help the state assess, prepare for, and minimize the potential impacts of sea-level rise (DNREC, 2011). The Sea-Level Rise Technical Workgroup developed projections of SLR that spanned the published assessments, reports, and scientific literature available at the time. Three scenarios were selected, Low, Intermediate, and High, each representative of projections of sea level rise amounts by the year 2100 of 0.5, 1.0, and 1.5 meters, respectively (DNREC, 2009). The time evolution of sea level change followed a simple statistical model (USACE, 2009; NRC, 1987) and was not associated with any particular set of physical model runs.

The Delaware SLR Advisory Committee (SLRAC) was formed in 2010 to 1) assess Delaware's vulnerability to current and future inundation problems that may be exacerbated by sea-level rise, and; 2) to develop a set of recommendations for state agencies, local governments, businesses, and citizens to enable them to adapt programs, policies, and business practices and make informed decisions (DNREC, 2012). SLRAC was composed of members from a wide variety of interest groups, including state agencies, local governments, citizen organizations, business organizations, and environmental organizations. They developed inundation maps and statistics on potential impacts to numerous sectors and state resources across Delaware for each of the three scenarios, as well as three accompanying reports, ***Preparing for Tomorrow's High Tide: Sea Level Rise Vulnerability Assessment for the State of Delaware*** (DNREC, 2012), ***Preparing for Tomorrow's High Tide: Recommendations for Adapting to Sea-Level Rise in Delaware*** (DNREC, 2013), and ***Preparing for Tomorrow's High Tide: 2014 Workshop Proceedings and Interim Implementation Plan*** (DNREC, 2014a).

Both climate projections and SLR planning scenarios were specifically identified in *Executive Order 41: Preparing Delaware for Emerging Climate Impacts and Seizing Economic Opportunities from Reducing Emission*s by Governor Jack Markell in September 2013, establishing the precedent of agencies using the latest climate projections and SLR scenarios to implement future plans.

Coincidental to the SLR work noted above and leading up to 2013, DNREC and Delaware Climate Office (DCO) collaborated with Texas Tech University (Dr. Katherine Hayhoe) to develop temperature and precipitation projections for Delaware producing the following results:

- ***Climate Change Projections and Indicators for Delaware*** (2013) - a report on historical observations, trends, and future projections (based on CMIP3 and CMIP5) in temperature and precipitation. This study used historical weather observations for 14 Delaware weather stations during the period of 1895 - 2012. These historical observations provided the input for downscaling climate model simulations of projected future climate conditions through the end of the 21st century. A total of 13 different climate models, four different Coupled Model Intercomparison Project Phase 3 (CMIP3) global climate models and nine Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models were used to simulate future climate conditions, and each model was run under low- and high-emission scenarios to depict a range of possible climate changes that could occur over the next century. Data results provided output projections for temperature, precipitation, humidity, and hybrid variables.

- ***Climate Impact Assessment*** (2014) - an overall assessment of impacts to people, places, and resources in Delaware with the goal of providing a strong foundation for developing state mitigation and adaptation planning strategies. This assessment reflects the best available climate science, climate modeling, and projections to illustrate the range of potential vulnerabilities that Delaware may face from the impacts of climate change.

- **Delaware Climate Projections Portal** (2014) - a web-based data exploration tool that provides data visualization, data downloads, and general information resulting from climate model runs for temperature, precipitation, humidity, and hybrid downscaled projection data for 14 Delaware stations.

In 2017, the Delaware Sea-Level Rise Technical Committee (TC) was formed and the Delaware SLR scenarios from 2010-2013 were refined resulting in the release of the ***Recommendation of Sea-Level Rise Planning Scenarios for Delaware: Technical Report***. During this same time, digital inundation layers (by foot increments) became available for use by the public and for use in planning. The 2017 report scenarios projections were based on quantiles (5%, 50%, and 95%) of the model runs using the Kopp 2014 framework. Proper guidance and interpretation on their use evolved over the years as their projections became more widely used in state, county, and local planning.

Combining climate change projections from rising temperatures, heat waves, heavy precipitation events, and sea levels, their collective impacts across many sectors, and recognizing the importance of proactive action, the State of Delaware released the ***Delaware Climate Action Plan*** in 2021. Delaware's Climate Action Plan is the State's playbook of actionable strategies and goals to reduce greenhouse gas emissions, produce energy from renewable sources and protect our natural resources, communities, and people from the impacts of climate change (DNREC, 2021). The 2021 Climate Action Plan was the result of a year-long process that included 10 state agencies, residents (through a series of public participation workshops), businesses, and technical experts.

In 2023, the Delaware Climate Change Solutions Act (HB 99), introduced during the 152nd General Assembly, established a comprehensive and coordinated approach to reduce emissions of greenhouse gases (50% by 2030, net zero by 2050) and to maximize resiliency throughout the state. Primary outcomes of HB99 helped to create a schedule for updating the Climate Action Plan and progress reports, establish the Technical Climate Advisors (TCA) committee to issue climate scenarios, identify State agency Climate Change Officers, and develop an all of government strategy for implementing emissions reductions and resiliency.

1.4. Purpose of this Report

In 2023, DNREC requested an update of the climate projections for Delaware, including temperature, precipitation, and sea level rise. Researchers within the Delaware Climate Office (DCO) and the Center for Environmental Monitoring & Analysis (CEMA) then began reviewing literature, data options, and produced recommendations on next steps for the acquisition of data and methods for analysis. At this same time, the Technical Climate Advisors (TCA) committee, established in the Delaware Code (7 Del. Code § 10005) as part of the Climate Change Solutions Act of 2023 with individual members appointed by the Secretary of DNREC, held its first committee meeting and has met throughout the development of this report. At various stages throughout the analysis, CEMA has reported results to the TCA and DNREC staff. Each of these meetings were open to the public and were used to gather feedback on results and how these results may be used. This process has helped to inform this report and to outline the need for future research and analysis.

Several national and international reports have been released since Delaware's last climate change and SLR projection reports in 2013 and 2017, respectively. The IPCC has released both the AR5 (2013) and AR6 (2021) reports and the US has released both the Fourth (NCA4, Volume 1 in 2017, Volume 2 in 2018) and Fifth (NCA5, 2023) National Climate Assessments. Specifically for SLR, the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate was released in 2019 and the US Interagency Task Force SLR Technical Report in 2022. These reports note numerous advancements and updates to observations, models, and latest scientific understanding achieved in recent years.

As laid out in the Climate Change Solutions Act in 2023, DNREC is actively developing the 2025 Delaware Climate Action Plan, which builds on the work done in the 2021 Climate Action Plan and will focus on reducing emissions, increasing resiliency and achieving the goals established in the 2023 the Climate Change Solutions Act. This report aims to provide updates to the science, data, and projection information relating to Delaware's climate future for temperature, precipitation, and sea level rise. Findings from this work will be incorporated into the 2025 Climate Action Plan update[3] and will serve to support state policy makers, stakeholders, scientists and engineers, planners, and others requiring detailed projections for planning into Delaware's future.

1.5. Organization of this Report

This report is organized in the following way.

- **Chapter 1** (this chapter) provides an overview of Delaware's primary concerns relative to its geographic location and climate, including impacts and a brief overview of global and national climate trends. This chapter also gives a summary of past Delaware reports and efforts to document changes in temperature, precipitation, and sea level rise and their relative impacts. Finally, Chapter 1 provides the overall purpose of this report.

- **Chapter 2** provides background information on the current state of climate modeling and discusses the methodology employed in this report to select future scenarios, models, and downscaling methods to generate the Delaware climate projections. This chapter also provides an overview of SLR modeling and sea level rise scenario selection.

- **Chapters 3, 4, and 5** provide a detailed discussion on Delaware temperature, precipitation, and sea levels, respectively. Each chapter reviews data sources used in this study, provides a narrative on historical observations and trends, and summarizes future projections scenarios.

- **Chapter 6** provides a summary of the report and a general discussion of cautions and limitations on how these results can be interpreted.

References are provided at the end of each chapter.

[3] https://dnrec.delaware.gov/climate-plan/2025-update/

1.5. References

Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021. Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33−144. http://doi.org/10.1017/9781009157896.002

Boon, J. D., Mitchell, M., Loftis, J. D., & Malmquist, D. M., 2018. Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions. Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467. Virginia Institute of Marine Science, College of William & Mary. https://doi.org/10.21220/V5T17T

Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba. 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature 556(7700):191–196, https://doi.org/10.1038/s41586-018-0006-5

Callahan, John A., Benjamin P. Horton, Daria L. Nikitina, Christopher K. Sommerfield, Thomas E. McKenna, and Danielle Swallow, 2017. Recommendation of Sea-Level Rise Planning Scenarios for Delaware. Technical Report prepared for Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs, 117 pp.https://doi.org/10.13140/RG.2.2.17411.66082

Dangendorf, S., Hay, C., Calafat, F.M. et al., 2019. Persistent acceleration in global sea-level rise since the 1960s. Nature Climate Change 9, 705–710. https://doi.org/10.1038/s41558-019-0531-8

Dangendorf, S., Hendricks, N., Sun, Q. et al., 2023. Acceleration of U.S. Southeast and Gulf coast sea-level rise amplified by internal climate variability. Nature Communication, 14, 1935. https://doi.org/10.1038/s41467-023-37649-9

Delaware Department of Agriculture and National Agricultural Statistics Service. (2023). Delaware Agricultural Statistics Bulletin [Brochure]. https://www.nass.usda.gov/Statistics_by_State/Delaware/Publications/Annual_Statistical_Bulletin/2022/DE-2022-2023-Ag-Stats-Bulletin.pdf

DNREC, 2009. Recommended Sea-level Rise Scenarios for Delaware: Technical Report, Prepared by the DNREC SLR Technical Workgroup, 13 pp.

DNREC, 2011. Preparing for Sea Level Rise: Development of a Sea Level Rise Initiative. Project Compendium prepared by Delaware Coastal Programs section, 43 pp.

DNREC, 2012. Preparing for Tomorrow's High Tide: Sea-Level Rise Vulnerability Assessment for the State of Delaware. Technical Report, Prepared for the Delaware Sea Level Rise Advisory Committee for Delaware DNREC, 210 pp. https://documents.dnrec.delaware.gov/coastal/Documents/SeaLevelRise/AssesmentForWeb.pdf

DNREC, 2013. Preparing for Tomorrow's High Tide: Recommendations for Adapting to Sea-Level Rise in Delaware. Technical Report, Prepared for the Delaware Sea Level Rise Advisory Committee for Delaware DNREC, 118 pp. https://documents.dnrec.delaware.gov/coastal/Documents/SeaLevelRise/FinalAdaptationPlanasPublished.pdf

DNREC, 2014a. Delaware Climate Change Impact Assessment. Technical Report, Prepared by the DNREC Division of Energy and Climate, 215 pp.

DNREC, 2014b. Preparing for Tomorrow's High Tide: 2014 Workshop Proceedings and Interim Implementation Plan, Technical Report, Prepared for the Delaware Sea Level Rise Advisory Committee by the Delaware Department of Environmental Control, 134 pp. https://documents.dnrec.delaware.gov/coastal/Documents/SeaLevelRise/SLRImplementationWorkshopProceedingsComplete.pdf

DNREC, 2021. Delaware Department of Natural Resources and Environmental Control, Delaware's Climate Action Plan, by Jennifer de Mooy, Margaret Pletta, and Ian Yue (Dover, DE, November 2021), 112 pp. https://dnrec.delaware.gov/climate-plan/

DNREC, 2025. Delaware 2025 Climate Action Plan Update. Accessed Oct 31, 2024. https://dnrec.delaware.gov/climate-plan/2025-update/

Engelhart, S.E., B.P. Horton, B.C. Douglas, W.R. Peltier, and T. Tornqvist, 2009. Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States, Geology, 37(12):1115-1118. https://doi.org/10.1130/G30360A.1

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021. Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, https://doi.org/10.1017/9781009157896.011

Frederikse, T., F. Landerer, L. Caron, S. Adhikari, D. Parkes, V.W. Humphrey, S. Dangendorf, P. Hogarth, L. Zanna, L. Cheng, and Y.-H. Wu, 2020. The causes of sea-level rise since 1900. Nature, 584 (7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

Hamlington, B.D., Bellas-Manley, A., Willis, J.K., Fournier, S., Vinogradova, N., Nerem, R.S., Piecuch, C.G., Thompson, P.R., and Kopp, R., 2024. The rate of global sea level rise doubled during the past three decades. Communications Earth & Environment, 5, 601. https://doi.org/10.1038/s43247-024-01761-5

Hamlington, B.D., Fournier, S., Thompson, P.R., and Marcos, M., 2025. Sea level rise in 2024. Nature Reviews Earth & Environment, 6, 246–248. https://doi.org/10.1038/s43017-025-00667-w

Intergovernmental Panel on Climate Change (IPCC). Technical Summary. In: *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2022:39-70.

IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

Kolker, A.S., M.A. Allison, and S. Hameed, 2011: An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophysical Research Letters, 38 (21). https://doi.org/10.1029/2011gl049458

Kopp, R.E., 2013. Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability?, Geophysical Research Letters, 40:3981–3985, https://doi.org/10.1002/grl.50781

Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, Earth's Future, 2:383–406. https://doi.org/10.1002/2014EF000239

Lambeck K., H. Rouby, A. Purcell, Y. Sun, and M. Sambridge, 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, Proceedings of the National Academy of Science, USA, 111(43):15296–15303. https://doi.org/10.1073/pnas.1411762111

Lee, C.-Y., Sobel, A. H., Tippett, M. K., Camargo, S. J., Wüest, M., Wehner, M., & Murakami, H., 2023. Climate change signal in Atlantic tropical cyclones today and near future. Earth's Future, 11, e2023EF003539. https://doi.org/10.1029/2023EF003539

MRLC Viewer, www.mrlc.gov/viewer/. Accessed 27 May 2025.

Marvel, K., W. Su, R. Delgado, S. Aarons, A. Chatterjee, M.E. Garcia, Z. Hausfather, K. Hayhoe, D.A. Hence, E.B. Jewett, A. Robel, D. Singh, A. Tripati, and R.S. Vose, 2023. Chapter 2. Climate trends. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH2

May, C.L., M.S. Osler, H.F. Stockdon, P.L. Barnard, J.A. Callahan, R.C. Collini, C.M. Ferreira, J. Finzi Hart, E.E. Lentz, T.B. Mahoney, W. Sweet, D. Walker, and C.P. Weaver, 2023. Chapter 9. Coastal effects. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global

Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH9

NASA, 2025a. Understanding Sea Level: Global Mean Sea Level. Accessed Jan 10, 2025. https://sealevel.nasa.gov/understanding-sea-level/global-sea-level/overview/

NASA, 2025b. Understanding Sea Level: Regional Relative Sea-Level Change. Accessed Jan 10, 2025. https://sealevel.nasa.gov/understanding-sea-level/regional-sea-level/overview/

Pringle, W. J., Wang, J., Roberts, K. J., & Kotamarthi, V. R., 2021. Projected changes to cool-season storm tides in the 21st century along the northeastern United States coast. Earth's Future, 9, e2020EF001940. https://doi.org/10.1029/2020EF001940

Rahmstorf, Stefan, 2024. Is the Atlantic Overturning Circulation Approaching a Tipping Point? *Oceanography*. https://doi.org/10.5670/oceanog.2024.501

Sallenger, A. H., K. S. Doran, and P. A. Howd, 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America, Nature Climate Change, 2:884–888, https://doi.org/10.1038/nclimate1597.

Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi: 10.1017/9781009157896.013.

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://sealevel.globalchange.gov/internal_resources/756/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Terhaar, J., Burger, F.A., Vogt, L. et al., 2025. Record sea surface temperature jump in 2023–2024 unlikely but not unexpected. Nature 639, 942–946. https://doi.org/10.1038/s41586-025-08674-z

Whitehead, J.C., E.L. Mecray, E.D. Lane, L. Kerr, M.L. Finucane, D.R. Reidmiller, M.C. Bove, F.A. Montalto, S. O'Rourke, D.A. Zarrilli, P. Chigbu, C.C. Thornbrugh, E.N. Curchitser, J.G. Hunter, and K. Law, 2023: Ch. 21. Northeast. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH21

2. Scenario Projections and Downscaling Methods

This chapter will provide an overview of climate modeling at the global level, how data can be translated to the local level, and the data sources and methodologies used in developing the Delaware-specific climate projections for temperature, precipitation, and sea level rise. Because each data type requires specific processing in the final analysis, detailed discussions of the data processing and methodologies can be found in the respective chapters for temperature (**Chapter 3**), precipitation (**Chapter 4**), and sea level (**Chapter 5**).

2.1. Global Climate Models and Future Climate Scenarios

In order to assess future climate scenarios, we can rely on the efforts of the global climate community and the long history of research that has informed our understanding of the forces at play in our changing climate and have also provided the innovation and technology to model these changes into the future. Since the late 19th century, scientists have been applying our understanding of the physical realm to quantify changes in the Earth's atmosphere (Pearce, 2023). Over the past century, these representations of Earth's changing environment have developed into complex mathematical models that require vast computer resources to analyze and predict future climate scenarios. These models, generally referred to as Global Climate Models (GCMs), aggregate the mathematical representations over the Earth's surface using a grid that can represent latitude, longitude, and altitude from the Earth's surface to produce 3D approximations of reality (**Figure 2.1**).

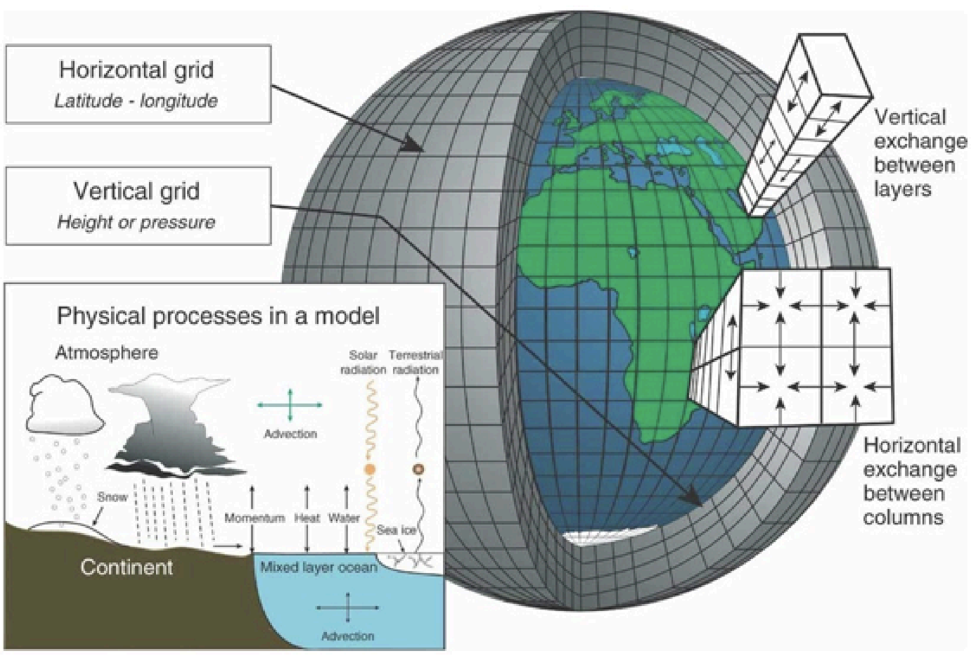


Figure 2.1 Schematic representation of the Cartesian grid structure used in finite-difference GCMs (Edwards, 2011).

Using known scientific principles, an input change to any one of these grid boxes can have effects on both itself and its surrounding grid boxes producing a dynamic example of global impacts of large-scale climate variation or changes. For example, increased temperature in one grid box has physical effects on its surrounding grid boxes which in turn affect their neighbors and so forth. GCMs can quickly become complex and require increasing computational power as more information is added. Over the years, GCMs have been able to leverage innovations in computing and the availability of both storage and processing capabilities to improve model capabilities to represent complex dynamics in the real world and to make the Earth grid boxes smaller (from the original 500 km grid boxes to less than 50 km grid boxes) to help simulate the local climate influences. Even so, GCMs require very robust supercomputers and can take weeks to months to run. Since the first GCM, there have been hundreds developed and each has a particular focus or specialty with a vast array aiming to project future global climate changes in temperature and precipitation.

2.1.1. Coupled Model Intercomparison Project (CMIP)

As the international climate community has become more organized around climate science and model development, there became a need to compare and contrast these models and their outputs. (Eyring, 2016) In 1995, the World Climate Research Programme (WCRP) established the Coupled Model Intercomparison Projection (CMIP) in an effort to help standardize model development and outputs so that the results are comparable among all models (Eyring, 2016; Carlson, 2016). An added benefit, and a requirement of modeling center's participation in CMIP, is that model output is freely available to the global research community, allowing for GCMs to be analyzed, compared, and reviewed, thereby providing documentation for future improvements (Eyring, 2016; Eyring, 2019). Over the years, each CMIP phase has evolved and grown to include more models and experiments than the previous phase. More information on CMIP phases can be found on the WCRP CMIP website[4].

The last Delaware Climate report, completed in 2013 (DNREC), used data from both CMIP3 and CMIP5 experiments to support Delaware projections. The CMIP6 model output was completed in 2023 and is the subject of this study and of the most recent international and national climate assessment reports currently available, including the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6) and the US National Climate Assessment (NCA5). At the time of this publication, CMIP7 is in development and the first data outputs are expected in mid-2025.

CMIP6 introduced a number of changes that improved model development processes, standardized the output, and improved data access further facilitating multi-model analyses (Eyring, 2016). A notable change in CMIP6 was the addition of socioeconomic variables to the radiative forcings allowing for more exploration in possible changes given alternative future scenarios. See Section 2.1.2. for more information.

[4] https://wcrp-cmip.org/cmip-phases/

2.1.2. Representative Concentration Pathways and Shared Socioeconomic Pathways

An overall benefit of running models, like GCMs, allows scientists to change input scenarios to investigate how these changes will impact the final result. This is especially so with GCMs as climate scientists wish to see how changes in major climate drivers, such as greenhouse gases (eg. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbon emissions) and atmospheric pollutants (eg. aerosols and trace gases such as ozone), can change how future climates will respond. More specifically, combinations of trends in greenhouse gases result in concentrations that lead to radiative forcing, or energy imbalances of the Earth (van Vuuren, 2011). To this end, the climate modeling community has included radiative forcing metrics in GCMs, which over the years has become standardized as **Representative Concentration Pathways (RCPs)**. Each RCP is labeled by the radiative forcing, measured in Watts per meter squared (W/m^2), reached at the end of the century (2100). Four RCP scenarios were included in the IPCC AR5 report and three more were added in the IPCC AR6 report. (**Table 2.1**)

Table 2.1. This table reviews the average warming by 2100 for different Representative Concentration Pathways (RCPs) and identifies the RCPs used in the IPCC AR5 and those that were added in the IPCC AR6. Source: carbonbrief.org

IPCC AR5 Scenarios for CMIP5	IPCC AR6 added scenarios for CMIP6	Average warming by 2100 (IAMs)	Description
	RCP 1.9	1.4°C	A pathway focusing on limiting warming to below 1.5°C, the aspirational goal of the Paris Agreement.
RCP 2.6		1.8°C	A mitigation intensive scenario. Pre-Paris, the research community was focused on limiting warming to 2°C as the most ambitious climate outcome.
	RCP 3.4	2.3°C	An intermediate pathway between the “very stringent” RCP2.6 and less stringent mitigation efforts associated with RCP4.5.
RCP 4.5		2.7°C	An intermediate-emissions scenario, with emissions increasing slightly before starting to decline around 2040. It falls short with the goals of the Paris Agreement and is broadly aligned with the emissions profiles that would result from implementing the 2015 NDCs (out to 2030), followed rapidly by peaking and then reduction of global emissions by 50% by 2080.
RCP 6.0		3.3°C	High-to-intermediate emissions scenario where GHG emissions peak at around 2060 and then decline through the rest of the century.
	RCP 7.0	-	Recently added to represent the medium-to-high end range of future emissions as a baseline outcome (a “Business-as-usual” type scenario not a mitigation target). Average warming not available yet.
RCP 8.5		5.1°C	High-emissions worst-case no-mitigation policy representing a very high baseline emission scenario corresponding to the 90% highest level of no-policy baseline scenarios available at the time. Often referred to as the “Business-as-usual” scenario of IPCC (2014).

Climate futures also hold social and economic variations as our societies adapt to and influence the changing climate. This concept led to the development of the **Shared Socioeconomic Pathways (SSP)** for the latest IPCC AR6 report. SSPs look at five different ways in which the world might evolve in the absence of climate policy: **SSP1**, a world of sustainability-focused growth and equality; **SSP2**, a “middle of the road” world where trends broadly follow their historical patterns; **SSP3**, a fragmented world of “resurgent nationalism”; **SSP4**, a world of ever-increasing inequality; and **SSP5**, a world of rapid and unconstrained growth in economic output and energy use (O’Neill, 2014).

When each RCP is paired with one or more SSP, a plausible narrative emerges of how the future might unfold with regards to socioeconomic, demographic, and technological trends. A global agreement on four combinations as standard scenarios (“Tier 1”) was reached to include SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 and are described below (O’Neill, 2016).

- **SSP1-2.6**: This scenario with 2.6 W/m² by the year 2100 is a remake of the optimistic scenario RCP2.6 and was designed with the aim of simulating a development that is compatible with the 2°C (3.6°F) target. *This scenario also assumes climate protection measures being taken.*
- **SSP2-4.5**: As an update to scenario RCP4.5, SSP2-4.5 with an additional radiative forcing of 4.5 W/m² by the year 2100 represents the medium pathway of future greenhouse gas emissions. *This scenario assumes that climate protection measures are being taken.*
- **SSP3-7.0**: With 7 W/m² by the year 2100, this scenario is in the upper-middle part of the full range of scenarios. It was newly introduced after the RCP scenarios, closing the gap between RCP6.0 and RCP8.5. *This scenario envisions regional rivalry, where countries prioritize national and regional security over environmental considerations, leading to slower economic growth and increased inequalities.*
- **SSP5-8.5**: With an additional radiative forcing of 8.5 W/m² by the year 2100, this scenario represents the upper boundary of the range of scenarios described in the literature. It can be understood as an update of the CMIP5 scenario RCP8.5, now combined with socioeconomic reasons. *This scenario assumes that **NO** climate protection measures are being taken.*

SSP1-2.6 is often perceived as highly unlikely since it requires stringent climate policies to reach the 2.6 W/m2 radiative forcing (van Vuuren, 2011). As such, the SSP-RCP pathways used in this report only include the latter three scenarios: SSP2-4.5, SSP3-7.0, and SSP5-8.5.

2.1.3. SLR Modeling in IPCC AR6

Since the release of the last Delaware SLR projections report in 2017, the IPCC has released two reports that included projected estimates of sea levels until at least year 2100: the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) in 2019, supported by CMIP5 modeling efforts, and the Sixth Activity Report (AR6) in 2021, supported by CMIP6 modeling efforts. Information in AR6 formed the basis for the projections in the US SLR Interagency Task Force Technical Report (2022) and the Fifth National Climate Assessment (2023). These two US reports form the basis for the current Delaware 2025 SLR projections summarized in this report. Hence, some relevant notable improvements and new features of CMIP6 models and AR6 results specific to oceans and coasts are mentioned here.

In addition to the improvement and new features of CMIP6 models mentioned previously, AR6 included additional recent sea level observations (e.g., tide gauges, satellite altimetry, ice sheet mass loss) that also allowed for improved estimates of individual sea level change components that are consistent with the global mean sea level budget. CMIP6 modeling incorporated a more refined ocean stratification to better model circulation and expansion due to density changes. Recent paleoclimate reconstructions and model simulations of global mean sea levels (GMSL), dating back to the Mid-Pliocene Warm Period and the Last Interglacial Period (and other paleo time periods), were included in the CMIP6 modeling efforts to narrow constraints of GMSL and provide insight into feedbacks of contributing mechanisms, strengthening the overall assessment. Note the Last Interglacial period was a time when GMSL was 5-10 meters higher than today at similar surface temperatures (0.5°C to 1.5°C above 1850-1900 mean) and less CO2 atmospheric concentrations (266-282 ppm) (Fox-Kemper et al., 2021).

Sea level projections included in AR6 were based on contributing processes that could be ascribed at least medium confidence. The suite of CMIP6 model runs for SLR included the following SSP/RCP forcing scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Note SSP1-1.9 was not included in the suite of scenarios used for Delaware temperature and precipitation projections but plays a more significant role in the lower end of SLR projections. SSP1-1.9 limits warming by 2100 to approximately 1.5°C above 1850-1900 levels after a slight overshoot, and implies net zero CO2 emissions around the middle of the century (Cross-Chapter Box 1.4 in Arias et al., 2021).

In regards to generating the plausible range of future sea levels, AR6 also included the use of high-impact, low-confidence (HI/LC) projections related to ice sheet dynamics and the response of GMSL changes. They include unexpected ice-shelf disintegration in Antarctica, sudden marine ice-sheet and ice-cliff instability, and rapid changes in Greenland's ice balance (Fox-Kemper et al., 2021). There is little formal understanding and very few available ocean/ice models that can reliably simulate these processes. For both the Greenland and Antarctic ice sheets, the HI/LC projections integrate information from the Structured Expert Judgement study of Bamber et al. (2019). For the Antarctic ice sheet, the low confidence projections also incorporate results from a simulation study that incorporates Marine Ice Cliff Instability (DeConto et al., 2021). Although there is deep uncertainty concerning these processes, they are expected to contribute to rising sea level in most non-polar locations throughout the world under moderate to greater emissions in the later half of the century and beyond, with a larger role under greater warming. These HI/LC processes were included in separate model runs under low emission (SSP1-2.6 LC) and high emission (SSP5-8.5 LC) scenarios.

The low confidence dynamic processes of ice sheets also play a role in low emission scenarios at time frames beyond 2100. Based on historical comparisons, modeling, and the current process-based understanding of GMSL rise, there is a certain amount of already committed sea level rise, although the exact amounts and uncertainty ranges are relatively large. For example, under the SSP1-2.6 scenario, which keeps warming below 2.0C, the range of GMSLR by 2300 is 0.5 - 3.2 m (17-83%); under the SSP5-85 scenario, the range of GMSLR by 2300 is approximately 2-7 m. Further out, under a scenario limiting global warming to 1.5C by 2100, committed GMSL over the next 2000 years is expected to increase by 2-3 m, increasing to 6 m for global warming scenario under 2.0°C.

Based on only the medium confidence process (i.e., excluding the HI/LC processes) in AR6, GMSL is projected to rise between 0.18 m (0.15–0.23 m, 67% likely range; SSP1-1.9) and 0.23 m (0.20–0.30 m, 67% likely range; SSP5-8.5) by 2050. GMSLR amounts are relative to the mean sea level over 1995-2014, approximately 2005 as the mid-point year. By 2100, the projected rise is between 0.38 m (0.28–0.55 m, 67% likely range; SSP1-1.9) and 0.77 m (0.63–1.01 m, likely range; SSP5-8.5). Before 2050-2060 or so, there is little difference in projected GMSL among the scenarios, with uncertainty range around each scenario on par with the difference between the median scenario projections. Projected GMSL results for both the medium confidence and high-impact/low confidence processes are plotted in **Figure 2.2**.

Key SLR-related messages in AR6 (Fox-Kemper et al., 2021) include the following:

- It is *virtually certain* that GMSL will continue to rise until at least 2100, as all assessed contributors to GMSL are virtually certain to continue contributing throughout the century.
- Higher amounts of GMSL rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of marine ice sheet instability and marine ice cliff instability around Antarctica, and faster-than-projected changes in the surface mass balance and discharge from Greenland.
- Beyond 2100, GMSL will continue to rise for centuries due to continuing deep-ocean heat uptake and mass loss of the Greenland and Antarctic ice sheets, and will remain elevated for thousands of years (high confidence).

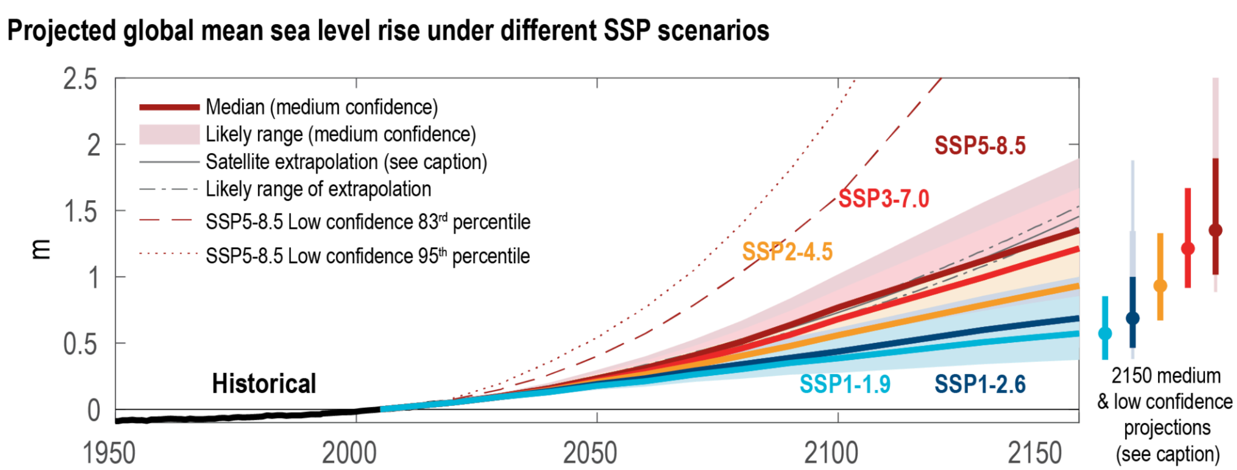


Figure 2.2. Projected global mean sea level under different Shared Socio-economic Pathway (SSP) - Representative Concentration Pathways (RCP) scenarios. Medium confidence process runs (solid lines) are distinguished from the SSP5-8.5 low confidence process runs (dashed lines, unlabeled). Reproduced from Fig 9.27 in IPCC AR6 Chapter 9 (Fox-Kemper, et al., 2021).

Lastly, as mentioned in the Introduction, the strength of AMOC also is a significant factor in sea levels and storm tracks along the US East Coast. While there is low confidence in the amount of AMOC change from 20th century observations, it is very likely that AMOC will decline over the 21st century. Future slowing of the AMOC is expected to result in an increase of sea levels along the East and Mid-Atlantic coasts. And although none of the CMIP6 models features an abrupt AMOC collapse before 2100, they neglect meltwater release from the Greenland Ice Sheet, and as a result, IPCC reduced its confidence level from high confidence in AR5 to medium confidence in AR6 that an abrupt collapse before 2100 would not occur.

More detailed information on IPCC AR6 sea level rise modeling efforts can be found in Chapter 9: Ocean, Cryosphere and Sea Level Change of the AR6 report (Fox-Kemper et al., 2021). Global maps and time series plots of the sea level projections are available through the NASA IPCC Sea Level Projection Tool[5].

2.2. Downscaling Models and Scenarios for Temperature and Precipitation

While GCMs provide the means to understand the climate futures at the global and continental scale, the grid box size (resolution) is not adequate to analyze the regional and local impacts (Vogel et al., 2023). For this reason, downscaling methods are used to interpret model output at a much finer spatial scale. Downscaling methods are generally classified as dynamical or statistical. *Dynamical models* use the coarse-scale GCM output as inputs to a finer-scale regional climate model that provides a physically-based result. These models often retain biases from the coarse GCM inputs and those inherent in the regional climate model. Most importantly, this method is computationally expensive in both time and computer power. *Statistical models* make use of existing local, high-resolution observation data to derive statistical relationships from the coarse-scale GCM to a finer-scale resolution. This method is less computer-intensive than its counterpart and relies on a robust historical record to provide local accuracies, which are generally quite robust in the United States (Jones, 2023). This report reviewed relevant and available statistically downscaled products that would provide the finer-scale required to investigate Delaware's future scenarios, and two products emerged as the best options for this work: the Seasonal Trends and Analysis of Residuals Empirical-Statistical Downscaling Model (STAR-ESDM) and the Localized Constructed Analogs version 2 (LOCA2). Both STAR-ESDM and LOCA2 products were used in the NCA5 and have been analyzed for their efficacy for local studies such as this one.

In the past, statistically downscaled methods relied on station-based observations and would be statistically aligned to that station's historical records. This provided a set of points on which to run the downscaling, but the end result would only represent a time series at that point in space. Recently, downscaling methods are utilizing gridded observational products to give a more

[5] https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

continuous space for the downscaling methods, resulting in a spatially filled output product that matches the observational grid that is useful for local planning. For example, the two downscaling methods chosen for this study provide output in a 5km (STAR-ESDM) and 6km (LOCA2) grid and can provide local-level impacts that the course GCMs simply cannot provide. These downscaled products are briefly described below.

STAR-ESDM

As a statistical downscaling technique that uses signal decomposition (Hayhoe et al., 2024), the STAR-ESDM separates the observations and GCM output into four different components: the long-term trend, the static climatology (mean annual cycle over historical), the dynamic climatology (mean annual cycle accounting for annual variations) and high-frequency (daily) anomalies (Ullrich, 2023). Mappings are constructed between observations and historical GCM output for each of these different components. Using these mappings, future projections are then bias-corrected and recombined to produce a consistent estimate of a future time series. The CONUS STAR-ESDM product uses NClimGrid-Daily with approximately 5km grid spacing for training (Durre et al., 2022). (For a summary of these details, refer to **Figure 2.3**.) Data are available on the Earth Systems Grid Federation (ESGF)[6] or available from Texas Tech Climate Center[7]. This downscale method uses 27 GCM models to produce historical and projection data spanning from 1950 to 2100 for daily minimum temperature, daily maximum temperature, and daily precipitation for SSP2–4.5, SSP3–7.0, and SSP5–8.5, where GCM output was available. Downscaled station data are also available upon request.

LOCA2

The LOCA method, developed by Pierce et al 2014, uses GCM daily data to find the best matching or analogous day in a daily historical observation grid over a region and then downscales modeled precipitation and temperature data to the higher-resolution grid. The historical observation grid used by LOCA2, also referred to as the LOCA2 North American dataset, uses the Livneh-unsplit method for precipitation (Pierce, et al 2021) and the updated Liveneh et al. 2015 for the temperature data. This downscale method uses 27 GCM models to produce historical and projection data spanning from 1950 to 2100 for daily minimum temperature, daily maximum temperature, and daily precipitation for SSP2–4.5, SSP3–7.0, and SSP5–8.5, where GCM output was available. The Localized Constructed Analogs Version 2 (LOCA2)[8] was released in spring 2022 and updated in September 2024 to correct underestimated precipitation extremes as found by Ullrich in 2023. At the late stages of writing this report LOCA2 also released a Relative Humidity product, which was not used in this study and will be reviewed in later research. (For a summary of these details, refer to **Figure 2.3**.)

[6] https://tinyurl.com/2zyj457p
[7] https://www.depts.ttu.edu/csc/data/
[8] https://cirrus.ucsd.edu/~pierce/LOCA2/

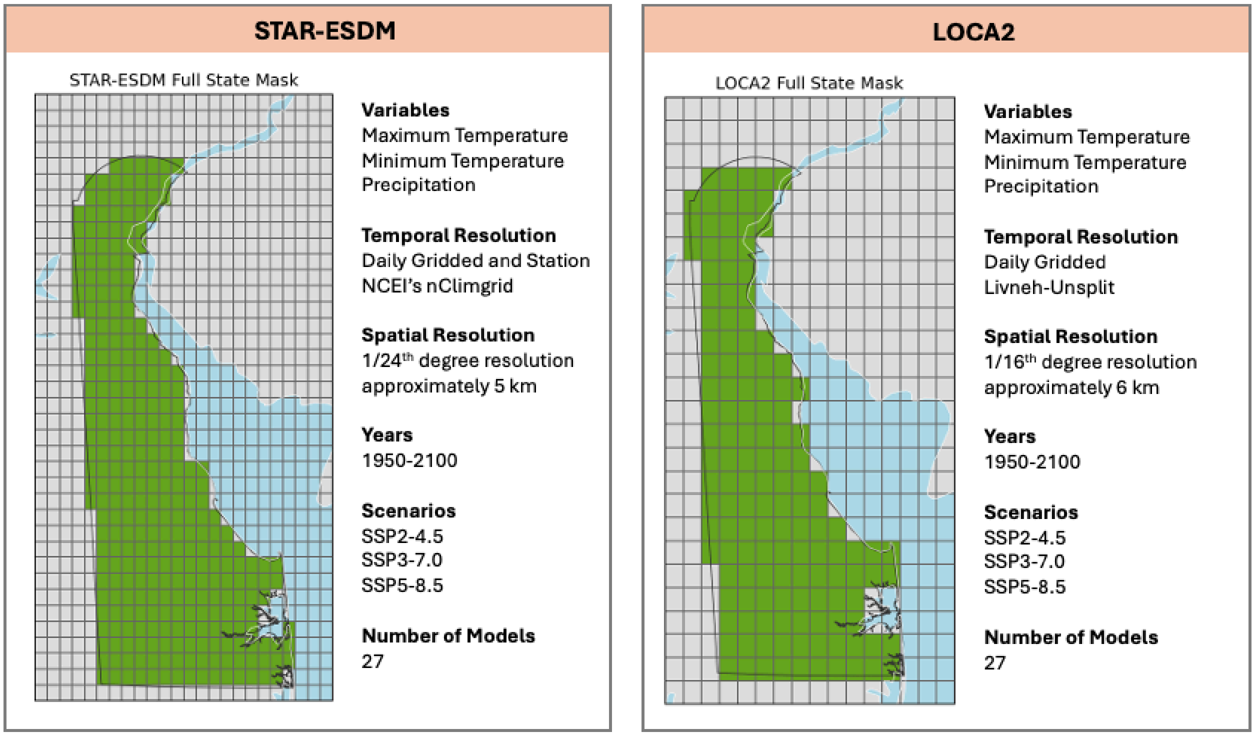


Figure 2.3. Summary of downscaling methods used in this report: STAR-ESDM (left) and LOCA2 (right). Notice the difference between the grid size (spatial resolution) of the two grids.

Scenarios and models used and assessed in this report are dependent on the products available from the downscaling methods chosen. Both STAR-ESDM and LOCA2 produced output for three SSP scenarios (SSP2–4.5, SSP3–7.0, and SSP5–8.5) and for 27 GCMs (**Figure 2.3**). For this study, the list of 27 GCMs were compared between the two downscaling methods and only those GCMs that existed in both downscaling products were retained. This subset of models were further reduced to a smaller subset of 13 models that were identified by Ashfaq et al. 2022 for their performance in the Northeast US. Note that SSP3–7.0 had limited availability from some of the GCM runs. When the GCM data were available for SSP3–7.0, they were downscaled and provided by LOCA2 and STAR-ESDM.

Important temperature and precipitation climate indicators relevant for assessing Delaware's changing climate were identified and recommended to DNREC staff and the TCA. A final list of desirable temperature and precipitation indicators was developed and is available in **Appendix B**. A more in-depth look at humidity-related variables to determine plausible impacts on the human environment and agriculture will be the subject of a separate study.

Once these elements were selected, techniques for aggregating the data for analysis and alignment to the historical analysis data were established. Finally, visualization and data summaries were considered to assist in messaging/comprehension of expected trends or impacts. These elements are discussed briefly in the following subsections.

2.2.1. Temperature Projection Data

Temperature data for STAR-ESDM were provided by the Texas Tech University Climate Center[9] via Globus data transfer. Temperature data for LOCA2 are downloaded from Scripps Institution of Oceanography[10] using standard file transfer protocols. The supplied data sets are provided in Network Common Data Form (NetCDF) format with a single product per file covering CONUS. This model footprint encompasses an area larger than required for the climate assessment for Delaware. As such, the supplied files were subset to an area defined as the Mid-Atlantic, 35° N to 42^0 N Latitude and 70^0 W to 80° W Longitude (**Figure 2.4 left panel**). While this area provides more coverage than just Delaware, the extended area would allow for regional studies beyond this study and determination of potential impacts adjacent to the Delmarva Peninsula.

Temperature products supplied by both downscaling methods include minimum and maximum daily temperature. The temperature products were converted from model units (degree Kelvin) to Fahrenheit as a generally accepted and understandable unit for use by stakeholders and the general public. The minimum and maximum daily temperatures were used to generate daily average temperatures using standard formulas before being aggregated to monthly and yearly timesteps.

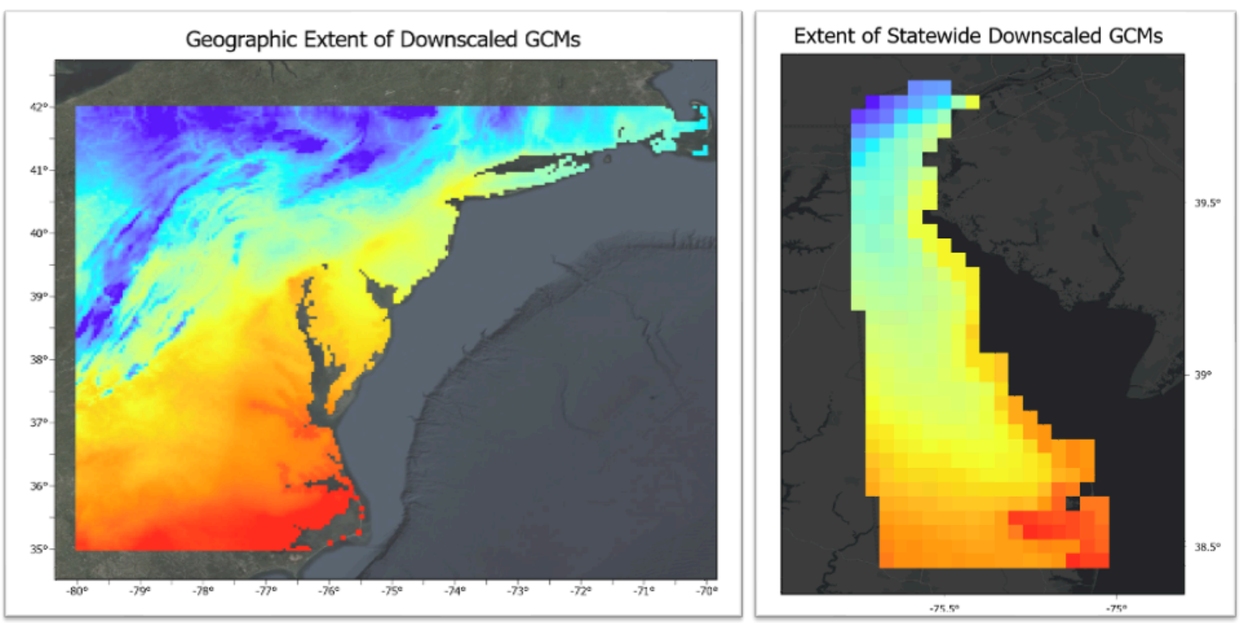


Figure 2.4. Map showing the initial geographic extent of the Mid-Atlantic downscaled GCM model data (left) and map showing the full state clipped downscaled GCM data used in this report (right).

9 https://www.depts.ttu.edu/csc/data/
10 https://loca.ucsd.edu/

2.2.2. Precipitation Projection Data

Precipitation data for STAR-ESDM were provided by the Texas Tech University Climate Center[11] via GLOBUS data transfer. Precipitation data for LOCA2[12] are downloaded from Scripps Institution of Oceanography using standard file transfer protocols.

The supplied data sets are provided in Network Common Data Form (NetCDF) format with a single product per file covering the Continental United States. This model footprint encompasses an area larger than required for the climate assessment for Delaware. The supplied files were subset to an area defined as the Mid-Atlantic Peninsula , 35° N to 42^{0} N Latitude and 70^{0} W to 80° W Longitude (**Figure 2.4 left panel**). While this area provides more coverage than just Delaware, the extended area would allow for regional studies beyond this study and determination of potential impacts adjacent to the Delmarva Peninsula.

The precipitation dataset was a single product containing daily precipitation. The precipitation product was converted from model units (kg m-2 s-1) to a standard unit of inches/day as this would be a more easily understood value. From here, the precipitation product was aggregated to monthly and yearly timesteps.

2.2.3. Additional Processing

All data from LOCA2 and STAR-ESDM were processed using python and relied heavily on the XClim[13] and Xarray[14] to combine ensemble outputs from each downscaling method and to derive the indicators. (See list of indicators and their "time step" in **Appendix B**.) Output from this processing resulted in a total approximately 39 files per indicator (13 models x 3 SSPs).

Once the data were preprocessed as described above, three different ensemble products (full state, division 1, and division 2) were produced for each indicator and SSP for use in the final projection analysis – reducing the number of files for analysis to 9 files per indicator (3 geographies x 3 SSPs). Using shapefile polygons delineating the State of Delaware and Delaware's two climate divisions to generate three separate masks, the larger Mid-Atlantic region was clipped and all 13 models were spatially averaged for the 3 masked regions – resulting in three ensemble means products for each indicator and SSP.

Finally, the spatial ensemble products were used to generate maps, time series (1950-2100), and vicennial (twenty year) products: 2021-2040, 2041-2060, 2061-2080, 2081-2100.

[11] https://www.depts.ttu.edu/csc/data/
[12] https://loca.ucsd.edu/
[13] https://xclim.readthedocs.io/en/stable/
[14] https://docs.xarray.dev/en/stable/

2.3. Scenarios and Projections for Sea Level Rise

Scenarios selected to produce the 2025 SLR projections for Delaware are taken from the U.S. Interagency Task Force (ITF) on Sea Level Change technical report *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines* (Sweet et al., 2022), hereafter referred to as simply the 2022 ITF SLR Report. That report utilized AR6 foundational knowledge and CMIP6 modeling results to generate projections out to year 2150 along U.S. Atlantic, Gulf, and Pacific Coasts and the Pacific and Caribbean Islands. It described factors across time scales driving mean sea level change, as well as coastal flood frequency and exceedance probability statistics, at the regional and local levels. Additionally, the 2022 ITF SLR Report laid the groundwork for the recent Fifth National Climate Assessment released in Fall 2023 and represents a cross-federal agency agreed upon set of data products and methods.

Key messages from the 2022 ITF SLR Report mimic those in AR6. For example, findings include that 1) sea level rise along U.S. coastline is predicted to rise 10-12 inches over the next 30 years, about the same amount as the past 100 years, and 2) in the next 30 years, coastal flooding is expected to occur, on average, more than 10 times as often than it does today. Data produced from the report are available as individual data files (MS Excel, CSV, and netCDF formats) with additional information available through interactive web applications in the U.S. Sea Level Change website[15] and the U.S. Sea Level Calculator[16] as well as the companion Application Guide[17].

Unlike in IPCC AR6 where many of the modeled projections used SSP/RCP-based scenarios (plus the additional Low Confidence process explained earlier in this chapter), the 2022 ITF SLR Report developed a new set of scenarios that span the plausible ranges of GMSLR by 2100. Five planning scenarios were developed to reduce complexity of projections with overlapping results among model members with the same SSP/RCP forcing and increase their ease of use and interpretability. They are separated by regular intervals that can be used in numerous types of planning strategies, including risk-based framing approaches (2022 ITF Report Application Guide, 2022). The scenarios and their associated GMSLR by 2100 are, namely: Low (0.3 m), Intermediate-Low (0.5 m), Intermediate (1.0 m), Intermediate-High (1.5 m), and High (2.0 m). Time evolution of each of these planning scenarios from 2020 to 2150 are shown in **Figure 2.6**. Note that in the previous US assessment of SLR projections in 2017, a “Very High” scenario of 2.5 m by 2100 was included, however, that scenario was deemed too unlikely and not included in the 2022 ITF SLR Report.

[15] https://sealevel.globalchange.gov/
[16] https://coast.noaa.gov/digitalcoast/tools/sea-level-calculator.html
[17] https://sealevel.globalchange.gov/resources/2022-sea-level-rise-technical-report/

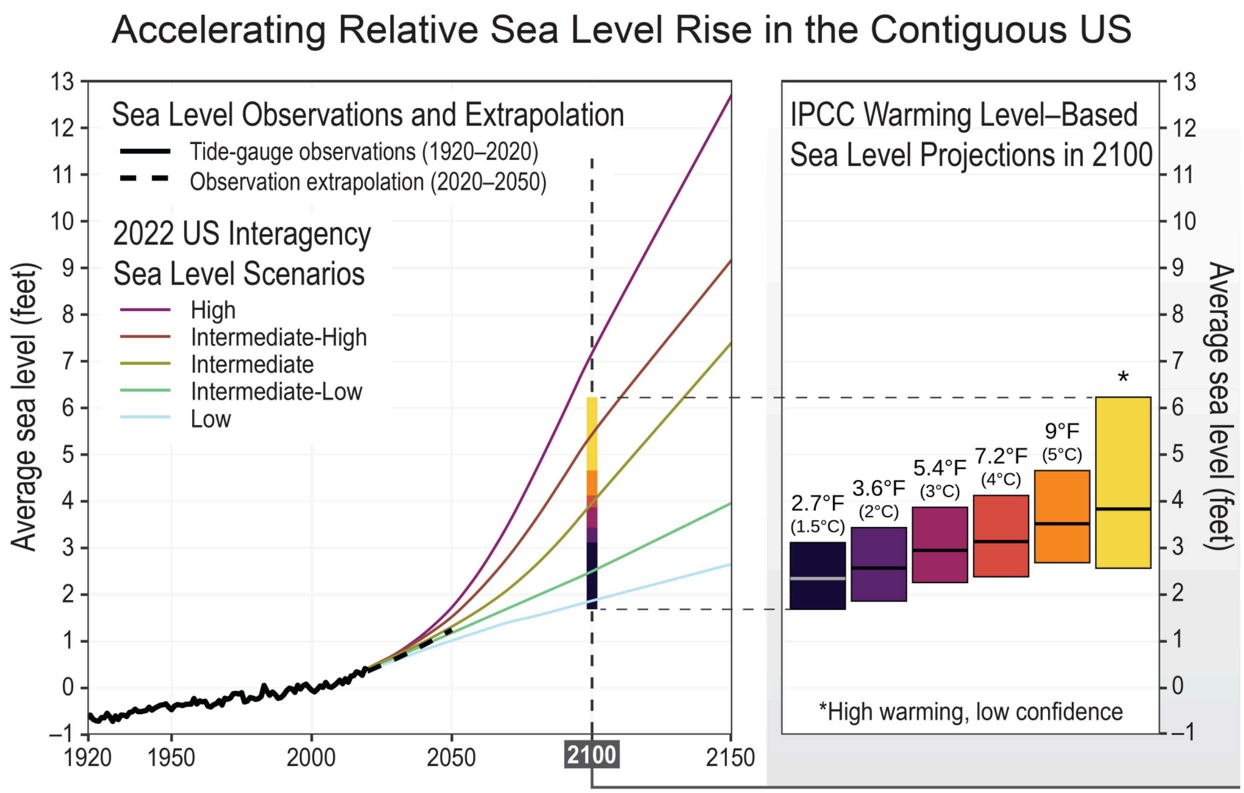


Figure 2.6. Contiguous U.S. mean sea level rise projections to year 2150 under the five planning scenarios developed in the 2022 U.S. Interagency Task Force SLR Technical Report (left panel) and in relation to IPCC AR6 SSP/RCP scenarios (right panel). Reproduced from Fig 9.1, NCA5 (2023).

The 2022 ITF SLR Report planning scenario projections span a similar range as the IPCC AR6 global-warming based projections in GSML magnitude at 2100 (**Figure 2.6**). The five planning scenarios were developed by summarizing all of the AR6 SSP/RCP scenario model runs (of which there are thousands accounting for all the SSP/RCP forcings, modelling groups, and parameterization combinations) that align with each scenario's GMSL by 2100 amounts. For example, only the AR6 model runs that result in 1.0 m by 2100 (plus or minus 2 cm) are included in the Intermediate planning scenario. **Figure 2.7** shows the schematic of how the distribution of AR6 model runs make up the planning scenarios.

In general, model runs forced by higher emission more heavily influence the higher planning scenarios, however, note that some model runs with low emissions can still contribute to the higher planning scenario in the upper end of its distribution. The AR6 SSP5-8.5 low confidence runs are the dominant source of information for the High (GMSL of 2.0 m by 2100) planning scenario. Albeit unlikely to occur based on current state of knowledge, since it would only occur under high emission futures with rapid ice sheet loss, plausible high end scenarios must be considered if their consequences to society, physical coastal structures, and natural ecosystems are too great. Likewise, the AR6 SSP1-1.9 model runs are the dominant source of information for the Low (GMSL 0.30 m by 2100) planning scenario. The Low planning scenario represents the case where recent linear rates of sea level rise continue into the future. Although this is inconsistent with models and observations that demonstrate acceleration at many local tide gauges as well as at global and national levels, it still falls within plausible range under the case where severe reductions in greenhouse gas emissions take place over the next few decades.

Both the Low and High planning scenarios are unlikely to occur, based on the physical assumptions behind them compared to observations. As shown in **Figure 2.7**, most of the AR6 modeling runs and widest breadth of forcings are included in the Intermediate-Low to Intermediate-High scenarios. However, it is impossible to assign an exact likelihood probability of occurrence to any one of the planning scenarios, or to any one of the SSP pathways, in a reliable fashion. Hence, it cannot be said which planning scenario is the most likely to occur at a specific location. Planning scenarios are designed to provide actionable information for policy-makers, planners, and stakeholders and should be incorporated into long-term planning activities based upon the use case and strategy being deployed. Strategies for implementing sea level rise projections into community planning activities are described in the 2022 Sea Level Rise Technical Report Application Guide[18].

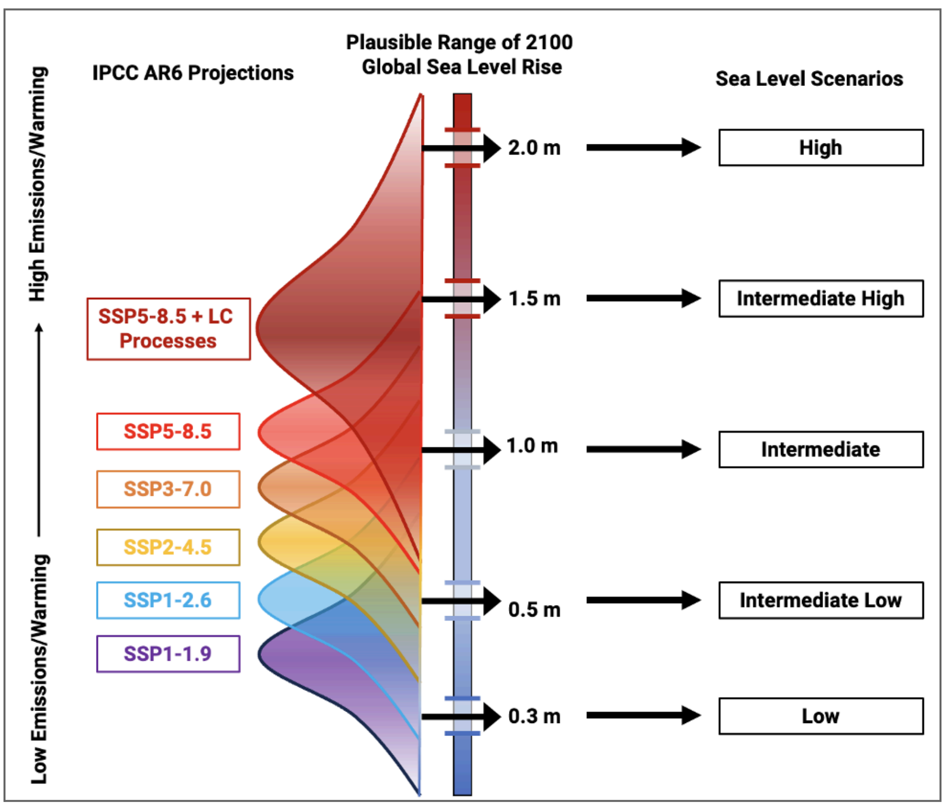


Figure 2.7. Schematic showing how 2022 ITF SLR Report SLR planning sea level scenario construction is based on SSP/RCP combinations, which inform a range of plausible future sea level rise. LC = Low Confidence processes related to dynamic ice sheet instabilities. Source: US Sea Level Change website.[19]

[18] https://earth.gov/sealevel/us/resources/2022-sea-level-rise-technical-report/#application-guide-download
[19] *https://earth.gov/sealevel/us/sea-level-101/future-sea-level/dive-deeper/*

Downscaling SLR Projections to Delaware

SLR projections resulting from the AR6 modeling efforts include both global (thermal expansion, land-based ice loss, and land-based water as storage) and regional (ocean circulation, GRD effects) factors influencing sea level change, which are unique for each of the model types and SSP/RCP forcings applied. Although the AR6-based projection plots in **Figure 2.2** show only the mean value of sea level change over all the world's oceans, global grids were also produced showing the spatial variation in the impacts from all of these factors using the Framework for Assessing Changes To Sea-level (FACTS) v1.0 (Kopp et al., 2023a, 2023b).

As part of AR6, the FACTS system produced downscaled SLR projections at numerous individual water level stations with long historical periods of record operating as part of the NOAA National Water Level Observation Network (NWLON). The localized projections that were generated across the suite of AR6 scenarios, models, and their variations, were then aggregated into each of the five SLR planning scenarios as part of the 2022 ITF Report (Sweet et al., 2022). Delaware has two such NWLON stations with projections: Lewes Breakwater Harbor (Station ID: 8557380), generally representing the southern part of the state including the southern Delaware Bay, the Atlantic Ocean shore, and the Delaware Inland Bays; and Reedy Point (Station ID: 8551910), generally representing the northern part of the state including the northern Delaware Bay, Chesapeake and Delaware Canal, and Delaware River regions. Extreme water level exceedance probability statistics and coastal flood frequency at the stations are also available through NOAA CO-OPS, and hence projections of these indicators were also produced in the 2022 ITF SLR Report (Sweet et al., 2022).

Local vertical land motion (VLM) rates are integrated within the projections through a sophisticated Gaussian process model (Kopp et al., 2013; 2014) that decomposes tide gauge historical record into three modes: 1) a globally uniform process that represents global sea level rise from Dangendorf et al., (2019); 2) a long-term linear but regionally varying trend, and; 3) non-linear local effects that vary in time and space. The second (linear) mode defines the VLM rate for that tide gauge. More accurately, that term is composed of multiple local VLM processes, such as GIA and land compaction, as well as background tectonic processes and other non-climatic local effects. The local VLM rate is assumed to be constant throughout the station's history, backward and forward in time. Localized SLR projections can then be made by combining the global and regional modeled factors under different scenario projections with the station-specific linear VLM rate.

In the previous 2017 Delaware SLR report (Callahan et al., 2017), projections generated for Lewes station were used to represent the entire state. In this report, a single set of SLR projections for the state is provided and includes combined downscaled information from both stations. The Reedy Point and Lewes stations, their respective historical records, and future projections of Delaware SLR is covered in Chapter 5 of this report.

2.4. References

Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021. Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33−144. http://doi.org/10.1017/9781009157896.002

Carlson, David & Eyring, Veronika. (2016). Contributions to Climate Science of the Coupled Model Intercomparison Project. Bulletin / World Meteorological Organization (WMO). 65.

Callahan, John A., Benjamin P. Horton, Daria L. Nikitina, Christopher K. Sommerfield, Thomas E. McKenna, and Danielle Swallow, 2017. Recommendation of Sea-Level Rise Planning Scenarios for Delaware. Technical Report prepared for Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs, 117 pp.https://doi.org/10.13140/RG.2.2.17411.66082

Dangendorf, S., C. Hay, F.M. Calafat, M. Marcos, C.G. Piecuch, K. Berk, and J. Jensen, 2019: Persistent acceleration in global sea-level rise since the 1960s. Nature Climate Change, 9 (9), 705–710. https://doi.org/10.1038/s41558-019-0531-8

Edwards, P.N., 2011. History of climate modeling. WIREs Clim Change, 2: 128-139. https://doi.org/10.1002/wcc.95

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016.

Eyring, V., Cox, P.M., Flato, G.M. et al. Taking climate model evaluation to the next level. Nature Clim Change 9, 102–110 (2019). https://doi.org/10.1038/s41558-018-0355-y

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021. Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working

Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, https://doi.org/10.1017/9781009157896.011

Hamlington, B.D., C.G. Piecuch, J.T. Reager, H. Chandanpurkar, T. Frederikse, R.S. Nerem, J.T. Fasullo, and S.-H. Cheon, 2020b: Origin of interannual variability in global mean sea level. Proceedings of the National Academy of Sciences, 117 (25), 13983. http://dx.doi.org/10.1073/pnas.1922190117

Hamlington, B.D., Bellas-Manley, A., Willis, J.K. et al., 2024. The rate of global sea level rise doubled during the past three decades. Commun Earth Environ 5, 601. https://doi.org/10.1038/s43247-024-01761-5

Hausfather, Z., 2018: Explainer: how 'shared socioeconomic pathways' explore future climate change. Carbon Brief, 19. https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/ (Accessed May 15, 2025).

Hayhoe, K., Scott-Fleming, I., Stoner, A., & Wuebbles, D. J. (2024). STAR-ESDM: A generalizable approach to generating high-resolution climate projections through signal decomposition. Earth's Future, 12, e2023EF004107. https://doi.org/10.1029/2023EF004107

Jones, A.D., Rastogi, D., Vahmani, P. et al. Continental United States climate projections based on thermodynamic modification of historical weather. Sci Data 10, 664 (2023). https://doi.org/10.1038/s41597-023-02485-5

Kopp, R.E., 2013. Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability?, Geophysical Research Letters, 40:3981–3985, https://doi.org/10.1002/grl.50781

Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, Earth's Future, 2:383–406.

Kopp, R. E., Garner, G. G., Hermans, T. H. J., Jha, S., Kumar, P., Reedy, A., Slangen, A. B. A., Turilli, M., Edwards, T. L., Gregory, J. M., Koubbe, G., Levermann, A., Merzky, A., Nowicki, S., Palmer, M. D., and Smith, C., 2023. The Framework for Assessing Changes To Sea-level (FACTS) v1.0: a platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change, Geosci. Model Dev., 16, 7461–7489, https://doi.org/10.5194/gmd-16-7461-2023.

Kopp, R. E., Garner, G. G., Jha, S., Hermans, T. H. J., Reedy, A., Slangen, A. B. A., Turilli, M., Merzky, A., & Koubbe, G., 2023a. Framework for Assessing Changes To Sea-Level (FACTS) (v1.1.2). Zenodo. https://doi.org/10.5281/zenodo.10403331

Livneh, B., Bohn, T. J., Pierce, D. W., Munoz-Arriola, F., Nijssen, B., Vose, R., Cayan, D. R., and Brekke, L., 2015a. A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950–2013, . Sci. Data, 2, 150042, https://doi.org/10.1038/sdata.2015.42.

Livneh, B., Bohn, T. J., Pierce, D. W., Muñoz-Arriola, F., Nijssen, B., Vose, R., Cayan, D. R., and Brekke, L., 2015b. A spatially comprehensive, meteorological data set for Mexico, the U.S., and southern Canada (NCEI Accession 0129374), NOAA National Centers for Environmental Information [data set], https://doi.org/10.7289/v5x34vf6,

May, C.L., M.S. Osler, H.F. Stockdon, P.L. Barnard, J.A. Callahan, R.C. Collini, C.M. Ferreira, J. Finzi Hart, E.E. Lentz, T.B. Mahoney, W. Sweet, D. Walker, and C.P. Weaver, 2023. Chapter 9. Coastal effects. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH9

O'Neill, B.C., Kriegler, E., Riahi, K. et al. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122, 387–400 (2014). https://doi.org/10.1007/s10584-013-0905-2

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Pearce, R. (2023, February 1). Timeline: The history of climate modelling. Carbon Brief. https://www.carbonbrief.org/timeline-history-climate-modelling

Pierce, D. W.: LOCA2 [data set], https://cirrus.ucsd.edu/~pierce/ LOCA2, last access: February 2025.

Pierce, D. W., D. R. Cayan, E. P. Maurer, J. T. Abatzoglou, and K. C. Hegewisch, 2015: Improved Bias Correction Techniques for Hydrological Simulations of Climate Change. J. Hydrometeor., 16, 2421–2442, https://doi.org/10.1175/JHM-D-14-0236.1.

Pierce, D. W., Cayan, D. R., and Thrasher, B. L.: Statistical Downscaling Using Localized Constructed Analogs (LOCA), J. Hydrometeorol., 15, 2558–2585, https://doi.org/10.1175/JHM-D14-0082.1, 2014.

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://sealevel.globalchange.gov/internal_resources/756/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Ullrich, P.: Validation of LOCA2 and STAR-ESDM Statistically Downscaled Products, Technical Report, U.S. DOE, https://doi.org/10.2172/2202926, 2023.

USGCRP: Fifth National Climate Assessment, US Global Change Research Program, https://doi.org/10.7930/NCA5.2023, 2023.

van Vuuren, D.P., Edmonds, J., Kainuma, M. et al. The representative concentration pathways: an overview. Climatic Change 109, 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

Vogel, E., Johnson, F., Marshall, L., Bende-Michl, U., Wilson, L., Peter, J. R., Wasko, C., Srikanthan, S., Sharples, W., Dowdy, A. H., Hope, P., Khan, Z., Mehrotra, R., Sharma, A., Matic, V., Oke, A., Turner, M., Thomas, S., Donnelly, C., & Duong, V. C. (2023). An evaluation framework for downscaling and bias correction in climate change impact studies. *Journal of Hydrology*, *622*(Part A), 129693. https://doi.org/10.1016/j.jhydrol.2023.129693

3. Temperature

This chapter will review changes in temperature across Delaware for the period 1895-2024 to put possible future changes into an historical perspective. An assessment of the performance of the downscaled models during the period of data overlap between observations and model projections (1950-2023) will be presented. Finally, downscaled model projections for Delaware will be reviewed for the remainder of the century (through 2099).

Located along the Atlantic Coast of the eastern United States, the State of Delaware is in a transition zone between humid subtropical climate conditions to the south and humid continental conditions to the north. The moderating effects of surrounding water bodies, including the Chesapeake Bay to the west and the Atlantic Ocean and Delaware Bay to the east, lessen temperature extremes compared to nearby locations not impacted by large water bodies. The state has a continental climate, with cold winter temperatures and hot summers. The largest variation in mean monthly temperatures occur during the cold season (**Figure 3.1**).

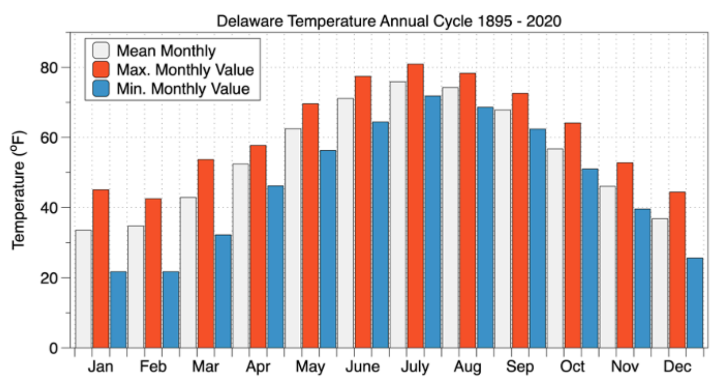


Figure 3.1. Annual cycle of temperature for the period 1895 - 2020 for Delaware. Graph shows mean monthly values for the period, in addition to maximum and minimum monthly values.

3.1. Temperature Data

Statewide and divisional temperature, are available for the period 1895 through the present from the National Centers for Environmental Information (NCEI) Climate at a Glance data portal[20]. The data are derived from the U.S. Climate Divisional Database (nClimDiv; Vose et al. 2014). These data are primarily intended for the study of climate variability, and therefore observations have been modified to take into account human impacts on the climate record. These impacts include station relocations, instrument changes, changes in the way observations were made,

[20] https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/

and increasing urbanization. Similar data are also available for the state's two climate divisions from the same website: division 1 (New Castle County) and division 2 (Kent and Sussex Counties). These data are available through both the Delaware Climate Office and the NCEI. These statewide and divisional data were used in the analysis of temperature variability in the historical analysis and in the model assessment.

In addition, data from individual weather stations located within Delaware were also used in the analysis of historical observations. The TD-3200 dataset from NOAA's National Centers for Environmental Information (NCEI) is the U.S. Cooperative Summary of the Day (TD-3200) dataset and consists of daily meteorological observations from the U.S. Cooperative Observer Network (COOP). This dataset has been largely integrated into NOAA's Global Historical Climatology Network-Daily (GHCN-D). The GHCN-D data include daily observations of maximum temperature, minimum temperature, total liquid precipitation, snowfall, and snow depth on the ground. More than twenty National Weather Service Cooperative stations have been located in Delaware at some point since the late 19th century. For this study, metadata on all stations were collected and analyzed to ascertain those stations and periods of record that were suitable for the investigation of temperature variability. The Cooperative station data identified as suitable for further evaluation are used in the analysis of temperature and temperature extremes, and potential asymmetric changes in temperature (changes in maximum compared to minimum temperatures). Three cooperative stations were retained for analysis including the Wilmington New Castle County Airport (079595), Dover (072730), and Lewes stations (075320) (**Figure 1.1**). These stations were chosen based on their data completeness, period of record, and because they provide a north-south transect through the State.

Model estimates used in the temperature projections were derived from the process discussed in Section 2.0 above, and specifically from the downscaled temperature projections outlined in Section 2.2.1.

The most widely used analysis technique to determine the existence of statistically significant trends in climate data is simple linear regression, which models the linear relationship between two variables. In climate studies, the two key variables are usually time and the meteorological variable of interest. To determine if there's a statistically significant trend between the independent variable (time) and the dependent climatological variable, linear regression techniques were employed in the current study. Various statistical tests were used to assess the significance of the relationship between time and the variable of interest.

3.2. Historical Analysis - Temperature

3.2.1. Statewide Results

An analysis of statewide mean annual temperature and seasonal temperature was conducted using the U.S. Climate Divisional Database (Vose et al., 2014). The results show a statistically significant ($p < 0.0001$) increasing trend in temperatures during the period 1895 through 2024 annually and for all seasons. An increasing trend of between 0.20º F per decade and 0.35º F per decade was identified for mean annual, and mean seasonal winter, spring, summer, and autumn temperatures (**Figure 3.2**). A modest increasing trend in statewide mean annual temperature is detectable before 1960, with a more apparent trend after that year. Individual seasons show a more monotonic long-term upward trend from 1895 through the present. Similar statistically significant increasing trends were found for annual and seasonal maximum and minimum temperatures (not shown). Significant increasing trends were also found for annual statewide cooling degree days and significant decreasing trends were found for annual heating degree days (not shown). These results are expected because cooling- and heating-degree day data are calculated directly from mean temperature statistics.

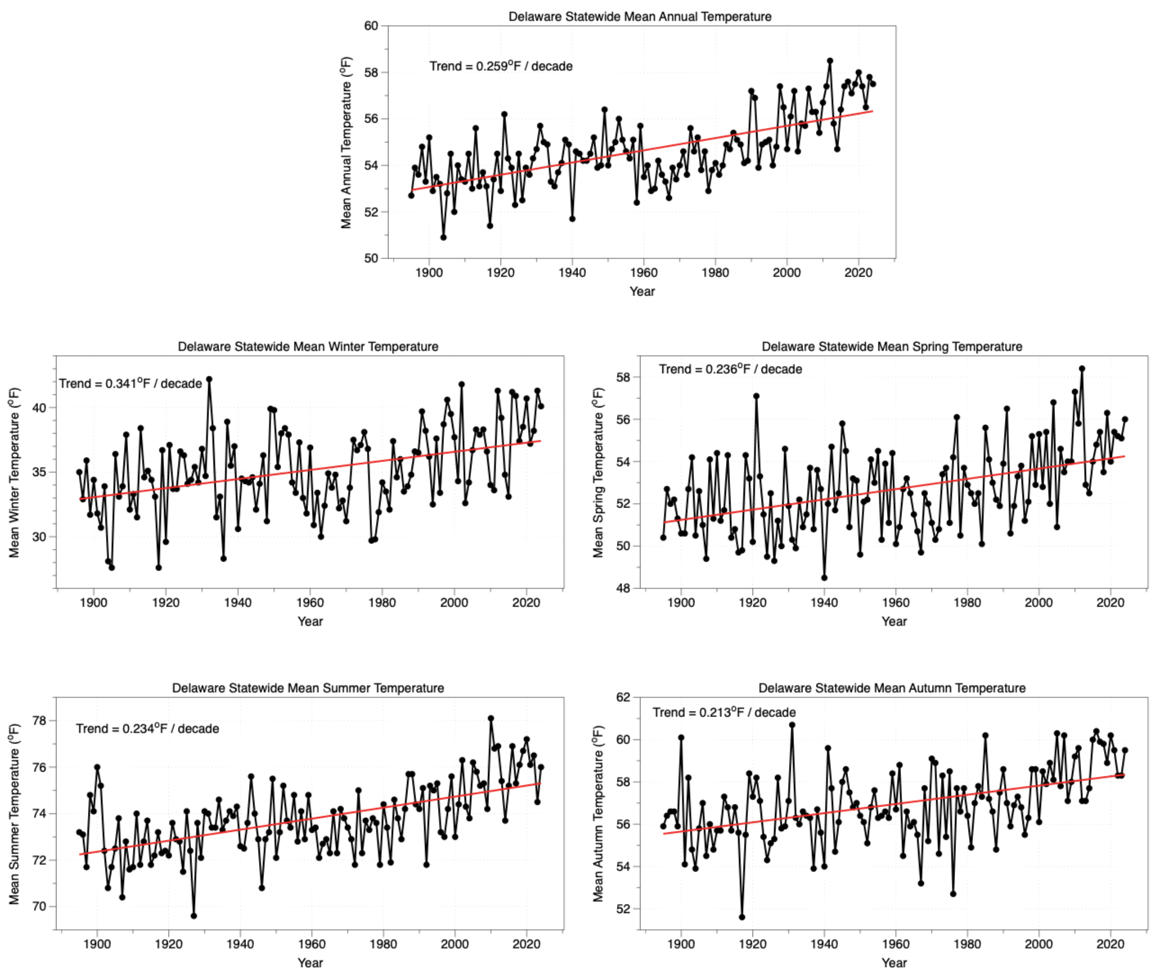


Figure 3.2. Mean annual temperature (top), mean winter temperature (middle left), mean spring temperature (middle right), mean summer temperature (bottom left), and mean autumn temperature (bottom right) for Delaware for the period 1895 - 2024. All trends are significant at the 95% significance level.

3.2.2. Cooperative Station Results

Daily data is needed for the calculation of several temperature-dependent climate indicators. For this analysis, cooperative station data from the Global Historical Climatology Network-Daily (GHCN-D) are used at the Wilmington-New Castle County Airport (079595), Dover (072730), and Lewes (075320) stations (**Figure 1.1**). Please note that numbers associated with each station are NWS cooperative station designations. An analysis of mean annual temperatures at the Cooperative stations indicates statistically significant increasing trends at each station (not shown). All three stations show significant increasing trends in growing season length (between 1.5 and 7 days per decade) associated with an earlier “last freeze” date in the spring and a later “first freeze” date in the fall (**Figure 3.3**). Examining the number of days per year with temperatures below 32ºF, all stations show significant decreasing trends in the number of days with minimum temperatures below freezing (between 2 and 6 days per decade; **Figure 3.4**). For minimum temperatures greater than 75ºF, all three stations show significant increasing trends of between 0.5 and 1.5 days per decade in the annual number of warm minimum temperatures (**Figure 3.5**). Interestingly, the number of days with maximum temperatures greater than or equal to 90º F (the hottest days) do not show trends significant at the 95% confidence level for any of the three stations. However, both Lewes and Wilmington do show increasing trends in the hottest days, but neither of the trends are significant (not shown).

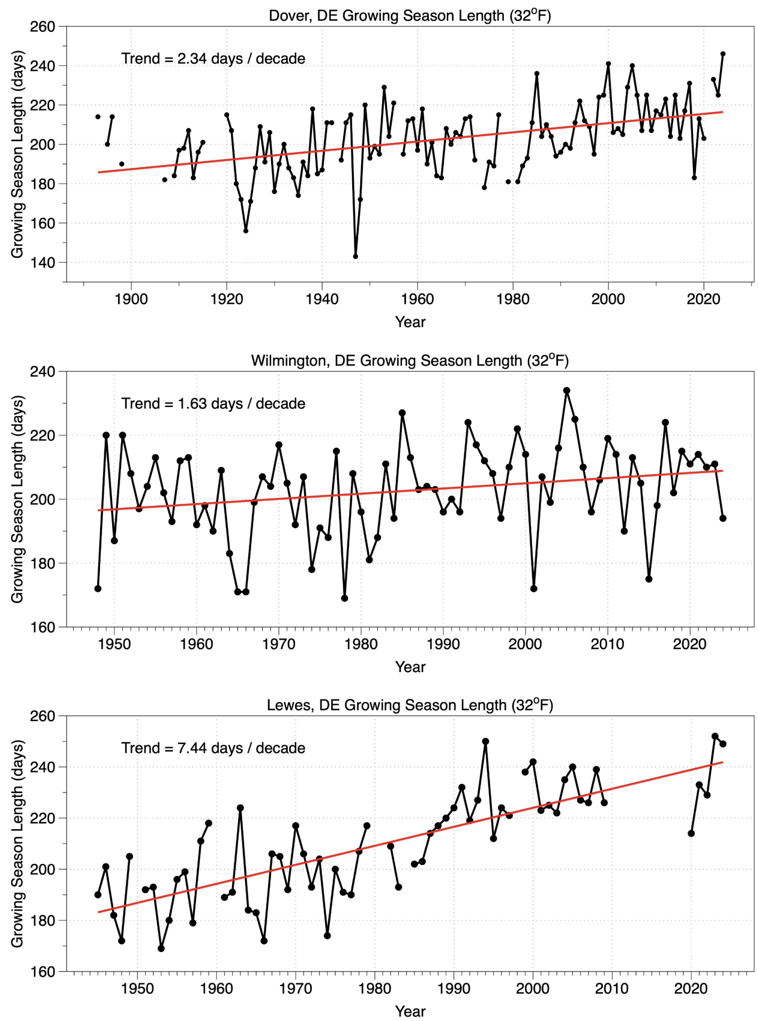


Figure 3.3. Growing season length at Wilmington/New Castle County Airport (top), Dover (middle), and Lewes (bottom). All trends are significant at the 95% confidence interval.

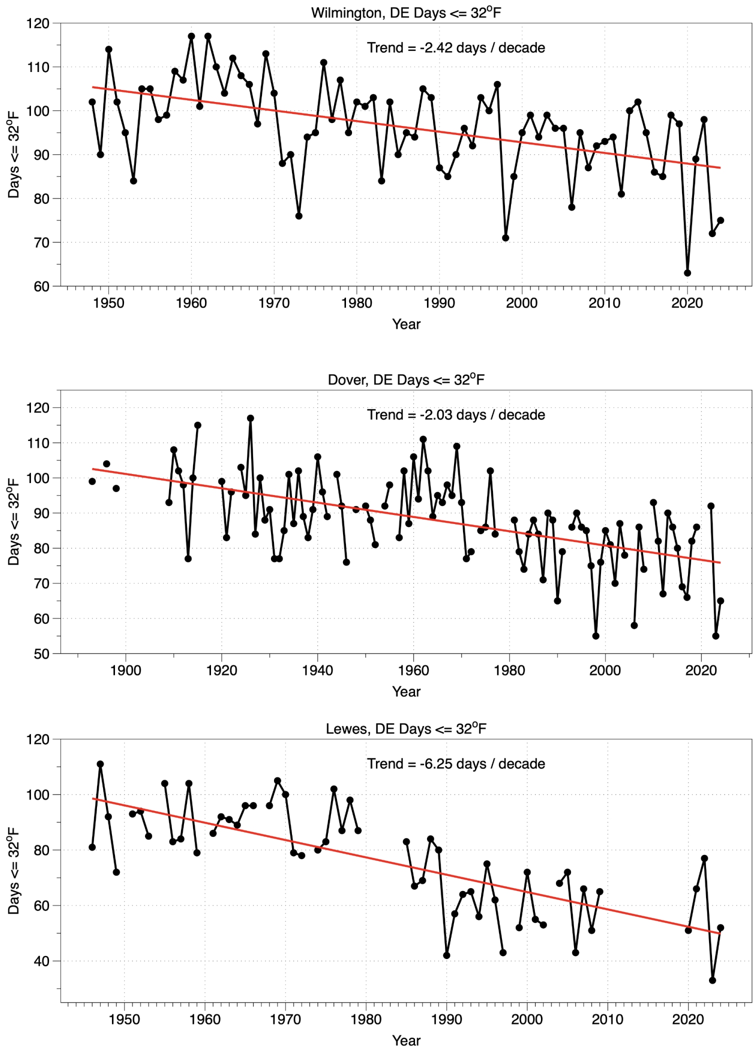


Figure 3.4. Number of days with minimum temperatures less than or equal to 32°F at Wilmington/New Castle County Airport (top), Dover (middle), and Lewes (bottom). All trends are significant at the 95% confidence interval.

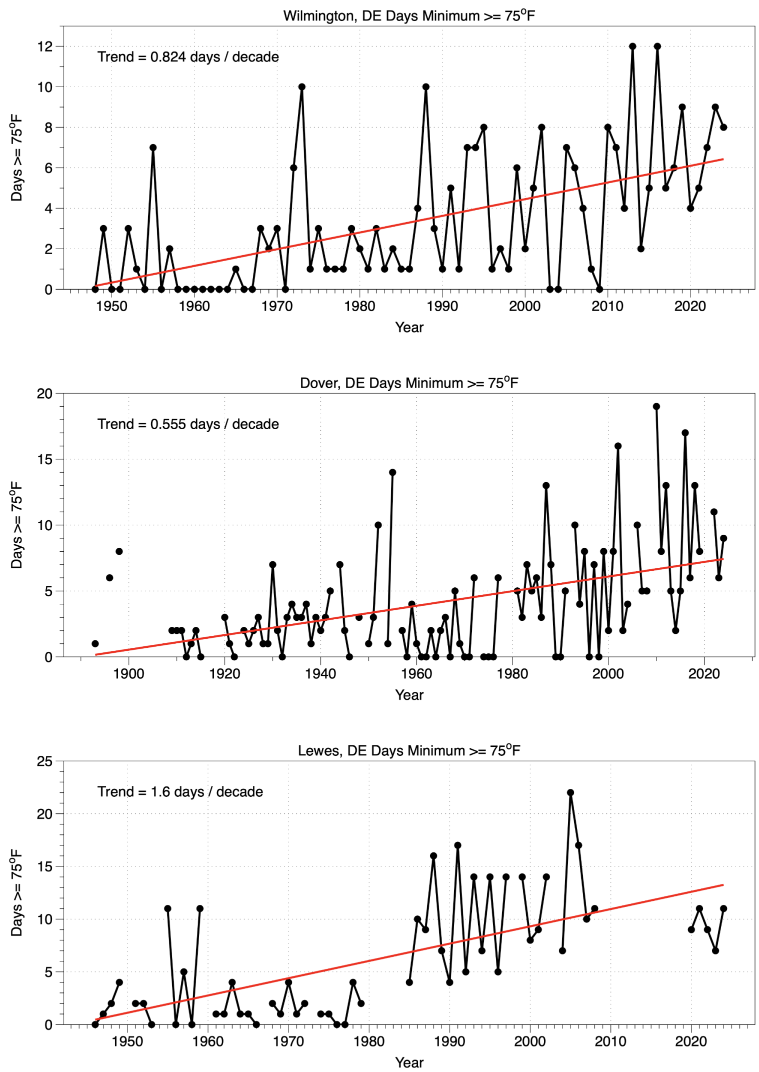


Figure 3.5. Number of days with minimum temperatures greater than or equal to 75°F at Wilmington/New Castle County Airport (top), Dover (middle), and Lewes (bottom). All trends are significant at the 95% confidence interval.

3.2.3 Temperature Historical Analysis Summary

In summary, the analysis of historical statewide mean annual temperature data indicates that temperatures across Delaware have been increasing at a rate of between 0.20° F and 0.35° F per decade since 1895 (this is an accumulated increase of approximately 3° F since 1895), depending upon the season. An analysis of the Cooperative station data shows that the increasing mean annual temperatures are reflected in large, statistically significant positive trends in growing season length at all locations across the State. In addition, the number of days with minimum temperatures less than or equal to 32° F has seen strong, statistically significant decreasing trends at each station, suggesting that the number of coldest days are decreasing. Moreover, an analysis of warm minimum temperatures (days with minimum temperatures greater than or equal to 75° F) shows a significant increase at each station. No significant trends were found in the number of warmest days (days with maximum temperatures greater than or equal to 90° F) at any of the three cooperative sites. The finding that days with minimum temperatures below 32° F (cold nighttime low temperatures) are decreasing, while days with minimum temperatures above 75° F (warm nighttime low temperatures) are increasing in recent decades, and that there are no significant trends in our warmest days (maximums greater than or equal to 90° F) suggests that nighttime low temperatures are asymmetrically increasing across Delaware compared with daytime maximum temperatures, especially in the later portion of the period of record.

3.3. Model Assessment - Temperature

3.3.1. General Temperature Comparison

To evaluate the reliability of the global climate models used to forecast future climate conditions, modeled and observed historical trends were analyzed using mean annual temperature from 1950 to 2023, a 74-year period of overlap between observations and model projections. Statewide and divisional mean annual temperature from the U.S. Climate Divisional Database (Vose et al. 2014), were used in this analysis and were compared to the historical hindcast model ensemble means derived from the 13 downscaled LOCA2 and STAR-ESDM models (see section 2 above). **Figure 3.6** shows the mean annual temperature for Delaware for the period 1950 through 2023. The thick gray lines are the observations from the U.S. Climate Divisional Database, while the red and blue lines are the *ensemble mean values* derived from the LOCA2 (red line) and STAR (blue line) downscaled model projections. The trends in the three time series are generally similar, but as expected there are differences in year-to-year variations. **Table 3.1** gives the mean, median, and standard deviation for each time series. It is apparent that over the 74-year period, the downscaled models closely conformed to observations. Mean temperatures during that period varied by only 0.03° F between the STAR-ESDM downscaled projections and observations, while LOCA2 was warmer than observations by 0.84° F. The similarity in the distributions between the three time series is more clearly seen in the box plots of **Figure 3.7**. It is clear that the downscaled models have similar means and medians to observations, but the variability in the ensemble means of the models is smaller than observations (see **Figure 3.6 and Table 3.1**). The smaller variability is due to the averaging of diverse downscaled models to obtain the ensemble mean value. The individual downscaled models have variability similar to observations.

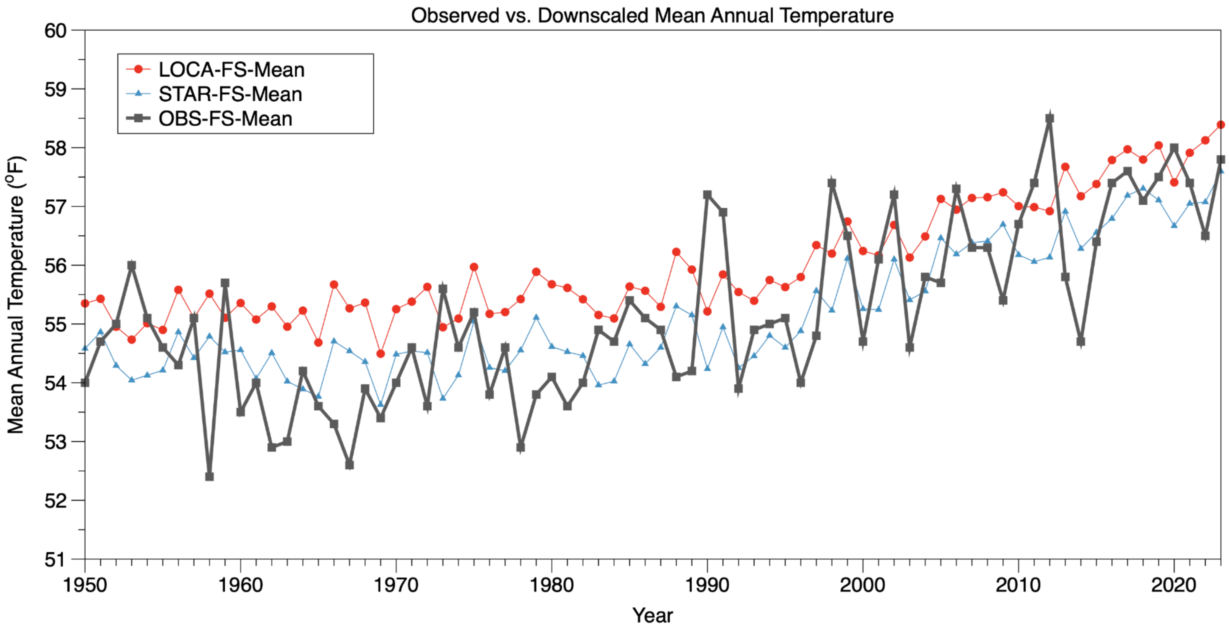


Figure 3.6. Observed mean annual temperatures (gray line) and ensemble mean annual temperatures for the STAR-ESDM (blue) and LOCA2 (red) downscaling techniques.

Table 3.1. Mean, median, and standard deviation for each time series of mean annual temperatures for the historical overlap period 1950 - 2023 for the entire state of Delaware.

Mean Annual Temp	Mean	Median	Standard Deviation
Observed	55.17ºF	54.90ºF	1.47ºF
LOCA2	56.01ºF	55.63ºF	1.00ºF
STAR-ESDM	55.14ºF	54.74ºF	1.05ºF

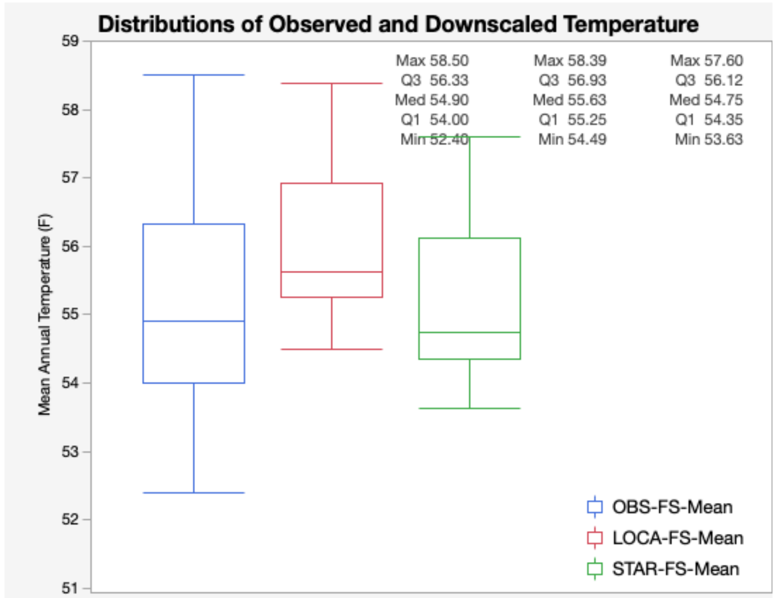


Figure 3.7. Box plots showing the distribution of the observed mean annual temperatures (blue) and ensemble mean values for both STAR-EADM (green) and LOCA2 (red).

3.3.2. Comparison of Trends

Linear regression is a powerful tool for comparing trends across various datasets by quantifying the relationships between variables over time. By applying regression models to multiple datasets, researchers can compare the slopes of trend lines to determine if different variables exhibit similar rates of change or if one trend is more prominent than another. For instance, in climate studies, linear regression can be employed to compare temperature trends across different regions or to compare trends from diverse datasets such as observations and model projections. Linear regression was applied to the observations of mean annual temperature and the model projections using the SAS JMP software suite (SAS, 2024). Linear regression was used to establish the existence of a trend in each dataset, and to ascertain if the trends were similar between the observations and downscaled projections. The analysis was conducted for the entire state and for both NCEI defined climate divisions. Results indicate that each time series (observed and modeled) evidenced strong, statistically significant upward trends in temperature with probabilities of these trends being due to chance of less than 0.0001 (**Table 3.2**). Moreover, the trends in observations and LOCA2 and STAR-ESDM downscaled temperature were notably similar for the State as a whole, and for each NCEI climate division (**Table 3.2**). The strong correspondence between the magnitude and direction of the trends establishes a basis for confidence in the use of the models for projections of future climate.

Table 3.2. Trends in observed mean annual temperature, and for ensemble means of mean annual temperatures for STAR-ESDM and LOCA2 downscaling techniques. All trends were significant at the 95% confidence interval, and the magnitude of the trends were very similar between the observed and modeled time series.

Mean Annual Temp	R^2	Probability	Trend
Full State			
Observed	0.499	< 0.0001	0.483 ºF / decade
LOCA2	0.780	< 0.0001	0.409 ºF / decade
STAR-ESDM	0.710	< 0.0001	0.411 ºF / decade
Division 1			
Observed	0.480	< 0.0001	0.459 ºF / decade
LOCA2	0.800	< 0.0001	0.428 ºF / decade
STAR-ESDM	0.733	< 0.0001	0.432 ºF / decade
Division 2			
Observed	0.506	< 0.0001	0.490 ºF / decade
LOCA2	0.774	< 0.0001	0.404 ºF / decade
STAR-ESDM	0.702	< 0.0001	0.405 ºF / decade

A comparison of trends of temperature indicators and extremes (derived with daily data) including growing season length, number of days with minimum temperatures ≤ 32º F, number of days with minimum temperature ≥ 75º F, and number of days with maximum temperature ≥ 90º F was conducted (**Table 3.3**). In this case, statewide trends in these variables, from both STAR-ESDM and LOCA2, were compared to trends at the cooperative observing sites described above. Results show that observed and modeled trends were similar for most variables. In fact, for all variables, except for the number of days ≥ 90º F, trends in the models were smaller than those found in observations at the individual stations. This gives confidence that the models are providing a conservative estimate of trends in these daily derived indicators.

Table 3.3. Trends in temperature indicators and extremes for the STAR-ESDM and LOCA2 downscaling techniques, and for each of the cooperative station observations. Trends in the models are similar to observed, and provide for a conservative estimate of future climate. ***All trends are given in units of days/decade.*** *Trend values given in red and italicized are not significant at the 95% confidence level.*

	GSL 32° F	Tmin ≤ 32° F	Tmin ≥ 75° F	Tmax ≥ 90° F
Lewes	7.57	6.88	1.75	*0.839*
Dover	5.47	3.04	1.05	*0.759*
Wilmington	1.77	2.50	0.825	1.06
STAR (State)	2.96	2.84	0.363	2.23
LOCA2 (State)	2.66	2.78	0.560	2.66

3.3.3 Model Assessment Summary - Temperature

In summary, the downscaled model projections show strong, statistically significant upward trends in statewide annual temperature matching well with observations over the period of historical hindcasting (**Table 3.2**). Similarities between the downscaled models and observations extended to temperature indicators and extremes derived from daily data (**Table 3.3**). This comparison establishes the basis for confidence in the use of these models to generate future temperature projections.

3.3.4 Recommendation on Most Appropriate Downscaling Technique for Delaware - Temperature

STAR-ESDM and LOCA2 downscaling techniques are both commonly used statistical downscaling methodologies for the production of climate change scenarios (Ullrich 2023). However, the inclusion of two separate suites of climate change projections using both methods would likely lead to unneeded confusion for end-users of the scenarios. The model assessment conducted in Section 3.3 showed that the LOCA2 downscaled mean annual temperature was approximately 0.84° F warmer than the observed over the period 1950-2023, while STAR-ESDM downscaled mean annual temperature was cooler than observations by 0.03° F over the same period. It is likely that this difference is due to the historical gridded data used by the two downscaling techniques. LOCA2 uses the Livneh-Unsplit (Pierce et al. 2021) gridded data for downscaling, while STAR-ESDM uses the NClimGrid-Daily (Durre et al., 2022) gridded data. Ullrich (2023) has found that along both the Atlantic and Pacific coasts of the United States there are substantial differences between LOCA2 downscaled temperatures and those of several reference datasets. Ullrich (2023) attributes these differences to the Livneh-Unsplit product used in the LOCA2 downscaling as the Livneh-Unsplit does not moderate temperatures appropriately in coastal regions. **Given the important influence of coastal processes on Delaware climate, and the larger warm bias in the LOCA2 temperatures found in Section 3.3, the authors recommend the use of the STAR-ESDM downscaling methodology for temperature projections across Delaware**. Therefore, in the temperature projections to follow only STAR-ESDM projections will be discussed. However, all data and downscaled projections produced for STAR-ESDM (including all graphics) are available for LOCA2.

3.4. Temperature Projections

3.4.1. Mean Annual Temperature Projections

Since 1950, mean annual temperatures across Delaware have seen an increasing trend of 0.483° F / decade. To put temperature increases in Delaware in a broader context, **Figure 3.8**. shows the mean annual temperature trends for Delaware, the United States, and the globe over the same time period. Temperatures are increasing faster in Delaware than they are for the United States as a whole (0.329° F / decade) or for the globe (0.150° F / decade). Delaware's rapid temperature increase emphasizes the importance of understanding projected temperature changes across Delaware in the coming decades.

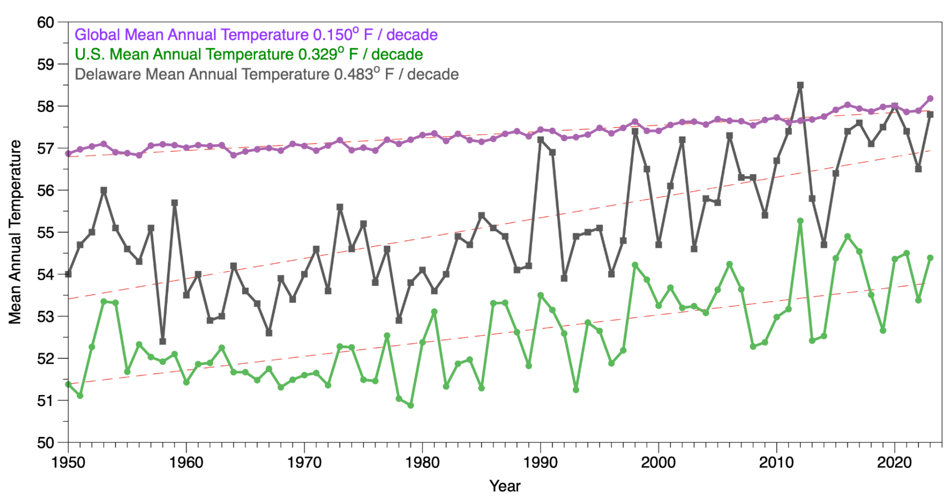


Figure 3.8. Time series of mean annual temperature for the globe (purple line), the United States (green line), and for Delaware (black line) for the period 1950 through 2023.

Mean annual average, maximum, and minimum temperature projections all show large temperature increases for Delaware in the future. The ensemble mean temperature time series for the STAR-ESDM downscaling technique are similar across all three annual variables and the SSP2–4.5 and SSP5–8.5 scenarios (**Figures 3.9 - 3.11**). Over the next several decades, projected temperature changes are expected to be similar regardless of the SSP scenario followed through that time. There is no significant difference between temperature projections from different scenarios over the short term. For example, the mean annual temperature by the vicennial period centered on 2050 is different by approximately 1° F between the SSP2–4.5 and SSP5–8.5 scenarios. However, it is later in the century where the diverse SSPs lead to large differences in mean annual temperature. By the last vicennial period of the century (2081-2099) a large difference of approximately 4° F is found between SSP2–4.5 projections, and the higher emissions scenario of SSP5–8.5 (**Figure 3.9**). Thus, the acceleration of warming in the higher emissions SSP5–8.5 generally occurs after 2050 in all of the mean annual variables. It is most useful to compare the end of century projections for each SSP with the current 30-year (1991-2020) normals for Delaware. For mean annual temperature, the models show an increase of approximately 6° F between the current 30-year (1991-2020) mean of 56.2° F and the end of the century for SSP2–4.5 (**Figure 3.9 top**), but a much larger increase of approximately 10° F for SSP5–8.5 (**Figure 3.9 bottom**).

Similar results are found for mean annual maximum temperatures (**Figure 3.10**). Overall, the downscaled model ensembles show an increase in mean annual maximum temperature of approximately 6° F between the current 30-year (1991-2020) mean of 66.1° F and the end of the century for SSP2–4.5 (**Figure 3.10 top**). The increase is larger for SSP5–8.5, approximately 10° F by the end of the century (**Figure 3.10 bottom**).

Projections indicate that mean annual minimum temperatures will continue to increase in the future, at approximately the same rate as mean annual, and mean annual maximum temperatures (**Figures 3.9 - 3.10**). Overall, the models show an increase in mean annual minimum temperature of approximately 6° F between the current 30-year (1991-2020) mean of 46.3° F and the end of the century for SSP2–4.5 (**Figure 3.11 top**). An end of century increase of approximately 10° F was found for SSP5–8.5 (**Figure 3.11 bottom**).

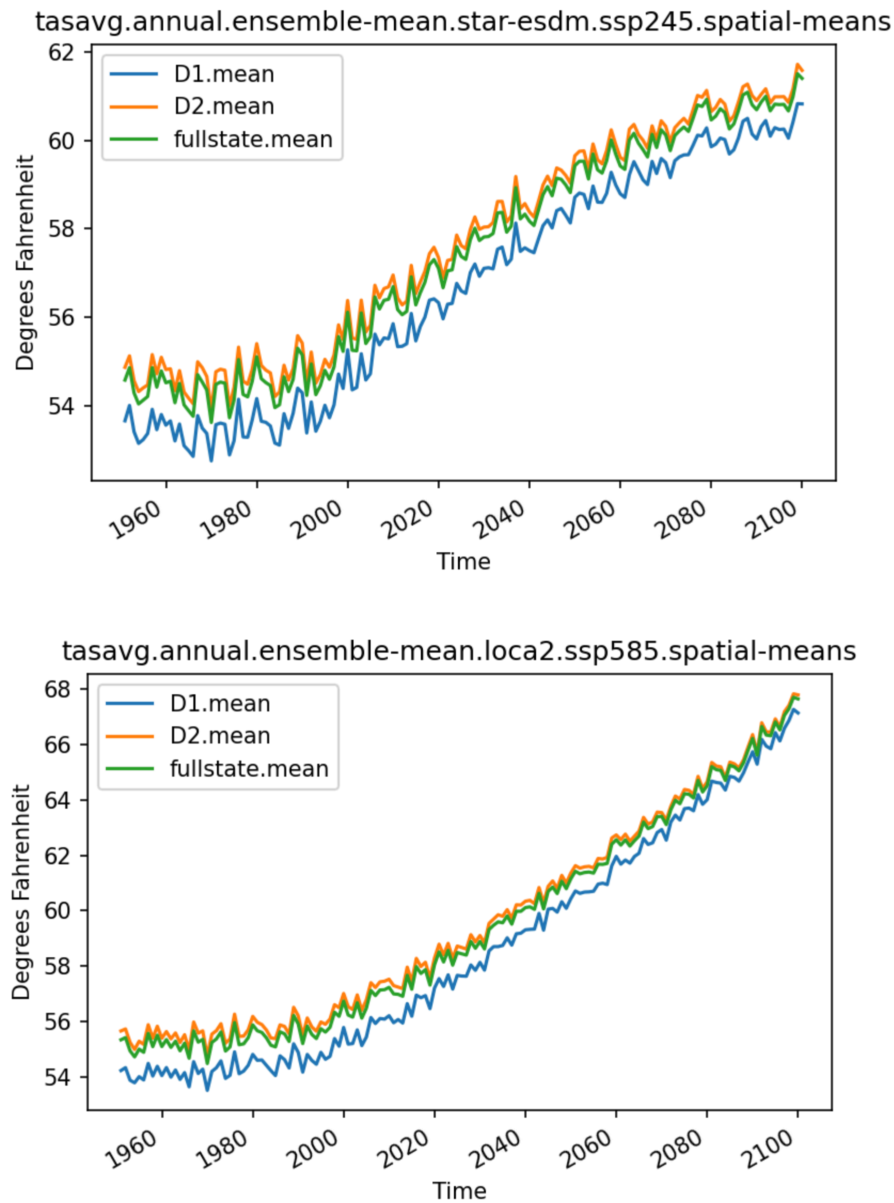
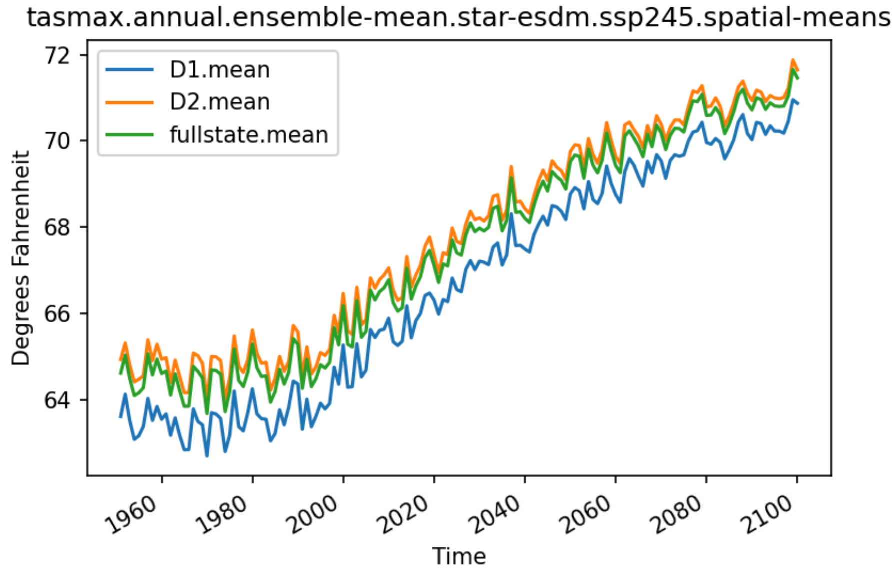


Figure 3.9. Ensemble mean time series of STAR-ESDM mean annual temperature projections under SSP2–4.5 (top), and SSP5-8.5 (bottom). Projections are shown for the full state (green), climate division 1 (blue), and climate division 2 (orange).



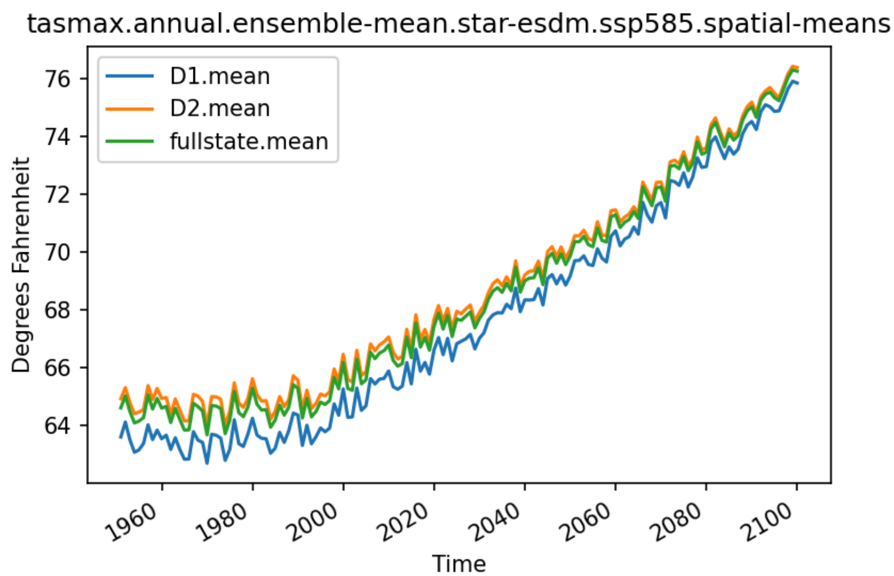
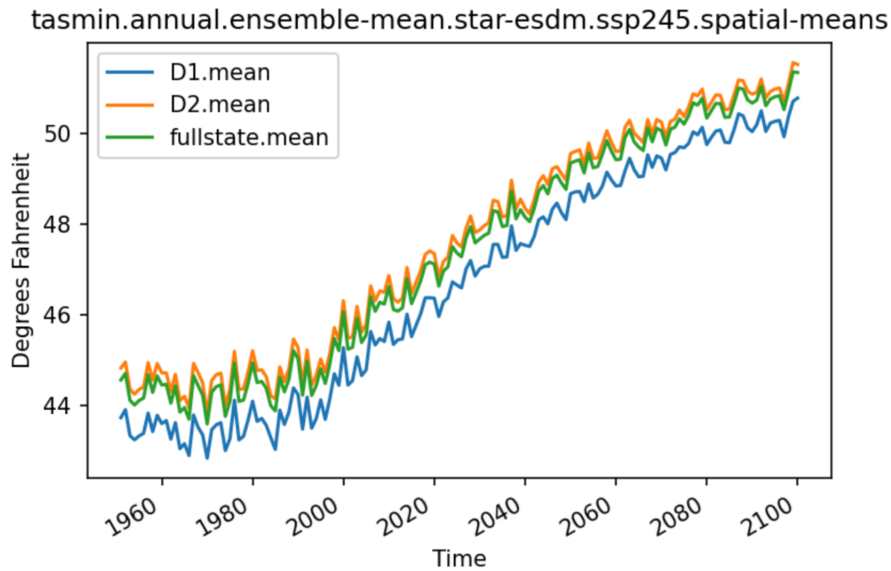


Figure 3.10. Ensemble mean time series of STAR-ESDM mean annual maximum temperature projections under SSP2–4.5 (top), and SSP5-8.5 (bottom). Projections are shown for the full state (green), climate division 1 (blue), and climate division 2 (orange).



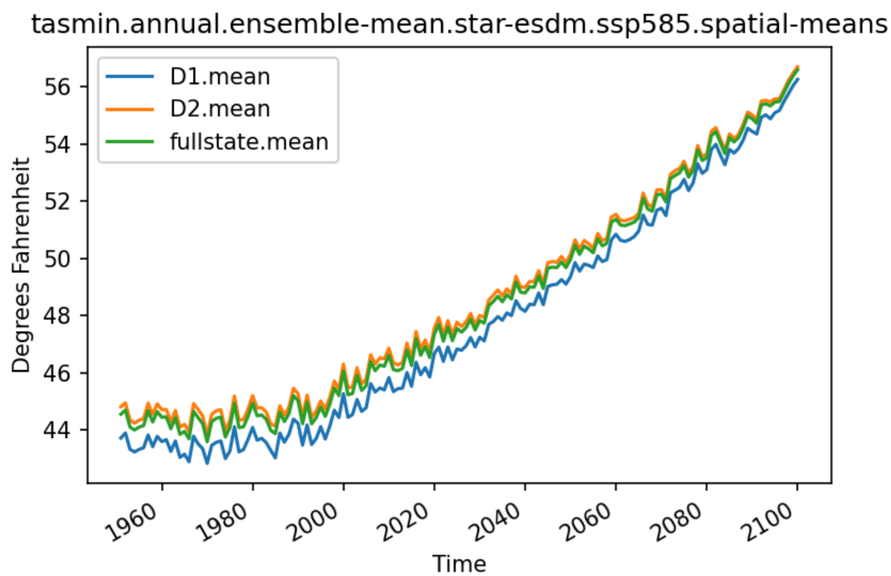


Figure 3.11. Ensemble mean time series of STAR-ESDM mean annual minimum temperature projections under SSP2–4.5 (top), and SSP5-8.5 (bottom). Projections are shown for the full state (green), climate division 1 (blue), and climate division 2 (orange).

3.4.2. Seasonal Temperature Projections

It is important to review the seasonal change in temperature projections as changes in seasonal temperatures may lead to important impacts to multiple societal sectors. By examining changes in temperature across seasons such as earlier springs, warmer summers, milder winters, and delayed autumns, it is possible to understand the potential impact of these changes to ecosystems, agriculture, water resources, and public health, to name just a few.

Figure 3.12 shows the 60-month running means of mean annual maximum temperature for each season for STAR-ESDM and for each SSP. All seasons show a general monotonic increase except for the autumn season. The autumn season actually shows a decrease in maximum temperature (SSP2-4.5) by the end of the century, or no change (SSP5-8.5). The winter season shows the strongest upward trend in maximum temperature of all seasons under the STAR-ESDM downscaling method, and the SSP5–8.5 scenario gives more pronounced upward trends than SSP2–4.5. Mean annual minimum temperatures are shown in **Figure 3.13**. All seasons follow the same general pattern described for mean annual maximum temperature.

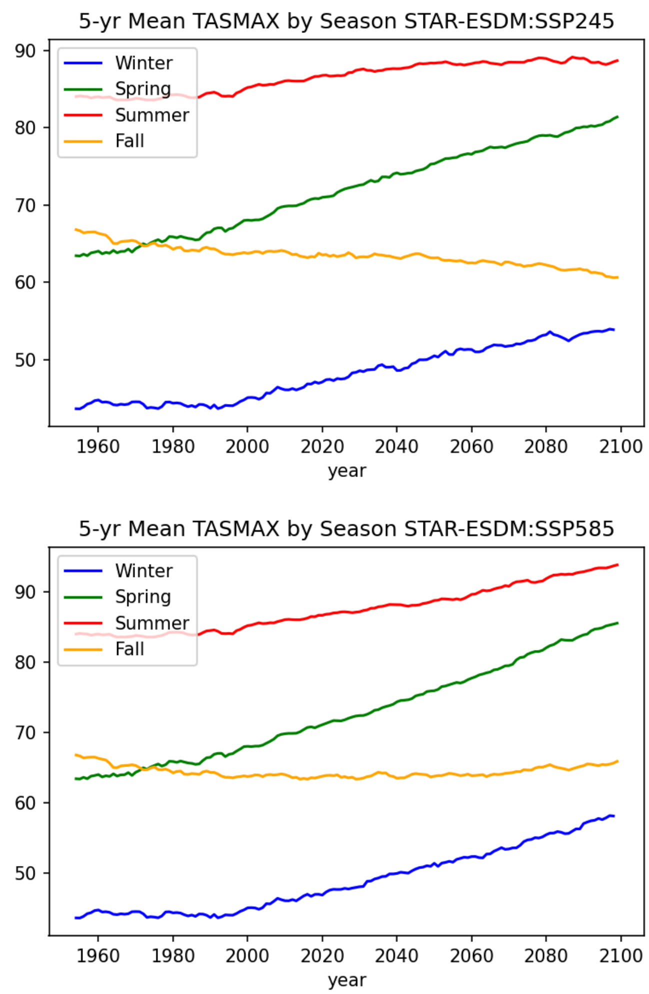


Figure 3.12. 60-month running mean times series of mean annual maximum temperature for each season for STAR-ESDM SSP2–4.5 (top), and for SSP5–8.5 (bottom).

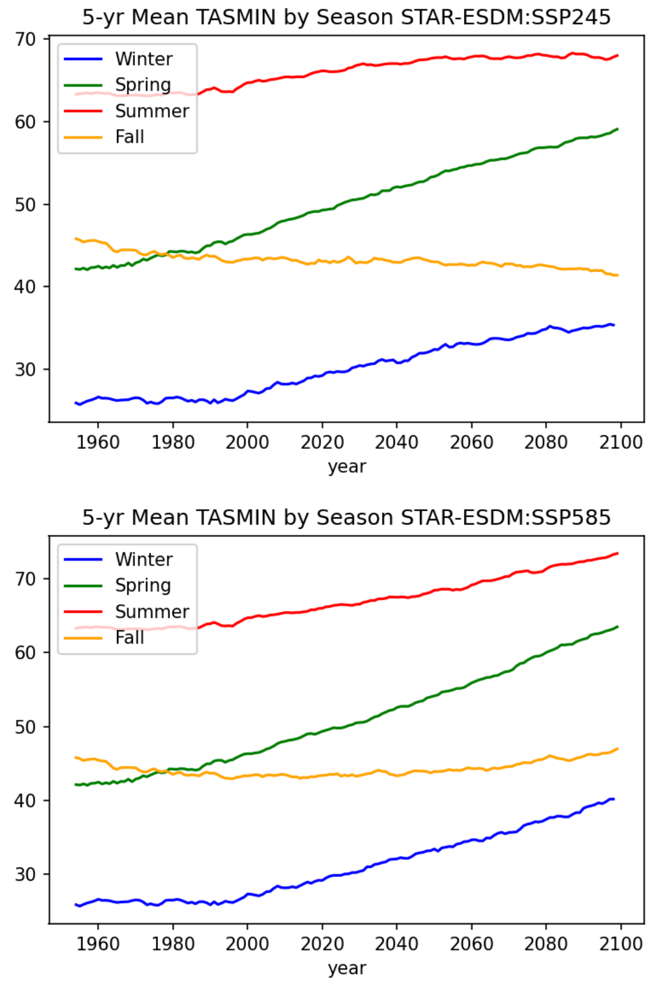
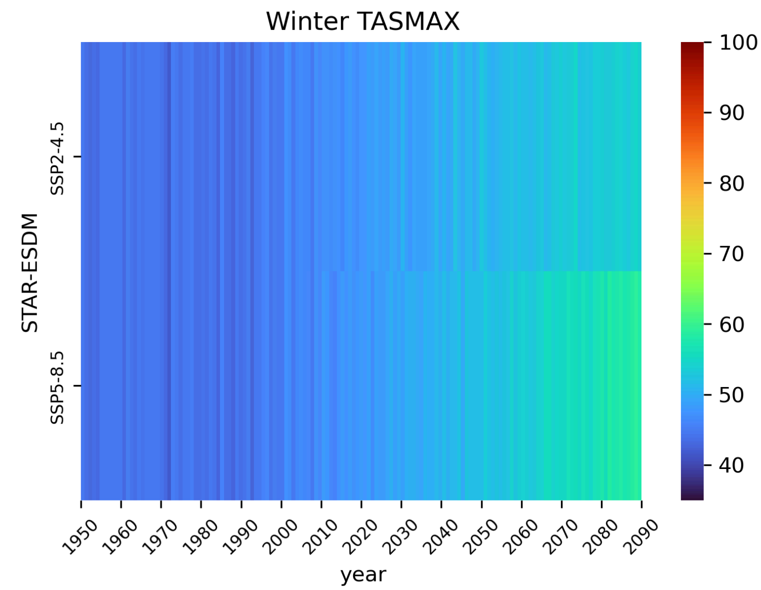


Figure 3.13. 60-month running mean times series of mean annual minimum temperature for each season for STAR-ESDM SSP2–4.5 (top), and for SSP5–8.5 (bottom).

3.4.2.1. Winter Mean Annual Maximum and Minimum Temperature Projections

The structure of future temperature projections can be seen in "temperature stripe" graphics as shown in **Figure 3.14** for winter mean annual maximum and minimum temperatures. In these graphs, each "stripe" represents the temperature for a given year. An inspection of the graphs shows that SSP5–8.5 more strongly increases winter temperatures near the end of the century in comparison to SSP2–4.5 for both maximum and minimum winter temperatures. Much of the warming occurs after 2040 for SSP5–8.5.



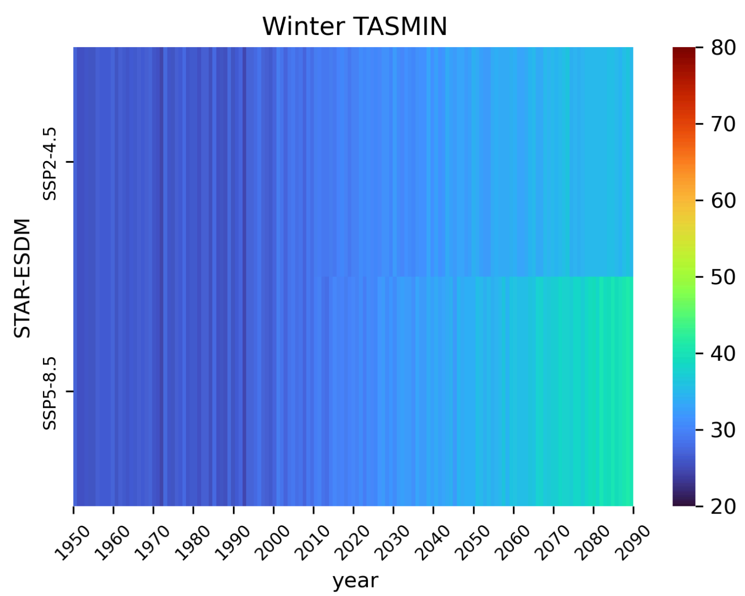
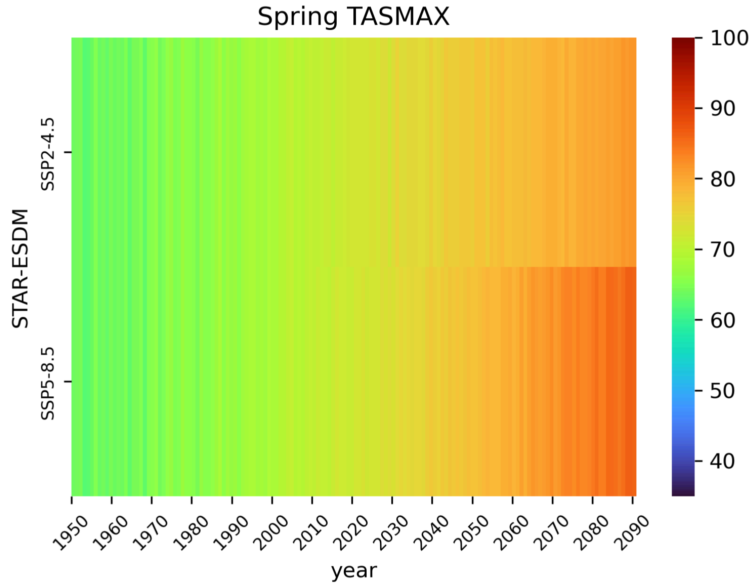


Figure 3.14. Temperature "stripe" graphs for mean winter maximum temperature (top) and minimum temperature (bottom) for each SSP scenario. Temperatures given in °F.

3.4.2.2. Spring Mean Annual Maximum and Minimum Temperature Projections

The spring season stripe graph (**Figure 3.15**) shows that STAR-ESDM downscaling aggressively increases spring maximum and minimum temperatures for both SSP scenarios. This is especially true for the SSP5–8.5 scenario, where mean spring temperatures increase by approximately 10° F by the end of the century.



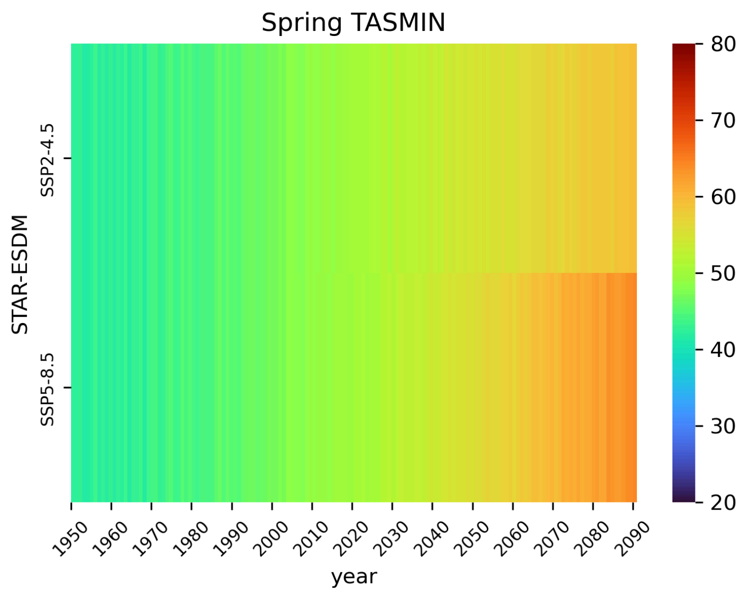
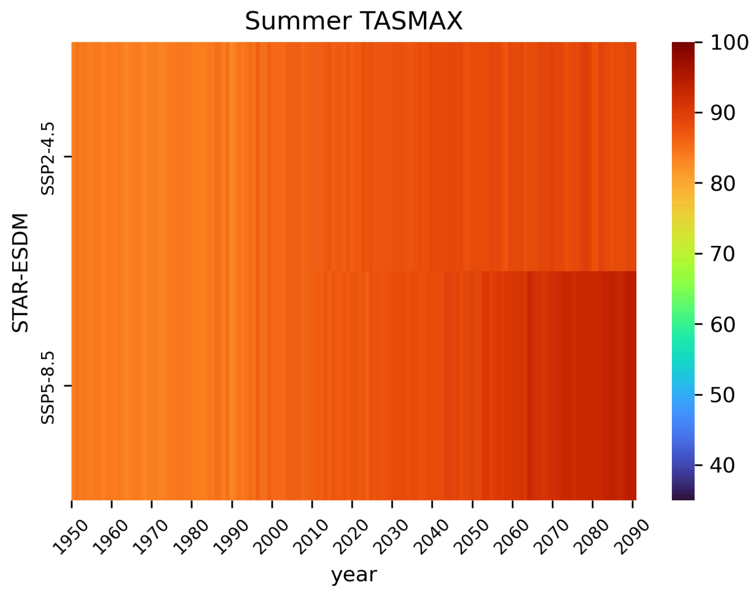


Figure 3.15. Temperature "stripe" graphs for mean spring maximum temperature (top) and minimum temperature (bottom) for each SSP scenario. Temperatures given in °F.

3.4.2.3. Summer Mean Annual Maximum and Minimum Temperature Projections

An inspection of the graphs in **Figure 3.16** shows that SSP5–8.5 increases summer temperatures significantly near the end of the century for both maximum and minimum temperatures, more so than for SSP2-4.5. Much of the most intense warming occurs after 2050 for SSP5–8.5 summer temperatures.



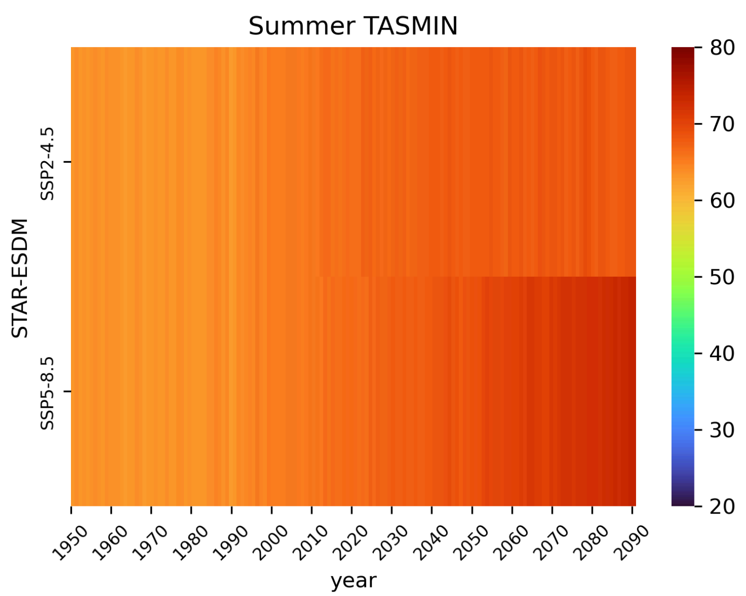


Figure 3.16. Temperature "stripe" graphs for mean summer maximum temperature (top) and minimum temperature (bottom) for each SSP scenario. Temperatures given in °F.

3.4.2.4. Autumn Mean Annual Maximum and Minimum Temperature Projections

Inspection of **Figure 3.17** shows that STAR-ESDM keeps autumn maximum and minimum temperatures nearly constant or cooling (SSP2-4.5), or increasing slightly (SSP5-8.5) from now to the end of the century. Thus the autumn season is the only season that does not see a significant temperature increase by 2100 for either SSP under the STAR-ESDM downscaling.

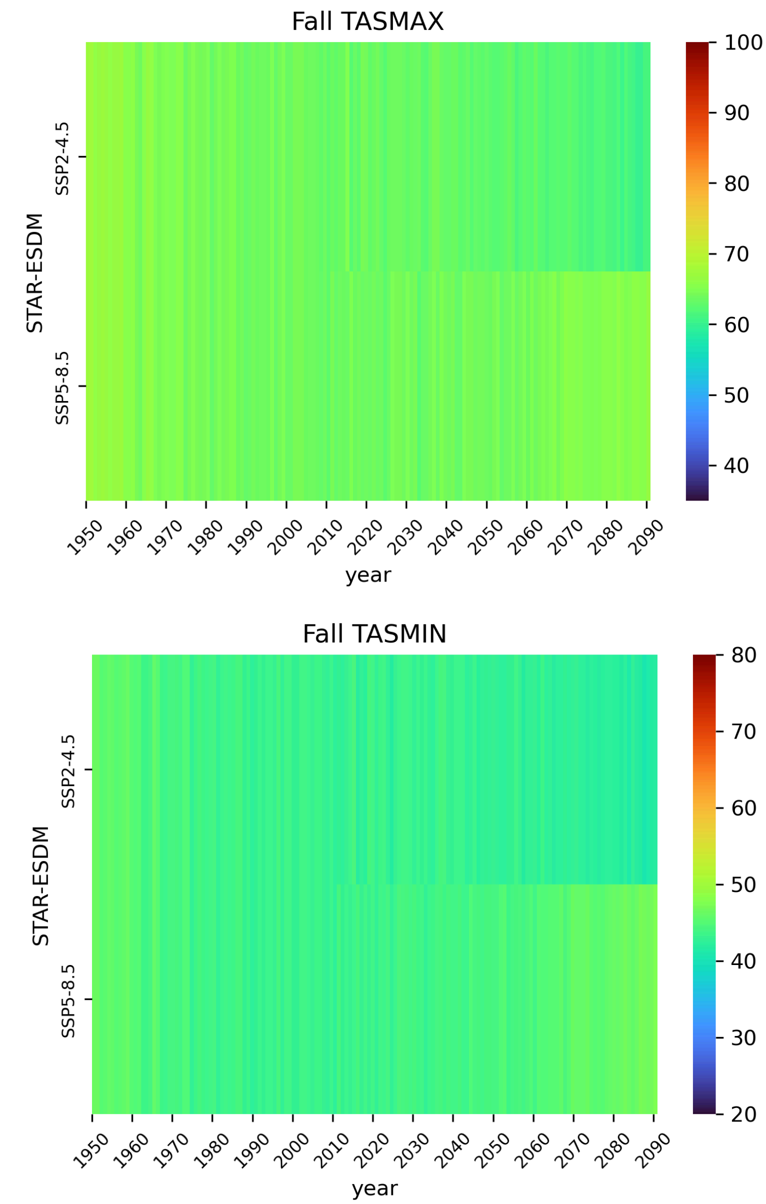
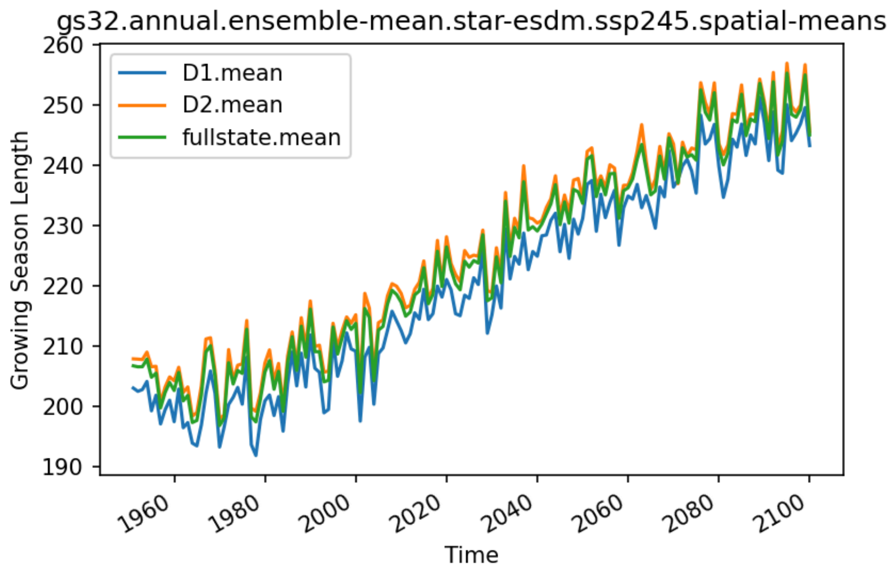


Figure 3.17. Temperature "stripe" graphs for mean autumn maximum temperature (top) and minimum temperature (bottom) for each SSP scenario. Temperatures given in °F.

3.4.3. Temperature Indicator Projections

3.4.3.1. Growing Season Length

The length of the growing season is generally defined as the number of days between the occurrence of the last recorded minimum temperature of ≤ 32° F in the spring, and the first occurrence of a recorded temperature of ≤ 32° F in the autumn. Annual growing season length projections for STAR-ESDM and each SSP are shown in **Figure 3.18**. For SSP2–4.5 the downscaled model ensemble shows an increase in growing season length of approximately 30 days by the end of the century compared to the current values. As expected, the higher emissions scenario of SSP5–8.5 (**Figure 3.18 bottom**) shows a greater increase in the length of the growing season of approximately 60 days compared to the present length.



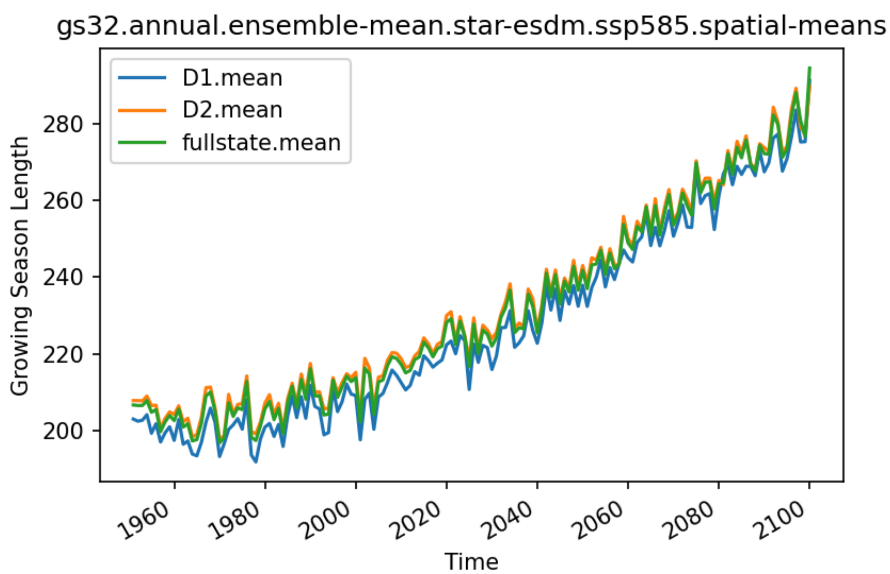


Figure 3.18. Time series of growing season length for STAR-ESDM SSP2–4.5 (top) and for SSP5–8.5 (bottom). Growing season length is given in days.

3.4.3.2. Heating Degree Days

Heating Degree Days (HDD) are a measurement used to estimate the energy demand required to heat buildings. It represents by how much the mean daily temperature was below a specific baseline temperature, in most cases the baseline is set at 65°F, which is generally considered a comfortable indoor temperature. The HDDs are accumulated for the year giving an annual value. The mean vicennial value of HDDs are given in **Table 3.4** for both scenarios under STAR-ESDM downscaling. The number of HDDs decreases by approximately 1000 units by the last vicennial period, compared to the current 1991-2020 statewide mean of 4,483, under SSP2–4.5 (top). The decrease in mean annual HDD is larger under SSP5–8.5 with decreases of approximately 1800 HDD units (bottom).

Table 3.4. Vicennial (20-year) mean projections for heating degree days for each SSP and for the State as a whole. SSP2–4.5 is shown at the top, while SSP5–8.5 is shown at the bottom.

	2021-2040	**2041-2060**	**2061-2080**	**2081-2099**
SSP2-4.5	4029	3730	3514	3412
SSP5-8.5	3971	3526	3095	2664

3.4.3.3. Cooling Degree Days

Cooling Degree Days (CDD) are a measurement used to estimate the energy demand required to cool buildings. It represents by how much the mean daily temperature was above a specific baseline temperature. In most cases the baseline is set at 65°F, which is generally considered a comfortable indoor temperature. The CDDs are accumulated for the year giving an annual value. The mean vicennial value of CDDs are given in **Table 3.5** for both scenarios. The number of CDDs increases by approximately 800 units by the last vicennial period, compared to the current 1991-2020 statewide mean of 1,141, under SSP2–4.5 (**Table 3.5 top**). The increase in mean annual CDD is larger under SSP5–8.5 with increases of approximately 1500 CDD units, more than doubling the current statewide mean value (**Table 3.5 bottom**).

Table 3.5. Vicennial (20-year) mean projections for cooling degree days for each SSP and for the State as a whole. SSP2–4.5 is shown at the top, while SSP5–8.5 is shown at the bottom.

	2021-2040	**2041-2060**	**2061-2080**	**2081-2099**
SSP2-4.5	1457	1648	1788	1906
SSP5-8.5	1500	1772	2197	2683

3.4.3.4 Growing Degree Days

Growing Degree Days (GDD**)** are a measure of heat accumulation used to predict the growth and development of plants and pests during the growing season. The base temperature, which is the minimum temperature needed for growth to begin for a specific plant or pest, is commonly set to 50°F (although this can vary depending on the plant or pest under consideration). It represents by how much the mean daily temperature was above the chosen baseline temperature. The GDDs are accumulated for the year giving an annual value. The mean vicennial value of GDDs are given in **Table 3.6** for both SSPs. The number of GDDs increases by approximately 1000 units by the last vicennial period, compared to the current 1991-2020 statewide mean of 4,000, under SSP2–4.5 (**Table 3.6 top**). The increase in mean annual GDD is larger under SSP5–8.5 with increases of approximately 2100 GDD units (bottom). The increase of GDDs is associated with the growing season length discussed above.

Table 3.6. Vicennial (20-year) mean projections for growing degree days (base 50°F) for each SSP and for the State as a whole. SSP2–4.5 is shown at the top, while SSP5–8.5 is shown at the bottom.

	2021-2040	**2041-2060**	**2061-2080**	**2081-2099**
SSP2-4.5	4304	4614	4842	5014
SSP5-8.5	4361	4822	5453	6158

3.4.4. Temperature Extremes Projections

3.5.4.1. Number of Days with Minimum Temperature ≤ 32º F

The annual number of days with minimum temperatures ≤ 32º F across the state (freezing days) are important to both natural and human systems, and is an important temperature extreme to monitor. Projections of the change in number of days with minimum temperatures ≤ 32º F are shown **Figure 3.19** for both SSPs. The number of freezing days decreases in the last vicennial period by approximately 25 days/year under SSP2–4.5, compared to the 1991-2020 mean of approximately 75 days/year **(Figure 3.19 top**). The decrease is greater under SSP5–8.5 with freezing days decreasing by approximately 50 days by the end of the century (**Figure 3.19 bottom**).

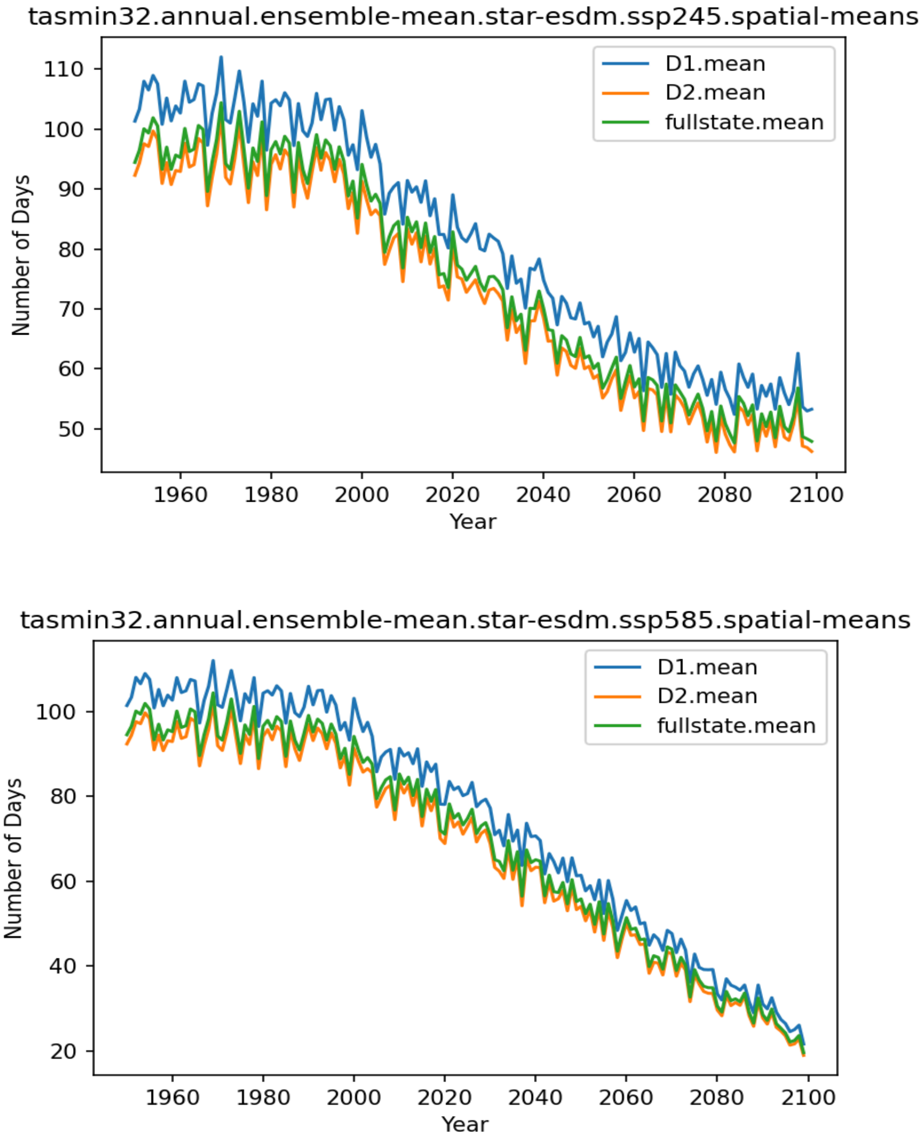
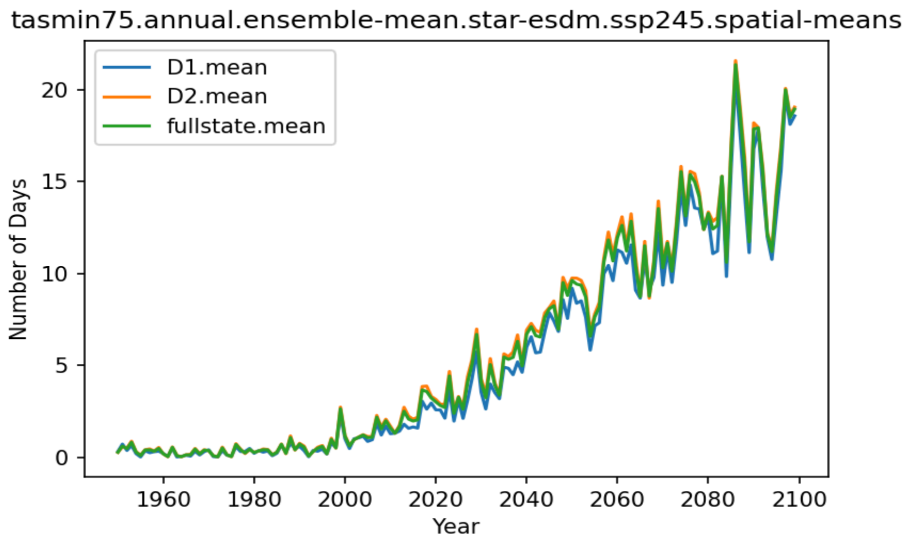


Figure 3.19. Time series of number of days with minimum temperatures ≤ 32°F for STAR-ESDM for SSP2–4.5 (top), and for SSP5–8.5 (bottom).

3.4.4.2. Number of Days with Minimum Temperature ≥ 75° F

The annual number of days with minimum temperatures ≥ 75° F across the state (warm nights) is important as it is an indicator of extreme heat, especially in urban areas. Moreover, these warm nights can pose considerable health risks, especially to vulnerable populations. Projections of the change in number of days with minimum temperatures ≥ 75° F are shown in **Figure 3.20** for both SSPs. The number of warm nights increases in the last vicennial period by approximately 10 days/year for SSP2–4.5, compared to the 1991-2020 mean of approximately 7 days/year (**Figure 3.20 top**). The increase is greater under SSP5–8.5 with warm nights increasing by nearly 50 days/year by the end of the century (**Figure 3.20 bottom**).



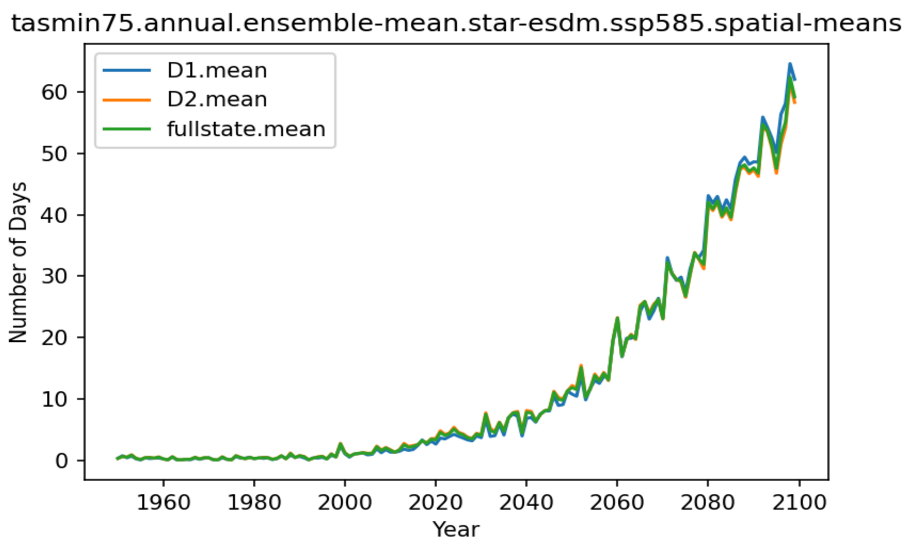
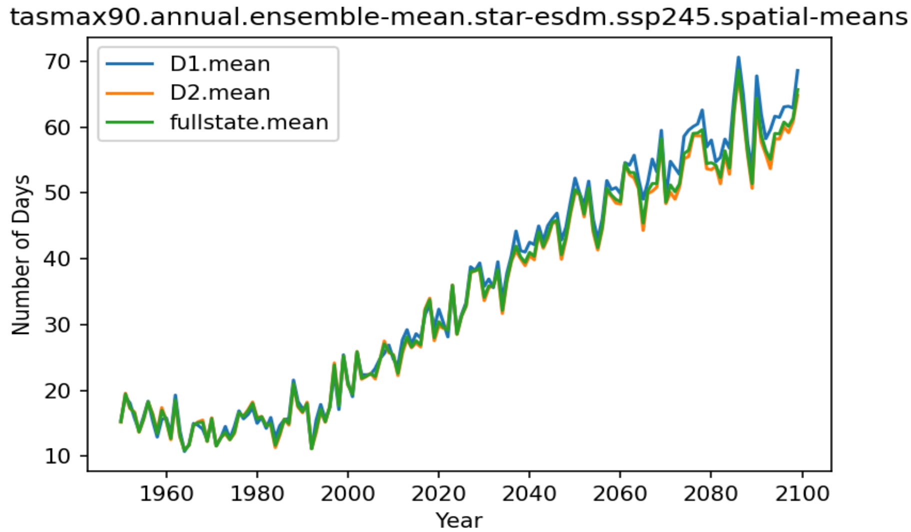


Figure 3.20. Time series of number of days with minimum temperatures ≥ 75°F for STAR-ESDM for SSP2–4.5 (top), and for SSP5–8.5 (bottom).

3.4.4.3. Number of Days with Maximum Temperature ≥ 90º F

The annual number of days with maximum temperatures ≥ 90º F across the state (warmest days) highlight the frequency of extreme heat, which has significant implications for public health, energy demand, agriculture, and the maintenance of diverse ecosystems. Projections of the change in number of days with maximum temperatures ≥ 90º F are shown **Figure 3.21** for both SSPs. The number of hottest days increases in the last vicennial period by approximately 35 days/year under SSP2–4.5, compared to the 1991-2020 mean of approximately 25 days/year (**Figure 3.21 top**). The increase is greater under SSP5–8.5 with warm nights increasing by approximately 75 days/year by the end of the century (**Figure 3.21 bottom**).



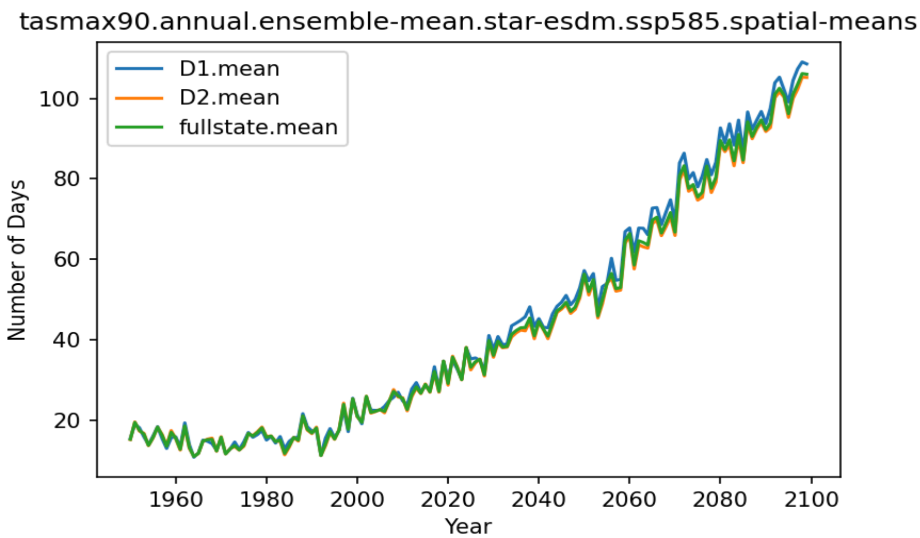


Figure 3.21. Time series of number of days with minimum temperatures ≥ 90°F for STAR-ESDM for SSP2–4.5 (top), and for SSP5–8.5 (bottom).

3.5. Summary of Temperature Trends and Projections

Mean annual maximum, minimum, and average temperature projection results are summarized in **Table 3.7**. Under SSP2–4.5 there is an increase of between 5º F and 6º F between the current 30-year normal (1991-2020) and the end of century vicennial period (2081-2100) for each variable. The vicennial temperature increase between the current normal (1991-2020) and the end of century normal (2081-2100) for SSP5–8.5 is significantly greater with values of between 8º F and 9º F under STAR-ESDM downscaling. Seasonally, winter generally has the strongest upward trend of maximum and minimum temperatures of all the seasons. Autumn season temperatures actually decrease or stay nearly steady through the end of the century for SSP2-4.5 and increase only slightly for SSP5-8.5, while all other seasons see an upward trend for each SSP with SSP5–8.5 seeing the largest temperature increases. Projections of temperature indicators are influenced by the significant warming that occurs in the models. The length of the growing season, cooling degree days, and growing degree days all show substantial increases between current “normals” and the end of the century vicennial period, while heating degree days show a substantial decrease over the same period. Temperature extremes follow the same pattern with the number of days with minimum temperatures less than or equal to 32º F (the coldest nights) decreasing significantly between the current normals period of 1991-2020 and the end of the century (2081-2100). The number of days with minimum temperatures greater than or equal to 75º F (warmest nights) show a strong increase during the same period (greater than 50 days per year under SSP5–8.5), while the number of days with maximum temperatures greater than or equal to 90º F (hottest days) increases by approximately 70 days per year under SSP5–8.5. Thus, the models project Delaware to be substantially warmer by the end of the century by every measure.

Table 3.7. Summary of temperature changes (degrees Fahrenheit) for each vicennial period from 2021-2100 for both SSPs for mean annual, mean minimum and mean maximum temperature. Numbers in parentheses indicate the change in temperature between that vicennial period and the previous (+ means increase; - means decrease). The last column shows the difference between the end of century vicennial period (2081-2100) and the current normals period (1991-2020).

Annual Temperature	Near-century 2021-2040		Mid-century 2041-2060		Postmid-century 2061-2080		End-century 2081-2100		End of Century Diff from 1991-2020 Normal	
	SSP2-4.5	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*
Minimum	48 (+2)	48 (+2)	49 (+1)	50 (+2)	50 (+1)	52 (+2)	52 (+2)	55 (+3)	5.7	8.7
Mean	59 (+3)	58 (+2)	60 (+1)	60 (+2)	61 (+1)	62 (+2)	62 (+1)	65 (+3)	5.8	8.8
Maximum	68 (+2)	68 (+2)	69 (+1)	70 (+2)	70 (+1)	72 (+2)	71 (+1)	75 (+3)	4.9	8.9

3.6. References

Durre, I., M. F. Squires, R. S. Vose, A. Arguez, W. S. Gross, J. R. Rennie, and C. J. Schreck, (2022): NOAA's nClimGrid-Daily Version 1 – Daily gridded temperature and precipitation for the Contiguous United States since 1951. NOAA National Centers for Environmental Information, doi:10.25921/c4gt-r169.

Pierce, D.W., Su, L., Cayan, D.R., Risser, M.D., Livneh, B. and Lettenmaier, D.P., (2021). An extreme-preserving long-term gridded daily precipitation dataset for the conterminous United States. Journal of Hydrometeorology, 22(7), pp.1883-1895, doi: 10.1175/JHM-D-20-0212.1.

SAS Institute Inc. (2024). *JMP® Statistical Discovery Software.* Cary, NC: SAS Institute Inc. Available at: https://www.jmp.com

Ullrich, P. A. (2023). Validation of LOCA2 and STAR-ESDM Statistically Downscaled Products (LLNL-TR-856094; OSTI ID 2202926). Lawrence Livermore National Laboratory. https://doi.org/10.2172/2202926

Vose, R. S., Applequist, S., Squires, M., Durre, I., Menne, M. J., Williams, C. N., Fenimore, C., Gleason, B., & Arndt, D. (2014). *Improved Historical Temperature and Precipitation Time Series for U.S. Climate Divisions.* Journal of Applied Meteorology and Climatology, **53**(5), 1232-1251. https://doi.org/10.1175/JAMC-D-13-0248.1

4. Precipitation

This chapter will review changes in precipitation across Delaware for the period 1895-2024 to put possible future changes into an historical perspective. An assessment of the performance of the downscaled models during the period of data overlap between observations and model projections of precipitation (1950-2023) will be presented. Finally, downscaled model projections for Delaware precipitation will be reviewed for the remainder of the century (through 2099).

Precipitation across Delaware averages 44 inches annually (for the period 1895-2020), distributed fairly evenly throughout the year (**Figure 4.1**). However, Delaware's precipitation is subject to large interannual and intra-annual variability, with statewide annual values varying from as low as 27.37 inches in 1930 to as high as 60.05 inches in 1948. Large variability in monthly precipitation from year-to-year is also evident from inspection of **Figure 4.1**.

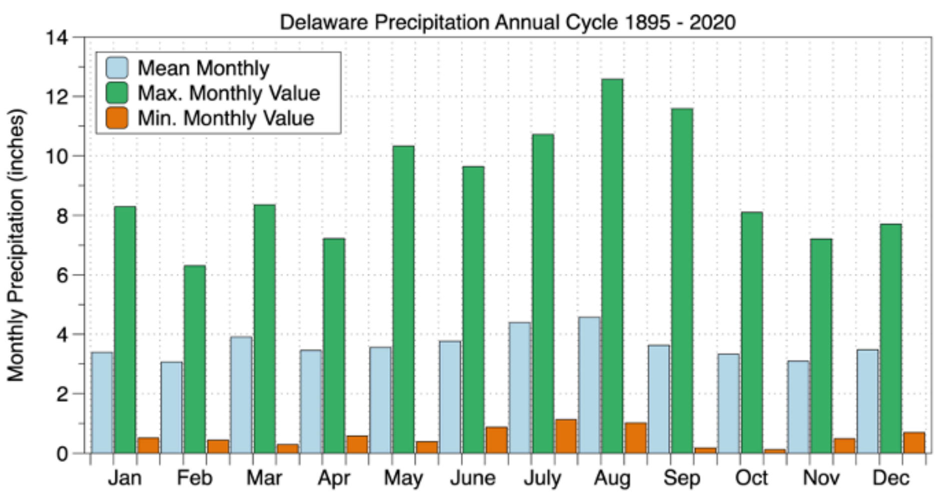


Figure 4.1. Annual cycle of precipitation for the period 1895 - 2020 for Delaware. Graph shows mean monthly values for the period, in addition to maximum and minimum monthly values for the period of record.

4.1. Precipitation Data

Statewide and divisional precipitation data, are available for the period 1895 through the present from the National Center for Environmental Information (NCEI) Climate at a Glance data portal[21]. The data are derived from the U.S. Climate Divisional Database (nClimDiv; Vose et al. 2014). For more information on the specifics of this dataset please see Section 3.1 above. Data are available for the state's two climate divisions from the website: division 1 (New Castle

[21] https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/

County) and division 2 (Kent and Sussex Counties). These data are available through both the Office of the Delaware State Climatologist and the NCEI. These statewide and divisional data were used in the analysis of precipitation variability in the historical analysis and in the model assessment.

In addition, data from individual weather stations located within Delaware were also used in the analysis of historical observations. The TD-3200 dataset from NOAA's National Centers for Environmental Information (NCEI) is the U.S. Cooperative Summary of the Day (TD-3200) dataset and consists of daily meteorological observations from the U.S. Cooperative Observer Network (COOP). This dataset has been largely integrated into NOAA's Global Historical Climatology Network-Daily (GHCN-D). Please see Section 3.1 above for more information on this dataset. For this study, metadata on all stations were collected and analyzed to ascertain those stations and periods of record that were suitable for the investigation of precipitation variability. The Cooperative station data identified as suitable for further evaluation are used in the analysis of precipitation extremes. Only one cooperative station was retained for analysis; the Wilmington New Castle County Airport (079595). This station was chosen based on its data completeness and lengthy period of record.

Model estimates used in the precipitation projections were derived from the process discussed in Section 2.0 above, and specifically from the downscaled precipitation projections outlined in Section 2.2.2.

To determine the existence of statistically significant trends in precipitation simple linear regression was used, similar to that used for temperature in Section 3.1. Various statistical tests were used to assess the significance of the relationship between time and the variable of interest.

4.2. Historical Analysis - Precipitation

4.2.1. Statewide Results

An analysis of statewide annual precipitation and seasonal precipitation was conducted using the U.S. Climate Divisional Database (Vose et al. 2014). No significant trends were identified in statewide precipitation for the period 1895-2024 annually, or during the winter, spring, or summer seasons (**Figure 4.2**). Only autumn season statewide precipitation was found to have a statistically significant increasing trend of 0.182" per decade. It is important to note two aspects of the statewide annual precipitation time series. First, is the very large interannual variability inherent in Delaware's annual precipitation which makes identification of significant trends difficult. In addition, it is important to note that the increasing trend in annual precipitation totals for Delaware was just below the 90% significance level.

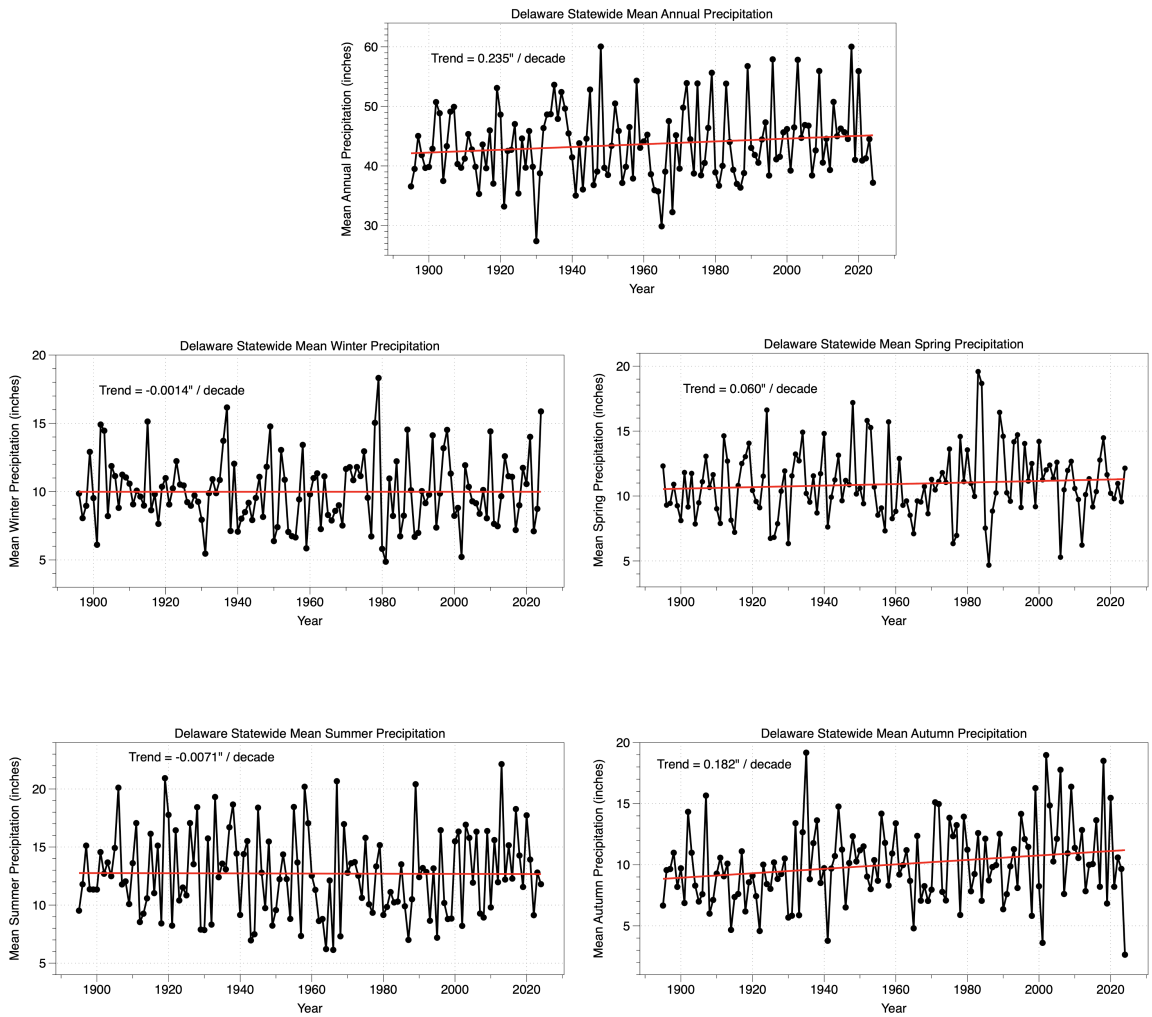


Figure 4.2. Total annual precipitation (top), total winter precipitation (middle left), total spring precipitation (middle right), total summer precipitation (bottom left), and total autumn precipitation (bottom right) for Delaware for the period 1895 - 2024. Only the autumn season trend is significant at the 95% significance level.

4.2.2. Cooperative Station Results

An analysis of Cooperative station precipitation was completed for annual totals, and for the number of days each year with greater than or equal to 1.0”, and 2.0” precipitation totals. Thresholds greater than two inch daily totals were not investigated as the number of days each year with three or more inches of precipitation was prohibitively small (many years with zero days). Results for precipitation show significant long-term trends at the Wilmington-New Castle County Airport for only two variables; annual precipitation totals and for the number of days with precipitation totaling greater than or equal to 1.0” (**Figure 4.3**).

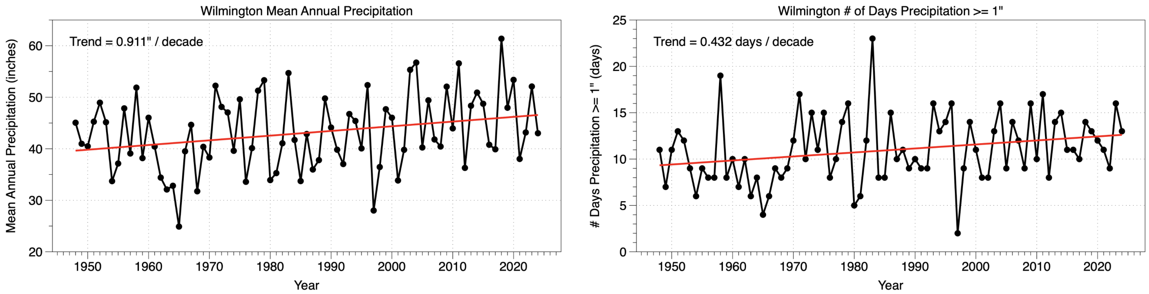


Figure 4.3. Total annual precipitation (left), and number of days with precipitation of greater than or equal to one-inch at the Wilmington/New Castle County Airport (right). Trends in both variables are significant at the 95% confidence level.

4.2.3. Precipitation Summary

In summary, Delaware statewide mean annual precipitation has shown no significant changes since 1895, except for a significant upward increasing trend during the autumn season. The major characteristic of precipitation across Delaware during this period has been large interannual and intra-annual variability. For example, average annual precipitation is approximately 44 inches, but statewide annual values have varied from as low as 27.37 inches in 1930 to as high as 60.05 inches in 1948. An analysis of Cooperative station precipitation data showed that the Wilmington-New Castle County Airport station has seen significant precipitation trends during the period 1948 through 2024. Wilmington experienced an increasing trend in both annual precipitation totals, and in the number of days each year with one inch or greater precipitation events. Finally, Leathers et al. (2019) examined extreme precipitation event frequency and magnitude using a high-resolution rain gauge network across Delaware. Results of the analysis indicate that NOAA Atlas 14, the nation's standard for estimating the magnitude and frequency of site-specific extreme precipitation events, underestimates the number and magnitude of extreme precipitation events across the state of Delaware at longer event durations (360- to 1,440-min). At shorter durations (5- to 240-min), the Atlas 14 estimates are more closely aligned with the observations from the high-resolution precipitation network. Thus, there is evidence of an increase in the magnitude of long duration extreme precipitation events across Delaware during the last 15 years.

4.3 Model Assessment - Precipitation

4.3.1 General Precipitation Comparison

In a manner similar to the evaluation of temperature, the similarities between observed and modeled precipitation were examined. Modeled and observed historical trends in precipitation were analyzed using total annual precipitation from 1950 to 2023. Statewide and divisional total annual precipitation from the U.S. Climate Divisional Database (Vose et al. 2014), was used in this analysis and was compared to the model ensemble means derived from the 13 downscaled LOCA2 and STAR-ESDM models. **Figure 4.4** shows the total annual precipitation for Delaware for the period 1950 through 2023. The thick gray line is the observations from the U.S. Climate Divisional Database, while the red and blue lines are the *ensemble mean values* derived from the LOCA2 (red line) and STAR-ESDM (blue line) downscaled model projections for SSP5–8.5. The trends in the three time series are generally similar, but it is clear that the models do not capture the interannual variability in Delaware's precipitation when using ensemble mean values. To ascertain whether the individual models are capturing the interannual variability in Delaware precipitation, the LOCA2 SSP5–8.5 raw model time series were plotted along with the ensemble mean. **Figure 4.5** shows the precipitation time series for all LOCA2 models for SSP5–8.5. It is clear that the individual models mimic the same magnitude of variability seen in the observations. **Figure 4.6** provides the standard deviation of total annual precipitation for each model used in the calculation of the ensemble mean for LOCA2 SSP5–8.5. The mean standard deviation of all models is 6.35", while the standard deviation of observations was 6.41". This result confirms that the individual models are closely representing both the mean and the variability in the observed total annual precipitation (STAR-ESDM models give a similar result, not shown). **Table 4.1** provides the mean and median for each time series. It is apparent that over the 74-year historical reference period, the downscaled models had mean and median values very close to observed values. Mean precipitation during that period varied by only 0.65" between the STAR-ESDM downscaled projections and observations (STAR drier), while LOCA2 was drier than observations by 0.86".

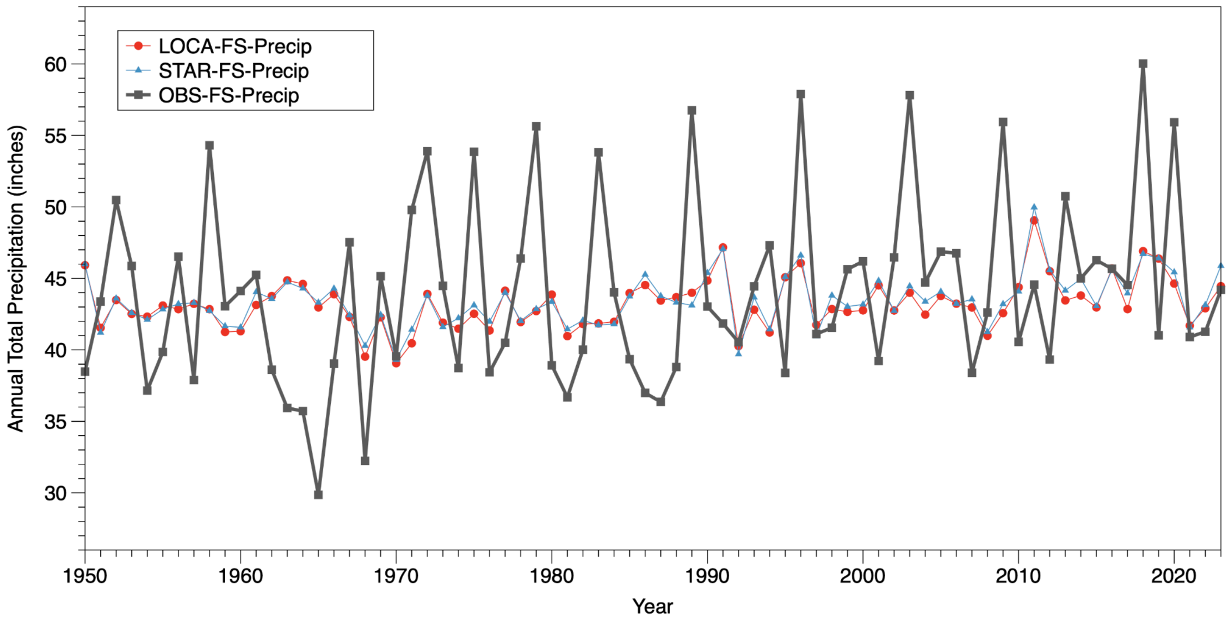


Figure 4.4. Total annual precipitation for Delaware for the period 1950 through 2023. The thick gray line is the observations from the U.S. Climate Divisional Database, while the red and blue lines are the ensemble mean values derived from the LOCA2 (red line) and STAR-ESDM (blue line) downscaled model projections for SSP5–8.5.

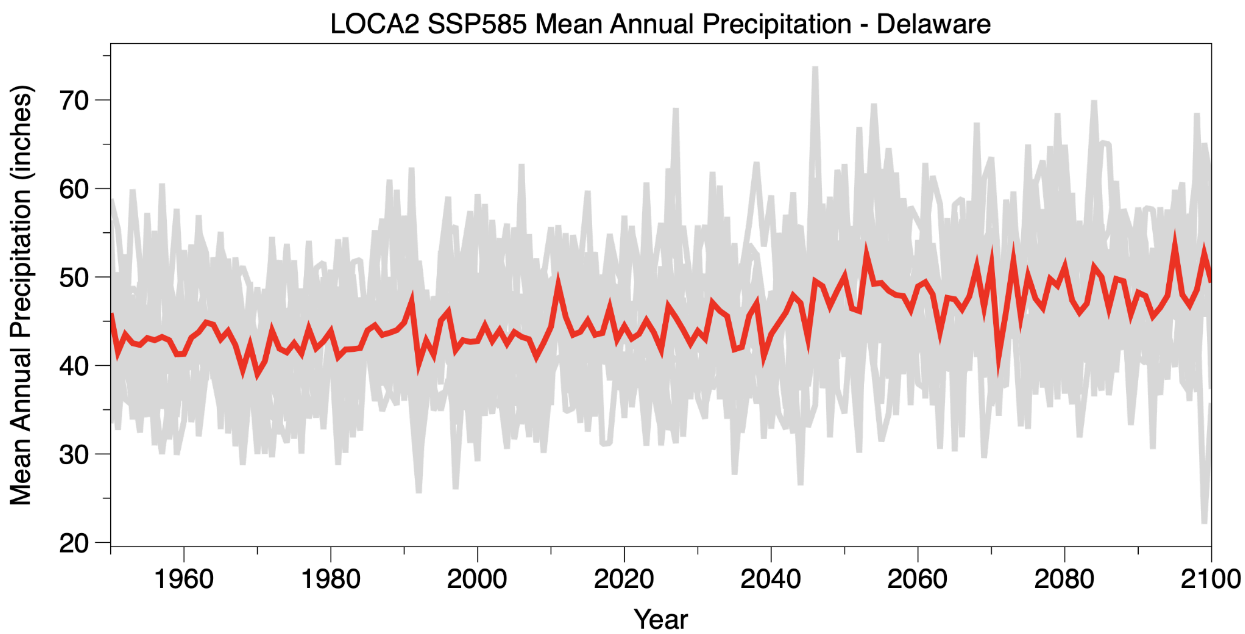


Figure 4.5. Time series of the 13 models used in the calculation of the LOCA2 ensemble mean for SSP5–8.5 (gray). The red line represents the ensemble mean.

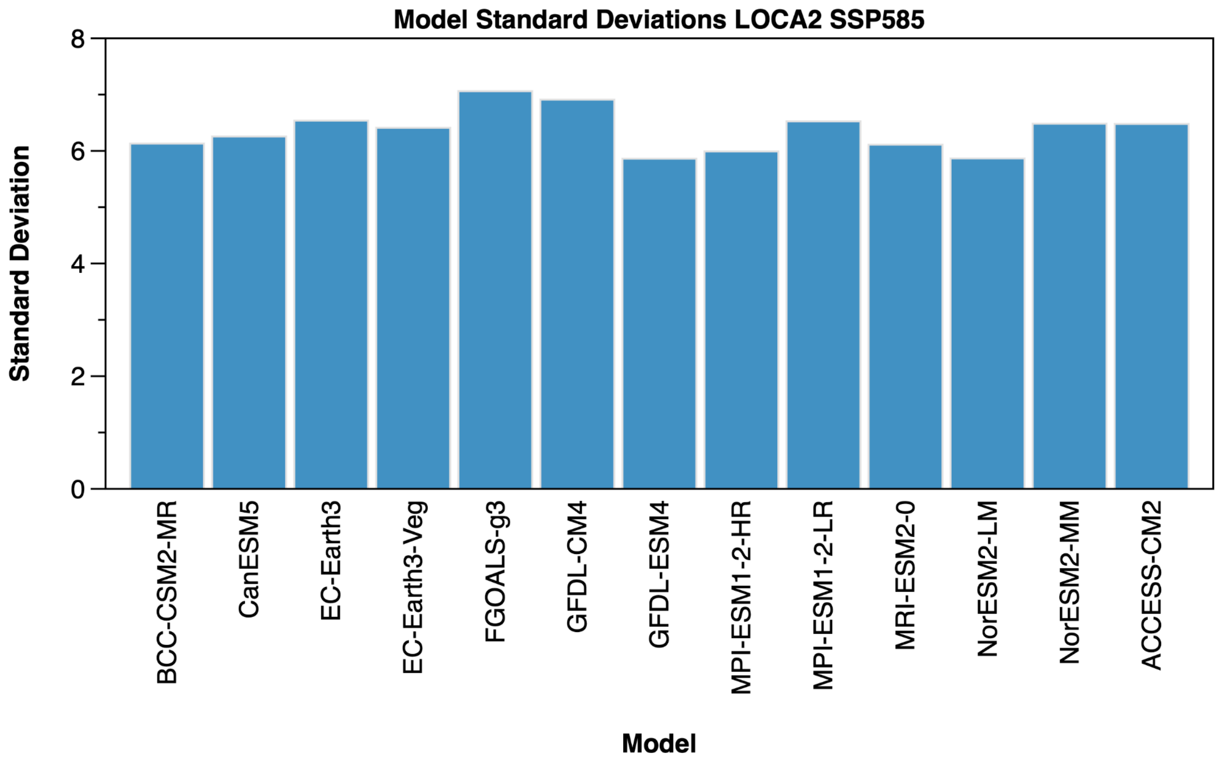


Figure 4.6. Precipitation standard deviations of all models (in inches) used to calculate the ensemble mean of LOCA2 SSP5–8.5. Mean standard deviation of all models is 6.35", while the standard deviation of observations was 6.41".

Table 4.1. The mean, median, and standard deviation for the observed total annual precipitation distribution and the ensemble values for both downscaling techniques for SSP5–8.5 for the full state of Delaware.

Annual Precipitation	Mean	Median
Observed	44.05"	43.70"
LOCA2	43.19"	43.06"
STAR-ESDM	43.40"	43.34"

4.3.2. Comparison of Trends

Linear regression was applied to the observations of total annual precipitation and the model projections using the SAS JMP software suite (SAS, 2024). Linear regression was used to establish the existence of a trend in each dataset, and to ascertain if the trends were similar between the observations and downscaled projections. The analysis was conducted for the state as a whole. Results indicate that the ensemble modeled time series evidenced statistically significant upward trends in total annual precipitation for each downscaling technique (**Table 4.2**). However, the observed precipitation time series was significant only at the 90% level (p=0.054). This suggests that although an upward trend in precipitation across the State is likely, there is a probability of between 5% and 10% that this trend is due to chance (**Table 4.2**). Notably, the trends in observations and downscaled precipitation projections were broadly similar for the State, with the observations suggesting a trend of 0.671”/decade for observations and 0.253”/decade for LOCA2 and 0.305”/decade for STAR-ESDM. The larger trend found in the observed precipitation provides a basis for confidence in the use of the models as a conservative estimate of possible future precipitation.

Table 4.2. Trends in observed total annual precipitation, and for ensemble means of total annual precipitation for STAR-ESDM and LOCA2 downscaling techniques for the full state of Delaware. The trend in observed total annual precipitation was significant at just less than the 95% confidence level, while LOCA2 and STAR-ESDM downscaling techniques had trends that were significant at the 99% confidence level (for the ensemble mean).

Annual Precipitation	R^2	Probability	Trend
Observed	0.051	P=0.054	0.671” / decade
LOCA2	0.097	P=0.007	0.253” / decade
STAR-ESDM	0.133	P=0.001	0.305” / decade

4.3.3. Model Assessment Summary

Modeled projections of annual precipitation over the historical period of overlap showed statistically significant upward trends for both the LOCA2 and STAR-ESDM downscaled ensemble means. These trends closely mimic the trend in observed precipitation. However, the trend in observed precipitation is larger than those of the models, and the observed trend is significant only at the 90% level. Moreover, the models also underestimate the number of extreme precipitation events during the last 30-year normal period. The larger trend found in the observed precipitation provides a basis for confidence in the use of the models as a conservative estimate of possible future precipitation. Notwithstanding, the use of the models for precipitation projections should be undertaken with added caution as the relationships during the historical period were not as strong as those between the models and observed temperature.

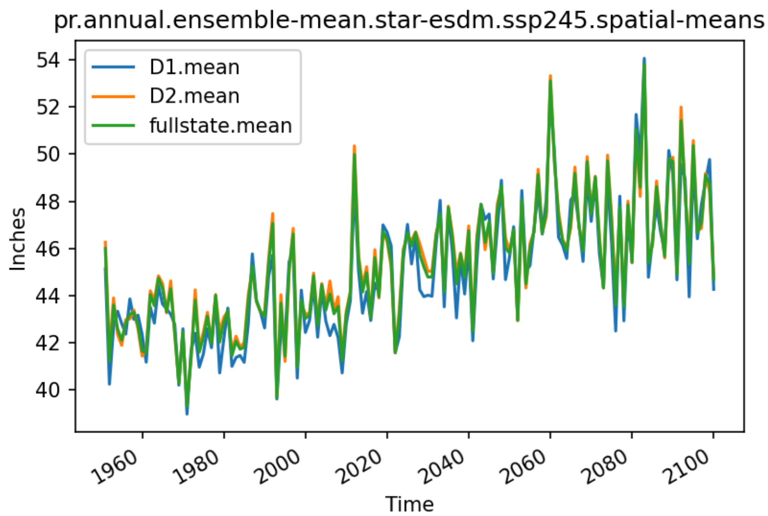
4.3.4 Recommendation on Most Appropriate Downscaling Technique for Delaware - Precipitation

As in Section 3.3.4 above, STAR-ESDM and LOCA2 downscaling techniques are both commonly used statistical downscaling methodologies for the production of climate change scenarios for precipitation (Ullrich 2023). However, the inclusion of two separate suites of climate change precipitation projections, using both methods, would likely lead to unneeded confusion. The model assessment conducted in Section 4.4 showed that the LOCA2 downscaled total annual precipitation was approximately 0.84 inches drier than the observed over the period 1950-2023, while STAR-ESDM downscaled total annual precipitation was drier than observations by 0.65 inches over the same period. Although STAR-ESDM downscaled total annual precipitation is only slightly closer to observed values, for the same reasons as in Section 3.3.4 above (and for consistency across variables), **the authors recommend the use of the STAR-ESDM downscaling methodology for precipitation projections across Delaware**. Therefore, in the precipitation projections to follow only STAR-ESDM projections will be discussed. However, all data and downscaled projections produced for STAR-ESDM (including all graphics) are available for LOCA2.

4.4. Precipitation Projections

4.4.1. Total Annual Precipitation

The total annual precipitation projections indicate an upward trend in precipitation for the State as a whole, and for each climate division in the coming decades. For the STAR-ESDM downscaled projections, the increase in statewide precipitation is approximately 2 inches for the SSP2–4.5 scenario (**Figure 4.7 top**), and 4 inches for SSP5–8.5 (**Figure 4.7 bottom**), between the current normals period (1991-2020; average total annual precipitation 45.7”) and the end of century vicennial period (2081-2099). For each SSP, the upward trend in total annual precipitation tends to decrease after approximately 2050, with a stable mean but large year-to-year variability through the end of the century. The change in the likelihood of total annual precipitation values is shown in **Figure 4.8** for STAR-ESDM using probability density functions. A probability density function, or PDF, is a way to describe how likely it is to find a value when those values can be any number within a range (like total annual precipitation values). Instead of giving the exact chance for a given precipitation total, the PDF shows how likely different values are overall by forming a smooth curve. The higher the curve at a certain point, the more likely values around that point will occur. If you add up (or more precisely, calculate the area under) the curve over a range of values, it tells you the total probability of getting a value within that range. For the current vicennial period (near; 2021-2040) the most probable value is approximately 45” while the “tails” of the distribution peak at about 50” for both SSPs. Moving through the rest of the century (the mid (2041-2060), post (2061-2080), and end (2081-2100) vicennial periods) there are two important points to note. First, the peak total annual precipitation probability moves to higher values, peaking at approximately 50” in the last vicennial period for both SSPs (**Figure 4.8**). In addition, the tails for the distribution move to higher total annual precipitation values later in the century reaching approximately 57.5” for each scenario (**Figures 4.8**).



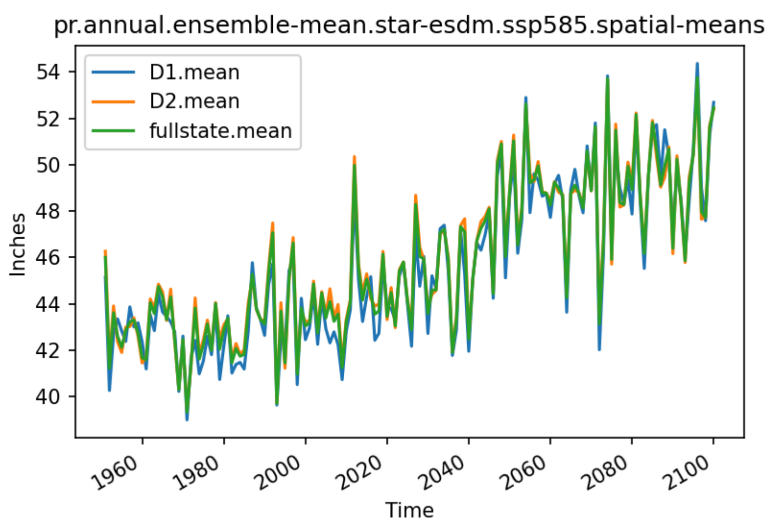


Figure 4.7. Ensemble mean time series of STAR-ESDM annual total precipitation projections under SSP2–4.5 (top), and SSP5-8.5 (bottom). Projections are shown for the full state (green), climate division 1 (blue), and climate division 2 (orange).

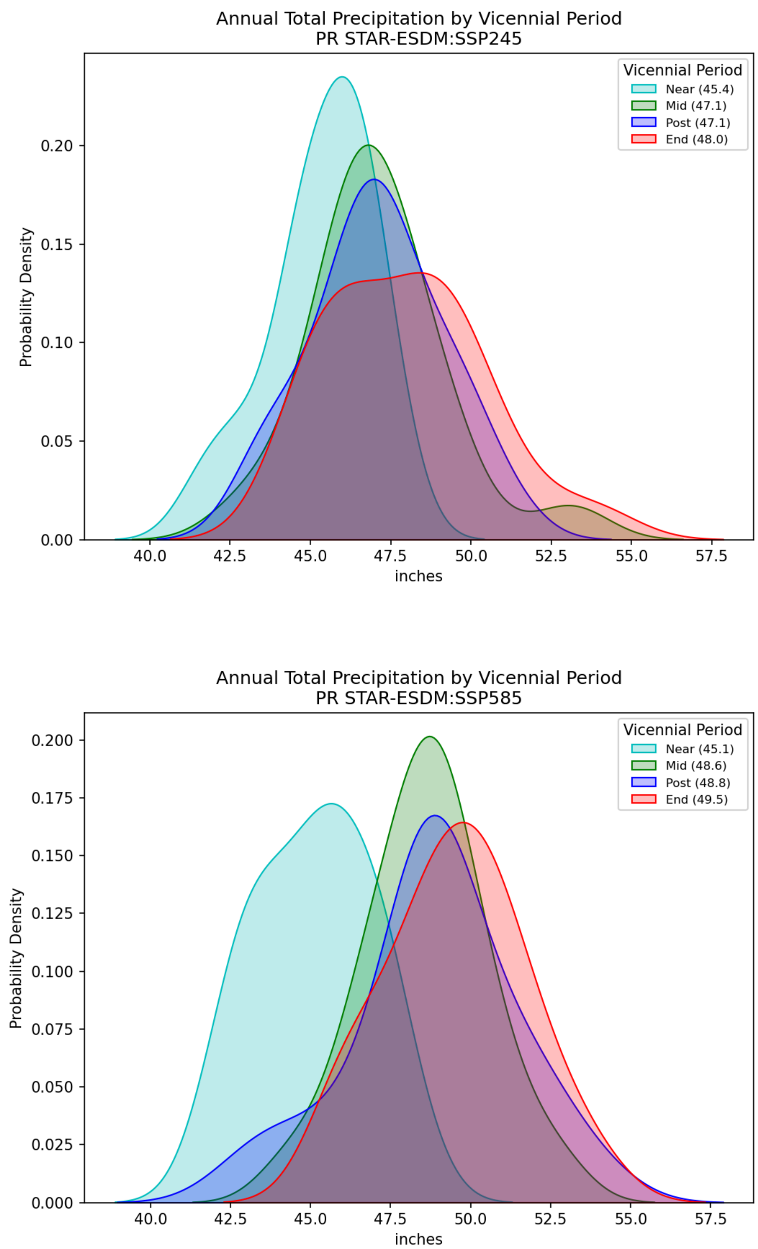


Figure 4.8. Probability density functions for each vicennial period for STAR-ESDM projections for SSP2–4.5 (top) and SSP5–8.5 (bottom).

4.4.2. Total Seasonal Precipitation

To ascertain the existence of seasonal trends in total precipitation each season was analysed individually. The seasons were constructed as winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November). Seasonal precipitation trends are of great importance, as shifting rainfall and snowfall patterns may have profound impacts on Delaware's environment, infrastructure, and economy. For example, more frequent and intense precipitation events could increase the risk of flooding, overwhelm stormwater management systems, and disrupt agriculture and water supply. Alternatively, longer dry spells or reduced snowfall in winter may impact ecosystems, reduce groundwater recharge, and affect agriculture, and other industries reliant on consistent water availability. **Figure 4.9** shows the 60-month running means of total precipitation for each season for the STAR-ESDM downscaling technique and for each SSP. All seasons show a small increasing trend except for the autumn season for SSP2–4.5. The autumn season shows an initial increase in precipitation, followed by a leveling off after about 2060. In SSP5–8.5 the spring, summer, and autumn all show an increasing trend in precipitation until approximately 2070 to 2080, after which the trends level off to the end of the century. The winter season shows the strongest upward trend in precipitation of all seasons under both scenarios.

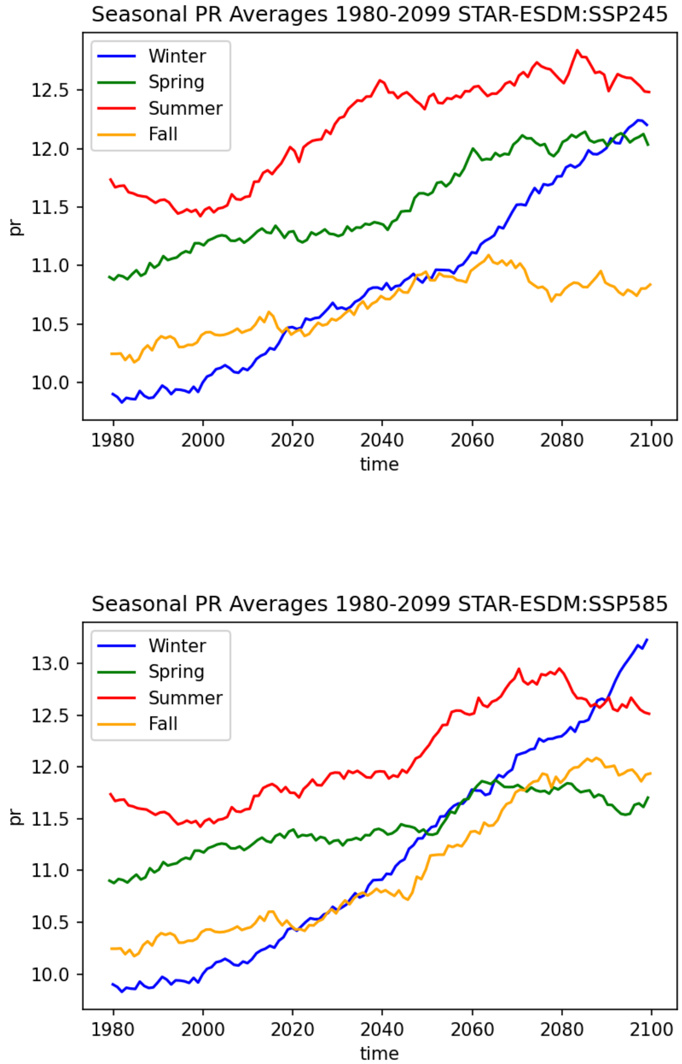


Figure 4.9. 60-month running mean times series of total annual precipitation for each season for SSP2–4.5 (top), and for SSP5–8.5 (bottom).

4.4.2.1. Winter

Winter annual precipitation totals show a consistent upward trend through the end of the century for each SSP, providing the largest projected increase in precipitation of any season by the end of the century. Winter precipitation increases from the current 1991-2020 mean value of 10.05 inches to approximately 14 inches by the end of the century in the SSP5–8.5 scenario (**Figure 4.10**). However, it is important to note that there was no trend apparent in the historical analysis of winter precipitation over the period from 1895-2024 described in the historical analysis of Chapter 3.

4.4.2.2. Spring

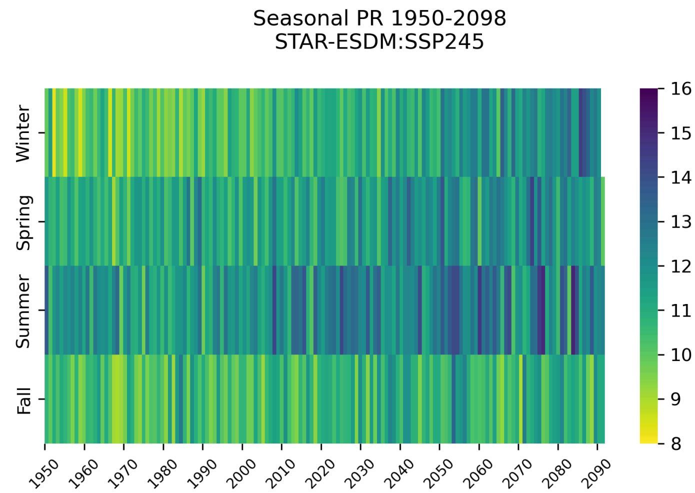
Mean spring precipitation for the current climate normals period of 1991-2020 averaged 11.18 inches across Delaware. Changes in spring precipitation by the end of the century are small for each scenario, with significant interannual variability (**Figure 4.10**). Again, it is important to note that there was no trend apparent in the historical analysis of spring precipitation over the period 1895-2024.

4.4.2.3. Summer

Mean summer precipitation for the current climate normals period of 1991-2020 averaged 13.20 inches across Delaware, the wettest season of the year. Changes in summer precipitation by the end of the century are small for each scenario (generally less than 2 inches; **Figure 4.10**). In addition, an increase in summer precipitation variability becomes apparent in later decades of the century. Similar to winter and spring, there was no trend apparent in the historical analysis of summer precipitation over the period from 1895-2024.

4.4.2.4. Autumn

Mean autumn precipitation for the current climate normals period of 1991-2020 averaged 11.42 inches across Delaware. Changes in fall precipitation by the end of the century are small for each scenario (generally less than 2 inches; **Figure 4.10)**, with little to no trend seen in the SSP2–4.5 scenario and a small positive trend apparent after 2050 in the SSP5–8.5 scenario which declines toward the end of the century. Interestingly, autumn was the only season that showed a significant trend in precipitation of 0.18” / decade from 1895-2024. A trend not replicated well by the models during the period of historical overlap (1950-2024).



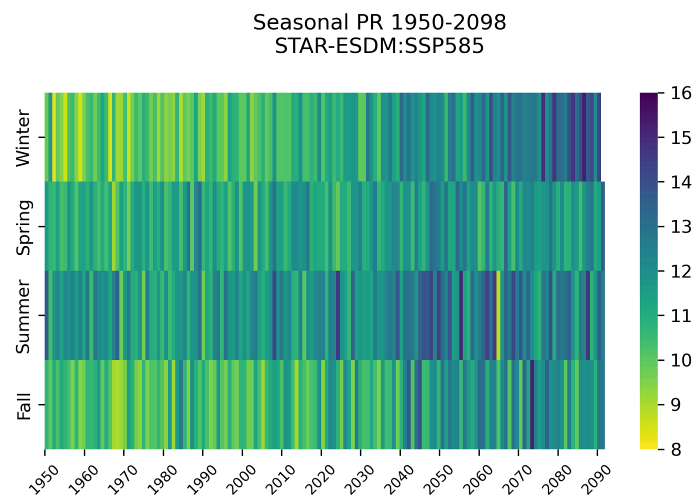


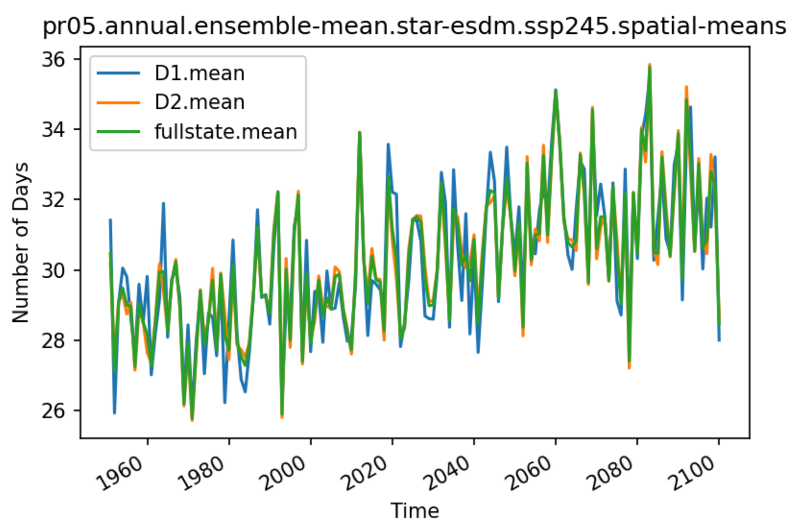
Figure 4.10. Precipitation "stripe" graphs for each season for STAR-ESDM SSP2–4.5 (top), and STAR-ESDM SSP5–8.5 (bottom).

4.4.3. Extreme Precipitation

Daily precipitation extremes have become a major topic in understanding the regional impacts of climate change, as the frequency and intensity of heavy rainfall events have shown an increase in recent decades (Leathers et al. 2019). Warmer conditions lead to an increase in the saturation vapor pressure of the atmosphere (the water holding capacity), leading to the potential for intense precipitation events when that moisture is released. Such extreme events can have important impacts, including flash flooding, infrastructure damage, soil erosion, and water quality degradation, to name just a few. In order to understand the changing nature of extreme precipitation across Delaware, gridded projections for each SSP were spatially averaged across the State for each year. **Put in simple terms, the number of days reaching a given threshold (0.5”, 1.0”, 2.0”) at each grid point across the State was first calculated for each year. Subsequently, the number of days for a given threshold value for each grid point was added together and then divided by the total number of grid points to produce a spatial average value for the entire State. It is also important to note that these thresholds are calculated using a calendar day total. These daily totals are not precipitation event totals which may span any 24-hour period, or last for more than a single 24-hour period.**

4.4.3.1. Number of Days with Precipitation ≥ 0.5 inch

The projected number of days with precipitation amounts greater than or equal to 0.5” across Delaware is shown in **Figure 4.11** for each SSP. The projections show an increase of between two days (SSP2-4.5) and four days (SSP5-8.5) in the number of days reaching 0.5” of rainfall between the current normal period and the end of the century. This suggests an approximate 6% to 12% increase in the number of days reaching a threshold of 0.5” by 2100, based upon the most recent 30-year normal period for the Wilmington/New Castle County Airport station (079595) which experienced an average of 31 days each year with precipitation greater than or equal to 0.5”.



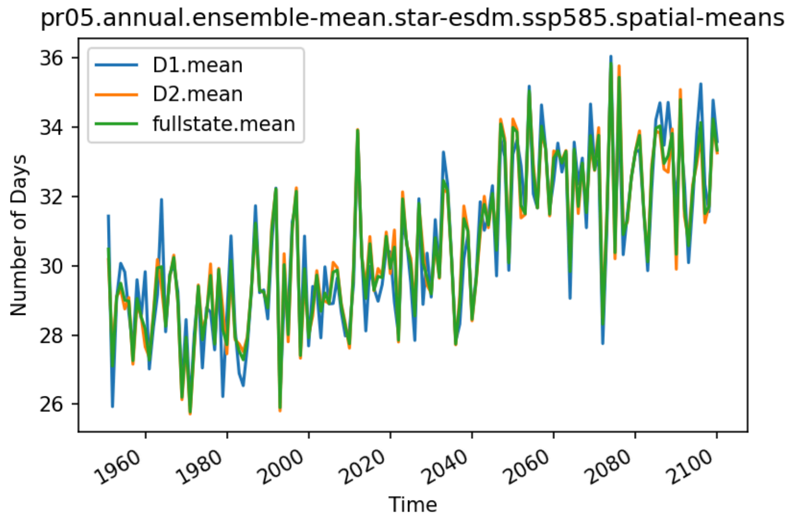
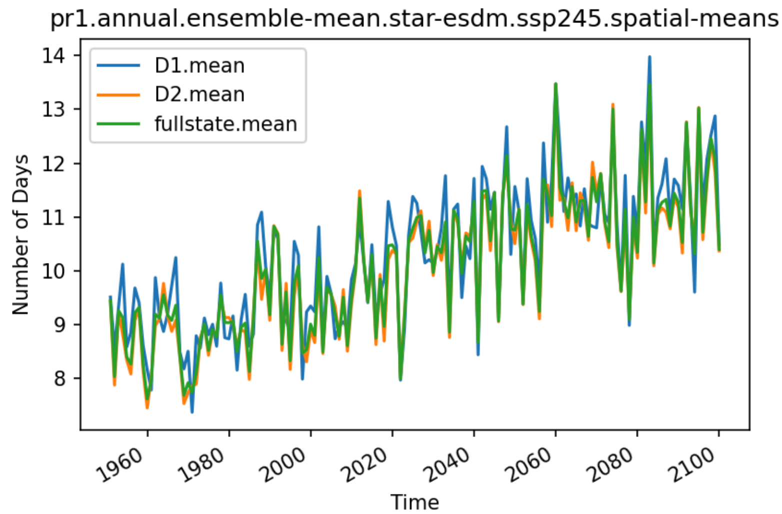


Figure 4.11. Number of days with precipitation greater than or equal to 0.5" for STAR-ESDM SSP2–4.5 (top), and SSP5–8.5 (bottom). All time series represent ensemble means. Full state (green), division 1 (blue), and division 2 (orange).

4.4.3.2. Number of Days with Precipitation ≥ 1 inch

The projected number of days with precipitation amounts greater than or equal to 1.0" across Delaware is shown in **Figure 4.12** for each SSP and downscaling technique. For SSP2–4.5, the projections show an increase of approximately 2 days in the number of days reaching 1.0" of rainfall between the current 30-year normal (1991-2020) and the end of the century. For SSP5–8.5 the increase is approximately 3 days. Thus SSP5–8.5 indicates an increase of approximately 25% in the number of days reaching the 1.0" threshold by 2100. The percentages are based upon the most recent 30-year normal in which Delaware experienced an average of 12 days with precipitation greater than or equal to 1.0" each year.



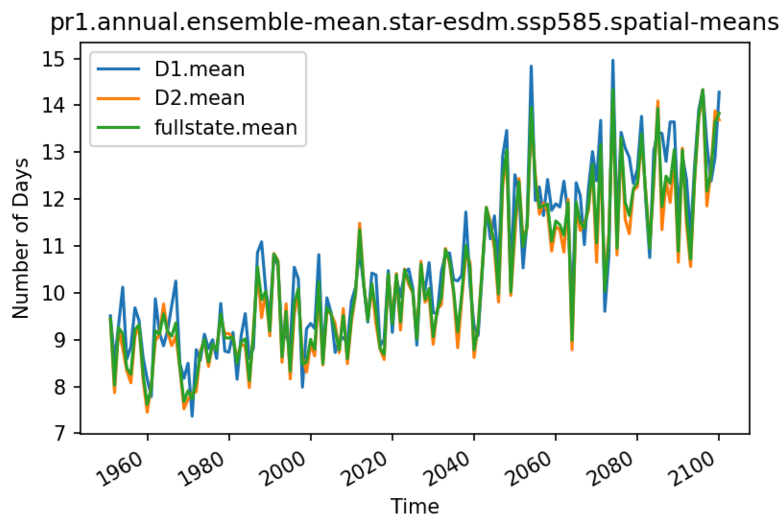
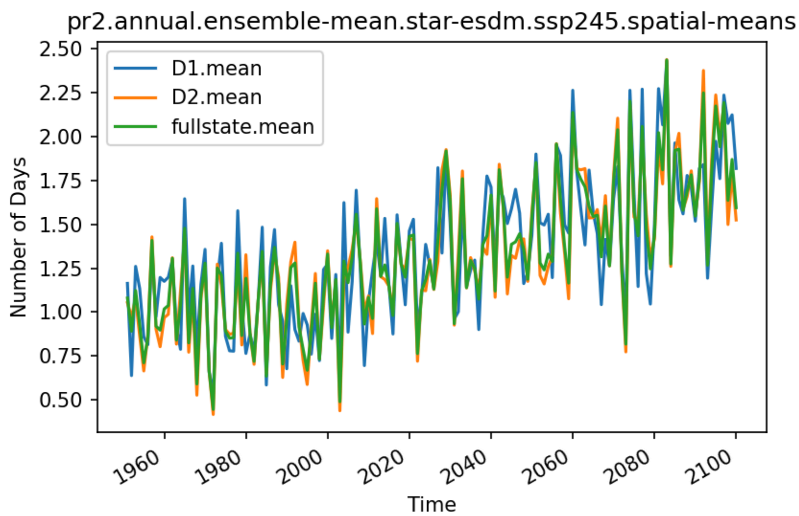


Figure 4.12. Number of days with precipitation greater than or equal to 1.0" for STAR-ESDM SSP2–4.5 (top), and SSP5–8.5 (bottom). All time series represent ensemble means. Full state (green), division 1 (blue), and division 2 (orange).

4.4.3.3. Number of Days with Precipitation ≥ 2 inches

The projected number of days with precipitation amounts greater than or equal to 2.0" across Delaware is shown in **Figure 4.13** for each SSP. The fractional number of days reaching the 2.0" threshold on the projection graphs is due to the spatial averaging across the State. For SSP2–4.5, the projections show an increase of less than one day in the number of days reaching 2.0" of rainfall between the current 30-year period (1991-2020) and the end of the century. For SSP5–8.5 the increase is approximately one day. Thus SSP5–8.5 indicates a 50% increase in the number of days with 2.0" rainfall, based upon the most recent 30-year normal in which Delaware experienced an average of only two days with precipitation greater than or equal to 2.0” each year. **However, it should be noted that each SSP shows only a small practical increase in the likelihood of 2.0” precipitation days across the State, of one additional day per year by the end of the century.**

Days with higher daily precipitation thresholds have occurred across Delaware in the historical record. However, daily values greater than 2.0” are rare. During the period 1991-2020 at the Wilmington/New Castle County Airport station (Coop 079595) the 3.0” threshold was reached on average once every other year, the 4.0” threshold once every 5 years, and the 5.0” threshold once every 10 years. Projections for each SSP give average statewide values for all higher thresholds of less than one day per year for all thresholds 3.0” and larger. Thus, the projections for thresholds greater than 2.0” are not shown since the number of these events is so small.



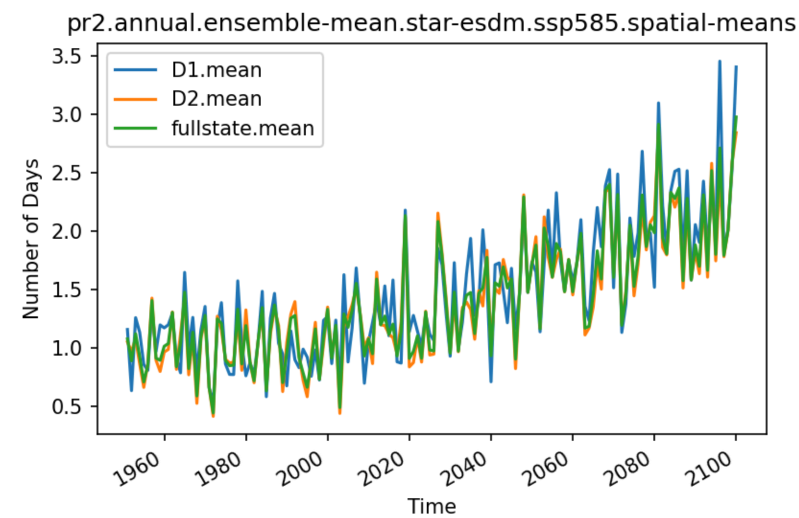


Figure 4.13. Number of days with precipitation greater than or equal to 2.0” for STAR-ESDM SSP2–4.5 (top), and SSP5–8.5 (bottom). All time series represent ensemble means. Full state (green), division 1 (blue), and division 2 (orange).

4.5 Precipitation Projections Summary

Total annual precipitation results are summarized in **Table 4.3**. The total annual precipitation projections indicate an upward trend in precipitation for the State as a whole, and for each climate division in the coming decades. For the STAR-ESDM downscaled projections the increase in precipitation between the current normal (1991-2020) and the end of century (2081-2100) is between 2" and 2.5" for the SSP2–4.5 scenario (5%; **Table 4.3**), and approximately 4" for SSP5–8.5 (9%; **Table 4.3**). Seasonally, winter generally has the strongest upward trend in precipitation of all the seasons. Autumn season precipitation actually decreases after 2060 under SSP2–4.5 and late in the century under SSP5–8.5. All other seasons see an upward trend for each SSP with SSP5–8.5 generally seeing the largest precipitation increases. Projections of extreme precipitation show an increase in the number of days of precipitation greater than or equal to 0.5" of approximately 12% under SSP5–8.5, and number of days of precipitation greater than or equal to 1.0" of approximately 25% by the end of the century for SSP5–8.5. The number of days greater than or equal to 2.0" increases by only one-day by the end of the century under SSP5–8.5. Higher precipitation thresholds (greater than 2.0") increase by less than one-day per year for both downscaling techniques and for both SSPs by the end of the century. Thus, the models project Delaware to receive more total annual precipitation by the end of the century, with associated increases in extreme precipitation days.

Table 4.3. Summary of precipitation changes (inches) for each vicennial period from 2021-2100 for both SSPs for mean annual, minimum annual and maximum annual precipitation for each vicennial period. Numbers in parentheses indicate the increase in precipitation between that vicennial period and the previous. The last column shows the difference between the end of century vicennial period (2081-2100) and the current normals period (1991-2020).

Annual Precipitation	Near-century 2021-2040		Mid-century 2041-2060		Postmid-century 2061-2080		End-century 2081-2100		End of Century Diff from 1991-2020 Normal	
	SSP2-4.5	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*	*SSP2-4.5*	*SSP5-8.5*
Minimum	41.6 (+1.9)	41.9 (+2.2)	42.9 (+1.3)	44.4 (+2.5)	43.6 (+0.7)	43.1 (-1.3)	44.7 (+1.1)	45.9 (+2.8)	-	-
Mean	45.4 (+1.2)	45.1 (+0.9)	47.1 (+1.7)	48.6 (+3.5)	47.1 (0.0)	48.8 (+0.2)	48 (+0.9)	49.5 (+0.7)	2.3	3.8
Maximum	47.7 (-2.3)	48.3 (-1.7)	53.1 (+5.4)	52.6 (+4.3)	51 (-2.1)	53.7 (+1.1)	53.8 (+2.8)	53.8 (+0.1)	-	-

4.6 References

Leathers, D. J., Brasher, S. E., Brinson, K. R., Hughes, C., & Weiskopf, S. (2020). A comparison of extreme precipitation event frequency and magnitude using a high-resolution rain gage network and NOAA Atlas 14 across Delaware. *International Journal of Climatology*, 40(8), 3748–3756. https://doi.org/10.1002/joc.6425

SAS Institute Inc. (2024). *JMP® Statistical Discovery Software.* Cary, NC: SAS Institute Inc. Available at: https://www.jmp.com

Ullrich, P. A. (2023). Validation of LOCA2 and STAR-ESDM Statistically Downscaled Products (LLNL-TR-856094; OSTI ID 2202926). Lawrence Livermore National Laboratory. https://doi.org/10.2172/2202926

Vose, R. S., Applequist, S., Squires, M., Durre, I., Menne, M. J., Williams, C. N., Fenimore, C., Gleason, B., & Arndt, D. (2014). *Improved Historical Temperature and Precipitation Time Series for U.S. Climate Divisions.* Journal of Applied Meteorology and Climatology, **53**(5), 1232-1251. https://doi.org/10.1175/JAMC-D-13-0248.1

5. Sea Level

Water levels have been monitored regularly in the State of Delaware for nearly a hundred years. Mean sea levels in Delaware have been increasing since at least when direct measurements began in the early 1900s. Historically, for thousands of years in the geologic past, GMSL has been relatively constant with Delaware experiencing only minimal increase due to land subsidence (Callahan et al., 2017). Delaware has also experienced its share of extreme coastal flooding events from storms that were both tropical (Hurricane of 1878, and Hurricanes Gloria in 1985, Isabel in 2003, and Sandy in 2012) and extratropical (Ash Wednesday Storm of 1962, and the back to back nor'easters in Jan/Feb of 1998) in origin. A predominantly coastal state with its low flat terrain, increasing coastal residential development, and significant amounts of its natural resources and human infrastructure located along the shoreline, Delaware's economy and culture are especially vulnerable to coastal flooding. In recent decades, mean sea levels in Delaware and the surrounding region have been accelerating (Sweet et al., 2022), further increasing the frequency of minor floods, the likelihood of extreme flooding events, and the risk of damage to private property, public infrastructure, and natural resources.

This chapter describes the NOAA water level monitoring stations used as primary data sources in this report and general descriptions of the dominant drivers of sea level change in Delaware. Past observations of sea levels are provided that form the basis of current sea level trends and to place projected future changes in context, including changes in mean sea level, frequency (i.e., annual counts) of minor coastal flooding events, and likelihood of more extreme coastal flooding events. It then presents projections of sea levels in Delaware for the rest of the 21st century based on the latest science prepared for the IPCC AR6 and US NCA5 reports.

5.1. Water Level Data and Monitoring Stations

Recent decades have seen increased environmental monitoring efforts throughout government, academic, and private sectors. For coastal water levels, NOAA's National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) is the authoritative source for accurate, reliable, and timely tides, water levels, currents, and other coastal oceanographic and meteorological information for the US[22]. These data help keep safe and efficient maritime commerce, protect coastal economies and infrastructure, and provide the foundation for numerous hydrologic and hydrographic products. In particular for climate studies, CO-OPS manages the National Water Level Observation Network (NWLON)[23], a permanent observing system for observing, communicating, and assessing the impact of changing water levels nationwide. Delaware is home to two NWLON stations: Lewes Breakwater Harbor and Reedy Point (**Figure 5.1**).

[22] https://tidesandcurrents.noaa.gov/about_us.html
[23] https://tidesandcurrents.noaa.gov/nwlon.html

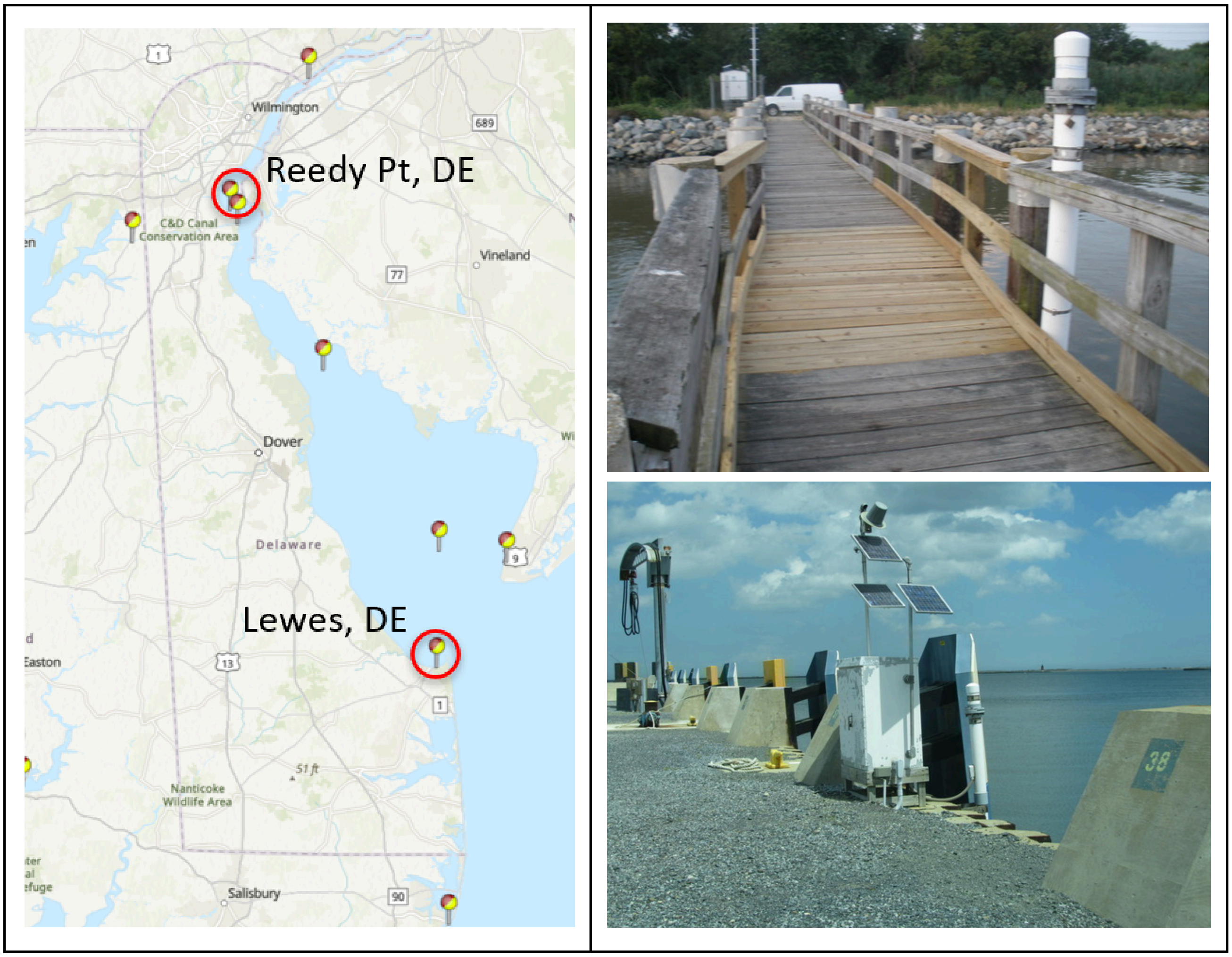


Figure 5.1. (Left) Map of NOAA CO-OPS active water level stations in and around the State of Delaware. Reedy Point and Lewes stations are both part of the National Water Level Monitoring Network (NWLON). Photos of the Reedy Point (right top) and Lewes (right bottom) installations.

Reedy Point (**Table 5.1**) is located on the east end of the Chesapeake and Delaware (C&D) Canal, immediately south of Delaware City, at the confluence of the northern Delaware Bay and mouth of the Delaware River. It is generally representative of coastal marine conditions in the northern parts of the state. NWS uses real-time conditions and forecasts at this site to provide coastal flood advisories for New Castle County. Lewes is located near the town of Lewes, immediately to the west of Cape Henlopen State Park, situated behind a human-made breakwater in southern Delaware Bay. Observations and forecasts at Lewes are generally representative of the southern part of the state and often used by NWS to provide advisories in those regions. Both stations have long periods of record as well as high quality vertical reference, datums, and tide predictions. Note water levels measured by tide gauges inherently include influences from most contributing processes, such as astronomical tides, storm surge, discharge from nearby rivers and streams due to precipitation and runoff, ocean currents, and other forces. However, tide gauge installations are specifically designed to minimize the effects of waves; oftentimes tide gauge observations are referred to as “stillwater” levels.

Table 5.1. Basic metadata for Lewes and Reedy Point CO-OPS stations. NOAA Station IDs are hyperlinked to station home pages. Tidal datum and NAVD88 offset values are referenced to National Tidal Datum Epoch (NTDE) 1983 - 2001.

	Reedy Point	Lewes
NOAA Station ID	8551910	8557380
Latitude, Longitude	39.558333, -75.571944	38.782833, -75.119278
Period of Record	1957 - present	1919 - present
MLLW	-0.890 m / -2.92 ft	-0.68 m / -2.23 ft
MHHW	0.890 m / 2.92 ft	0.738 m / 2.42 ft
Tidal Range	1.779 m / 5.84 ft	1.418 m / 4.65 ft
NAVD88 Offset	0.015 m / 0.05 ft	0.121 m / 0.40 ft

The Delaware Bay has a classical funnel shape with a width of about 18 km at its mouth between Cape Henlopen and Cape May and expanding to ~45 km at its widest point (Wong and Münchow, 1995). Average bathymetry is about 7 meters although deep scour in the middle of the lower part of the bay can extend to over 20–25 m (Eagleson and Ippen, 1966; Harleman, 1966; Salehi, 2018). The converging coastlines toward the head of the bay amplifies tides in the northern regions, where the tidal range is over 2 m compared to <1.5 m near the mouth (Lee et al., 2017; Ross et al., 2017). Northern portions of the Delaware Bay are more influenced by discharge from the Delaware River (during heavy precipitation runoff events) and more influenced by water entering into the Bay from the ocean due to near shore currents or remote winds. The southern portion of the Bay also has a higher frequency of being impacted by tropical systems than the northern portion (Callahan, et al., 2022). Measured over the current National Tidal Datum Epoch (NTDE) time period of 1983 - 2001, the tidal range at Reedy Point and Lewes tide gauges are 5.84 ft (1.78 m) and 4.66 ft (1.42 m), respectively (**Table 5.1**). Tidal range, by definition, measures the difference between the mean lower-low water (MLLW) and mean-higher high water (MHHW) datums, which are -2.92 ft to 2.92 ft for Reedy Point, and -2.23 to 2.42 ft for Lewes, all values relative to mean sea level. The higher MHHW datum at Reedy Point is indicative of the geomorphological shape of the Delaware Bay.

Although hourly water levels in Delaware predominantly follow astronomical tides, with two high tides and two low tides per day, coastal flooding is mostly driven by meteorological processes that raise waters above the tides. Tides explain only about 35% and 41% of the daily maximum variance at Reedy Point and Lewes, respectively (Dusek et al., 2022). The remaining percentage is made up of mostly storm surge, atmospheric pressure effects, river discharge, and waves. Wave runup (a combination of both wave setup and wave swash), contributes a larger proportion during more extreme events as the magnitude of the flood levels increases (see Box 3.1 in the 2022 ITF Report, Quadrado and Serafin, 2024; McKeon and Piecuch, 2025).

5.2. Process Contributions to Mean Sea Level Change

As mentioned in the Introduction, GMSL rise is directly related to changes in the global ocean's volume, which can be separated into two primary drivers: 1) thermal expansion due to warming, and 2) increase in ocean mass due to the meltwater from land-based mountain glaciers, GIS, and AIS, with interannual variation due to LWS. Regional drivers from changing ocean circulation patterns and ice sheet GRD effects, as well as VLM due to GIA and groundwater extraction, all further increase sea levels along Delaware coasts (Callahan et al., 2017). IPCC AR6 modeling efforts combined some of these components together to estimate changes at point locations. Sterodynamic refers to changes in ocean density, including both ocean thermal expansion (which is a global process) and changes to nearby Atlantic Ocean currents (which is a regional process)[24]. Increases in the ocean's mass come from melting of mountain glaciers, GIS, and AIS, as well as reductions in LWS. VLM in this context includes the combined effects of GIA, GRD, and other background non-climatic factors.

Since the satellite altimetry era began, the rate of GMSL rise is approximately 3.4 mm/yr, resulting in a total GMSL increase of 0.335 ft in the last 31 years (NASA, 2025). Prior to the 1970s, the leading driver was thermal expansion (Kemper-Fox et al.,, 2021). Since that time, increases in the ocean's volume of water from GIS and AIS have become a larger factor than thermal expansion (NASA, 2025). Several studies have noted that GMSL has accelerated in recent decades and is expected to continue (Nerem et al., 2022; Cazenave et al., 2018; Dangendorf et al., 2019; Kemper-Fox et al., 2021; Frederiske et al., 2020; Hamlington et al., 2024). The primary components of US mean sea level change (1993 - 2023) were sterodynamic changes (45%), ice melt and land water storage (30%), and VLM (40%) (**Figure 5.2**).

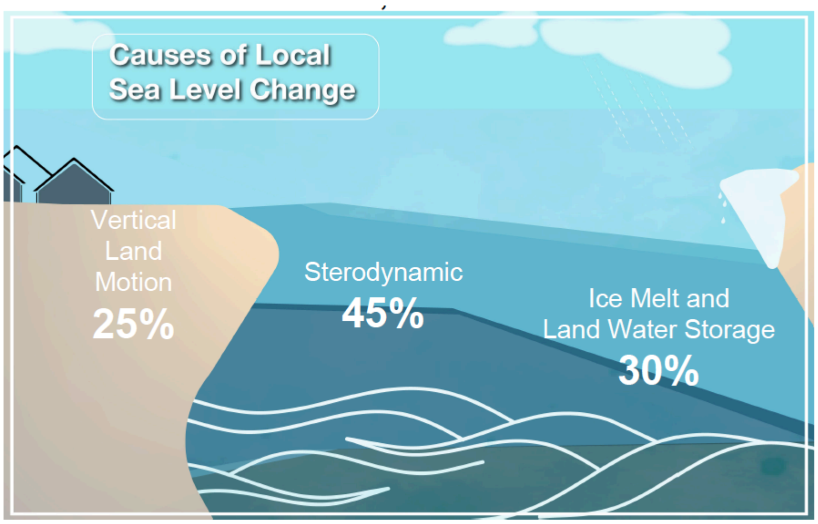


Figure 5.2. Contributions of observed changes in relative sea level rise averaged over the contiguous US for the time period 1993 to 2024. Source: US Sea Level Change website[25]

[24] https://earth.gov/sealevel/us/sea-level-101/local-sea-level-change/dive-deeper/
[25] https://earth.gov/sealevel/us/national-sea-level-explorer/?type=regional&region=USA&scope=section_1

5.3. Historical Observations of Sea Level in Delaware

Observations of the past provide insight about what sea levels may be like in the future and are essential in assessing risk associated with a changing climate. They help identify main drivers of sea level change that are occurring in Delaware and whether they are driven by regional, global, or local processes. They allow us to quantify changes in mean sea levels, internal seasonal and interannual variability, and episodic extreme coastal flooding events. Historical records combined with modeling can help estimate how fast and by how much these processes may change in the future, coincident with other expected changes in the ocean, atmosphere, land surface, and hydrologic cycle.

Although sea levels have been changing along the Delaware for thousands of years in the geologic past, this report covers only modern observations over approximately the past hundred years. Observed data in this chapter come directly from the Reedy Point and Lewes tide gauges. Only data approved and made publicly available by CO-OPS are used in the analysis.

In this section, we highlight three primary types of measures for tracking historical sea levels: mean sea level, flood frequency, and extreme events.

- Mean sea levels: average of the hourly water level observations for each month. Includes past trends and variability, process contributions, and seasonal cycle.
- Flood frequency: annual counts (e.g., number of days each year) water levels reached or exceeded defined flood impact thresholds. Includes past trends and variability.
- Extremes: the highest coastal flooding events, the water levels associated with rare return periods (e.g., the 100-year return level), and the probability distributions of daily maximum water levels.

5.3.1. Mean Sea Level Change

Monthly mean sea level observations (blue) and a smoothed curve with an approximate 5-year window (red) at the Reedy Point and Lewes tide gauges are provided in **Figure 5.3**. Monthly mean data seen here is the mean of all hourly observations for each month. Data is quality checked and published every month by CO-OPS. Each of these plots show all available monthly mean data over the station’s complete period of record (POR). Values are in feet relative to the mean sea level for the year 2000 (i.e., the observation curves cross the zero line at approximately year 2000).

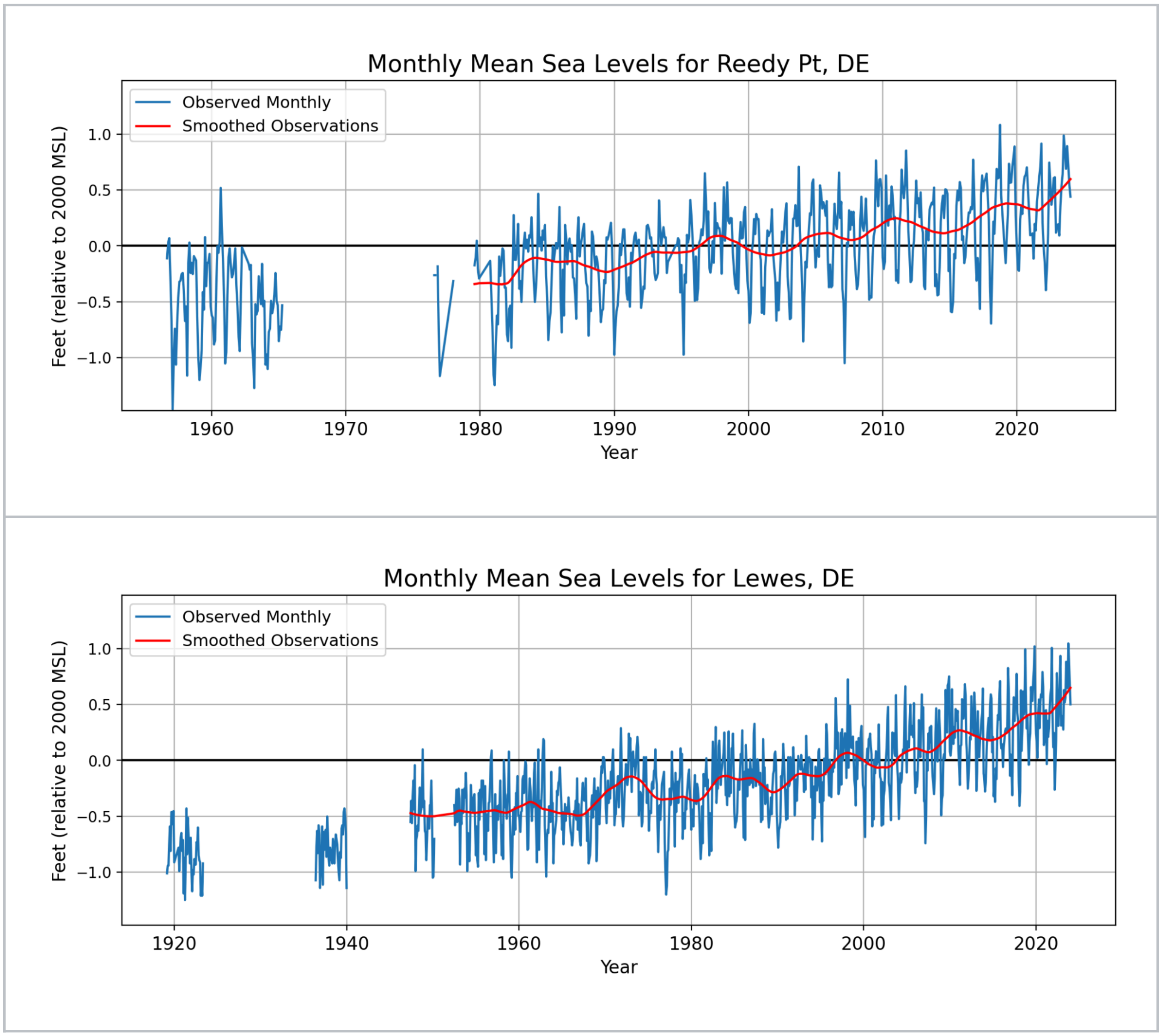


Figure 5.3. Monthly mean sea levels observed at Reedy Point (top) and Lewes (bottom) tide gauges over their full period of record. Red line shows LOWESS smoothing using approximately a 5 year smoothing window. Strong seasonality and long term trend can be seen in the observations. The smoothed curve also exhibits at approximately 4-7 year time periods.

Several things stand out. First, sea levels have been increasing, which is well known to be occurring in Delaware and has been documented in several past state and national reports (Callahan et al., 2017; Sweet et al., 2022). Second, the data shows a very strong seasonal signal (see next section) and interannual variation, seasonal of which is larger than the year to year variations. Third, the 5-year smoothed curve shows periodicity at annual time scales of approximately 4-7 year intervals.

Identical information in **Figure 5.3** is shown in heatmap form in **Figure 5.4** (below). In these visualizations, trends and seasonality are easily depicted through the concentration of more red colored boxes in the later part of the records during the late summer and fall and more blue boxes in the early part of the records in the winter months. Spring and late fall months show the highest year to year variation. Note the last couple of years are colored red for all months for each of the tide gauges. The lowest monthly sea levels in the most recent years are higher than the highest months at the beginning of record for each tide gauge.

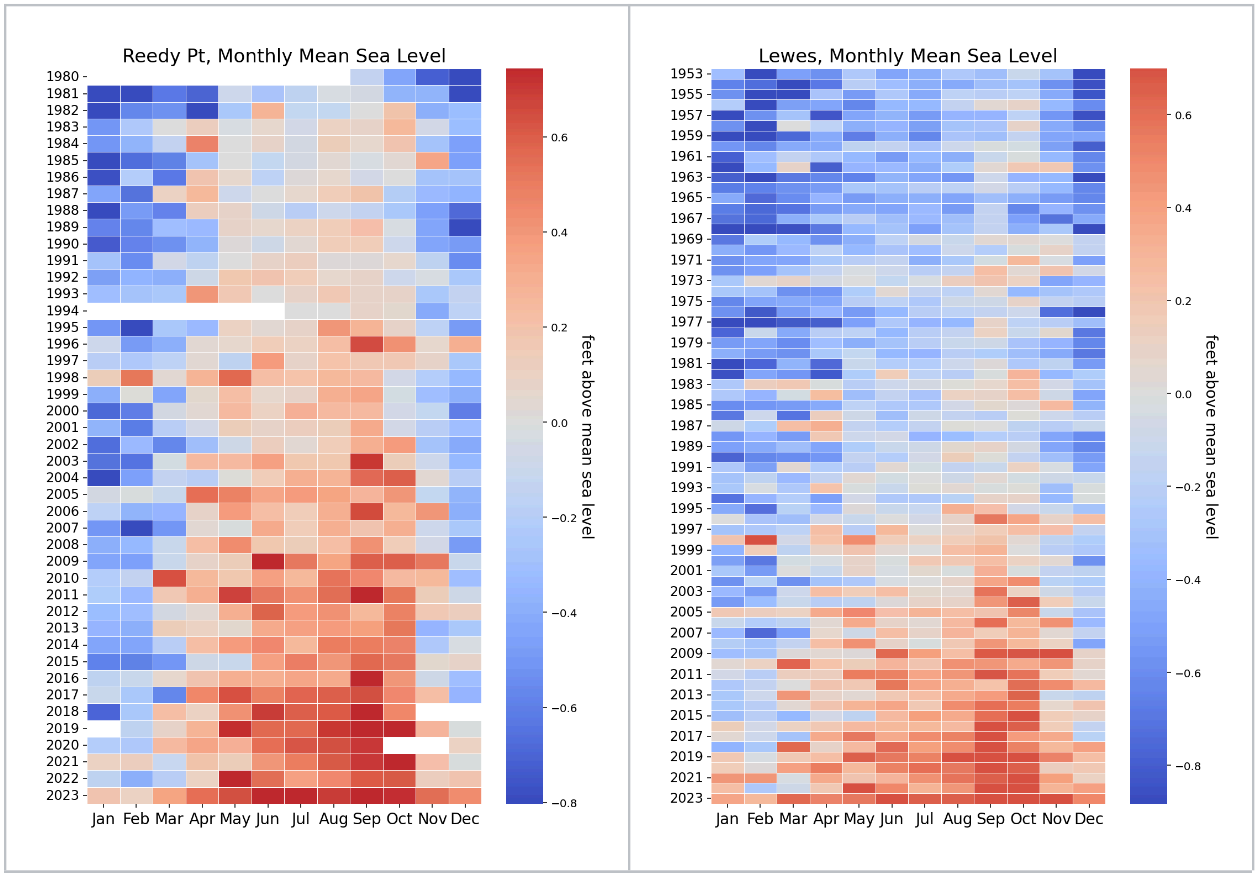


Figure 5.4. Heatmap of monthly mean sea levels observed at Reedy Point (left) and Lewes (right) over their full periods of record. Red colors indicate higher sea levels; blue colors lower sea levels. Data are relative to year 2000 mean sea level. The strong seasonal cycle and long-term trend occurring at both gauges are easily depicted in these visualizations.

Both gauges show very similar patterns of sea level variability, as demonstrated by periods of the monthly anomalies above and below the trend line in **Figure 5.5** and cycles of the monthly observations in **Figure 5.3**, implying similar forcing mechanisms at both locations over the seasonal, interannual, and decadal time scales. Although it is beyond the scope of this report to decompose the observational time series into individual components, studies have shown that interannual variations in the Mid-Atlantic region are influenced by the lunar perigean cycle (4.4/8.85 years), El Niño Southern Oscillation (ENSO, ~4-7 years) (Sweet and Park, 2014; Sweet et al., 2012, 2018), and to a lesser extent, the strength of the nearby Gulf Stream/AMOC and atmospheric pressure patterns. At longer time scales, low frequency mean sea levels along the Mid-Atlantic coasts are influenced by the lunar nodal cycle (18.61 years) (Thompson et al., 2021), Atlantic Ocean sea surface temperatures and tropical cyclone frequency, and North Atlantic Oscillation (NAO) atmospheric pressure patterns.

Linear trends of monthly anomalies were produced for each tide gauge over 1984 to 2023 (**Figure 5.5**). This 40-year time period was chosen to be at least as long as the typical 30 year period for determining a climate reference of temperature and precipitation normals, and be inclusive of two complete lunar nodal (18.61 year) cycles. The statistical methodology followed in computing the linear trend uses an Autoregressive Integrated Moving Average (ARIMA, with lag 1) model and is identical to methods followed by CO-OPS in their Sea Level Trends product (CO-OPS, 2025; Zervas, 2009). The rate of SLR is recorded as the slope of the trend line. Rates of SLR from tide gauge observations include all factors affecting water levels at that location, such as form global, regional, and local VLM processes.

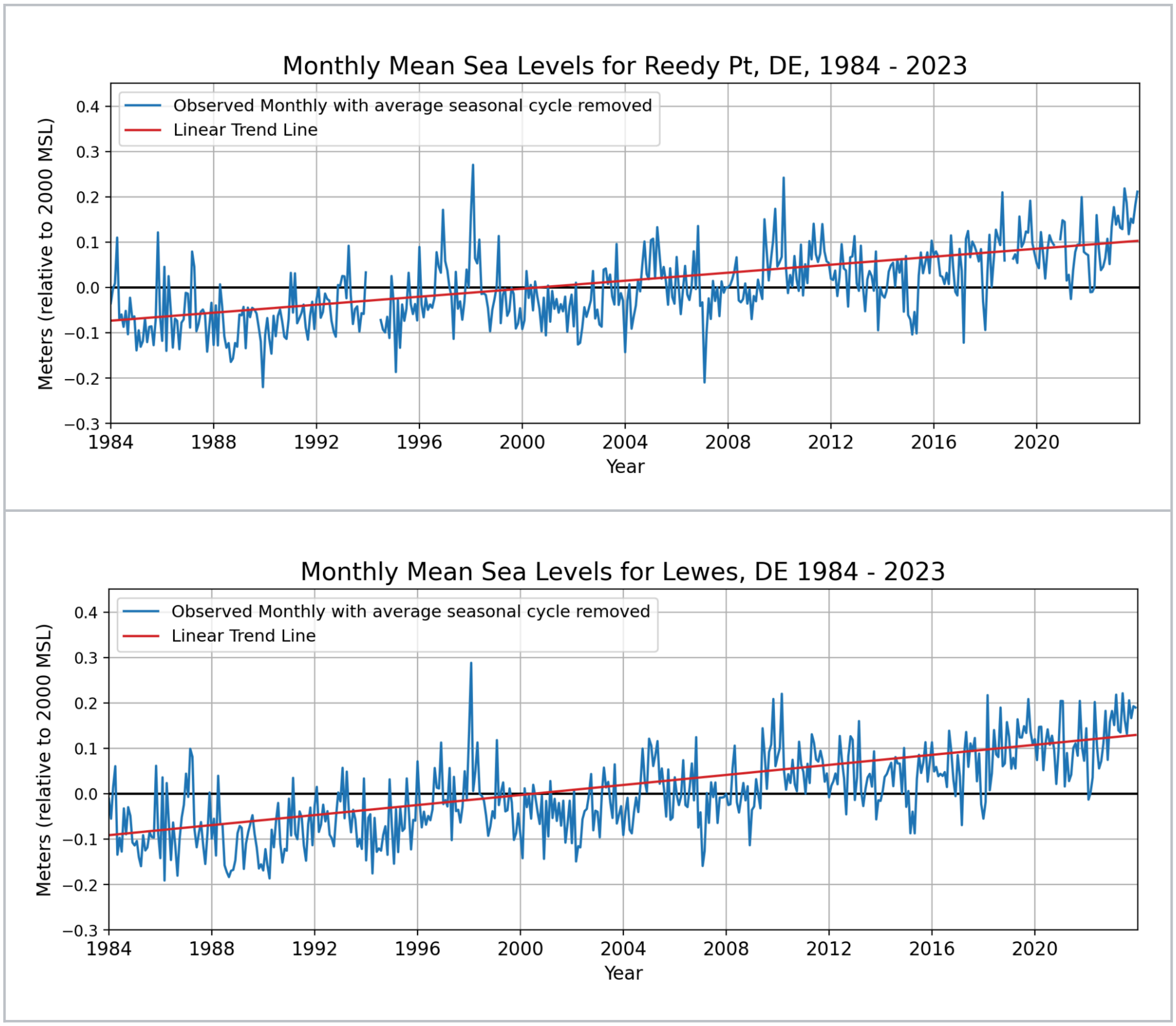


Figure 5.5. Monthly mean sea level observations with average seasonal cycle removed (blue line) and the linear trend fit (red line) at the Reedy Point (top) and Lewes (bottom) tide gauges over 1984 to 2023. Data are relative to year 2000 mean sea level.

Linear SLR rates for each station's period of record as well as the most recent 20, 30, and 40 year time periods are provided in **Table 5.2**. Relative mean sea levels at the Lewes gauge are increasing faster over the past 40 years (5.52 mm/yr) than at the Reedy Point gauge (4.41 mm/yr), with very similar 95% confidence intervals of 0.75 and 0.71 mm, respectively.

Table 5.2. Linear trend rates of mean sea level observations at the Reedy Point and Lewes tide gauges. The four columns represent linear rates over different time periods using identical statistical methodologies. Higher rates for recent shorter time periods indicate acceleration of mean sea levels.

Station (Period of Record)	**Linear Rates of Sea Level Rise at Delaware Tide Gauges**			
	Last 20 years 2004 - 2023	**Last 30 years 1994 - 2023**	**Last 40 years 1984 - 2023**	**Period of Record through 2023**
Reedy Point (67 years)	5.82 +/- 2.04 mm/yr	4.86 +/- 1.27 mm/yr	4.41 +/- 0.75 mm/yr	3.91 +/- 0.42 mm/yr
Lewes (104 years)	7.09 +/- 1.83 mm/yr	6.19 +/- 1.08 mm/yr	5.52 +/- 0.71 mm/yr	3.71 +/- 0.24 mm/yr

Rates of sea level rise in Delaware have increased in recent years, continuously increasing over shorter time periods. The far right column in **Table 5.2** shows the linear rates computed over the entire period of record at each location, which are understandably lower. The much longer period of record at Lewes, going back to 1919, supports its lower SLR rate given similar sea level patterns and forcing mechanisms. Similarly, compared to the rates reported in the last Delaware SLR report released in 2017 (which included data up to year 2016), linear rates have increased from 3.53 to 3.91 mm/yr at Reedy Point and 3.42 to 3.71 mm/yr at Lewes, indicative that sea levels have risen faster in approximately the last 7 years since 2017.

This acceleration has been previously noted in Delaware (DNREC, 2012; Callahan et al., 2017) and throughout the Mid-Atlantic region (Sallenger et al, 2012; Kopp 2013; Boon et al., 2018; Sweet et al., 2022). A 40-year time period nearly aligns with two complete lunar nodal cycles, which we have seen are influenced in coastal water levels in Delaware, and linear rates over that time period may be a reasonable approximation to average change in the recent past. However, due to the observed acceleration and monthly-to-annual variation, a linear trend over any past time period should not be used to estimate sea levels in the future.

The linear SLR rate over the last 40 years is higher at Lewes than at Reedy Point. The higher rate at Lewes may be due to its location near the mouth of the Delaware Bay which is more influenced by ocean warming, changing ocean currents, and storm/wind patterns. However, additional factors, such as local variations in VLM, dredging in the Delaware River, activities along the C&D Canal, and local development and land use changes, may also play a role. Also note that Reedy Point shows slightly higher variability, likely due to its more inland location influenced by the Delaware River, precipitation, and additional hydrodynamics as well as greater tide range and a much smaller water body fetch.

Over the recent satellite monitoring era since 1993, the primary components of mean sea level change at Reedy Point are sterodynamic changes (50%), vertical land motion (25%), and ice melt and LWS (25%) (**Figure 5.6)**. At Lewes, the top two primary components are reversed, vertical land motion (40%), sterodynamic changes (35%), and ice melt and LWS (25%). Recall that: 1) VLM includes GIA and other background non-climatic factors, 2) sterodynamic includes thermal expansion and changing ocean currents, and 3) the remaining component includes combined contributions from mountain glaciers, ice sheets, and LWS. The differences between the locations could be attributed to a higher background VLM processes near Lewes, varying influences of Atlantic Ocean currents or heating/advection (i.e., sterodynamic processes), or other factors. More research is required to determine the exact nature of the contributions of relative mean sea level rise between the north and south portions of the Delaware Bay.

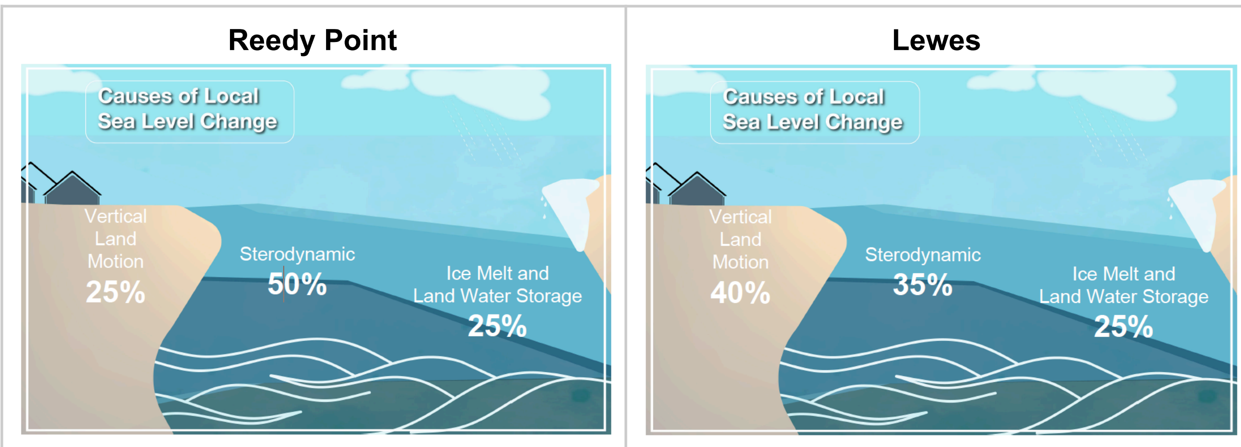


Figure 5.6. Contributions of observed changes in relative sea level rise at Reedy Point (left) and Lewes (right) tide gauges for the time period 1993 to 2024. Source US Sea Level Change website

5.3.2. Coastal Flood Frequency

A clear and natural consequence of rising relative sea levels is a coincident increase in the frequency of coastal flooding events. Quantifying coastal flooding over wide regions is difficult as it is extremely sensitive to local topography, hydrologic connectivity to tributaries and back bay systems, and any shoreline protections in place. Instead, it is common to define an impact threshold level at a nearby monitoring site (i.e., a CO-OPS tide gauge) that represents when flooding begins to happen in some locations throughout the immediate area. Since coastal flooding does not occur the great majority of the time, there are many more days when the daily maximum water level remains below the impact threshold level than exceeds it. **Figure 5.7** shows an example distribution of daily maximum water levels over the course of a year. Threshold levels are located on the positive side where the distribution exhibits a steep gradient, which is most often the case. As mean sea levels increase, shifting the distribution to the right (step 1 in **Figure 5.7**), the likelihood of water levels exceeding the impact threshold also increases (step 2 in **Figure 5.7**). The steeper the curve of the distribution, the larger the increase in the likelihood of exceeding the threshold. Hence, even moderate rates of SLR can cause significant increase in coastal flood frequency.

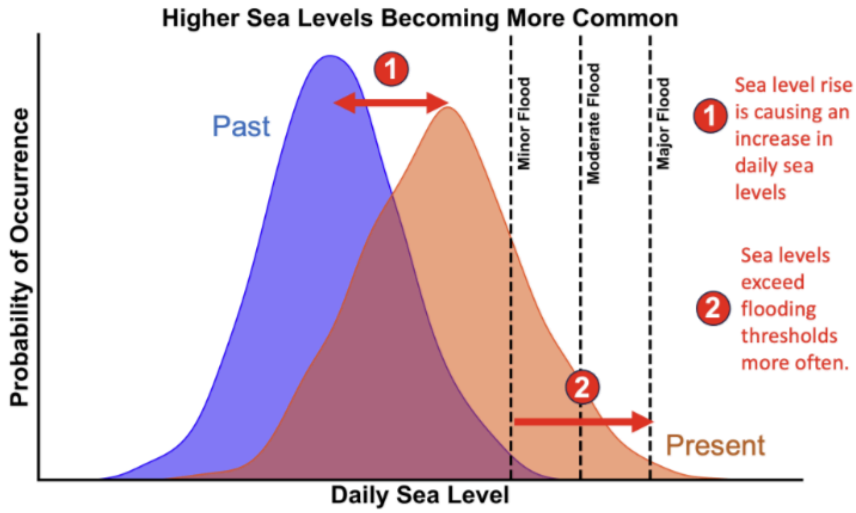


Figure 5.7. Theoretical characterization of how the statistical distribution of daily maximum water levels change over time due to sea level rise. Source: US Sea Level Change website.

Both the Reedy Point and Lewes tide gauges have defined flood impact thresholds (**Table 5.3**). The NWS Mt. Holly Weather Forecast Office (WFO) developed these thresholds based on observations of flooding (e.g., water on roads, flooded personal property). Thresholds are used by NWS to generate coastal flood advisories and are designed to assist the emergency management community in their preparation. Threshold levels are classified into three categories based on the relative damage and disruption caused by flood water at that level:

- ***Minor threshold (disruptive)*** - also called shallow water or high tide flooding; impacts some low elevation and vulnerable areas; low threat of significant damage; occurs at about 1-2 feet above MHHW
- ***Moderate threshold (damaging)*** - widespread flooding in most vulnerable areas; elevated risk of significant damage; occurs at about 2-3 feet above MHHW
- ***Major threshold (destructive)*** - severe, expansive flooding; significant threat of damage to property, infrastructure, public safety; occurs at about 3-5 feet above MHHW

The three threshold severity levels defined at Reedy Point and Lewes tide gauges are listed in **Table 5.3**. NWS uses these threshold levels and modeled forecasts at Reedy Point to generate advisories for the northern regions of the state, and at Lewes for the southern regions.

Table 5.3. Flood impact thresholds used for NWS coastal flood advisories for the State of Delaware. Values are above MHHW datum computed over NTDE8301.

Station	NWS Minor	NWS Moderate	NWS Major
Reedy Point	0.42 m / 1.36 ft	0.72 m / 2.36 ft	1.03 m / 3.36 ft
Lewes	0.41 m / 1.35 ft	0.72 m / 2.35 ft	1.02 m / 3.35 ft

Events when water surface reaches or minimally exceeds the Minor threshold are typically termed high tide flooding (HTF) events as they are generally driven by the seasonal and fortnightly (i.e., spring) high tides with only minor influence from the weather. Events when water reaches the moderate or major levels requires a significant amount of contribution from the local meteorology, usually in the form of a low pressure extratropical storm, a tropical system, or strong pressure-gradient winds. Note that moderate and major events are included when counting HTF events as they also exceed the minor threshold level.

Plots of daily maximum water levels at each tide gauge, with thresholds plotted as horizontal lines, are provided in **Figure 5.8**. Minor threshold levels (orange) are plotted closest to the observed water levels and the moderate and major thresholds each spaced 1 foot higher. Data are relative to the MHHW datum over NTDE 1983-2001. Due to SLR, many daily maximum values are negative in earlier years.

Note that the threshold level does not necessarily indicate flooding is occurring at all locations within the region. Flooding is hyperlocal and dependent upon wind direction, duration, antecedent conditions, protective barriers in place, and more. Events when water levels reach or exceed the minor threshold at a tide gauge are termed “flooding” events regardless if flooding on the ground occurs, as the threshold indicates that typically, based on past NWS experience, some of the more vulnerable areas in the surrounding region will begin to experience disruptions due to flooding at this level.

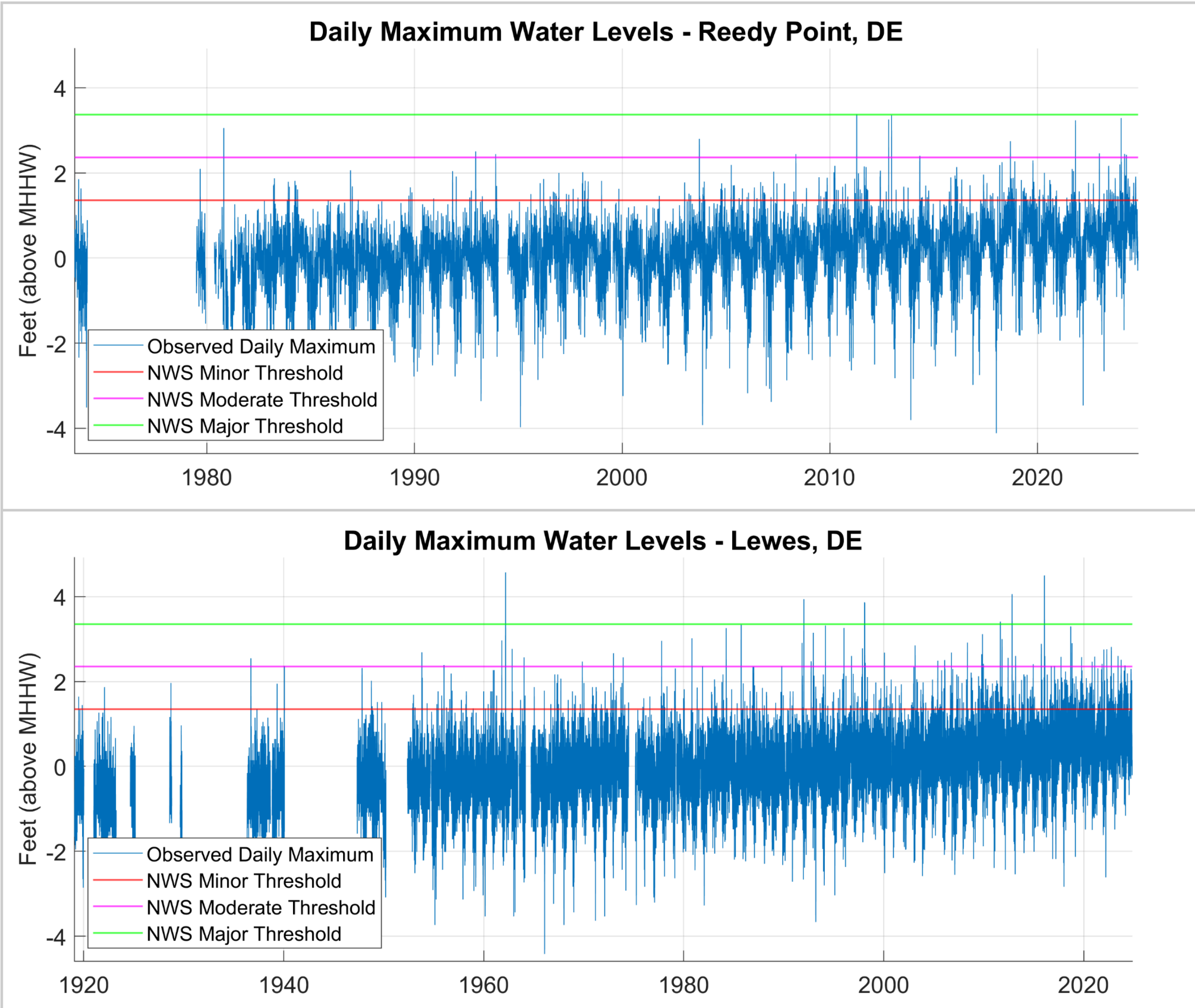


Figure 5.8. Daily maximum water levels at Reedy Point (top) and Lewes (bottom) tide gauges over each station's complete period of record. Data are in feet above Mean Higher High Water (MHHW) datum.

The data in **Figure 5.8** show strong trend and seasonality. Largest Influences on the increasing frequency minor coastal flooding events are the tides (such as at those locations where large tidal ranges or the fortnightly spring tides bring high tides close to the minor threshold) and rate of SLR, as opposed to changing storm conditions (Dusek et al., 2022; Hague and Talkes, 2024).

A good metric of the changing flood regime due to SLR is the associated increase of coastal flooding frequency, computed as the number of days per year where water levels reached or exceeded the minor threshold level. Annual counts of flood days at each tide gauge are shown in **Figure 5.9**. These data are summed over each calendar year from Jan to Dec to reduce the seasonality variability influence on the annual trends. Each year had a minimum allowable completeness percentage of 80% of days; otherwise that year is not included in the plots. Although there is significant year to year variation, the increase in recent years is easily seen, with acceleration occurring over the past few decades, as would be expected under SLR.

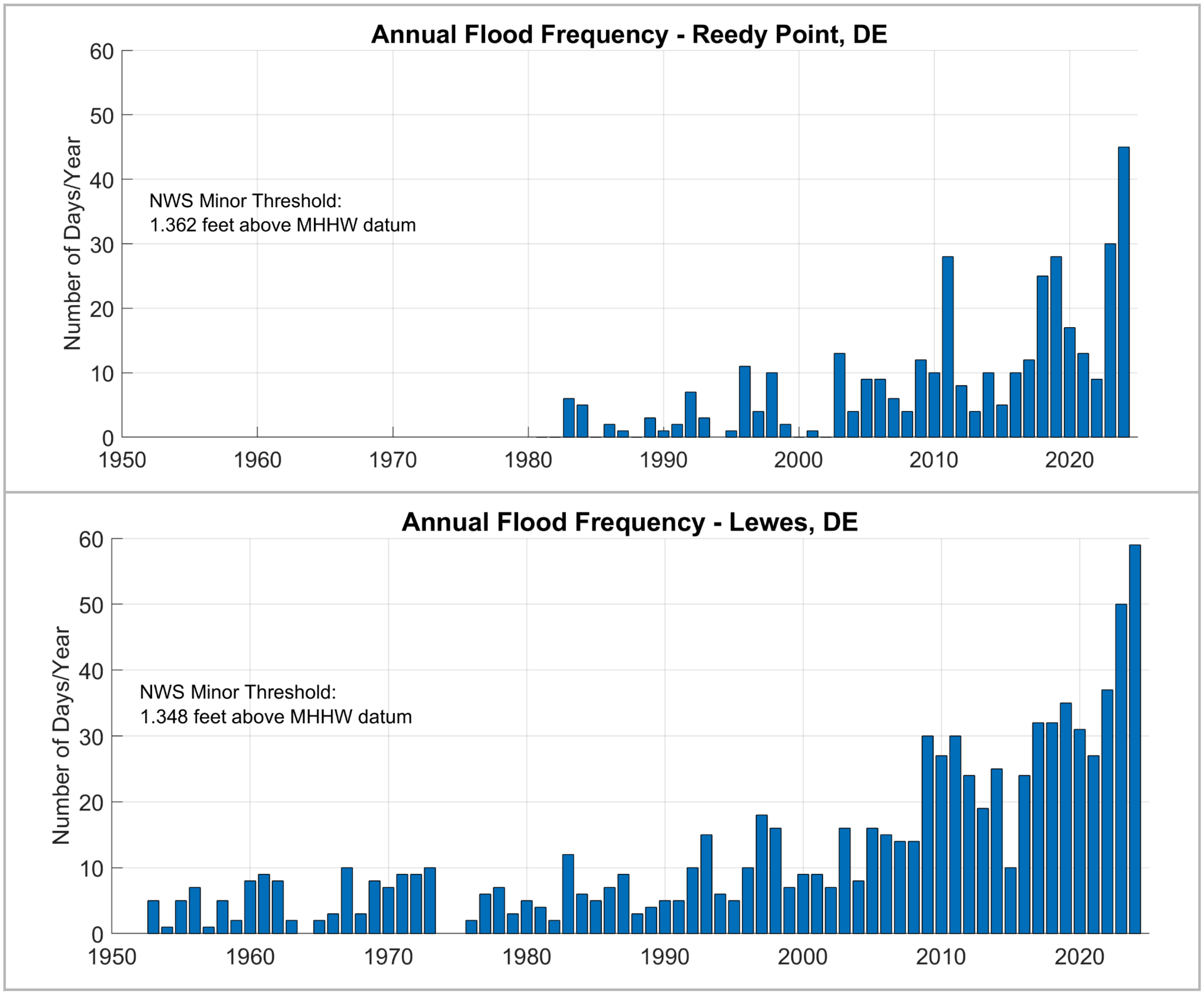


Figure 5.9. Annual counts of the number of days water levels reached or exceeded the NWS minor flood threshold at the Reedy Point (top) and Lewes (bottom) tide gauges.

Both gauges show significantly nonlinear increasing trends, from less than 10 days per year in the 1950s (Lewes) and 1980s (Reedy Point) to recent counts of over 50 days per year (Lewes) and 30 days per year (Reedy Point). The recent amounts equate to approximately 8% (30/365) of the days during a year at Reedy Point and 14% (50/365) at Lewes. Lewes consistently shows a higher count of flooding days per year, potentially due to its location near the month of the Delaware Bay which is more influenced by strong onshore winds and surge from the Atlantic Ocean and more frequent impacts from tropical cyclones (Callahan et al, 2022, 2023). Both gauges also follow similar interannual and decadal patterns. As with mean sea levels, these patterns align with lunar nodal cycles (Thompson et al., 2021). Water levels in the Mid-Atlantic are also significantly influenced by El Niño conditions through teleconnection of atmospheric (wind and storm) weather patterns (Sweet et al., 2018; CO-OPS, 2023)

The bar charts in **Figure 5.9** are summarized by decade in **Table 5.4**. Data are the average number of annual coastal flood days for each decade. Missing years are not included in the average computation. The averages for the 2020s are expected to rise through the second half of the decade as SLR is expected to continue, and accelerate, at both locations.

Table 5.4. Decadal averages of the annual flood frequency counts over the NWS Minor flood impact thresholds at the Reedy Point and Lewes tide gauges.

Decadal Average Coastal Flood Frequency		
Decade	**Reedy Point**	**Lewes**
1950 - 1959	--	3.7 days/year
1960 - 1969	--	5.9 days/year
1970 - 1979	--	6.3 days/year
1980 - 1989	1.9 days/year	5.7 days/year
1990 - 1999	4.6 days/year	9.7 days/year
2000 - 2009	5.8 days/year	13.8 days/year
2010 - 2019	14.0 days/year	25.8 days/year
2020 - 2024	22.8 days/year	40.8 days/year

5.3.3. Extreme Water Levels

Extreme water levels are defined as water levels that are reached on rare occasions, for example, once per year or once per 100 years. In the language of extremes, these would be referred to as 1-year or 100-year return levels (RLs). High Tide Flooding events from the previous section, those that reach the NWS minor threshold, can be considered as minor extremes, i.e., events that occur only a few times per year. As mean sea levels increase, the likelihood of extreme events occurring also increases.

In this report, we review historical extreme water levels at each gauge in three ways:

1. Top 10 water levels that have been observed over its period of record
2. Exceedance probability statistics derived for return levels from 1-year to 100-years
3. Distribution of daily maximum water levels for each decade over its period of record

Top 10 Events

NOAA CO-OPS maintains a list of top water levels observed at each NWLON tide gauge over its entire period of record. Peak event values are derived from a combination of hourly and 6-minute gauge observations plus select historic monthly observations and surveyed high water marks before the hourly gauge observations were available. These lists are actively updated each month once observations are verified by CO-OPS. Peaks for these events can be compared to sea level change amounts for future planning or research studies.

Top 10 events for the Reedy Point and Lewes tide gauges are reproduced here in **Tables 5.5 and 5.6**. Date and description of each event are included next to the peak water level. NWS flood impact thresholds are also provided for context. At both gauges, water levels for all of the top 10 events exceeded the NWS minor and moderate thresholds. In general, levels are higher at Lewes than at Reedy Point, owing to its longer period of record and vulnerability to offshore forcing (Callahan and Leathers, 2022). A great majority of these events were non-tropical in nature (only two at Reedy Point and three at Lewes), inline with research focused only on the non-tidal surge component (Callahan et al., 2022).

At Reedy Point, only two events surpassed the NWS major threshold, an extratropical nor'easter that occurred in December 2012 and strong cold front that passed through in April 2011. At Lewes, seven events surpassed the NWS major threshold, with the largest two being the Jan 2016 storm (short-lived but very strong winds and surge) and a strong, long-lived nor’easter in March 1962. Although it ranks second at Lewes, the March 1962 event, also known as the Ash Wednesday Storm of 1962 or the Great Storm of March 1962, was a long-lived through five high tides and generating waves as high as 20-40 feet that caused extensive damage to beaches, roadways, homes and businesses as well as loss of life (Delaware Sea Grant, 2002). (Note that the Reedy Point tide gauge was not in operation in 1962 to record that event.) The March 1962 event, even without the benefit of 60 years of sea level rise, is still considered the “storm of record” when it comes to coastal flooding and the damage it caused.

Table 5.5. Top 10 water level events recorded at the CO-OPS Reedy Point tide gauge. NWS flood impact thresholds and selected extreme return levels provided in ***red bold italics*** *font for reference. Top 10 event peaks obtained from NOAA CO-OPS Coastal Inundation Dashboard. Data relative to MHHW.*

Rank	Event Date	Feet	Meters	Event Type
		3.98	***1.21***	***50-year (2% annual chance) Return Level***
1	April 17, 2011	3.42	1.042	April Cold Front Passage/Strong Winds
2	December 21, 2012	3.36	1.024	December Nor'easter
		3.36	***1.024***	***NWS Major Threshold***
3	October 29, 2021	3.31	1.009	Oct Coastal Low Pressure/Strong Winds
4	January 10, 2024	3.28	1.000	January 9-10 East Coast Winter Storm
5	October 30, 2012	3.26	0.994	Hurricane Sandy
6	October 25, 1980	3.05	0.930	Nor’easter
		2.88	***0.88***	***10-year (10% annual chance) Return Level***
7	September 19, 2003	2.82	0.860	Hurricane Isabel
8	September 10, 2018	2.79	0.850	Frontal Passage & Onshore Winds
9	March 10, 2024	2.52	0.768	March East Coast Storm
10	December 11, 1992	2.5	0.762	Great Nor’easter
		2.36	***0.72***	***NWS Moderate Threshold***
		1.83	***0.56***	***1-year (~100% annual chance) Return Level***
		1.36	***0.415***	***NWS Minor Threshold***

Table 5.6. Top 10 water level events recorded at the CO-OPS Lewes tide gauge. NWS flood impact thresholds and selected extreme return levels provided in ***red bold italics*** *font for reference. Top 10 event peaks obtained from NOAA CO-OPS Coastal Inundation Dashboard. Data relative to MHHW.*

Rank	Event Date	Feet	Meters	Event Type
		5.00	***1.52***	***50-year (2% annual chance) Return Level***
1	January 23, 2016	4.61	1.405	January Blizzard
2	March 7, 1962	4.57	1.393	Ash Wednesday Storm
3	January 4, 1992	4.09	1.247	Nor'easter
4	October 29, 2012	4.05	1.234	Hurricane Sandy
5	January 28, 1998	4.02	1.225	Nor'easter
6	February 5, 1998	3.84	1.170	Nor'easter
		3.67	***1.12***	***10-year (10% annual chance) Return Level***
7	August 28, 2011	3.55	1.082	Hurricane Irene
		3.35	***1.021***	***NWS Major Threshold***
8	September 27, 1985	3.34	1.018	Hurricane Gloria
9	March 3, 1994	3.32	1.012	Nor'easter
10	September 10, 2018	3.29	1.003	Frontal Passage & Onshore Winds
		2.35	***0.72***	***NWS Moderate Threshold***
		2.30	***0.70***	***1-year (~100% annual chance) Return Level***
		1.35	***0.411***	***NWS Minor Threshold***

Exceedance probability statistics

Exceedance probability statistics is a common metric to describe the likelihood of occurrence for rare events. It is a statistical analysis of past observations to answer questions about the likelihood of extreme rare events that have only been observed a few times or for potential storm-driven levels that have not been observed yet. Example questions this type of analysis can answer include, "What is the chance that water levels will reach 3 feet at Reedy Point for some storm event this year?" or "Hurricane Sandy produced water levels that reached 4.05 feet at Lewes. Is that expected to happen once every 50 years, 100 years, or 500 years?"

The 2022 ITF Report calculated exceedance probability statistics at numerous NOAA NWLON stations, including Reedy Point and Lewes, ranging from levels that are expected to be reached or exceeded from 10 times per year to once every 100 years. A regional frequency analysis (RFA) of daily maximum water levels was used by combining observations from several tide gauges in the surrounding area into a single time series. This RFA-based approach extends the collective time period of the observations (to the longest record of all stations in that region) at the expense of location-specific information, i.e., it prioritizes time for space. It also captures events that may have missed Reedy Point or Lewes tide gauges but did significantly impact other nearby locations. The specific statistical methodology follows the Peaks-Over-Threshold approach using a 98% threshold of daily maximum water levels fit to the Generalized Pareto Distribution (GPD). More details are provided in the 2022 ITF Report.

Although the extreme water levels provided in this report for Delaware were taken from the 2022 ITF Report, it's important to note there exists two other federal datasets of extreme water levels: NOAA CO-OPS and the US Federal Emergency Management Agency (FEMA). These groups provided very similar statistics using different methodologies. CO-OPS methodology only includes data from an individual tide gauge and uses the Block Maxima approach for extracting annual maximum values fit to the Generalized Extreme Value distribution. FEMA methodology produces large scale maps and includes physical hydrodynamic modeling, synthetic storms, and includes waves. The RFA-based approach in the 2022 ITF Report was chosen here for Delaware as it extends and fills in missing data while preserving observational records, includes more events in its analysis (98% threshold equates to about 7 events per year on average, more than the single annual maximum value used in CO-OPS' method), and is robust for return levels of high frequency (multiple times per year) and low frequency (up to once per 100 years).

Return levels (RLs) for Reedy Point and Lewes are displayed in **Figure 5.10**. Data represent water levels above MHHW datum for return periods (more accurately, average recurrence intervals) up to 100 years. Note the x-axis is a log (base 10) plot, with each major tick mark 10 times the previous one. A return period of 0 years on this plot is physically meaningless but represents levels that would occur 10 times per year, the shortest interval computed in this analysis. The 100-year RL can also be thought of as the level with a 1% probability of being reached or exceeded in any single year, at an average rate of 0.01 times per year.

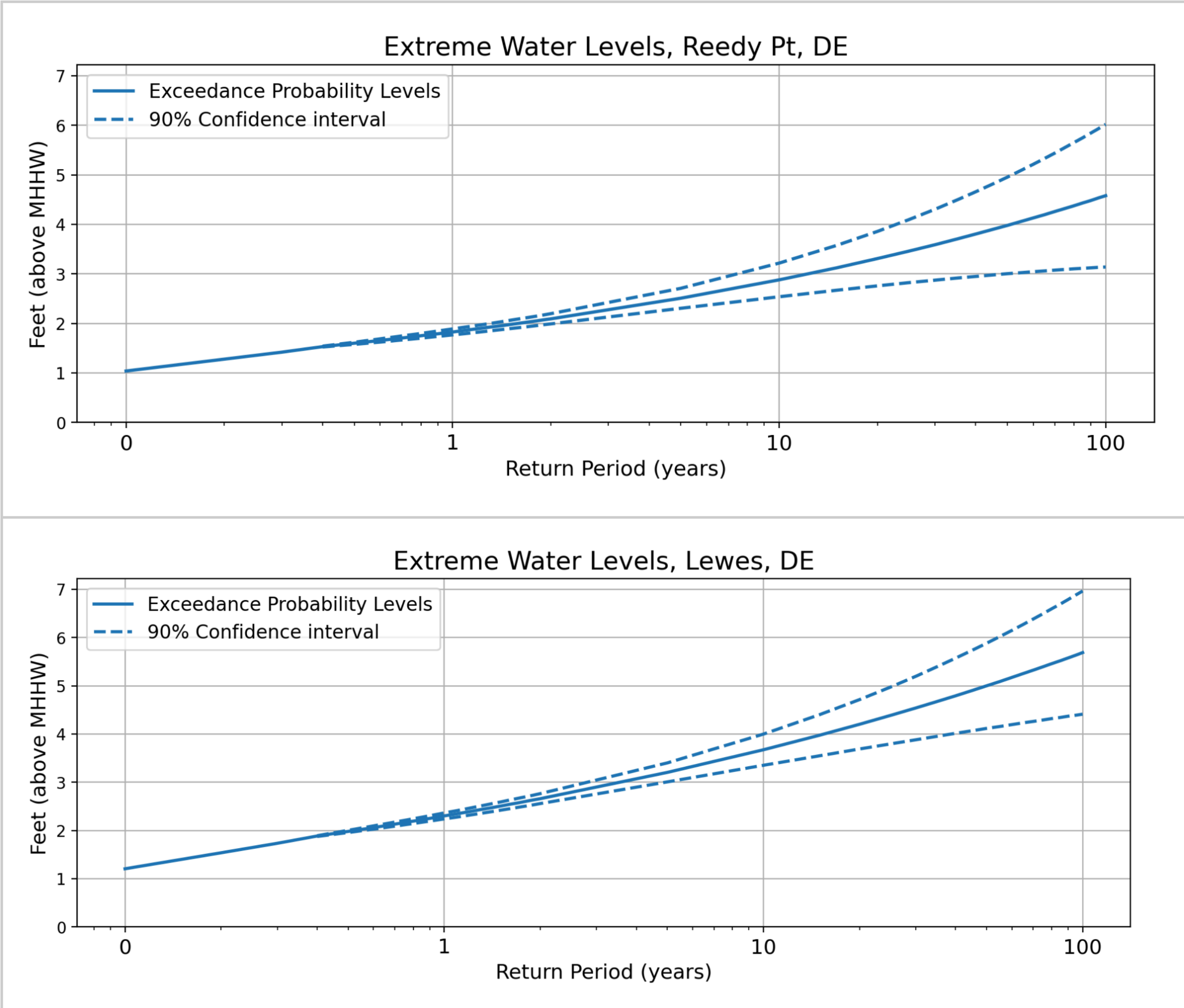


Figure 5.10. Extreme water levels for the Reedy Point (top) and Lewes (bottom) tide gauge as produced in the 2022 ITF Report. The statistical methodology follows the regional frequency analysis of daily maximum water levels using the Peaks-Over-Threshold fit to Generalized Pareto Distribution approach. Data are feet over MHHW datum. Dashed lines represent the 90% (5-95%) confidence levels.

Both gauges show similar behavior, with values approximately 1 foot above MHHW at the 10 times per year level and increasing exponentially to 100 years. The 90% confidence intervals (5-95%) also expand exponentially, becoming less reliable as the return period increases. Water levels for Lewes are generally higher than at Reedy Point, consistent with data shown in previous sections, The confidence interval at Reedy Point is larger, likely due to its shorter and more variable data record. The width of the confidence interval at Reedy Point 100-year return period is approximately 3 feet, and makes up a significant portion of the median/expected value of 4.58 ft. Select RLs extracted from **Figures 5.10** are also listed in **Table 5.7** for convenience. Also listed are analogous approximate terminology to describe each return period.

Table 5.7. Selected extreme return levels (RLs) for the Reedy Point and Lewes tide gauge as produced in the 2022 ITF Report. Data relative to MHHW datum.

Return Period	Annual Exceedance Probability	Average Event Frequency	Reedy Point	Lewes
6 months	-	2 events/yr	0.49 m / 1.60 ft	0.60 m / 1.98 ft
1 year	~100%	1 event/yr	0.56 m / 1.83 ft	0.70 m / 2.30 ft
10 years	10%	0.1 events/yr	0.88 m / 2.88 ft	1.12 m / 3.67 ft
50 years	2%	0.02 events/yr	1.21 m / 3.98 ft	1.52 m / 5.00 ft
100 years	1%	0.01 events/yr	1.40 m / 4.58 ft	1.73 m / 5.69 ft

Statistical analyses are only as good as the input data, which are collected at particular locations over a finite time period. It is difficult to gather enough data on events that, by definition, occur only rarely. Statistics presented here represent “on average” values; inferred expected values over an theoretical infinite number of repeated time periods in an unchanging environment. It is therefore entirely possible (and often happens) that an event classified as expected to occur once every 10 years on average, can occur multiple years in a row, or not occur at all over back to back decades.

Statistical data provided here are based on observations only. Since tide gauges have not been in operation very long relative to extreme event return intervals, observations may not cover the span of impacts that have occurred in the past. However to more thoroughly accomplish this, modeling and synthetic events would be needed to sufficiently span the plausibility space of coastal flood levels. Practitioners need to prepare for uncommon events to occur more frequently than their expected return periods, especially in regions such as Delaware where conditions are changing due to SLR, coastal land use, and storm activity.

Daily maximum water level distributions

The last aspect of extreme water levels to examine is the distribution of the daily maximum values. Daily maximum data form the source of the coastal flood frequency, top 10 water level events, and exceedance probability statistics discussed in previous sections. **Figure 5.7** (in section 5,3,2 above) shows a hypothetical example of daily maximum water levels. It demonstrates how the intersection of the NWS flood impact thresholds within the distribution upper tails may change under sea level rise conditions. These distributions inform the likelihood percentages of water levels being reached or exceeded for any threshold level, and are particularly useful when examining the extreme events found in the lower and upper tails.

Figure 5.11 shows the empirical probability density distributions (using the kernel density estimation (KDE) with normal smoothing) of daily maximum water levels at Reedy Point and Lewes tide gauges over each decade. Daily data must have at least 50% (12 hours) of the valid hourly observations and begin in the 1970s at Reedy Point and 1950s at Lewes. Earlier decades in the record are colored blue and later decades red. It is easy to see a progression from lower to higher values over time due to SLR. NWS flood impact minor, moderate, and major thresholds (not shown) are approximately 1.35, 2.35, and 3.35 feet above MHHW, respectively. In later decades, those thresholds intersect more of the main bulk of the distribution, indicating more frequent and higher likelihood of those events occurring. Note that the 2020s decadal distribution includes only the first half of the decade (2020 through 2024).

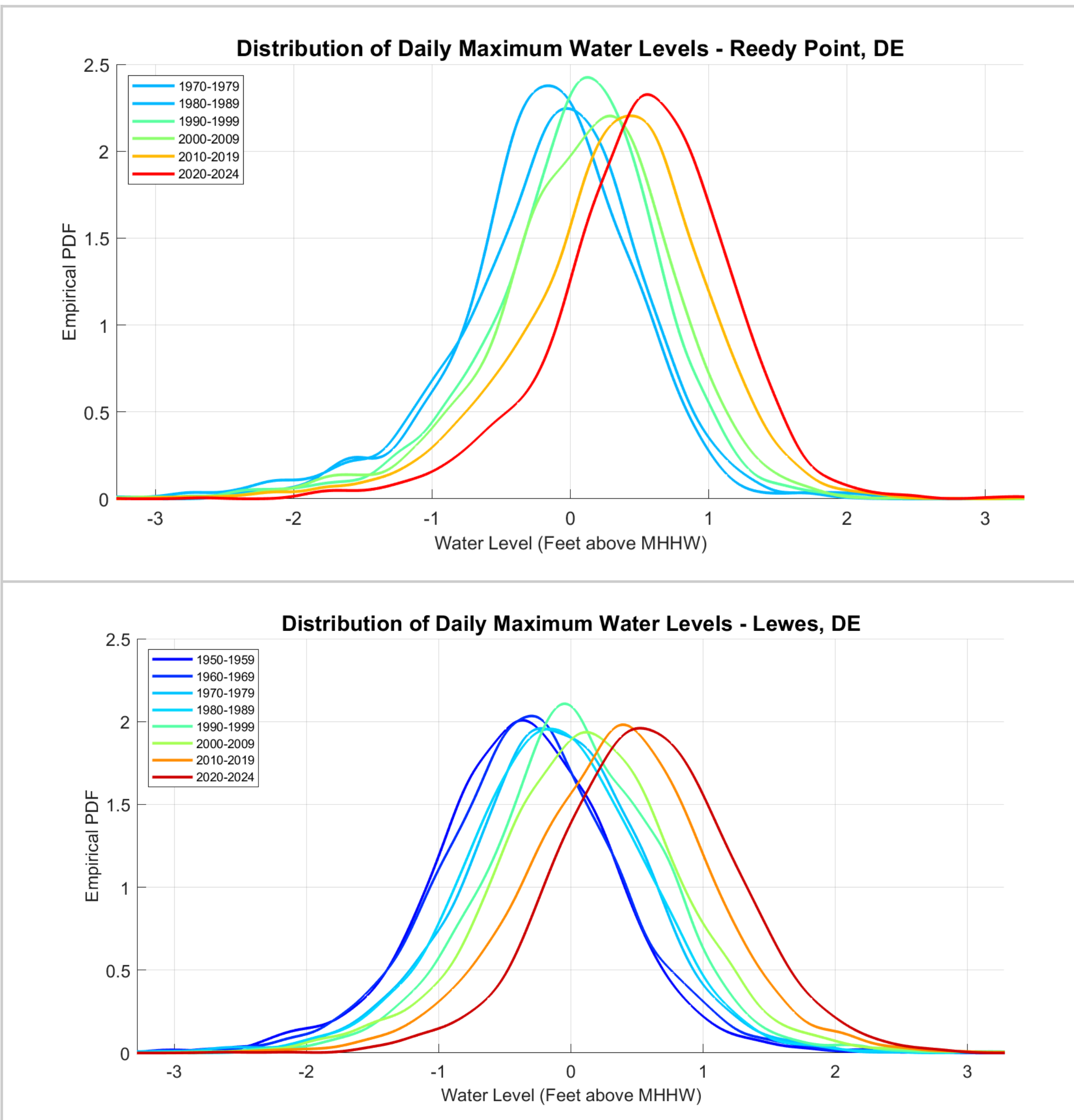


Figure 5.11 Empirical probability distributions of daily maximum water levels for Reedy Point (top panel) and Lewes (bottom panel) tide gauges. All days with at least 50% of the hourly observations within that decade are included. Data are in feet above MHHW.

Changes in the peak and shape of these distributions over time would indicate changing patterns of coastal flooding. In **Figure 5.11**, a shift to higher values is indicative of increasing mean sea levels whereas increases in the bulk width or tail thickness may be indicative of changes in the variability or likelihood of extreme events occurring due to some other factors. **Figure 5.12** provides quantitative metrics of how these distributions are changing over time.

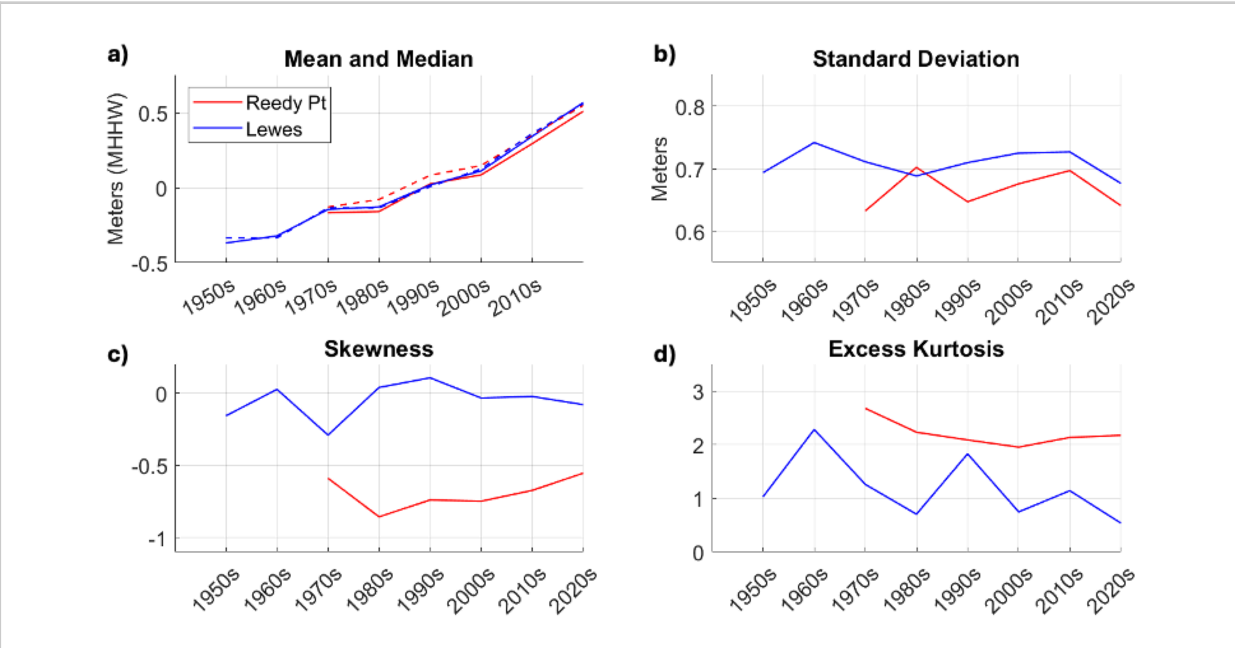


Figure 5.12. First four moments of the empirical probability distributions of daily maximum water levels for Reedy Point and Lewes tide gauges over each decade. Panels show: a) mean and median, b) standard deviation, c) skewness, and d) excess kurtosis. For reference, a standardized Normal distribution would have standard deviation, skewness, and excess kurtosis values of 1, 0, and 0, respectively.

Panel a shows the continuous increases of the mean and median, i.e., translation to higher values, echoing SLR. It is very likely that 2020s decadal distribution will continue sliding to the right as SLR continues throughout the decade. Over each decade for each tide gauge, the mean and median have minimal differences, a characteristic indication that these daily maximum water levels are normally distributed.

Panels b, c, and d show standard statistical moments that describe the shape of the distribution: standard deviation (panel b) measures the central width of the distribution, skewness (panel c) measures the asymmetry or lean of the distribution, and kurtosis (panel d) measures the thickness of the tails. Even if sea level rise was not occurring, i.e., the mean stayed constant over time, changes in the shape of the distribution by itself could indicate changing coastal flooding patterns. For reference, the standardized Normal distribution that is commonly used for describing the behavior of water levels (and many other environmental variables) has a standard deviation, skewness, and excess kurtosis values of 1, 0, and 0, respectively. Reedy

Point exhibits slightly larger kurtosis (thicker tails) and less skewness (negatively or left skewed) than Lewes. In all three metrics, Lewes exhibits more of a Normal-like distribution than Reedy Point. Although the bulk of the distributions are shifting to the right, none of the other three metrics show obvious trends, other than a possible slight negative trend in kurtosis at Lewes, coming closer to Normal distribution. These metrics support other studies that indicate increases in the likelihood of extreme events, under similar environmental conditions, are primarily driven by SLR (Boumis et al., 2023; Sweet et al., 2024).

5.3.4. Seasonal Cycle

The seasonal cycle of sea levels provides insight into the differences between what is experienced throughout the year and the annual-average trends and projections. Due to seasonal changes in land and ocean temperatures and weather patterns, mean sea levels and coastal flooding experiences a significant seasonal cycle. This information aids in planning purposes through many perspectives, such as allocation of resources for construction, engineering or workforce deployments; coincidence with other natural hazards with strong seasonal cycles, such as heat waves, cold outbreaks, tropical cyclones, droughts, and snowfall; development of nature-based infrastructure such as beach dune/berm systems and coastal marshes; protection of marine habitats and coastal ecosystems; and assessment of future impacts on economic systems through coastal tourism or business development.

Average monthly mean sea levels over the past 40 years (1984 to 2023, same period as was in section 5.3.1 above) at both tide gauge locations show very similar patterns (**Figure 5.13**). Note that these values may be different from the average seasonal cycle currently published online through the NOAA CO-OPS Sea Level Trends product[26]. CO-OPS uses a different statistical method and the full period of record for each gauge. However, the general patterns and months of maximum and minimum means sea levels are the same between this report and CO-OPS.

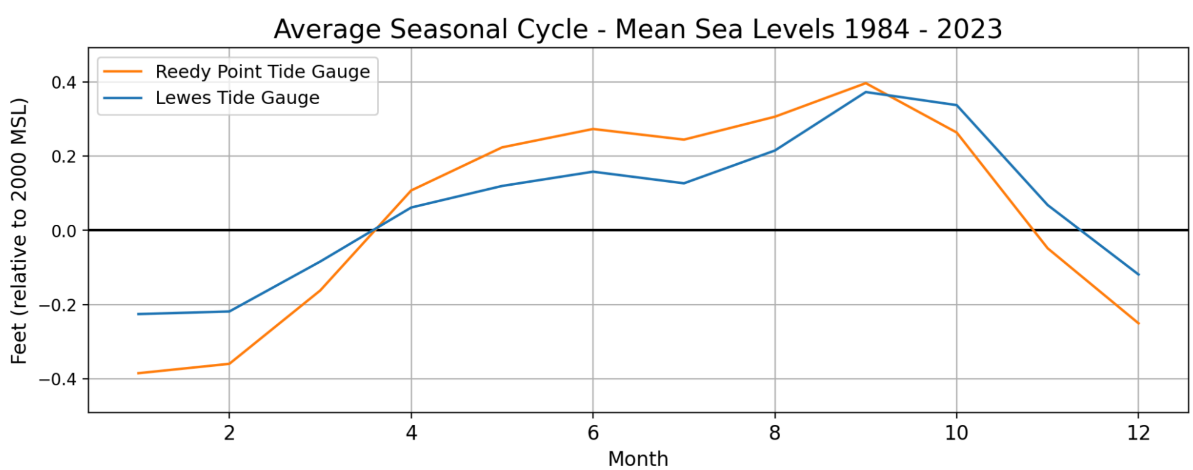


Figure 5.13. Average monthly mean sea level computed for each month over the past 40 years, 1984 - 2023 at Reedy Point and Lewes tide gauges. Data are in feet above 2000 MSL.

[26] https://tidesandcurrents.noaa.gov/sltrends/calc_avg_seasonal_us.html

As qualitatively noted earlier in this chapter, maximum monthly mean sea levels occur in Late summer/early fall (Aug-Sep-Oct) and minimums during the winter seasons (December-January-February). However, the distribution at both locations is bimodal with a second peak occurring in late spring (May-June). Reedy Point has a slightly larger annual range than Lewes, coinciding with its larger tidal range and influence of the Delaware River. The timing drivers of the cycle are predominantly due to thermal expansion, changing coastal ocean currents, atmospheric wind and pressure patterns, and the inverse barometer effect from atmospheric pressure loading (both locations), and precipitation and river discharge (Reedy Point).

A similar bimodal distribution is shown for the average seasonal cycle in flood frequency above NWS minor threshold at both gauges (**FIgure 5.14**). As with the annual counts in section 5.5, the number of flooding days include both minor and major flood events, i.e., any day that has reached or exceeded the NWS minor threshold. Only data from the last 10 years, 2014 to 2023, are included here instead of the longer 40-year time period used to compute average mean sea levels. This is due to the low number of occurrences in the winter to spring months for years earlier and the high rates of sea level rise. The average number of days per month expected to undergo high tide flooding at present and into the near future should be better estimated using the last 10 years rather than the last 40 years. Note that the NOAA Sea Level Calculator and the NOAA CO-OPS Monthly HIgh Tide Flooding Outlook use a rolling past 20 year time period and show a very similar pattern although with lower counts as for the last 10 years shown here.

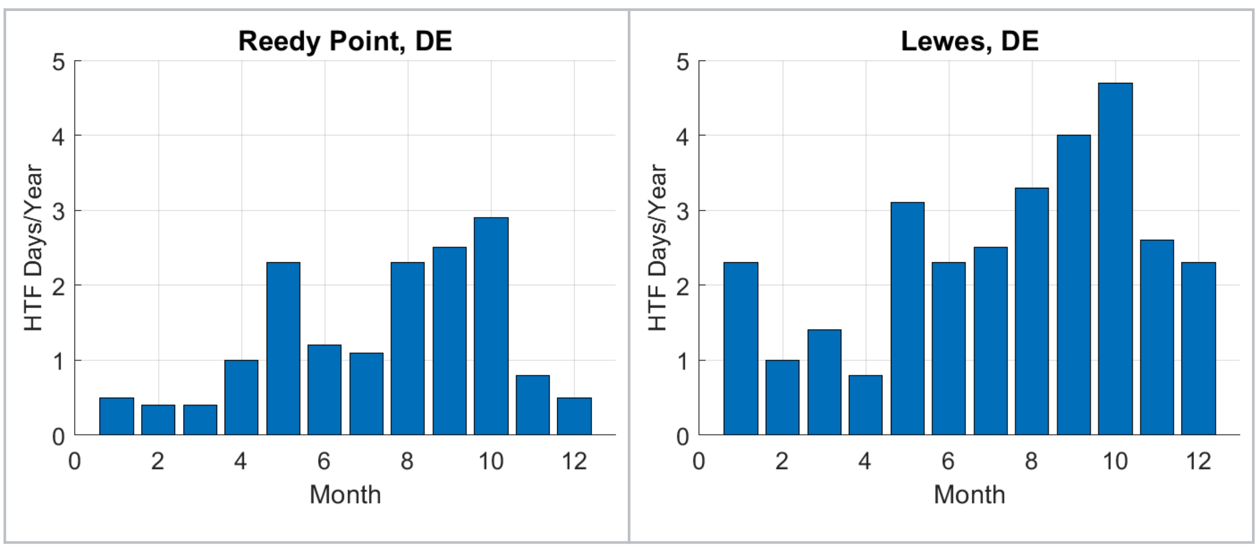


Figure 5.14. Average monthly counts of high tide flooding days over NWS minor threshold over 2014 - 2023 at Reedy Point (left) and Lewes (right) tide gauges. Both gauges show similar patterns with a maximum peak in the early fall, a secondary peak in late spring, and minimums in the late winter/early spring. However, at Lewes, coastal flood days also commonly occur in the colder months (Nov - Jan).

Annual counts of HTF days are driven by sea level rise and lunar cycles, however, when those floods occur during the year are highly seasonally dependent, driven by a combination of ocean and atmosphere forces. Seasonal mean sea levels increase the base water level closer to the threshold level where smaller meteorological contributions are required to cause flooding. The late summer/early fall months are peaks for both mean sea levels and HTF food days, a time of year when the oceans are still very warm and tropical cyclones impact the Mid-Atlantic, which influence lower Delaware Bay more than the upper Bay. Likewise, the higher mean sea levels in May coincide with springtime storms. Although the cold months (Dec through Mar) are popular times for winter storms, mean sea levels are low, making flood events more heavily dependent upon stronger storms. Winter nor'easters commonly result in northerly to northeasterly winds, lowering sea levels in the upper Delaware Bay near Reedy Point but increasing water levels in lower Delaware Bay near Lewes, resulting in higher values in Lewes over the winter months.

The average seasonal cycle of the 10-year (10% AEP) and 100-year (1% AEP) extreme water levels at Lewes is provided in **Figure 5.1**. (Monthly extremes at Reedy Point are not available at this time.) Note these data were produced by NOAA CO-OPS following their own extremes methodology (described briefly in Section 5.3.3 above. Therefore, the relative seasonal patterns rather than the exact magnitude are of interest for context in this report.

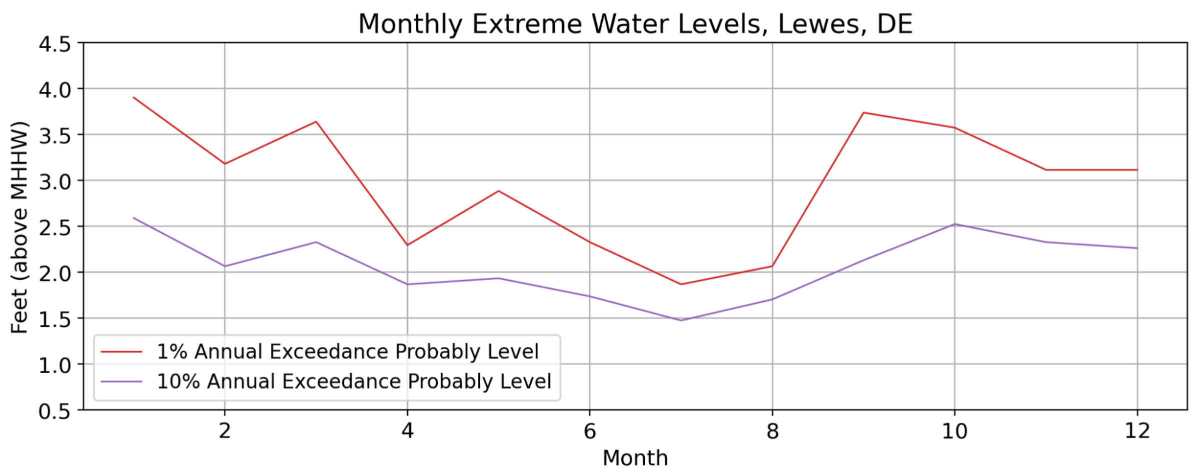


Figure 5.15. Extreme return levels for the 10-year (10% annual probability) and 100-year (1% annual probability) coastal flooding events for each month at the Lewes tide gauge. Data are relative to MHHW. Source: NOAA CO-OPS Extreme Water Level[27].

Drivers of seasonal extreme water levels are driven by storm patterns that push large amounts of surge, waves, and precipitation into the region, with only minor contributions from mean sea levels or low-frequency tidal lunar cycles. Accordingly, the average seasonal cycle of extremes looks very different that that of mean sea levels or HTF frequency. Peaks in September to October and January to March correspond to the most popular times for tropical and extratropical cyclones, which contribute to coastal flood levels through storm surge and waves (Callahan et al., 2023; Quadrado and Serafin, 2024).

[27] https://tidesandcurrents.noaa.gov/est/

5.4. Future Sea Level Projections

Previous Delaware SLR reports have highlighted the impacts of continued SLR and associated flooding to Delaware and provided projections for various future scenarios. The current report provides updated SLR projections based on more recent observations and new science resulting from the CMIP6 modeling efforts and IPCC AR6 and NCA5 assessments. Future potential sea level changes in three different metrics are assessed:

- Mean sea level
- Frequency in annual flood days (above NWS flood impact threshold)
- Selected extreme return levels for 1-, 10-, 50-, and 100-year return periods

For mean sea levels, future potential changes are estimated through two, uniquely different approaches: 1) trajectories and 2) projections.

1. ***Trajectories*** are observation-based statistical extrapolations to the year 2050. These are purely data driven, based on monthly observations since 1970, and adjusted for the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO), the first two of which have been shown to correlate with sea levels in the Mid-Atlantic region. Details are provided in the 2022 ITF Report (Sweet et al, 2022). Trajectories are most beneficial for near-term assessment of future water levels and how projections are tracking based on observations.

2. ***Projections*** are predominantly model-driven, generated through coupled ocean-atmosphere GCM modeling under a suite of future climate scenarios, defined in IPCC AR6 and NCA5. Projections under each scenario are provided to year 2100. Projections are ideal for longer term assessment and provide a range of the magnitude and time evolution of mean sea levels under plausible future scenarios.

In the previous sections summarizing historical sea level observations, we looked individually at each of the CO-OPS Reedy Point and Lewes tide gauges. For future mean sea level change in Delaware, however, we provide a single statewide assessment using both trajectories and projections. Primary drivers of long-term SLR around Delaware are global or regional in nature, such as thermal expansion, melting land-band glaciers and ice sheets, and changing ocean currents. Differences in the impacts from these processes as well as between VLM rates between Reedy Point and Lewes locations are minor. As well, the range among future SLR scenarios and variability inherent within each projection, is often larger than differences between statewide projection and at either of the Reedy Point or Lewes locations.

Once scenario projections of mean sea level are identified, an assessment of the uncertainty ranges and SLR process contributions are provided. Projections are also applied to the frequency of coastal flood events and likelihood of more extreme water levels. Only a basic assessment is performed here in order to provide guidance on how these indicators may change in accordance to changes in mean conditions. Projections of flooding, at both minor and major levels, are also significantly influenced by future changes in offshore storm frequency and onshore land development, which are also dependent upon any flood barriers or protections put in place. Hence, projections of flood frequency and extreme water levels are generated at each Reedy Point and Lewes tide gauge and not as a single statewide assessment.

5.4.1. Mean Sea Level Trajectories

The mean sea level trajectory for Delaware is based on monthly mean observations from 1970 to 2023 (**Figure 5.16**). Data are first statistically adjusted to account for ENSO, NAO, and PDO climate modes, and then fit to a smooth non-linear curve extrapolated out to year 2050 (Sweet et al., 2022). Accounting for the climate modes smoothes out the interannual variation, particularly for ENSO and NAO which affects sea levels and storm frequency in the Mid-Atlantic, allowing for a more robust tracking (less sensitive to anomalous weather patterns) of mean sea levels with smaller statistical uncertainty ranges. However, the trajectories do not take into account the lunar perigean and nodal cycles of 4.42/8.85 and 18.61 years, respectively. Since the lunar cycles oscillate around mean sea level, incorporating them would likely not have a significant influence on the trajectory of the statistically fit curve.

Note that these extrapolations are not predictions for any particular year but rather represent extrapolations of mean conditions over longer time periods. Trajectories are analogous to fitting linear trends over the past several decades as was done in section 5.3.1 of this report. They are ideal for quantifying how mean conditions change over time. Past trends should not be used to predict future behavior if the surrounding environment changes, in this case, including storm patterns, future global/regional SLR, and land use changes. Although there is no specific time threshold when the trajectory should not be used, it does provide a reasonable middle ground between past observations and future model projections from two mostly independent methods.

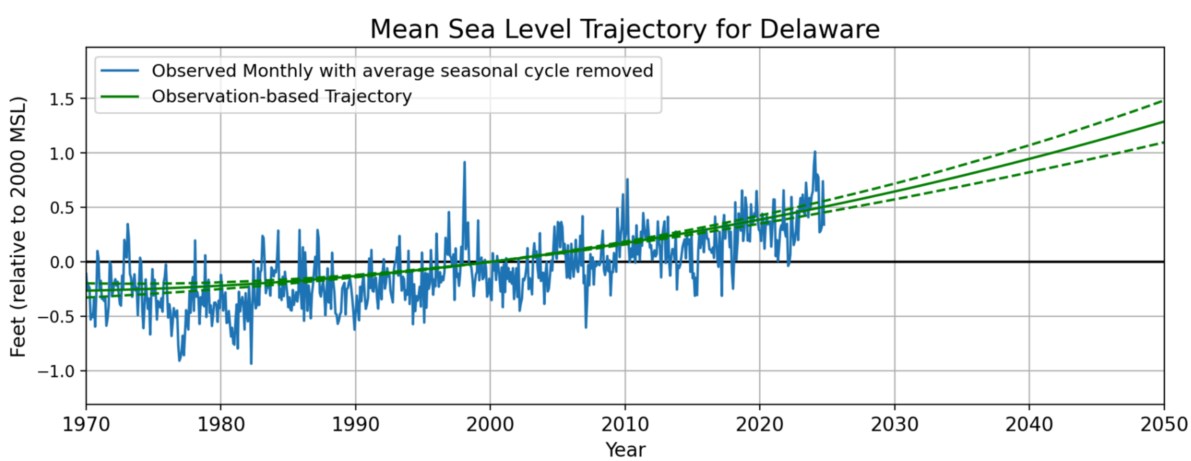


Figure 5.16. Mean sea level observation-based trajectory for Delaware. Observations are from 1970 to 2023 with the smoothed curve fit extrapolated to 2050. Data are relative to 2000 MSL.

Based on the observation-based trajectory, mean sea levels in Delaware had increased by 0.52 ft (about 6.25 in or 16 cm) over the past 30 years from 1990 to 2020. Over an equal amount of time in the future, the change in mean sea level is expected to be 0.90 ft (about 10.8 in or 27 cm), continuing the currently observed acceleration. Sea level change in Delaware from present to 2050 is larger and expected to show greater acceleration than the US Northeast and the contiguous US (CONUS, i.e., the lower 48 states) regions (**Table 5.8** and **Figure 5.17**).

Regional Comparison Sea Level Change (since 2000)			
Year	**Delaware**	**Northeast**	**CONUS**
2020	0.39 ft	0.37 ft	0.32 ft
2030	0.65 ft	0.62 ft	0.55 ft
2040	0.95 ft	0.91 ft	0.81 ft
2050	1.29 ft	1.24 ft	1.11 ft

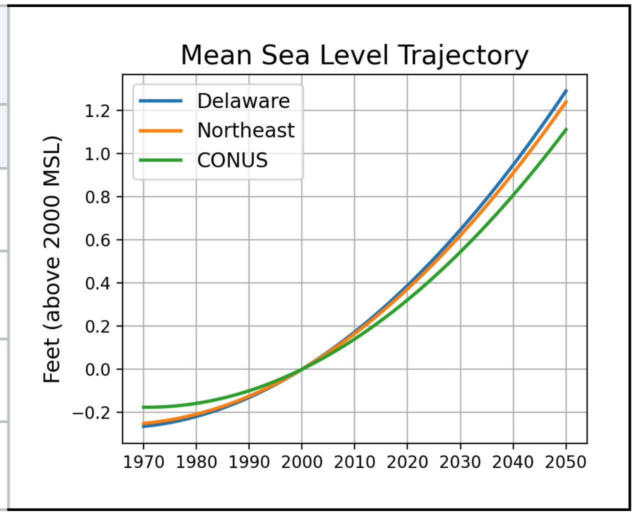


Table 5.8 and Figure 5.17. Mean sea level change based on observation-based trajectory for Delaware, the US Northeast, and the contiguous US (CONUS). Trajectories are generated from observations from 1970 to 2023 and extrapolated to 2050. Northeast and CONUS regional values are from median trajectories among all tide gauges within that region. Data are relative to 2000 MSL.

5.4.2. Mean Sea Level Projections

Projections of mean sea levels are generated primarily through physical modeling from CMIP6 efforts with additional information provided by external assessments of low-confidence, high-impact ice sheet instability processes, background vertical land motion from tide gauge observations, land-water storage estimates, and other components, as described in IPCC AR6. A suite of SLR projections were made ranging the span of SSP1 to SSP5 and RCP1.9 to RCP8.5 radiative forcing future climates scenarios. The 2022 ITF Report, in preparation for NCA5, utilized the same suite of global mean and local sea level rise projections but summarized the results in a different way. Instead of characterizing the likelihood of different future outcomes tied to forcing, the 2022 ITF Report focus was to produce a set of plausible global and regional sea-level scenarios to guide decision-making (Kopp et al., 2023a). The five planning scenarios selected were based on amounts of global mean sea level change by 2100: Low (0.3 m), Intermediate-Low (0.5 m), Intermediate (1.0 m), Intermediate-High (1.5 m), and High (2.0 m). All of the AR6 modelling projections are relative to the mean sea level averaged over 1995 to 2014 with a midpoint of 2005 but were adjusted to year 2000 levels in the 2022 ITF report. AR6 scenarios with higher radiative forcing generally had larger weights in generating the higher planning scenarios. More details are provided in Chapter 2 of this report.

In contrast to trajectories, projections are ideal for estimating increases in Delaware under the plausible range of global mean SLR under various future scenarios until 2100 and beyond. The projection magnitude, time evolution, and uncertainty range associated with each scenario can be used to assess the risk and likelihood of sea level reaching various threshold water levels. Projections of mean sea level, from 2020 to 2100, under the five planning scenarios for Delaware are plotted in **Figure 5.18**. Data are relative to 2000 MSL.

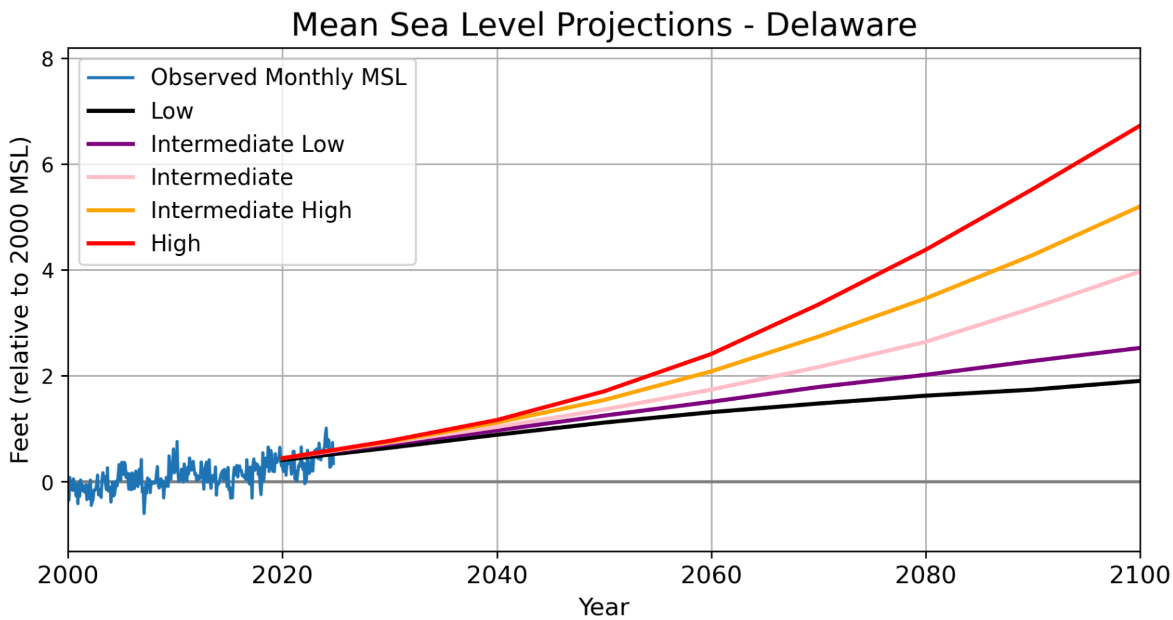


Figure 5.18. Mean sea level rise projections for Delaware under the Low, Intermediate-Low, Intermediate, Intermediate-High, and High planning scenarios defined in the 2022 ITF Report and NCA5. Plots are the median value of model projections generated within each scenario. Data are relative to 2000 MSL.

By 2100, mean sea levels are projected to reach from 1.90 ft (Low scenario) to 6.73 ft (High scenario) (**Table 5.9**). All of the scenarios above Low are designed to have equal increments of 0.5 meters by 2100 and bring a realistic time evolution of sea levels in Delaware under each scenario. Separation among the scenario projections do not become apparent until 2040-2050. The Low scenario is essentially a continuation of past long term linear trends at regional tide gauges and displays the slowest rates of change. It is considered unlikely to occur as it does not account for the past observed or projected acceleration. The amounts of mean sea level rise by 2100 are similar to linear average rates of about 5.5-6 mm/year, rates we have already reached or exceeded in recent decades. The High scenario displays continuously increasing rates of SLR (i.e., a continuation of the observed acceleration) and is heavily influenced by the high impact/low confidence processes of long-term physical responses to the warming (e.g., ice sheet melting and ocean currents). Although neither the Low nor High scenarios are likely to occur, they are included here as they span the plausible range of mean sea levels at future time periods, regardless of the pathway or time evolution ultimately followed from present day amidst the uncertainty of future greenhouse gas emissions.

Table 5.9. Mean sea level rise projections for Delaware for selected decades under the Low, Intermediate-Low, Intermediate, Intermediate-High, and High planning scenarios defined in the 2022 ITF Report and NCA5. Data are relative to 2000 MSL.

	Projected Sea Level Change (relative to 2000 MSL)			
Scenario	**2030**	**2050**	**2070**	**2100**
Low	0.64 ft	1.12 ft	1.48 ft	1.90 ft
Intermediate-Low	0.71 ft	1.25 ft	1.79 ft	2.53 ft
Intermediate	0.74 ft	1.36 ft	2.17 ft	3.97 ft
Intermediate-High	0.76 ft	1.54 ft	2.74 ft	5.20 ft
High	0.77 ft	1.71 ft	3.35 ft	6.73 ft

Planning for SLR also could be based on time rather than an amount of SLR. For example, 1.5 ft SLR will occur under all scenarios but is expected to be reached in the early 2040s under the High scenario and around 2070s under the Low scenario. Planning could answer the question, “What year should we plan for this particular amount of SLR?” This is opposed to planning for SLR amounts by selecting a time frame first, such as 2070, and answering the question, “What amount of SLR should we plan for during that year?”

It should be noted that projected SLR values may occur without following a single scenario time evolution pathway. Rather, it could result from following multiple scenario pathways or a pathway not associated with a scenario. The broad range of SLR amounts (relative to year 2000) over the five planning scenarios for any one given year are plausible, regardless of pathway. Future conditions could be highly variable, switching between SSPs/RCPs, and the resultant sea level in Delaware would hence follow suit.

Regional Comparison Sea Level Change (since 2000) Intermediate Scenario Projection			
Year	**Delaware**	**Northeast**	**CONUS**
2030	0.74 ft	0.71 ft	0.57 ft
2050	1.36 ft	1.34 ft	1.10 ft
2070	2.17 ft	2.14 ft	2.28 ft
2100	3.97 ft	3.93 ft	3.57 ft

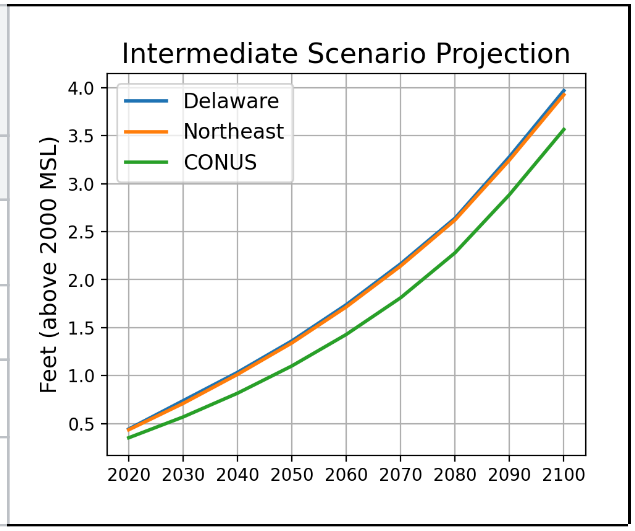


Table 5.10 and Figure 5.19. Mean sea level rise projections for Delaware, the Northeast region, and the contiguous US (CONUS) for selected decades under the Intermediate scenario. Plots are the median value of model projections generated within each region. Data are relative to 2000 MSL.

Using the Intermediate scenario (associated with GMSL rise by 2100 of 1.0 m), mean sea levels in Delaware are projected to be 1.36 ft (0.42 m) by 2050 and 3.97 feet (1.21 m) by 2100 above the year 2000 levels. This is nearly the same as the median value across all tide gauges in the Northeast region (**Table 5.10** and **Figure 5.19**). The projected amount of mean sea level change in Delaware is consistently larger, and at a slightly greater rate, than for the CONUS median.

The likelihoods of reaching or exceeding the projected amounts of mean sea level by 2100 in Delaware, given different global warming (GW) level futures, are provided in **Table 5.11**. These values were computed using the median values of projections. GW levels are defined by the global mean air temperature by 2100 and is an alternate way to categorize the results of the suites of IPCC AR6 model runs of potential future conditions (and very similar in fashion to the development of SLR planning scenarios). Across all GW level projections, it is extremely likely (> 92 to 99%) Delaware mean sea levels in 2100 will reach the amount projected under the Low scenario. Conversely, under the 1.5C GW-level scenario (possible under Low Emissions), there is a 92% and 37% probability that Delaware will reach the Low (1.9 ft) and Intermediate-Low (2.53 ft) projected amounts by 2100, respectively, and it's extremely unlikely (<1%) Delaware will reach the projected amounts of the higher scenarios. Under the Very High Emission (GW level of 5.0C and higher), there is a 23% and 49% probability, with and without the LC processes, that Delaware will reach the Intermediate scenario projections (3.97 ft) by 2100. Under the 3.0C GW-level, which is closer to current global estimates by 2100, there is a 5% probability Delaware will reach the Intermediate scenario and a 82% it will reach the Intermediate-Low scenario projected amounts.

Table 5.11. Likelihoods of Delaware mean sea levels to reach or exceed projected amounts by 2100 for each SLR planning scenario under varying projected global warming levels. Emissions Scenarios represent the amount of greenhouse gas emissions into the atmosphere.The GW level was not quantified under the high-impact, low-confidence runs that were forced under SSP5-8.5.

Global Air Temperature by 2100	Emissions Scenarios	Delaware Sea Level Rise Scenario by 2100				
		Low	Int-Low	Int	Int-High	High
2.7°F / 1.5°C	Low Emissions (SSP 1-2.6)	92%	37%	<1%	<1%	<1%
5.4°F / 3.0°C	Intermediate-High Emissions	>99%	82%	5%	<1%	<1%
9.0°F / 5.0°C	Very High Emissions	>99%	>99%	23%	2%	<1%
--	Very High Emissions, Rapid Ice Sheet Loss (LC processes)	>99%	96%	49%	20%	8%

5.4.3. SLR Scenario Tracking

The trajectories provide useful information on the trends of mean sea levels in recent decades, derived directly from observations. It is useful to understand how these trends overlap with the modeled based projections and to which scenario's projection the observations most closely align. The trajectories are specifically designed to be smoothed curves with reduced interannual variation due to major climate patterns, making for a more direct comparison to model results than observations alone. Assuming processes that drive relative sea level rise in Delaware are assumed to remain similar for the next few decades as in the recent past, the trajectory is a good indicator on how well the scenario projections are tracking in the near future.

Figure 5.20 shows the observation-based trajectory and all five of the SLR planning scenarios for Delaware. For the 2020s and 2030s, the trajectory tracks close to the Intermediate-Low scenario projection. Throughout the 2040s, the trajectory crosses the Intermediate-Low and approaches the Intermediate scenario projection. By 2050, the trajectory (1.29 ft) is between the Intermediate-Low (1.25 ft) and Intermediate (1.36 ft) projections. These two scenarios could provide a reasonable bound for likely SLR amounts between present and 2050. However, since the rate of increase of the trajectory is slightly faster than the modeled projections, a more conservative approach to SLR planning and protection is to use the Intermediate-Low to Intermediate-High scenarios as a plausible range.

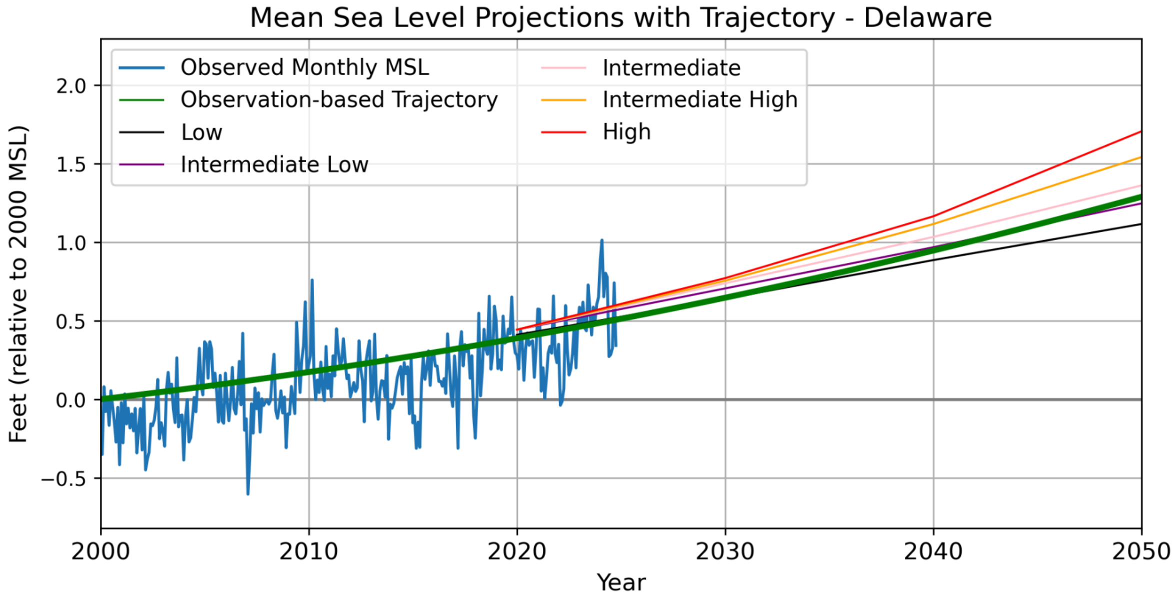


Figure 5.20. Mean sea level rise projections and the observation-based trajectory for Delaware. The trajectory is bounded by the Intermediate-Low and Intermediate scenario. Data are relative to 2000 MSL.

Beyond the near-term time period (past 2050), the trajectory should not be used to assess the extent the scenarios projections are tracking against observations. Scenario projections begin to diverge and additional factors play a role; partially local factors such as VLM, land use, coastal development, local geomorphology but more prominently are large scale factors such as ice sheet melt and ocean currents. As described in the Introduction, there is considerable uncertainty on future behavior of many regional and global processes.

Although the suite of SLR planning scenarios span the plausibility space of SLR in Delaware and should be integrated into planning activities according to the intended purpose, the range between Intermediate-Low to Intermediate-High could be generally considered more likely to occur than either the Low or High scenario.

5.4.4. SLR Projection Process Contributions

Through the IPCC AR6 process, contributions from each of the major drivers of sea level change are estimated through a combination of coupled ocean-atmosphere physical modeling, expert assessments, and observations from satellites and tide gauges under a suite of future forcing SSP/RCP scenarios and models, and their variations (Fox-Kemper et al., 2021; Kopp et al., 2023a). Relative contributions from each of these major components are assessed independently and aggregated into the five SLR planning scenarios (Sweet et al., 2022).

Between 1993 and 2023, the primary drivers of sea level rise in Delaware were vertical land motion (40%), sterodynamic changes (35%), and combined processes of ice sheet melt, mountain glacier melt, and land water storage (25%). **Table 5.12** breaks down the contribution from each of the major processes to mean sea level rise by 2050 and 2100 under each SLR planning scenario. (The Low scenario is not listed as it has a low likelihood of occurring and does not exhibit significant differences from past process contributions.)

VLM in this context included GIA and other background non-climatic factors (see section 5.3 for more details). As sea levels continue to rise, the relative contribution of VLM decreases as it's integrated at a constant rate whereas several other components are accelerating. By 2050, VLM contributes 27% to 21% of total mean sea level rise, with the lower percentages associated with the higher scenarios. By 2100, VLM contributions drop to only 25% to 10%.

Sterodynamic effects also decrease under higher scenarios and longer time scales but remain a significant contributor throughout, contributing 46% to 38% by 2050 and 39% to 23% by 2100. Mountain glaciers remain a relatively consistent contributor at 11% to 13% by 2050 and 12% to 7% by 2100. Although the percentage contributions decrease for the sterodynamic effects and mountain glaciers, their absolute contributions increase, and the lower relative percentages is indicative of accelerating contributions of the Greenland and Antarctic ice sheets.

GIS remains a relatively minor contributor (< 10%) by 2050 and under the lower scenarios by 2100. AIS plays the most dynamic role, increasing from 8-20% by 2050 to 14-45% by 2100. Relative contributions increase significantly under the Intermediate-High scenario, even as early as 2050. Likewise, the uncertainty ranges of AIS contributions are also wide under the higher scenarios by 2100, ranging 13% to 40% under the Intermediate-High scenario and 31% to 46% under the High scenario. Note that the Intermediate-High and High scenarios are weighted more by the AR6 low-confidence runs specifically focused on ice sheet instabilities.

Table 5.12. Relative percentage contribution to mean sea level rise by 2050 and 2100 from major component processes under SLR planning scenarios. Median percentiles are listed.

Process	**Relative Percentage Contribution to Sea Level Rise**							
	2050				**2100**			
	Int Low	**Int**	**Int High**	**High**	**Int Low**	**Int**	**Int High**	**High**
Sterodynamic	46%	47%	42%	38%	39%	38%	31%	23%
Greenland	5%	5%	7%	8%	6%	6%	10%	14%
Antarctica	8%	8%	16%	20%	14%	26%	35%	45%
Glaciers	11%	13%	11%	11%	12%	11%	9%	7%
Vertical Land Motion	27%	25%	22%	21%	25%	16%	13%	10%
Land-Water Storage	3%	3%	2%	2%	4%	3%	2%	2%

5.4.5. SLR Scenario Uncertainty and Divergence

There are primarily two main sources of uncertainty when assessing future climate projections: process uncertainty and emissions uncertainty (more details in Box 2.1 in 2022 ITF Report).

Process uncertainty encompasses the sensitivity of models in estimating sea level changes to future increased emissions. Future warming conditions give rise to melting mountain glaciers, thermal expansion, altered ocean currents, melting land based ice, and changes to the hydrologic cycle, all of which comes with some uncertainty in the model physics. Uncertainty may be amplified by the interaction of these processes, and additional sensitivities (e.g., ice sheet and ice cliff instabilities) that may result. Additionally, VLM may not continue in the future at the same rate as in the past, due to changes in natural processes or human activities. Differences in how each of the models simulate these contributing processes under different forcings are partially offset by using the median values of all model runs within each planning scenario (i.e., the model ensemble median), however, uncertainty still exists due to unresolved or unknown processes in the models.

Emissions uncertainty, also called scenario uncertainty, encompasses our inability to predict how much greenhouse gas (GHG) emissions will occur, and hence what the GHG atmospheric concentrations will be, in the future. In IPCC AR6 efforts, GHG forcing was determined based on a set of plausible futures, (i.e., SSPs), each with its own set of GHG-driven radiative forcing amounts (i.e., RCPs). A quantitative estimate of the probability of which SSP/RCP will occur is not possible in the same way as we produce probabilities of sea levels across models given a selected SSP/RCP future timeline. In fact, this is the driving reasoning behind the development of the "planning" scenarios for sea level rise, in order for local decision makers to assess the SLR risk in their local communities based on given global SLR amounts, regardless of which combination of SSP/RCPs come to pass. Although a quantitative estimate cannot be made, both the Low and High are less likely to occur compared to the Intermediate-Low, Intermediate, and Intermediate-High scenarios.

Figure 5.20 and **Table 5.13** provide the 17th-83rd percentiles around the median within each of the planning scenario projections (a measure of the process uncertainty) and the differences between the median values of each of the projections (a measure of the emission uncertainty). The 17th and 83rd percentiles span the 67% of the model estimates that fall within this range, which is approximately 1 standard deviation width assuming the data are normally distributed about the median value. In **Figure 5.21**, the thick solid lines represent the median values and the dotted lines of the same color represent the 17th-83rd percentiles. Projections are shown for 2020 onward to 2100 and values are relative to 2000 MSL.

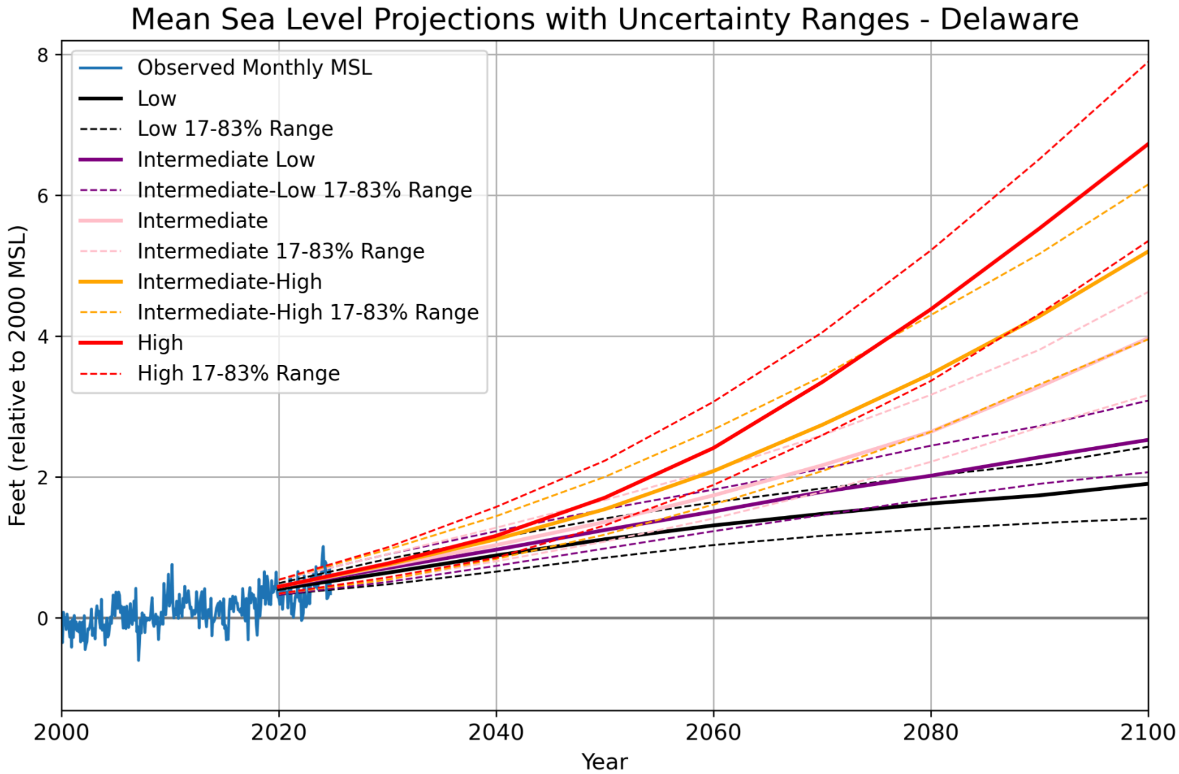


Figure 5.21. Mean monthly observations (blue lines) and SLR planning scenario projections for Delaware. Median (thick solid line) and 17th-83rd percentiles (dotted lines of same color) are plotted. Data are relative to 2000 MSL.

Under all scenarios, the uncertainty ranges are more narrow in near future years and increase for longer time periods. For example, the uncertainty ranges under the Intermediate scenario are 0.36 ft in 2030, 0.59 ft in 2050, 0.80 ft in 2070, and 1.46 ft in 2100. However, that is primarily due to the lower sea level rise amounts. The uncertainty range-to-median ratio is often higher at near future decades than far future decades, e.g., ~50% in 2030 to 37% in 2100 for the Intermediate scenario again. The three Intermediate scenarios will have smaller uncertainty ratios simply due to the sheer large number of model runs that produced the scenario.
In some other studies, larger uncertainties may be provided, e.g., 90% or 95%. However, for projections of the future, especially when incorporating low confidence processes, these uncertainty ranges would be significantly larger than the 67% provided here, and would provide only very little additional insight. This approach follows guidance put forth in the 2022 ITF Report and should provide a reasonable measure of process uncertainty inherent to each scenario projection.

Higher scenarios will have large uncertainties due to their intentionally higher sea level values (allowing for more spread underneath median) and inclusion of more contributing processes, such as the low-confidence processes from ice sheet instabilities. For example, the High scenario uncertainty ranges (0.92 in 2050, 2.54 ft) are significantly higher than the Low scenario (0.56 ft in 2050, 1.02 ft in 2100). In fact, the AIS process alone has uncertainty ranges of 0.84 ft by 2050 and 3.5 ft by 2100 (larger than the uncertainty ranges after combining all major contributing processes). The very large range at 2100 results from a combination of higher emissions, long time periods, and low confidence processes. As mentioned previously, AIS, and GIS to a lesser extent, are expected to have a larger contribution at long time periods, but it will also include larger process uncertainties. Projections of the ice sheet processes are expected to be improved in future IPCC modeling efforts due to improved physics and integration of additional observations.

Table 5.13. Median and 17th-83rd percentiles of mean sea level projections for Delaware under the five SLR scenarios. These are the same data as shown in Figure 5.21 for selected decades.

Scenario	**Projected Sea Level Change (relative to 2000 MSL) Median (17th-83rd Percentile)**			
	2030	**2050**	**2070**	**2100**
Low	0.64 (0.48-0.84)	1.12 (0.85-1.41)	1.48 (1.16-1.84)	1.90 (1.41-2.43)
Int-Low	0.71 (0.51-0.90)	1.25 (0.98-1.54)	1.79 (1.46-2.12)	2.53 (2.07-3.08)
Intermediate	0.74 (0.54-0.90)	1.36 (1.08-1.67)	2.17 (1.79-2.59)	3.97 (3.17-4.63)
Int-High	0.76 (0.54-0.97)	1.54 (1.18-2.00)	2.74 (2.08-3.43)	5.20 (3.95-6.15)
High	0.77 (0.57-1.00)	1.71 (1.31-2.23)	3.35 (2.59-4.05)	6.73 (5.35-7.89)

Uncertainty ranges of each scenario often overlap the median projections of adjacent scenarios, particularly in near future years where the process uncertainty is larger than the emissions uncertainty. For these years, there is little sensitivity to scenarios and the observation-based trajectories provided additional guidance of future mean sea levels. The High and Low scenarios start to diverge from one another, i.e., their median projections can be separated from their other uncertainty ranges, in the late 2040s. Median values from the three Intermediate scenarios start to separate around that same time, although it takes until the 2060s before they more clearly diverge. Uncertainty ranges larger than the 67% presented here would result in divergence occurring in later future decades.

A different kind of uncertainty that should be considered comes from natural variability. Projections provided here are smooth curves of mean sea levels, averaged over several years. They do not include projections of variability on the interannual and seasonal time frames. For example, sea levels in Delaware are influenced by ENSO (~3 to 7 years, sea levels and flood frequency are higher during the El Niño phase), Atlantic Ocean circulation patterns, lunar nodal (18.61 years), and lunar perigean (4.42/8.85 years) cycles, as well as exhibits strong seasonality and tidal monthly cycles (section 5.3). Periods in the future may be much higher or lower than mean sea level projections based on the phase of these cycles. Variations in the natural climate cycles also influence the generation of the mean sea level trajectories. ENSO and the NAO were statistically adjusted for however other climate oscillations, ocean patterns, and lunar cycles were averaged over when fitting the smooth curve. Potential increases to mean sea levels due to natural variations should be taken into account when estimating the SLR magnitude and the complete risk posed by SLR.

5.4.6. Coastal Flood Frequency Projections

An inevitable consequence of increasing mean sea level is the associated increase in the frequency of coastal flooding events. Section 5.3.2 noted the exponential increase in the frequency of HTF days over the NWS Minor Flood Advisory thresholds at both Reedy Point and Lewes tide gauges in accordance with past SLR. Projections of coastal flood frequency continue that exponential trend, following on top of projections of mean sea level under each scenario. Since coastal flooding is a predominantly local phenomenon, and the observed counts of HTF days per year at the two tide gauges were notably different, projections of coastal flood frequency are computed at each individual tide gauge rather than a single statewide projection.

Empirical probability distributions (using the same kernel density estimator with normal smoothing as was used to analyze the historical record in section 5.3.3) of the daily maximum water levels were used to form probability curves to predict annual estimates of daily exceedances over NWS flood impact thresholds. The distribution is then shifted to higher water levels by increases determined by the mean sea level projections while keeping the shape of the distribution constant. This technique is supported in Delaware by the observational record (see **Figure 5.12**) that demonstrates little past change in these distribution moments. Details of the HTF projection methodology can be found in Sweet et al. (2018), Sweet et al. (2022), and Kavanaugh et al (2023).

Figure 5.22 displays projections of annual HTF days over the NWS minor flood threshold under each of the mean sea level planning scenario projections to year 2100. These data are also summarized by decade in **Table 5.14**. Only the projected HTF days under the median projection under each scenario are displayed here. Projections of days above the NWS moderate and major flood impact thresholds are not displayed within this report.

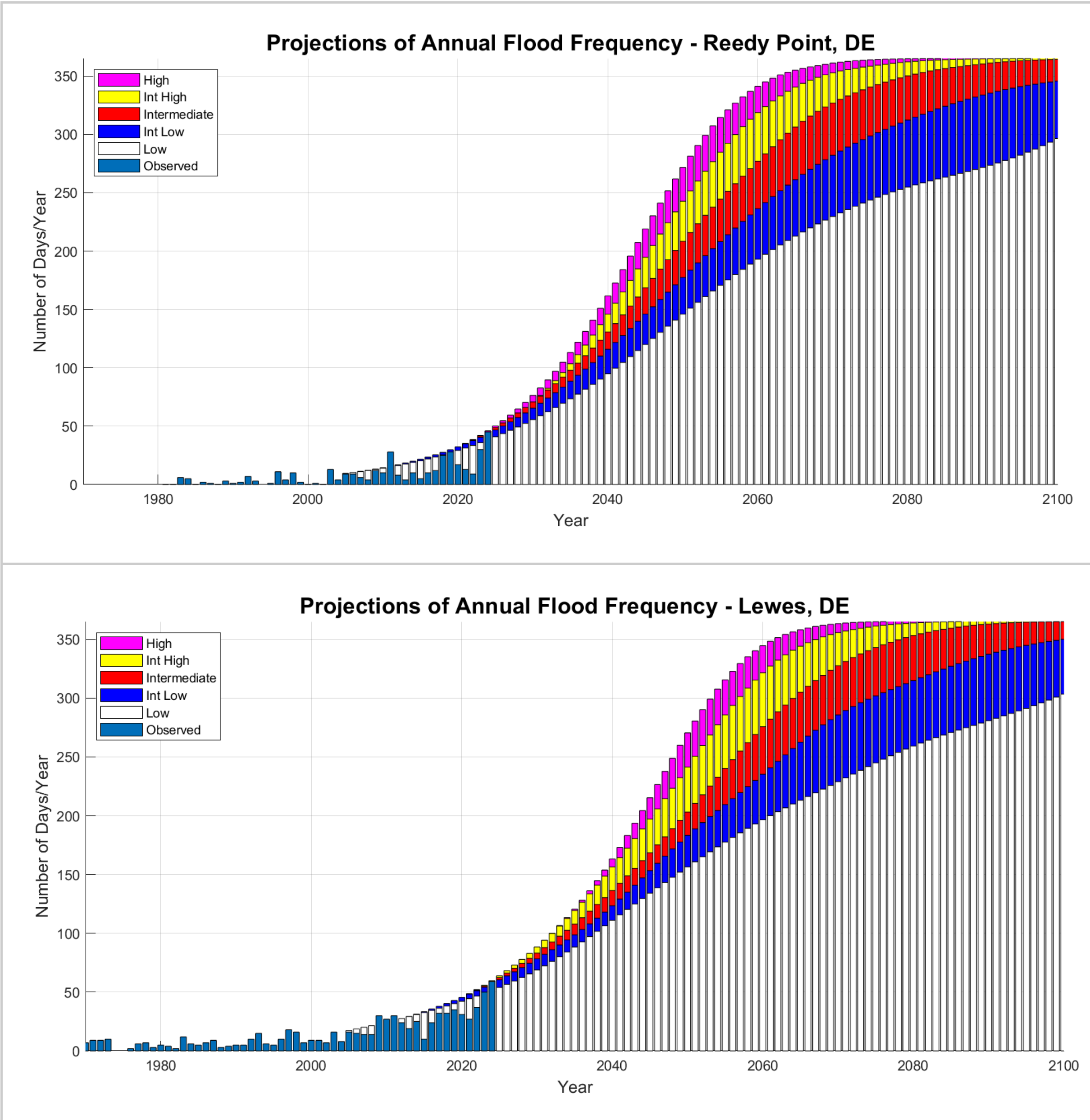


Figure 5.22. Projections of the annual number of High Tide Flooding (HTF) days above NWS minor threshold under the five mean sea level rise planning scenarios for Reedy Point (top) and Lewes (bottom). Blue vertical bars represent observed counts of HTF days from 1970 through 2023.

Projections at both gauges show very similar patterns and exhibit continued rapid acceleration under all scenarios, including the Low planning scenario that represents the lowest rate of SLR and on par with past recent linear (non-accelerating) trends. There is little difference among scenarios until the 2040s, therefore the Intermediate planning scenario (tracking most closely to the current mean sea level trajectories), could be used for planning in the near future. The number of days per year increases from 2020-2024 observed values of 22.8 and 40.8 days/year at Reedy Point and Lewes, respectively, to 37-38 and 52-56 days/year over the full 2020s decade, and 136-190 and 144-192 days/year over the 2050s. The period between the late 2040s and 2070s exhibits the largest difference among scenarios. Once sea levels reach high enough, flooding would occur on a nearly daily basis, during at least one of the daily high tides, under all scenarios.

Table 5.14. Annual HTF frequency projections averaged over selected decades under median projections of Intermediate-Low to Intermediate-High SLR planning scenarios. Values represent the average days per year water levels are expected to reach or exceed the NWS minor threshold.

Decade	Projected Coastal Flood Frequency above NWS Minor Threshold					
	Reedy Point			Lewes		
	Int-Low	Int	Int-High	Int-Low	Int	Int-High
2021 - 2030	37	40	39	52	54	56
2041 - 2050	136	161	190	144	160	192
2061 - 2070	259	305	339	259	304	343
2091 - 2100	339	363	365	344	364	365

Due to SLR, high tides in the region are fast approaching the NWS minor flood threshold, which is approximately 1.35 ft above the MHHW. During half of the higher-high tides that occur each day, the difference between the tides and the threshold is smaller than 1.35 ft, and can be thought of as a decreasing freeboard. Furthermore, during positively contributing phases of the lunar nodal, perigean, and fortnightly spring tide cycles, as well as during the late spring/early fall months or years associated with exceptional ocean warmth or slower ocean currents, only minimal contributions from the weather are needed to push water levels above this flood threshold. Similarly, the thresholds used to compute these counts are generalized through the surrounding region. There are many low-lying vulnerable communities and roads that begin to flood before the NWS minor threshold is reached at either gauge.

The persistence of minor flooding without significant need from weather systems puts Delaware as transitioning into a new flood regime and should be included in climate smart planning, building and maintaining coastal protections, infrastructure development, and natural resource and agriculture management on equal footing alongside more extreme coastal flooding events.

5.4.7. Extreme Water Level Projections

Similar to HTF frequency, median projections of mean sea level are applied to the exceedance probability statistics computed in section 5.3.2 at each tide gauge. The likelihood of more extreme events occurring increases as sea levels continue to rise, for example, events that would occur once every ten years may soon occur every year, particularly if higher warming scenarios come to pass. However, unlike the frequency of minor flooding, extreme events require significant contributions from the weather in the form of strong winds, waves, and surge, regardless of the time of year or phase of the lunar cycles.

Figure 5.23 shows select return levels applied to the Intermediate SLR planning scenario projection of mean sea level. Extreme RLs for historic years (previous to 2020) follow the 40-year linear trend centered on the midyear of the NTDE 1983-2001, over which the MHHW datum was computed. This method also assumes the difference between MSL and MHHW does not change in the future. This is the same procedure followed in the NOAA Sea Level Calculator[28] and CO-OPS Extremes Water Levels Product[29].

Although this is a rather rudimentary method as it does not include future projections of tropical cyclone development, storm track, storm intensity, geomorphology, land use, human coastal development, or anything other than mean sea level. However, it does provide some insight as to how the likelihood of extreme events change based on increases of mean sea level alone. Projected return levels in this way assume environmental conditions influencing extreme events play the same role in the future as they did in the past. In this case, there is some justification to this as the upper tail of the daily maximum water levels has only minimally changed at the Delaware tide gauges during the past several decades (see **Figure 5.12**).

28 https://coast.noaa.gov/digitalcoast/tools/sea-level-calculator.html
29 https://tidesandcurrents.noaa.gov/est/

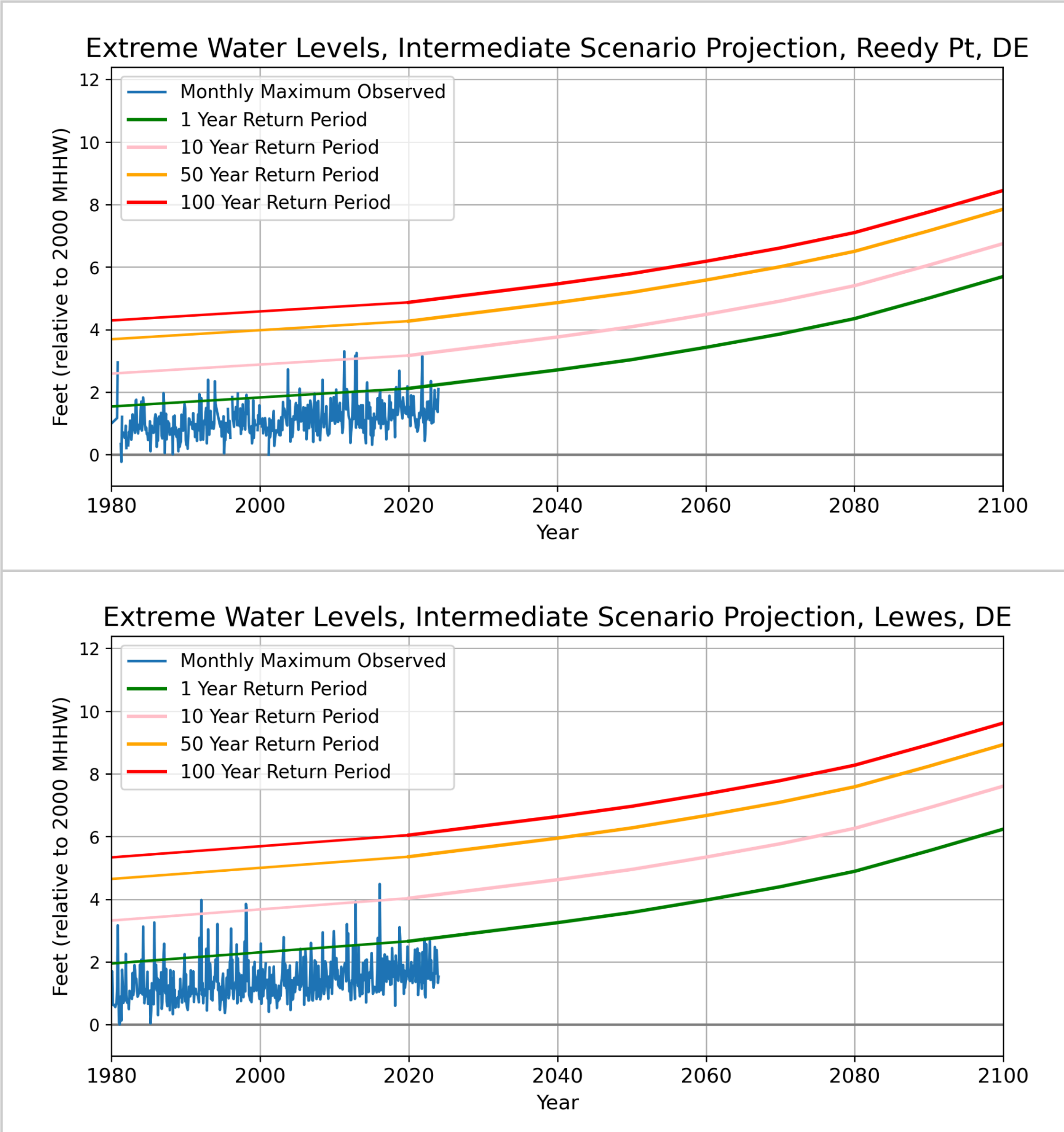


Figure 5.23. Projections of the 1-, 10-, 50-, and 100-year extreme return levels under the five mean sea level rise planning scenarios for Reedy Point (top panel) and Lewes (bottom panel). Monthly maximum values (blue lines) are displayed for reference from 1980 through 2023. Data are relative to 2000 MSL.

Increases in the extreme RLs noted here are determined solely by the amounts of mean sea level change produced by each scenario projection. Under the Intermediate scenario projection, mean sea level would increase 1.36 ft by 2050 and 3.97 ft by 2100. The 10-year RL at Reedy Point increases from about 3 ft above MHHW in 2020 to almost 7 ft above MHHW in 2100. At Lewes, the 10-year RL increases from about 4 ft above MHHW in 2020 to almost 8 ft above

MHHW in 2100. Other RLs would have identical amounts of increase within the same scenario. Higher SLR amounts under warmer scenarios would result in concomitant larger and more rapid increases to the extreme RLs.

As with mean sea levels, future changes in extreme RLs also can be viewed as to “when” a predefined amount of change is expected to occur rather than “how much” of a change is expected to occur at a predefined time in the future. As noted in the above example, the 10-year RL at Lewes is approximately 4 ft above MHHW in 2020. That same amount is projected to be the 1-year RL in 2060. Likewise, the 100-year RL of 6 ft above MHHW in 2020 is projected to be the 10-year RL in about 2075.

Uncertainty ranges around extreme RLs projections are not shown in **Figure 5.23** for simplicity. Refer to the 90% uncertainty ranges from the historical analysis in section 5.3.3, plus the 67% range of the process uncertainty around each of the mean sea level projections to get a sense of the large uncertainty in estimating future extreme RLs. Statistical uncertainty increases rapidly towards the more rare events with very large ranges greater than 50-year RL, due to the inherent rare nature of these events and relative short periods of records compared to these large return periods. Observations alone are insufficient for modeling plausibility of rare events, in the past or future. These uncertainties should be considered with larger process uncertainties associated with higher warming scenarios. Long term climate planning should consider the exact amounts of projected increases of future extreme RLs as low confidence and may want to consider the upper bounds of the uncertainty ranges, higher emission scenarios, and the additional influences of seasonal weather, lunar tidal cycles, and interannual natural variability.

Although increases in mean sea level may be a primary driver, the increased likelihood of extremes have experienced faster rates than from MSL change alone (Menendez and Woodworth, 2010; Boumis et al., 2023; Falasca et al., 2023; Sweet et al., 2024; Morim et al., 2025). Projections of extreme events therefore should be presented in context with other potential changes affecting the frequency or magnitude of extreme events in future environments.

5.5. Summary of Delaware Sea Level Rise

Sea levels have been rising in Delaware for at least as long as observations began at the NOAA tide gauges, since 1956 at Reedy Point and 1919 at Lewes. Recent acceleration has been observed at these tide gauges and several locations throughout the Mid-Atlantic region. Sea levels in Delaware are impacted by global, regional, and local processes. GMSL has been increasing since the start of the 20th century with acceleration beginning around approximately 1970. Dominant drivers of GMSL rise are increases to the ocean’s mass of water through melting of land-based mountain glaciers, the Greenland and Antarctic ice sheets, and increases to the ocean’s volume through thermal expansion. Affecting Delaware sea levels are additional drivers that further enhance SLR through changes in the Atlantic Ocean circulation patterns, GRD effects of ice-sheet melting, and local land subsidence.

This chapter first described the two NOAA tide gauges that have been responsible for collecting water level data as well as briefly describes the primary drivers of sea level change in Delaware. It then summarized past observations of sea levels over the past 20th century, including changes in mean sea level, the frequency (i.e., annual counts) of minor coastal flooding events, and the likelihood of more extreme coastal flooding events. It then presented projections of sea levels in Delaware for the 21st century under five SLR planning scenarios based on the latest science prepared for the IPCC AR6 and NCA5 reports.

Historical linear trends at Reedy Point and Lewes over the past 40 years are 4.41 and 5.52 mm/yr, respectively, significantly higher than the linear trends over their long-term period of records, 3.91 and 3.71 mm/yr, respectively. This in turn has led to an exponential increase in the frequency of flood days impacting the region, measured counting the number of days water levels reached or exceeded the NWS minor flood threshold. HTF annual frequency rates have increased at Reedy Point and Lewes from 1.9 and 5.7 days/year in the 1980s to 22.8 and 40.8 days/year during the 2020s (using only the first years of the decade, 2020 to 2024), respectively. The likelihood of extreme water levels are also expected to increase as sea levels rise. Current return levels at Reedy Point and Lewes are 2.88 and 3.67 feet for the 10-year return level (10% AEP) event, and 4.58 and 5.69 feet for the 100-year return level (1% AEP) event. The shape of the daily maximum distributions has not significantly changed over the recent decades, supporting other studies that future increases in extremes likely will be dominated by SLR. Additionally, both tide gauges exhibit strong seasonality and interannual variability, the cycles and ranges of which must be taken into account in addition to changes in mean sea level to properly assess the plausible risk associated with coastal flooding across Delaware.

Contributions from each of the main processes driving sea level change were combined through numerical modeling, expert assessments, and tide gauge observations under various greenhouse gas emission scenarios through the IPCC AR6 efforts. Results from the suite of AR6 model runs were combined into five SLR planning scenarios based on the amount of global mean sea level rise by 2100 (Low: 0.3 m, Intermediate-Low: 0.5 m, Intermediate: 1.0 m, Intermediate-High: 1.5 m, and High: 2.0 m) in the 2022 US Interagency Task Force SLR report. Planning scenarios were then used to generate SLR projections out to 2150 at many NOAA NWLON tide gauges, including Reedy Point and Lewes in Delaware (although in the current report for Delaware, we limit the projections to year 2100). The 2022 ITF Report also produced mean sea level trajectories by fitting smooth curves to monthly water level observations from 1970 to present, adjusting for major climate interannual variations, and extrapolating to 2050. Observation-based trajectories offer an independent data source to track projections for near future years.

By 2100, Delaware mean sea levels are projected to reach from 1.90 ft (Low scenario) to 6.73 ft (High scenario) relative to year 2000 levels. The mean sea level trajectory is currently tracking from the Intermediate-Low and increasing to the Intermediate scenario projection. The Intermediate-Low to Intermediate-High scenarios provide reasonable bounds for likely future sea levels in Delaware, providing a median range of 1.25 to 1.54 ft by 2050 and 2.53 to 5.20 ft by 2100 (above 2000 MSL). Process uncertainty (how well models capture the major contributing processes and feedbacks given a selected scenario), emissions uncertainty (which SLR scenario to use for a particular purpose), and natural variability (seasonal and interannual variations that normally occur in our climate system) should be taken into account when using any of these projections. Mean sea levels could also extend above the 83rd percentile presented in this report under any of the scenarios. Hence, the process 67% uncertainty range around the median projections for any given scenario should be provided, such as the values provided in **Table 5.13**. For example, under the Intermediate scenario, the 17-83% range of mean sea level change by 2100 is 3.17 ft to 4.63 ft (above 2000 MSL) with a 17% chance mean sea levels will be under 3.17 ft and 17% chance mean sea levels will be over 4.63 ft. Also note these values are averaged values, mean levels for any future month or year may be above or below the scenario projections for shorter periods of time.

Vertical land motion and sterodynamic (thermal expansion plus changing ocean currents) processes remain the largest contributing factors to SLR in Delaware by 2050. By 2100, melting of the AIS plays a more influential role, particularly at higher warming scenarios. The Antarctic ice sheet also contributes the largest portion of the process uncertainty ranges around the projections in the later half of the century. Projections begin to diverge from each other, and from the mean sea level trajectory, around the 2050s.

Coastal flood frequency and likelihood of extremes also will continue to increase accordingly. Under the Intermediate-Low to Intermediate-High scenarios, the number of HTF days per year increases from observed values of 22.8 and 40.8 over 2020-2024 at Reedy Point and Lewes to 37-38 and 52-56 days/year over the full 2020s decade, respectively. At both locations, this further increases to about 140-190 days/year over the 2050s to nearly everyday by the 2090s. For extreme water levels at longer return periods (50 years and greater), the exact likelihoods and return levels should be considered low confidence as additional factors in future environments (synthetic modeled events, changes in storm patterns, changes in human activities) also should be considered. Regardless of the scenario, global and regional sea levels will continue to rise (IPCC, 2019) and both minor and major coastal flooding will subsequently become more frequent throughout the 21st century.

5.6. References

Boon, J. D., Mitchell, M., Loftis, J. D., & Malmquist, D. M., 2018. Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions. *Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467*. Virginia Institute of Marine Science, College of William & Mary. https://doi.org/10.21220/V5T17T

Boumis, G., Moftakhari, H. R., & Moradkhani, H., 2023. Coevolution of extreme sea levels and sea-level rise under global warming. *Earth's Future*, 11, e2023EF003649. https://doi.org/10.1029/2023EF003649

Callahan, John A., Benjamin P. Horton, Daria L. Nikitina, Christopher K. Sommerfield, Thomas E. McKenna, and Danielle Swallow, 2017. Recommendation of Sea-Level Rise Planning Scenarios for Delaware. Technical Report prepared for Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs, 117 pp. https://doi.org/10.13140/RG.2.2.17411.66082

Callahan, John A., and Daniel J. Leathers, 2021. Estimation of Return Levels for Extreme Skew Surge Coastal Flooding Events in the Delaware and Chesapeake Bays for 1980 – 2019. *Frontiers in Climate*, Vol. 3:684834. https://doi.org/10.3389/fclim.2021.684834

Callahan, John A., Daniel J. Leathers, and Christina L. Callahan, 2022. Comparison of Extreme Coastal Flooding Events Between Tropical and Mid-Latitude Weather Systems in the Delaware and Chesapeake Bays for 1980- 2019. *Journal of Applied Meteorology and Climatology*, Vol 64:4. https://doi.org/10.1175/JAMC-D-21-0077.1

Callahan, John A., Bailey Armos, Tigist Jima, William Sweet, and Robert Urick, 2025. Downscaling Gridded Extreme Water Level Estimates at Short-term Tide Gauge Locations. *NOAA Technical Report NOS CO-OPS 109*, 52 pp. https://doi.org/10.25923/8rrq-1y08

Cazenave, A. et al., 2018. WCRP Global Sea Level Budget Group: Global sea-level budget 1993–present. *Earth System Science Data*, 10, 1551–1590. https://doi.org/10.5194/essd-10-1551-2018

[CO-OPS] Center for Operational Oceanographic and Services, 2023. Annual High Tide Flooding Outlook. *NOAA NOS Technical Report*. https://tidesandcurrents.noaa.gov/publications/2023_Annual_High_Tide_Flooding_Outlook.pdf

[CO-OPS] Center for Operational Oceanographic and Services, 2025. Sea Level Trends Product. Accessed March 4, 2025. https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

DNREC, 2012. Preparing for Tomorrow's High Tide: Sea-Level Rise Vulnerability Assessment for the State of Delaware. Technical Report, Prepared for the Delaware Sea Level Rise Advisory Committee for Delaware DNREC, 210 pp. https://dnrec.delaware.gov/coastal-programs/planning-training/adapting-to-sea-level-rise/

Delaware Sea Grant, 2002. The Great Nor'easter of 1962: Delaware's Storm of the Century. Delaware Sea Grant Report DELU-G-02-001. https://repository.library.noaa.gov/view/noaa/38117/noaa_38117_DS1.pdf

Dangendorf, S., Hay, C., Calafat, F.M. et al., 2019. Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change,* 9, 705–710. https://doi.org/10.1038/s41558-019-0531-8

Dangendorf, S., Hendricks, N., Sun, Q. et al., 2023. Acceleration of U.S. Southeast and Gulf coast sea-level rise amplified by internal climate variability. *Nature Communications,* 14, 1935. https://doi.org/10.1038/s41467-023-37649-9

Dusek G., Sweet W.V., Widlansky M.J., Thompson P.R., Marra J.J., 2022. A novel statistical approach to predict seasonal high tide flooding. *Frontiers in Marine Science*, 9. https://www.frontiersin.org/articles/10.3389/fmars.2022.1073792

Eagleson, P. S., and Ippen, A. T., 1966. Estuary and Coastline Hydrodynamics. New York, NY: McGraw-Hill Book Co.

Falasca F, Brettin A, Zanna L, Griffies SM, Yin J, Zhao M. Exploring the nonstationarity of coastal sea level probability distributions. *Environmental Data Science*, 2023;2:e16. https://doi.org/10.1017/eds.2023.10

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021. Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362. https://doi.org/10.1017/9781009157896.011

Frederikse, T., F. Landerer, L. Caron, S. Adhikari, D. Parkes, V.W. Humphrey, S. Dangendorf, P. Hogarth, L. Zanna, L. Cheng, and Y.-H. Wu, 2020. The causes of sea-level rise since 1900. *Nature*, 584 (7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

Hague, B. S., & Talke, S. A., 2024. The influence of future changes in tidal range, storm surge, and mean sea level on the emergence of chronic flooding. *Earth's Future*, 12, e2023EF003993. https://doi.org/10.1029/2023EF003993

Hamlington, B.D., Bellas-Manley, A., Willis, J.K. et al., 2024. The rate of global sea level rise doubled during the past three decades. *Communication Earth Environment*, 5, 601. https://doi.org/10.1038/s43247-024-01761-5

Harleman, D. R. F., 1966. "Real estuaries, in estuary and coastline hydrodynamics," in Tidal Dynamics in Estuaries: Real Estuaries. *Estuary and Coastline Hydrodynamics,* ed A. T. Ippen (New York, NY: McGraw-Hill), 522–545.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds.

Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

Kavanaugh, K., Keeney, A., Callahan, J., and Sweet, W., 2023. Notice of Methodology Update: NOAA High Tide Flooding Outlooks. *NOAA Technical Service Publication NOS CO-OPS 001*. 15 pp. https://tidesandcurrents.noaa.gov/publications/HTF_Notice_of_Methodology_Update_2023.pdf

Kopp, R.E., 2013. Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability?. *Geophysical Research Letters*, 40:3981–3985. https://doi.org/10.1002/grl.50781

Kopp, R. E., Garner, G. G., Hermans, T. H. J., Jha, S., Kumar, P., Reedy, A., Slangen, A. B. A., Turilli, M., Edwards, T. L., Gregory, J. M., Koubbe, G., Levermann, A., Merzky, A., Nowicki, S., Palmer, M. D., and Smith, C., 2023. The Framework for Assessing Changes To Sea-level (FACTS) v1.0: a platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change. *Geoscience Model Development*, 16, 7461–7489. https://doi.org/10.5194/gmd-16-7461-2023.

Kopp, R. E., Garner, G. G., Jha, S., Hermans, T. H. J., Reedy, A., Slangen, A. B. A., Turilli, M., Merzky, A., & Koubbe, G., 2023b. Framework for Assessing Changes To Sea-Level (FACTS) (v1.1.2). Zenodo. https://doi.org/10.5281/zenodo.10403331

Lee, S. B., Li, M., and Zhang, F., 2017. Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*, 122, 3917–3938. https://doi.org/10.1002/2016JC012597

McKeon, K., & Piecuch, C. G., 2025. Compound minor floods and the role of discharge in the Delaware River Estuary. *Journal of Geophysical Research: Oceans*, 130, e2024JC021716. https://doi.org/10.1029/2024JC021716

May, C.L., M.S. Osler, H.F. Stockdon, P.L. Barnard, J.A. Callahan, R.C. Collini, C.M. Ferreira, J. Finzi Hart, E.E. Lentz, T.B. Mahoney, W. Sweet, D. Walker, and C.P. Weaver, 2023. Chapter 9. Coastal effects. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH9

Menéndez, M., and P. L. Woodworth, 2010. Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal Geophysical Research*, 115, C10011. http://doi.org/10.1029/2009JC005997

Morim, J., Wahl, T., Rasmussen, D.J. et al., 2025. Observations reveal changing coastal storm extremes around the United States. *Nature Climate Change*, 15, 538–545. https://doi.org/10.1038/s41558-025-02315-z

Nerem, R.S., B.D. Beckley, J.T. Fasullo, B.D. Hamlington, D. Masters, and G.T. Mitchum, 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proc. Natl. Acad. Sci. U.S.A.,* 115 (9) 2022-2025. https://doi.org/10.1073/pnas.1717312115

Nerem, R. S., Frederikse, T. & Hamlington, B. D., 2022. Extrapolating empirical models of satellite-observed global mean sea level to estimate future sea level change. *Earth's Future*, 10, e2021EF002290. https://doi.org/10.1029/2021EF002290

Quadrado, G. P., & Serafin, K. A., 2024. The timing, magnitude, and relative composition of extreme total water levels vary seasonally along the U.S. Atlantic coast. *Journal of Geophysical Research: Oceans*, 129, e2023JC020557. https://doi.org/10.1029/2023JC020557

Ross, A. C., Najjar, R. G., Li, M., Lee, S. B., Zhang, F., and Liu, W., 2017. Fingerprints of sea level rise on changing tides in the Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans*, 122, 8102–8125. https://dor.org/10.1002/2017JC012887

Salehi, M., 2018. Storm surge and wave impact of low-probability hurricanes on the lower Delaware Bay—calibration and application. *Journal of Marine Science Eng*ineering, 6:54. https://doi.org/10.3390/jmse6020054

Sallenger, A. H., K. S. Doran, and P. A. Howd, 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*, 2:884–888. https://doi.org/10.1038/nclimate1597.

Sweet, W.V. and J. Park, 2014. From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, 2 (12), 579–600. https://doi.org/10.1002/2014EF000272

Sweet, W.V., G. Dusek, J. Obeysekera, and J.J. Marra, 2018. Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. *NOAA Technical Report NOS CO-OPS 086.* National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 44 pp. https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022. Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. *NOAA Technical Report NOS 01*. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://sealevel.globalchange.gov/internal_resources/756/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Sweet, W. V., Genz, A. S., Menendez, M., Marra, J. J., & Obeysekera, J., 2024. Implications of variability and trends in coastal extreme water levels. *Geophysical Research Letters*, 51, e2024GL108864. https://doi.org/10.1029/2024GL108864

Thompson, P.R., M.J. Widlansky, B.D. Hamlington, M.A. Merrifield, J.J. Marra, G.T. Mitchum, and W. Sweet, 2021. Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*, 1–7. https://doi.org/10.1038/s41558-021-01077-8

Wong, K.–C., and Münchow, A., 1995. Buoyancy forced interaction between estuary and inner shelf: observation. *Continental Shelf Research*, 15, 59–88. https://doi.org/10.1016/0278-4343(94)P1813-Q

Zervas, C., 2009. Sea Level Variations of the United States 1854-2006. *NOAA Technical Report NOS CO-OPS 053*. 194 pp. https://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

6. Conclusion

The current report builds on previous work put forth by the State of Delaware to assess future climate conditions of temperature and precipitation (published in 2014) and sea level rise (published in 2017). Projections of each of these were updated based on the latest CMIP6 modeling efforts and the most recent assessments from the IPCC AR6 and NCA5. Changes in the mean conditions and in the frequency of extreme events were assessed under a variety of potential future scenarios spanning the range of plausibility. The current report also included the most recent observations to update past trends, adding 7 years of sea level observations and 10 years of temperature and precipitation observations since their last Delaware reports, respectively.

Across the board, the trends observed in all three major climate indicators are consistent with those documented in previous Delaware climate reports. Temperature and sea level continue to rise, and the frequency of extreme temperatures, and coastal flooding continue to increase. Projections show that these trends are expected to continue into the future with greater amounts of change associated with higher warming scenarios. Advances in modeling, scientific understanding, downscaling methods, and recent observations have improved our confidence in plausible ranges of future outcomes. In the coming decades, over all scenarios, Delaware will be substantially warmer and sea levels will be substantially higher. After the year 2050, the choice of scenario becomes increasingly important and should be selected based on the intended use of the projection.

6.1. Key Takeaway Messages

Key messages derived from the major findings of this report are as follows:

Temperature

- **Historical Warming**: Since 1895, Delaware has experienced a consistent warming trend of about 0.3°F per decade, amounting to over 3°F of total warming. This trend applies equally to maximum, minimum, and average temperatures.

- **Model Reliability**: Downscaled model projections (especially STAR-ESDM) align closely with observed temperatures from 1950 to 2023, providing confidence in their use for future temperature projections and extremes.

- **Projected Temperature Increases**: By 2081–2100, average temperatures in Delaware are projected to rise by 5–6°F under SSP2–4.5 and 8–9°F under SSP5–8.5, with winter temperatures showing the strongest seasonal increases and autumn showing the least change.

- **Shifting Climate Indicators**: Significant increases in growing season length, cooling degree days, and growing degree days are projected, while heating degree days are expected to decline substantially—mirroring historical trends.

- **More Frequent Extremes**: By the end of the century under SSP5–8.5, Delaware is projected to have 70 more days per year with highs ≥90°F and over 50 more nights with lows ≥75°F, while cold nights (≤32°F) are expected to decline sharply.

Precipitation

- **Historical Trends Modest and Statistically Insignificant**: Since 1895, Delaware's precipitation has increased by about 3 inches (0.23" per decade), but this trend—and most seasonal changes—are not statistically significant, except for a small increase in autumn.

- **Model Agreement**: Downscaled precipitation models (especially STAR-ESDM) show small, conservative upward trends that align with observed precipitation data from 1950–2023, supporting their reliability for future projections.

- **Projected Annual Increases**: By 2081–2100, Delaware's annual precipitation is projected to increase by 2–2.5 inches under SSP2–4.5 (5%) and about 4 inches under SSP5–8.5 (9%), with winter showing the strongest seasonal increase.

- **Autumn Reversal and Seasonal Variability**: While most seasons are projected to get wetter, autumn precipitation may actually decline after 2060 under both SSP scenarios, especially SSP2–4.5.

- **Limited Increase in Extreme Events**: Despite overall increases, extreme precipitation events are projected to rise only modestly—e.g., days with ≥1.0" increase by 17% under SSP5–8.5, but days with ≥2.0" increase by just one day or less annually.

Sea Level

- **Historical sea level rise:** SLR has been occurring in Delaware since measurements began over a hundred years ago. Following the long-term linear trend, mean sea levels have increased 10.5 inches since 1956 at Reedy Point and 15.5 inches since 1919 at Lewes. Concomitantly with increases in mean sea levels, the frequency of coastal flooding has increased exponentially and extreme events have occurred more often.

- **Accelerated change:** Acceleration in mean sea levels has been observed at both locations, with sea level rise over the last 40 years of approximately 7 inches at Reedy Point and 8.7 inches at Lewes. Due to this acceleration and significant interannual variation, past long-term linear trends should not be used to predict future conditions.

- **SLR "planning" scenarios:** Projections of SLR in this report are based on the five scenarios developed in Sweet et al (2022) to support NCA5. Rather than based explicitly on SSP or RCP forcing, these scenarios were designed to span the plausible range of global mean sea level rise outcomes by 2100 from 0.5 to 2.0 meters in equal increments of 0.5 meters (with an additional Low scenario of 0.3 m to approximate long-term past trends). Hence, Delaware SLR projections in this report cannot be directly compared to those presented in previous Delaware reports and need to be interpreted accordingly.

- **Scenario tracking:** Observation-based trajectories are incorporated into Delaware's SLR projections. Extrapolating trajectories to 2050 tracks between the Intermediate-Low and Intermediate planning scenario and increasing at a rate faster than modeled projections. Although the Low and High scenarios may be reached, a reasonable range of future sea levels in Delaware is the Intermediate-Low to Intermediate-High scenario.

- **More frequent extremes:** Even moderate SLR can result in large, rapid increases in coastal flood frequency as monthly and seasonal high tides begin to approach flood impact thresholds. Under all scenarios for all future years, both minor and major flooding events are projected to occur more often.

- **Model agreement in the first half of the 21st century:** There is little difference of projected mean sea level change among the planning scenarios for the next few decades. For near-future estimates, the observation-based trajectories offer a reasonable alternative and constraint to the modeled projections.

- **Ice sheet instabilities may play a large role in the latter half of the 21st century:** Due to the large process uncertainty surrounding the instabilities of the Antarctic and Greenland ice sheets, there exists a wide range of possible sea levels over the second half of the 21st century. The high impact/low confidence models play a large role in assessing SLR in later years (past 2050) and under high global warming levels, resulting in potentially very high increases in mean sea level in Delaware by 2100 and beyond.

- **Long-term commitment**: Under all scenarios, SLR in Delaware is expected to continue throughout the 21st century and beyond, primarily driven by continued thermal expansion, land-based ice melt, and local VLM. Even the Low planning scenario with minimal warming results in SLR rates comparable to what's recently been observed in Delaware. The amount of future warming will dictate the severity of sea level increase.

6.2. Cautions and Limitations

Climate projections are essential tools for understanding potential future climate conditions for regions. However, it's crucial to recognize their limitations and understand how to interpret the projections. Unlike the specific predictions of short-range meteorological models used to predict hourly to weekly conditions, climate projections are "what if" scenarios that explore a range of plausible futures. The projections discussed in this report do not account for natural variability within the climate system, such as phenomena like the ENSO or NAO (IPCC AR6, 2021). Interannual variability will still remain high with extended periods of time above or below the projections.

While projections can suggest environments that may favor the occurrence of extreme weather events, they do not predict specific occurrences of such events. Instead, they provide an estimate of how often these extremes might occur under changing climate conditions (NCA5, 2023). Many other factors with very low predictability at long time scales, such as position of the atmospheric jet stream or development of tropical cyclones, must be considered when assessing likelihood of extreme events. This is an important consideration when discussing the potential for extreme events in a future climate.

Uncertainty in climate projections arises from multiple sources including gaps in understanding climate system dynamics and scenario uncertainty, which reflects the unpredictability of future global economic activity. Rather than following a single trajectory, the actual climate outcome is likely to be a blend of scenarios (IPCC AR6, 2021). This includes inherent uncertainty at both spatial and temporal scales, meaning projected changes may not be consistent across regions or time periods (NCA5, 2023). GCMs that are downscaled through methods like STAR-ESDM and LOCA2 can enhance spatial resolution of the original GCM output, however, these products will have their own set of limitations that must be considered. Statistical downscaling relies on historical relationships between large-scale climate features and local conditions which add a source of uncertainty. These historic relationships may behave differently in a future climate based on changing socio-economic and environmental conditions. Climate dynamics are impacted by many variables, some of which may not be included or accurately represented in global climate models. For example, these models typically do not fully account for ocean temperature variability, despite the ocean storing approximately 90% of the excess heat energy trapped by heat-trapping gases (NOAA, 2023). Climate dynamics includes many feedback loops such as those involving cloud formation and changes in surface reflectivity due to loss of ice and snow across the globe. Such processes are especially difficult to handle accurately due to the sensitivity of the feedback system (IPCC AR6, 2021). Land surface properties also play a crucial role in climate dynamics and can influence atmospheric conditions at many different scales. Urbanization, deforestation, and agricultural changes can modify surface energy balances which directly affects surface temperatures. Alterations in vegetation and forest cover impact wind patterns and moisture fluxes. Downscaling attempts to capture the complexity of land surface interactions but it remains a challenge in climate modeling (NCA5, 2023).

For sea level rise, there is increased confidence in near-future changes through extrapolation of the observation-based trajectories of mean sea level. These trajectories also provide an independent assessment of how mean sea level projections are tracking. On the other hand, there are still many unknowns in the processes involved in the mass loss instabilities of the Antarctic and Greenland ice sheets. Contributions to sea level in Delaware, and in many non-polar areas of the world, play a larger role in the second half of the 21st century and under higher warming scenarios, essentially decreases our confidence at longer time frames.

While climate projections are invaluable for anticipating future conditions, it is essential to approach them with an understanding of their limitations. Recognizing the inherent uncertainties in model outputs due to assumptions, simplifications, and excluded variables is necessary for responsible interpretation.

6.3. Next Steps

Projections of temperature, precipitation, and sea levels will be used by Delaware state agencies, decision makers, state and local planners, and others to support the Delaware Climate Action Plan, first released in 2021 and currently being updated in 2025. The Plan will focus on reducing emissions, increasing resiliency and achieving the goals established in the 2023 Climate Change Solutions Act. Climate projections can help to achieve The Plan's goals in developing strategies and resilience plans for Delaware's future. Furthermore, the development of tools, apps, and maps can support engagement efforts with various levels of Delaware stakeholders and educate users on how best to incorporate these projections into their activities.

Several economic, industry, and disciplinary sectors in Delaware may be significantly affected by changes in temperature, precipitation, and sea levels. These changes, mentioned earlier in this and past reports, include impacts on agriculture, water supply and quality, human health, ecological systems, damage to public infrastructure and personal property, and many others. Future research is required to better understand potential impacts to these sectors and which projections provided in this report will help develop more resilient strategies.

High quality monitoring of temperature, precipitation, and sea levels were critical in developing past trends and forming the basis of future projections. Observations of sea levels were directly used to compute vertical land motion rates, extreme event likelihood and flood frequency, and percentage contributions from regional/global processes. Observations of temperature and precipitation are used to develop large scale regional and national maps, capturing the high spatial and temporal heterogeneity of weather systems, enabling comparisons of past weather patterns across the country. Historical observations provide constraints and validation on climate models. Support and coordination of continued, high quality environmental monitoring across the state is essential.

As our climate continues to shift to a warmer environment, previously unobserved impacts or feedback mechanisms may emerge. Delaware is located in a regional hotspot for sea level rise, and has a transitional climate regime where shifts in large-scale weather patterns or ocean/ice processes can result in significant changes to Delaware's climate. Improved downscaling methods or increased spatial resolution of climate models may provide more insight into the differences in projections between Delaware's north and south climate divisions as well as between coastal and inland regions. Delaware’s climate leadership, including the newly established Technical Climate Advisors committee, should stay abreast of the latest climate science research and national climate assessments in order to continuously reassess the risks associated with climate change.

6.4. References

Sweet WV, Hamlington BD, Kopp RE, Weaver CP, Barnard PL, Bekaert D, Brooks W, Craghan M, Dusek G, Frederikse T, et al. 2022. Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along U.S. coastlines. US Dept Commer NOAA Technical Report NOS 01. 111 p. Accessible at: https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate change 2021: The physical science basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

U.S. Global Change Research Program (USGCRP). (2023). *Fifth National Climate Assessment (NCA5)*. U.S. Global Change Research Program.

National Oceanic and Atmospheric Administration (NOAA). (2023). *Ocean heat storage and climate effects*. National Oceanic and Atmospheric Administration.

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022. Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. *NOAA Technical Report NOS 01*. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://sealevel.globalchange.gov/internal_resources/756/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

Appendix A. Global Climate Models Used

This report used statistically downscaled data from 13 GCMs (listed below) for three SSP scenarios: SSP2-4.5, SSP3-7.0, SSP5-8.5. There were outputs from 2 different downscaling methods: STAR-ESDM and LOCA2. For models listed below, three primary variables (Minimum Temperature, Maximum Temperature, Precipitation) were available at the time of this report's analysis and writing. NOTE: Only r1i1p1f1 run was used for both STAR–ESDM and LOCA2 products.

ACCESS-CM2	Australian Community Climate and Earth System Simulator Coupled Model 2
BCC-CSM2-MR	Beijing Climate Center Climate System Model 2 - Medium Resolution
CanESM5	Canadian Earth System Model version 5
EC-Earth3	European community ESM version 3
EC-Earth3-Veg	European community ESM version 3 - Vegetation
FGOALS-g3	Flexible Global Ocean-Atmosphere-Land System Model: Grid-Point version 3
GFDL-CM4*	Geophysical Fluid Dynamics Laboratory's Climate Model version 4.0
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory's Earth System Model version 4.0
MPI-ESM1-2-LR	Max Planck Institute Earth System Model 1.2 - Low Resolution
MRI-ESM2-0	Meteorological Research Institute Earth System Model Version 2.0
NORESM2-LM	Norwegian Earth System Model 2 - low-resolution atmosphere–land and medium-resolution ocean–sea ice
NORESM2-MM	Norwegian Earth System Model 2 - medium resolution of both atmosphere–land and ocean–sea ice
MPI-ESM1-2-HR	Max Planck Institute Earth System Model 1.2 - High Resolution

*SSP3-7.0 scenario was not available from this model group.

Appendix B. Projection Variables

The following is a list of the projection variables generated and used in this study.

All variables have annual values. Items with an asterisk (*) have daily, monthly, and annual values. Items with a Dagger (†) have monthly and annual values.

Temperature Indicators (Fahrenheit)

- Mean, Maximum (Max), Minimum (Min) Temperature*
- Cooling Degree Days Base 65
- Heating Degree Days Base 65
- Growing Degree Days Base 40, 50†
- Date of First Fall Frost 24, 28, 32
- Date of Last Spring Frost 24, 28, 32
- Growing Season Length 24, 28, 32
- Longest Period of Days with Max Temp ≥ 90, 95, 100, 105, 110
- Days with Max Temp ≥ 90, 95, 100, 105, 110
- Days per Year with Min Temp ≤ 32, 20
- Nights with Min Temp ≥ 70, 75, 80, 85, 90

Precipitation Indicators (inches)

- Total Precipitation*
- Days per Year ≥ 0.5, 1, 2, 3, 4, 5

Sea Level Rise Indicators (Mean Sea Level)

- Observation-based Trajectories & Planning Projections
- Avg Seasonal Cycle
- High Tide Flood Frequency
- Coastal Flood Frequency
- Extreme Water Levels

Appendix C. Data Availability

All data and graphics presented in this report are available through the Delaware Climate Office website at:

> **[climate.udel.edu]**

In addition, a GitHub repository was created for hosting the scripts used to develop the data products and graphics for this report.

For questions regarding the data, please contact the report authors at:

> **cema-info@udel.edu**