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New Jersey Climate Change Resource Center

State of the Climate

New Jersey 2022

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Foreword

The *New Jersey State of the Climate Report* summarizes annually updated scientific information on climate trends and projections that can be used by state and local decision-makers, researchers, hazard planning and climate resilience professionals, and residents. The *New Jersey State of the Climate Report* is developed by Rutgers University through its hosting of the New Jersey Climate Change Resource Center. The report provides end users with the information they need to monitor changing climate conditions to prepare for future impacts. This report is organized in the following sections:

1. An overview summary of New Jersey Climate trends from 1895 to 2022 and climate projections through 2100.

2. A brief discussion of global climate trends that affect conditions in New Jersey.

3. A synopsis of outstanding 2022 weather events followed by an in-depth analysis of historical climate data and future projections for New Jersey, with a focus on temperature, sea-level rise, precipitation, and extreme events such as tropical storms.

4. A discussion of summer 2022 warm and dry conditions that impacted water resources and agriculture in the context of past and future climate change in New Jersey.

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Executive Summary

This report focuses on changes in temperature, sea-level rise, precipitation, and extreme events:

Temperature – Like most locations globally, New Jersey has seen increases in annual and seasonal temperatures in recent decades. New Jersey's annual temperatures have risen by about 4 °F, roughly twice the global (over land and ocean surface) average and about 1.4 times the global overland average, since 1900. This warming trend is expected to accelerate with further climate change, presenting heat stress challenges to vulnerable residents and public health programs. By 2100, the annual average temperature in New Jersey is projected to increase by as much as an additional 4–5 °F with lower greenhouse gas emissions and as much as an additional 9–10 °F with higher greenhouse gas emissions.

Sea level – Sea level has been perennially increasing along New Jersey at about 0.16 inches/yr (~18.2 inches since the early 1900s) due to global sea-level rise and land subsidence. Heightened sea levels present a greater likelihood of flooding during coastal storms or very high tides and can salinate freshwater ecosystems and resources. By the end of the century, likely probabilistic range of sea levels in New Jersey is projected to be as much as 4.0–6.3 ft above the year 2000 mean sea level across low to high emissions scenarios.

Precipitation – The total annual rainfall within the state has increased by ~7% since the early 1900s, with the most intense events generating more rainfall compared to historical episodes. Future conditions are expected to see an increase in total annual rainfall of about 4–12% by the end of the century and extreme 24-h rainfall of about 5–15%. Despite increasing rainfall, rising temperatures increase water demand and evaporation, increasing the likelihood of drier soil conditions.

Extreme events – Summer (June–August) 2022 was the 3rd warmest summer on record in New Jersey (with the warmest August on record) and presented the hottest 31-day period in recorded climate history in many locations in the state. As summer temperatures in the northeastern U.S. increase and summer rainfall remains relatively unchanged, the frequency and intensity of short-term, very dry to drought conditions are likely to increase.

Global Climate

The increased atmospheric concentration of greenhouse gases (e.g., carbon dioxide [CO_2], methane [CH_4]) has caused an increase in global temperatures and changes in the global climate system. [1] In 2020, CO_2 and CH_4 concentrations accounted for approximately 66% and 16% of the observed global heating, respectively. [2] Most of the remaining 18% of the observed warming can be attributed to nitrous oxide (N_2O, 6.5%) and long-lived compounds like chlorofluorocarbons (CFCs) and halocarbons. [2] Since the 1960s, the growth rate of atmospheric CO_2 concentration has accelerated from roughly 1 part per million per year (ppm/yr) to over 2 ppm/yr in the 2010s. The current atmospheric concentration of CO_2 is above 418 ppm (Figure 1), the highest it has been in at least 800,000 years. [3] The growth rate of atmospheric CH_4 concentration has increased from 6.4 parts per billion per year (ppb/yr) over the period of 2008 to 2014 to 9.7 ppb/yr over 2015 to 2020. [2] Atmospheric N_2O has increased at a rate of about 1 ppb/year over the past decade and the concentration of CFCs has been declining since the year 2000. [2]

From the late 19th century to today, global temperatures have increased by roughly 2 °F [5] and have been rising more rapidly since the 1970s (Figure 2, next page). 2022 was the sixth warmest year on record, and the period of 2014–2022 represents the warmest nine years on record (Figure 2). Since the turn of the century, 19 of the 22 years have ranked in the top 20 warmest years in records dating back to 1880. The average rate of temperature increase has accelerated from roughly 0.14 °F/decade from 1880–present to an average rate of 0.34 °F/decade since 1981. [6] According to the Intergovernmental Panel on Climate Change (IPCC), it is unequivocal that human activity, mainly the burning of fossil fuels, is the primary cause of increased greenhouse gas concentrations and this observed warming. [1]

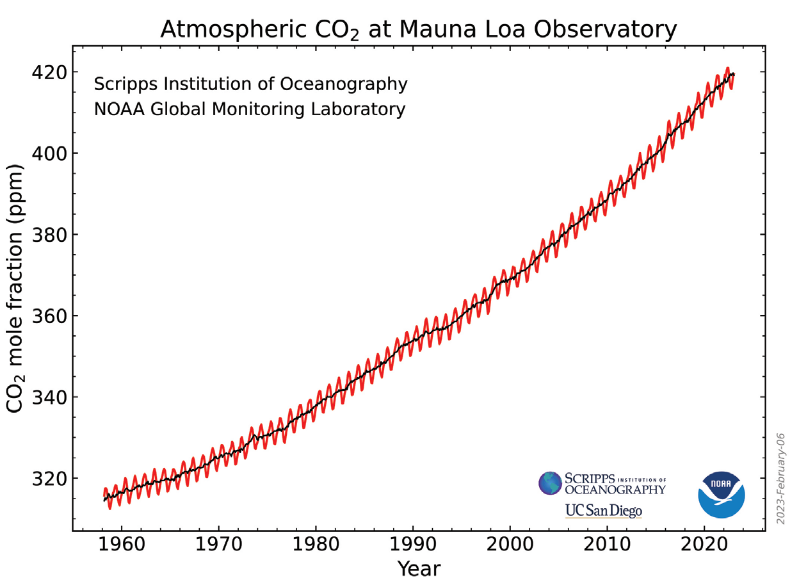


Figure 1. Atmospheric carbon dioxide concentrations in parts per million (ppm) measured at Mauna Loa, Hawaii. Red: monthly values; Black: 12-month running average. [NOAA Earth System Research Laboratory][4]

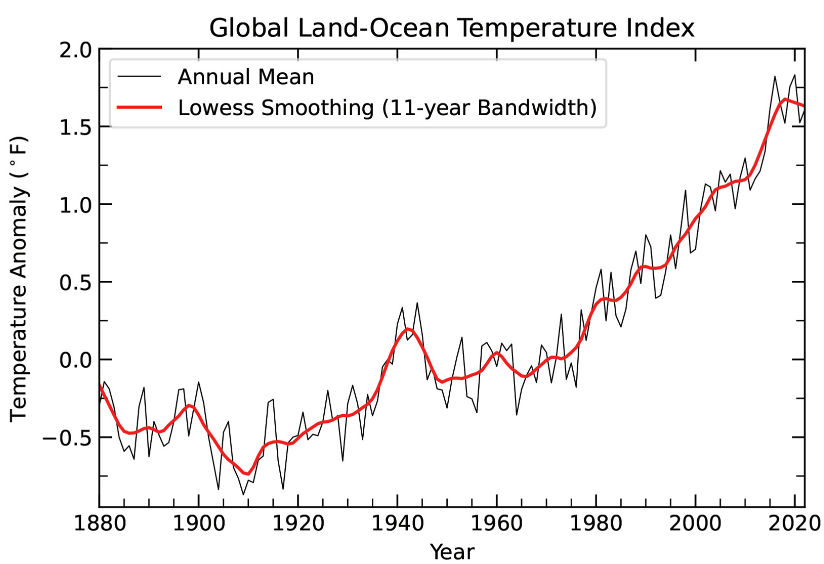
2022 was the sixth warmest year on record. The period of 2014–2022 represents the warmest nine years on record.

While global temperatures have consistently increased since the 1970s, year-to-year temperature changes are variable. For example, two recent strong El Niño years, 2016 and 1998, exhibited significantly warmer global temperatures relative to surrounding years (Figure 2). Additionally, temperature change varies by location. The Arctic has experienced more than twice the amount of warming as the global average [8] due to sea ice loss and other processes. [9] It should be noted that land areas generally warm more than regions over the ocean at the same latitude, particularly at high northern latitudes. [10]

As global greenhouse gas emissions continue to rise, temperatures are expected to continue increasing. Under the lowest IPCC greenhouse gas emissions scenario, which would require a drastic reduction of carbon emissions (and negative emissions), temperatures would change by -0.2 °F to +1.2 °F by the end of the 21st century (1.8 °F to 3.2 °F above pre-industrial levels). The high emissions scenario, heavily increasing greenhouse gas emissions, projects temperatures to rise an additional 4.0 to 8.3 °F by the end of the century (6.0 °F to 10.3 °F above pre-industrial levels). [1]

[Note, the works upon which much of this report is based and analyses within this report do not incorporate IPCC AR6 [1] climate projections because, at the time of publication, IPCC AR6 climate projections are not fully available for New Jersey. These projections are expected to be available later in 2023 for full analysis.]

Figure 2. Global land-ocean temperature index anomalies relative to 1951–1980 average temperatures. [NASA's Goddard Institute for Space Studies (GISS)] [7]



Warming temperatures have raised the global mean sea level by increasing ocean temperatures and melting glaciers and ice sheets. As the ocean warms, it expands, increasing volume and mean sea level. Simultaneously, melting glaciers and ice sheets raise sea level through water runoff into the ocean. Since 1979, Antarctic Ice Sheet melt is estimated to have contributed 0.55 inches to global sea-level rise [11] and the Greenland Ice Sheet loss has caused approximately 0.54 inches of sea-level rise since 1972. [12] Global sea level has risen about 7.6 inches since the early 20th century [13] and ~3.2 inches in the last 22 years alone with a rate of 1.8 inches/decade over the period of 2013 to 2021. [14,15]

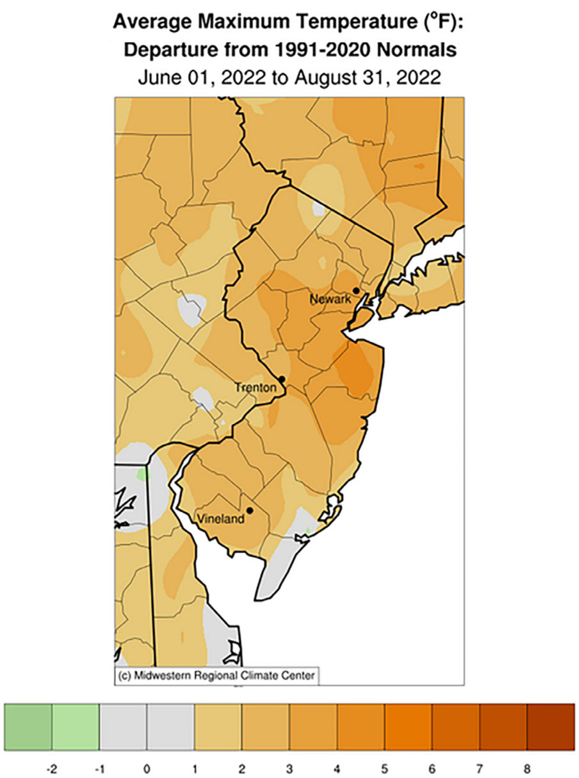
New Jersey Climate

The Office of the New Jersey State Climatologist (njclimate.org) serves as New Jersey's primary resource for statewide weather and climate data. Unless otherwise indicated, all observed data presented in the remainder of this report are from the Office of the New Jersey State Climatologist. New Jersey climate data are also archived at NOAA's National Centers for Environmental Information (ncei.noaa.gov).

2022 Weather Summary

Based on 128 years of records, 2022 was tied with 2002 and 2019 as the 12th warmest year, continuing the trend of increased warming in recent decades throughout New Jersey. The 2022 summer season drove much of this trend, being the third warmest on record with the warmest August average temperature at 77.1 °F; the next warmest August was in 2016 at 76.9 °F. The average daily maximum temperatures in central and eastern New Jersey were more than 3 °F higher than the summer daily maximum temperature average from 1991–2020 (Figure 3). In total, 53 days from May to September saw maximum temperatures of more than 90 °F throughout parts of the state. Similarly, November and March were unseasonably warm, with average maximum temperatures 3.3 °F and 3.5 °F above their 1991–2020 normals, respectively.

Figure 3. Interpolated contour map of the 2022 summer maximum average daily temperature anomaly in New Jersey as a departure from the 1991–2020 summer maximum daily temperature normal. Figure generated from NOAA Midwestern Regional Climate Center's Cli-MATE MRCC Application Tools Environment (https://mrcc.purdue.edu/CLIMATE/). [16]



Average precipitation through the state was 44.10 inches, 3.46 inches below the 1991–2020 normal of 47.56 inches, being the 54th driest since 1895. Coincident with the warm summer, 2022 also saw the fourth driest summer on record (the driest since 1966). Summer rainfall was 5.75 inches below the normal of 13.58 inches, with Wildwood Crest in Cape May County experiencing the driest conditions (4.19 inches) and Mantua in Gloucester County being the wettest (17.89 inches). A drought watch was issued by the New Jersey

What Are Emissions Scenarios?

How the future drivers of climate change, such as carbon dioxide emissions, will evolve by 2100 is unknown because they are rooted in global-scale technological, economic, population growth, and policy changes over the century. To assist in projecting how the climate may change, scientists use a range of illustrative scenarios to span the range of potential development of greenhouse gas emissions that vary based on socioeconomic assumptions, climate change mitigation strategies, and air pollution controls. [1] No one scenario is likely to completely predict future greenhouse gas emissions, but the range provides a series of guidelines on how the climate may evolve with enhanced or reduced anthropogenic emissions.

Department of Environmental Protection in August and persisted through the rest of the year, with the summer in various stages of Abnormally Dry, Moderate Drought, or Severe Drought, according to the U.S. Drought Monitor. [17]

These dry conditions were partially alleviated by the remnants of Hurricane Ian, which stalled off the coast of the Mid-Atlantic from September 30 to October 5. [18] Hurricane Ian caused significant damage across the southeast U.S., being the nation's third costliest weather disaster on record at $112.9 billion, as it traveled across Florida and up the East Coast until it dissipated over Virginia, [19] leaving remnants to affect New Jersey. Ian produced more than 9.00 inches of rain at Lacey and Berkeley Townships in Ocean County over this period but did not cause any significant rainfall-driven flooding. Ian's onshore winds, with gusts up to 50 miles per hour at Harvey Cedars in Ocean County, generated moderate coastal flooding, resulting in beach erosion along New Jersey's southern coastline. [18,20]

Other noteworthy events included high snowfall in southern New Jersey (from Burlington and Ocean Counties and further south) during the 2021–2022 winter season. Southern New Jersey experienced 24.8 inches of snowfall during this season, while central and northern New Jersey accumulated 16.6 inches and 22.7 inches, respectively. January 2022 was the second snowiest January on record in southern New Jersey in records dating back to the winter spanning 1895 and 1896. Finally, June saw the largest New Jersey wildfire since 2007 with the Mullica River Fire from June 18 to 21 burning 13,500 acres in Wharton State Forest in Burlington County. [21] No major damage was sustained from the blaze.

Temperature

Average annual temperatures in New Jersey have increased by nearly 4 °F since the end of the 1800s (Figure 4). The increase in New Jersey temperatures has been about twice the global land and ocean average and about 1.4 times the global overland average. [22] Between 1900 and 2022, New Jersey's annual average temperature has increased at a rate of 0.32 ± 0.03 °F/decade. There has been limited evidence that New Jersey warming has been partly fueled by greater offshore sea surface temperatures, [23] but scientific consensus has not yet been reached. Higher temperatures degrade air quality by increasing pollutants such as ground-level ozone, creating dry conditions conducive to wildfires that generate fine particulate matter, and extend/strengthen the allergy season. [24] Poor air quality can lead to higher rates of asthma, allergies, and deaths from respiratory-related illnesses. [25] Vector-borne diseases (such as West Nile virus) are also expected to have expanded ranges with increased temperatures (and humidity) as vector species, such as mosquitoes, spread to new locations. [24] Heightened temperatures will affect the agriculture sector by decreasing yields, reducing the viability of some crops (such as blueberries and cranberries) within New Jersey, and promoting the expansion of pest and weed species. [26]

Since 1970, New Jersey average temperatures have increased at a rate of 0.64 °F/decade (Figure 4), the equivalent rate of 6.4 °F/century. The warmest year on record is 2012 (55.9 °F) and the coldest is 1904 (47.8 °F). Despite relatively large year-to-year variability, recent temperature trends have been consistently increasing. Out of the 20 warmest years since 1895, 15 have occurred since 2000 (2022 was the 12th warmest year on record). Furthermore, none of the top 10 coldest years occurred after 1940.

As average annual temperatures rise in New Jersey, changes in seasonal temperatures vary substantially and are summarized in Table 1 (next page).

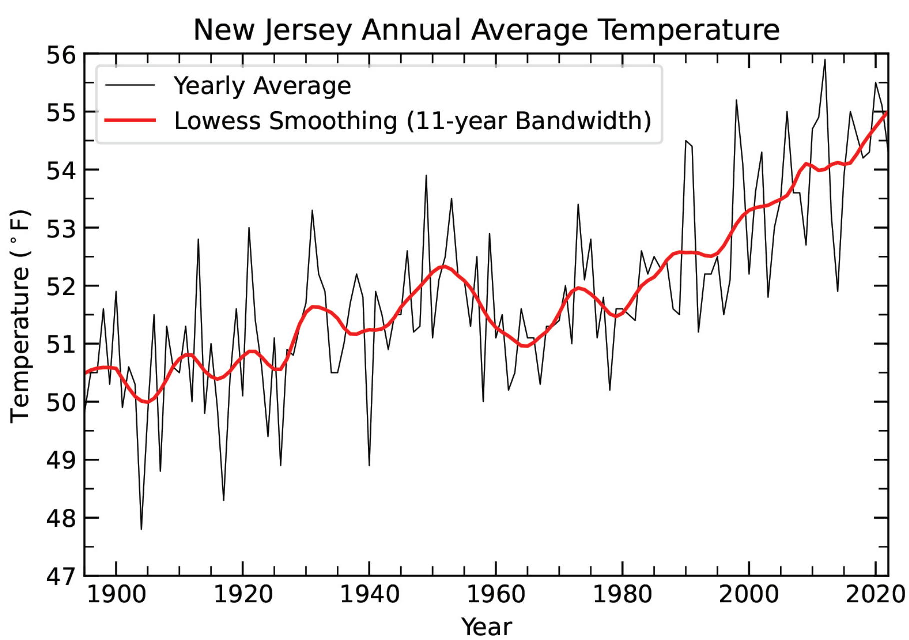


Figure 4: Average annual temperatures in New Jersey (°F). [Office of the New Jersey State Climatologist]

SEASON	TIME PERIOD			
	1900–2022		1970–2022	
	Linear Rate (°F/ decade)	Calculated Increase (°F)	Linear Rate (°F / decade)	Calculated Increase (°F)
Winter (December–February)	0.42 ± 0.07	5.2 ± 0.9	0.90 ± 0.24	4.8 ± 1.3
Spring (March–May)	0.27 ± 0.05	3.3 ± 0.6	0.52 ± 0.15	2.7 ± 0.8
Summer (June–August)	0.29 ± 0.03	3.6 ± 0.4	0.60 ± 0.10	3.2 ± 0.6
Fall (September–November)	0.26 ± 0.04	3.3 ± 0.5	0.58 ± 0.13	3.1 ± 0.7

Table 1. Average seasonal changes in New Jersey temperatures calculated by linear regression for 2022 and 1970–2022 with temperature increases calculated using the linear fit rate and its standard deviation.

Average temperatures during each season rose at higher rates over the past 53 years compared to the 123 years since 1900. Notably, the linear trend in winter temperatures increased by 4.8 °F ± 1.3 °F since 1970, a rate of 9.0 °F ± 2.4 °F/century, consistent with the U.S. northeast regional trend of winter temperatures warming at a higher rate than other seasons. [27] As the latest manifestations of this trend, the summer of 2022 ranked as the third warmest on record, averaging 74.9 °F (1.8 °F above the 1991–2020 normal).

Temperatures in New Jersey are expected to continue increasing as global greenhouse gas concentrations rise. Under a lower emissions scenario (as detailed in Runkle et al. (2023) [28]), average annual temperatures in New Jersey are projected to increase by as much as 8–9 °F by the end of the 21st century relative to the 1901–1960 average. [28] Under a higher emissions scenario, annual average temperatures are expected to increase by as much as 13–14 °F by 2100. [28] This projection is comparable with northeast regional projections of about a 10.1 °F increase with high emissions by the end of the century compared to the 1971–2000 average. [27] These higher annual temperatures are consistent with regional projections of increased temperature extremes (e.g., daily maximum temperatures or the number of days above 90 °F) in the northeast by the end of the century. [29] The range of projected temperatures in response to greenhouse gas emissions indicates that state- to global-scale emission policies will greatly influence New Jersey's future climate over the next century.

In addition to heightened average temperatures, heat stress caused by extreme heat events becomes more concerning with climate change. Heat stress is the leading cause of weather-related deaths in the United States. [30] Under high emissions, it is expected that approximately 70% of summers in New Jersey will be warmer than any prior to 2006 by the middle of the 21st century, growing to 90% by the end of the century. [31] Higher temperatures combined with high

Heat Vulnerability in New Jersey

In New Jersey, annual average temperatures have increased by about 4 °F (Office of the New Jersey State Climatologist), with summer temperatures averaging a 3.5 °F increase since 1900. Global and regional temperatures are expected to continue increasing, [1,28] with New Jersey summers becoming hotter [31] and heat waves becoming more frequent and longer. [60] Heat waves in New Jersey would increase from about 1.1 heat waves per year on average to about 3.8 per year by the middle of the century with moderate emissions. [60] These hotter summers will increase heat related illnesses, hospital admissions, and mortality, [24] especially among New Jersey's most vulnerable communities.

Heat vulnerability is the extent to which a community or person is likely to experience negative outcomes from extreme heat, such as increased hospitalization. It is difficult to assess the heat vulnerability of a community as often health emergencies exacerbated by extreme heat, such as asthma, are often not attributed to heat in medical records. [61] To highlight which communities may be more vulnerable to extreme heat, researchers review social and environmental factors that disproportionately exacerbate heat-related morbidity (worse health outcomes) and mortality. These factors range from environmental characteristics, such as the density of impervious surfaces, to community demographics, such as the number of residents aged 65 and older. The factors are combined into a single heat vulnerability index to help understand which communities may be more at risk during extreme heat. Figure S1 1 (next page) displays a map of the New Jersey heat vulnerability index developed by the New Jersey Climate Change Resource Center.

Individual factors are divided into three categories: Exposure, Sensitivity, and Adaptive Capacity. Exposure represents the physical environmental stressors or characteristics that lead to worse health outcomes such as poor air quality or impervious surface coverage that contributes to the urban heat island. [59,62,63]

Sensitivity is the degree to which individuals or communities may be affected by extreme heat, including information such as chronic health conditions [64–66] or age. [59,67] Finally, Adaptive Capacity is the ability to respond to, mitigate, and recover from extreme heat. This category contains economic information such as the percent of the population living below the poverty line [59] or without health insurance [68] that can hamper response efforts.

Where Are New Jersey's Most Heat Vulnerable Communities?

New Jersey's large urban areas like Newark, Jersey City, or Camden tend to have the highest heat vulnerability throughout the state. These locations have a high concentration of impervious surfaces, generating an urban heat island, and have a high proportion of sensitive populations with typically lower income (Figure S1 1).

The urban heat island effect, caused partly by the concentration of paved surfaces, intensifies heat vulnerability in cities such as Newark, Jersey City, and Camden (above).

Outside of the metropolitan regions, there are still small towns and cities such as Flemington, NJ, that are very vulnerable to heat due to a relatively higher proportion of the population with chronic health conditions and a higher rate of poverty and limited financial resources compared to the rest of the state. In some rural and suburban areas in southern New Jersey, higher vulnerability is due to low income, a high proportion of chronic health conditions, and a high number of people working outdoors.

The New Jersey heat vulnerability index allows public health officials to prioritize high-vulnerability areas for interventions and information campaigns and can be found within the New Jersey Climate Change Resource Center's NJADAPT tools (https://njclimateresourcecenter.rutgers.edu/nj-adapt/).

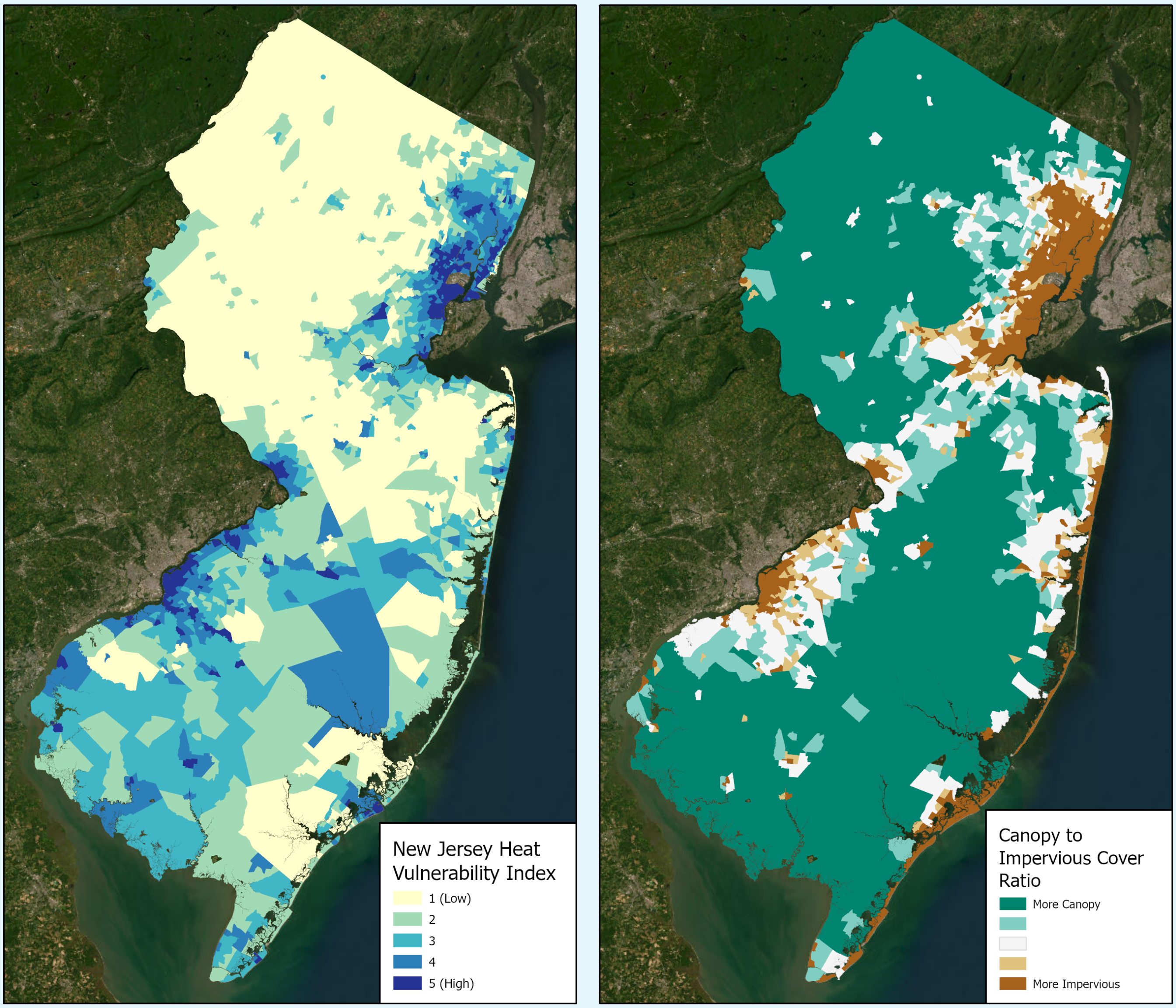


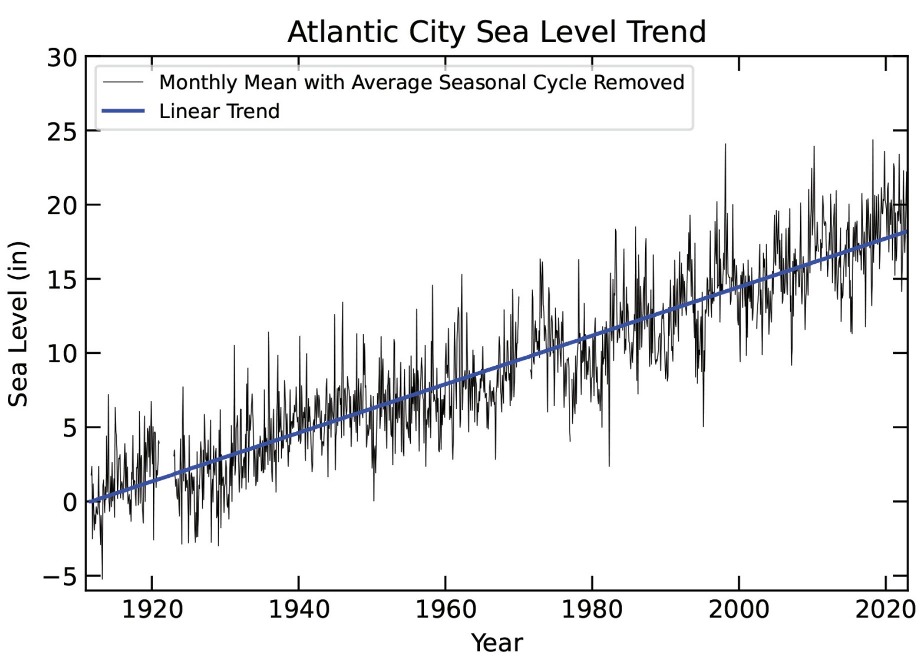
Figure S1 1. Left: Spatial distribution of the New Jersey heat vulnerability index where 1 (yellow) indicates a relatively low calculated vulnerability to extreme heat for a census tract and 5 (dark blue) indicates high vulnerability. Right: Spatial distribution of the canopy cover to impervious cover ratio by New Jersey census tract. More impervious cover (brown) is generally more conducive to producing a heat island (though the coastal and barrier islands are cooled by ocean winds).

humidity can lead to a higher risk of heat stress because the body's natural cooling from sweating becomes less effective in more humid conditions. In Atlantic City, summer dew point temperatures have risen by more than 3 °F since 1980, [32] creating more humid summers and increasing the potential for heat stress. Increased heat stress is expected to cause greater incidences of heat-related illnesses, hospital admissions, and deaths among vulnerable populations. [24] Extreme heat can also overburden building cooling systems or cause power outages, and high humidity keeps temperatures warmer overnight, limiting people's ability to find reprieve, worsening health outcomes. These effects are amplified in urban sectors where paved surfaces and lack of vegetation contribute to the urban heat island effect that heightens local temperatures compared to surrounding regions. [24]

Sea-Level Rise

Between 1911 and December of 2022, sea level rose approximately 18.2 inches at Atlantic City (Figure 5), more than double the global average. [13] The New Jersey coastline has exhibited a greater sea-level rise rate compared to the global average due in part to land subsidence. In New Jersey, subsidence, or the vertical sinking of the land surface, contributes to relative sea-level rise due to a slow vertical readjustment to the melting of ice sheets from the last ice age, natural sediment compaction, and groundwater withdrawal. [13] The average rate of sea-level rise since the early 20th century has been 0.17 inches/yr. [13] However, 8.2 inches of the total 17.6 inches of relative sea-level rise in Atlantic City (as of 2019) were observed since 1979, [13] a rate of 0.2 inches/yr, indicating that local sea-level rise is accelerating, and this rate has effectively continued through 2022. Higher sea levels can permanently inundate parts of the land, consuming property, infrastructure, and homes in low-lying locations near the coast. [33] Coastal flooding events become more frequent and larger as storm surges and wave effects are enhanced by a higher base sea level. [34] Sea-level rise can also exacerbate saltwater contamination of freshwater resources used for crop irrigation, salinate soils from coastal storm flooding, and threaten freshwater ecosystems by pushing salt water farther upstream in estuaries. [35]

Figure 5: Relative sea level trend (inches) at the Atlantic City Tide Gauge. [36]



Sea-level rise is expected to continue accelerating over the next century. Relative to the 1991–2009 baseline, sea level

Sea-level rise in New Jersey is expected to accelerate over the next century, causing more frequent and severe coastal flooding.

is projected to increase 0.5–1.1 ft by 2030 and 0.9–2.1 ft by 2050. [13] During this time frame, projections are largely independent from greenhouse gas emission scenarios, but after 2050, projections deviate depending on emission levels. In a low emissions scenario, [13] projected sea-level rise at 2100 is expected to be 1.7–4.0 ft compared to the year 2000. Under a high emissions scenario, sea level is projected to rise 2.3–6.3 ft. [13]

As a result of increased sea level, New Jersey's coast has become more subject to tidal flooding, also known as "sunny day" or "nuisance" flooding. Tidal flooding occurs when high tides cause flooding that is not associated with storm surge or extreme wave effects. Tidal flooding can disrupt roadways, damage buildings, reduce property values, and help overwhelm combined storm and wastewater systems, leading to public health concerns. [34] For example, in Atlantic City, the number of tidal flooding days has been increasing. From 2007 to 2016, the average number of yearly tidal flooding events was eight, while the average during the 1950s was less than one event per year. With moderate emissions, by 2030, 17 to 75 days per year are

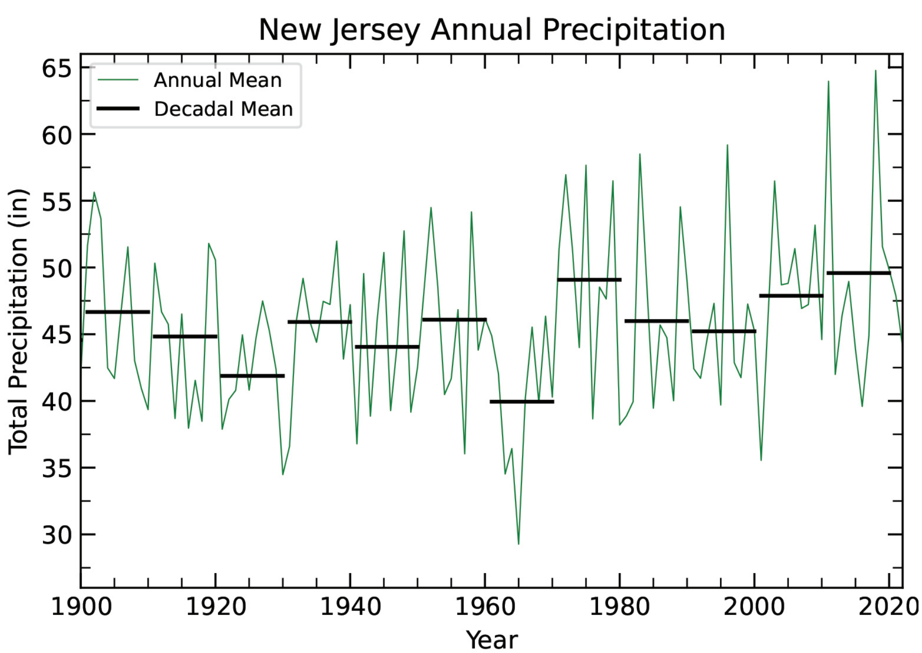
Tidal flooding, Harvey Cedars, N.J., December 2022 (Susan Kramer, MyCoast).

projected to experience tidal flooding, 85 to 315 days by 2060, and at least 240 days by the end of the 21st century. [13] In other words, as sea level continues to rise, Atlantic City's tidal flooding is likely to occur on most days of the year by 2100 across low to high emission scenarios.

Precipitation

Increasing temperatures allow the atmosphere to hold more water vapor, increase evaporation rates, and potentially produce more precipitation. Due to the large year-to-year variability of precipitation, this report uses decadal averages to analyze long-term trends. Decadal average precipitation in New Jersey increased roughly 3–5 inches (~7%) since the early 1900s (Figure 6). From 1901 to 1960, the average decadal precipitation was constrained between 42–46 inches/yr (Table 2). In the 1960s, the mean fell (coincident with drought conditions) to 40 inches/yr. From 1971–2020, the decadal means were generally within a slightly higher range of 45–49 inches/yr. Climate model data (accessed via the Applied Climate Information System, rcc-acis.org, managed by the Northeast Regional Climate Center, Cornell University) [37] project New Jersey to experience an increase in mean annual precipitation of 4–12% by the end of the century for moderate to high emissions compared to the 2001–2020 average, [38] similar to observed historical trends. Projected changes in annual precipitation by 2100 are smaller than the historic year-to-year variations in precipitation in New Jersey. So, while projections indicate a small increasing trend in annual precipitation, the high natural variability decreases confidence in the exact amount of projected increase.

Figure 6: New Jersey annual precipitation (inches). [Office of the New Jersey State Climatologist]



Observed increased precipitation magnitude has been coupled with an increase in interannual rainfall variability (Figure 6). Pre-1970, the average of the top five rainiest years was 54.14 inches, and post-1970 it was 60.81 inches (Table 3, next page). The average of the driest five years was 34.15 inches and 38.15 inches for each time period, respectively. This simple comparison elucidates that not only has annual rainfall been increasing, but that the range between rainiest years and driest years has also increased on average by ~2.66 inches (Table 3). In effect, these measurements indicate that interannual rainfall has become more variable, with some years fairly dry and others seeing excessive rainfall. This trend is expected to continue, and the northeastern U.S. will become wetter and experience greater precipitation variability by the end of the century. [39] A warming climate intensifies the hydrologic cycle, increasing precipitation variability globally, which can affect regional agricultural production, drought frequency, and flood conditions. [40] It should also be noted that precipitation patterns are naturally subject to high interannual, interdecadal, and location variability, so recent increases in precipitation amount may not be solely attributed to climate change.

Decade	Average Precipitation (inches/yr)
1901–1910	46.66
1911–1920	44.83
1921–1930	41.88
1931–1940	45.92
1941–1950	44.05
1951–1960	46.09
1961–1970	39.95
1971–1980	49.08
1981–1990	45.99
1991–2000	45.21
2001–2010	47.88
2011–2020	49.58

Table 2 (right). Decadal averages of New Jersey average annual precipitation from 1901 to 2020 [Office of the New Jersey State Climatologist]

Table 3 (below). The five highest and lowest annual New Jersey precipitation amounts in inches pre- and post-1970 with averages of each and the range between average highs and lows [Office of the New Jersey State Climatologist].

New Jersey yearly precipitation has increased more rapidly over the past 50 years compared to prior decades. Prior to 1961, annual precipitation amounts were effectively stable, displaying a small decreasing rate of 0.27 ± 3.40 inches/century. Since 1970, the linear rate has shifted to an increase of 2.21 ± 6.19 inches/century and 14.08 ± 7.93 inches/century since 1980. In general, the uncertainty ranges around each linear trend are large compared to the central value, emphasizing that large year-to-year rainfall variability is a dominant characteristic of New Jersey rainfall (Figure 6). The 1961–1970 period is not included in this analysis due to the large drought early in the decade

	Rank	1	2	3	4	5	Average	Range
Pre-1970	High	55.64	54.49	54.16	53.65	52.74	54.14	19.99
	Low	29.27	34.48	34.53	36.04	36.43	34.15	
Post-1970	High	64.76	63.95	59.18	58.50	57.66	60.81	22.66
	Low	35.55	38.20	38.66	38.88	39.46	38.15	

over-influencing the long-term trend. The top five wettest years since statewide records commenced in 1895 have all occurred since 1975, with a maximum of 64.76 inches in 2018. The lowest recorded yearly precipitation was 29.27 inches in 1965 (drought conditions). When assessing these precipitation trends and their societal impacts, it is important to consider the balance between evaporation and precipitation. Evaporation also increases with higher temperatures, transferring water back into the atmosphere more rapidly, making rainfall less available for water storage, agriculture, and other uses. Although it is projected that rainfall may increase in New Jersey on average, increasing temperatures and water demand will result in drier soils less suitable for agriculture and more conducive to wildfires in forest environments. More information regarding how changing water demand and drought conditions may impact water resources can be found on page 25 under *Summer Heat and Dryness in Context*.

In the northeastern U.S., summer precipitation is not projected to change substantially. Combined with higher temperatures and evaporation rates, the duration of future summer dry spells is expected to increase. Ultimately, while the frequency of extreme precipitation has increased in New Jersey [41] and is expected to continue, [42,43] the periods between rainfall events in the summer are projected to be longer and therefore drier (i.e., reduced water resources), resulting in more short-term drought conditions. [44] Due to increased temperatures, these more frequent dry periods could require increased irrigation and residential water usage, risking saltwater intrusion in New Jersey aquifers due to freshwater pumping. [26,44]

Extreme Events

As sea level rises in New Jersey, so does the risk of coastal flooding from storms. Storm surges induced by tropical cyclones and nor'easters and their potential damage are magnified by an increasing base sea level. For example, it has been estimated that approximately 12.8% of the total property damage from Hurricane Sandy in New Jersey can be attributed to human-caused sea-level rise, representing about $3.7 billion. [45] Following this trend, a coastal storm affecting New Jersey today would cause more flooding damage than the same storm 50 years ago, and today's 100-year intensity coastal flooding event is projected to occur five times as often by 2050. [46]

Extreme events can be defined as weather or climate events whose severity, magnitude, or impact rank above or below a (often subjective) threshold near the upper or lower ends of that type of event's historic range of intensity within a specific region.

Understanding Return Periods

Extreme events (primarily precipitation and flooding) are typically described in terms of return periods/intervals, such as the "x-year event." A 100-year event, typically referring to a flooding or extreme weather event, has a 1% or 1/100 probability of occurring each year at a specific location. Similarly, a 50-year event has a 2% or 1/50 probability of occurring each year at that location. A common misconception is that if a 100-year event occurred one year, it will not happen again for another 100 years or so. However, the probability remains at 1% each year no matter what happened in preceding years. A 100-year rainstorm on one day does not change the probability of receiving the same amount of precipitation the next.[47] Return period events are defined for a specific geographic scale (such as a point versus a county). For example, in a given year, multiple 100-yr rainfall events may be recorded throughout New Jersey. Those events characterize the specific locations in which the rainfall occurred but not the state as a whole. Finally, with climate change, a 100-year intensity event may become a 50- or 20-year event in the future as extreme event frequencies change. Note that what return level event is considered "extreme" is subjective and depends on the type of event, but the 100-year event is a common threshold used within scientific and planning assessments.

The extreme events described by the return period projection can be singular, such as the return period of a river flood elevation, but they can also include the event duration. For example, the measured rainfall over 24 hours and the rainfall measured over 2 days at a location may both present extreme conditions and different amounts. But each measured timeframe (24 hours vs 2 days) will have a separate set of return periods (e.g., the 10-yr return period of the 24-hour rainfall event is distinct from the 10-yr return period of the 2-day rainfall event).

A map of FEMA flood zones generated by NJ FloodMapper delineates 1% (blue) and 0.2% (orange) Annual Chance Flood Hazards, also known as 100-year and 500-year floodplains, in the area around Oceanport, N.J.

Heavy rain lashes an emergency vehicle (Edwin J. Torres, Governor's Office).

Extreme precipitation events in the northeast U.S. are becoming more frequent and intense. [48,49] Common practice is to use the NOAA Atlas 14 precipitation frequency estimates [50] for planning and design standards; however, this dataset ends in 2000. Incorporating data through 2019, most long-term weather stations throughout New Jersey have seen increases in the 2-, 5-, 10-, 25-, 50-, and 100-year return period precipitation events compared to the 2000 dataset. [41] At most locations, extreme precipitation amounts were found to be more than 2.5% greater than the 2000 dataset estimates. [41] This shift, by adding an additional 19 years of data, challenges a major assumption: that the past climate can accurately inform future expectations of extreme events. [51] It is therefore necessary that forward-looking metrics of extreme precipitation using historical data be supplemented by model projections to account for future climates.

More intense precipitation events will lead to more frequent and larger floods [44] that can cause loss of life and property/infrastructure damage in New Jersey. Flooding has compounding indirect effects through avenues such as carbon monoxide poisoning (personal power generator use after a flood) or contaminating food and water supplies. [24] Extreme rainfall can increase surface water turbidity and bacteria contaminants that can be ingested, causing gastrointestinal illnesses. [24] Frequent and intense precipitation can also lead to worse agricultural outcomes such as reduced plant growth, delayed planting, and soil saturation. [26]

There are multiple ways in which extreme precipitation can be quantified, and many studies offer different metrics to describe how the frequency of extreme precipitation has increased in recent decades. In New Jersey, the frequency of individual precipitation events producing more than 2 inches of rain has consistently been greater than the long-term 1900–2014 average since the late 1960s. The duration of these events can range from a few hours to several days. The five-year period between 1900 and 2014 with the most extreme precipitation (>2 inches) events was 2010–2014, indicating that extreme rainfall is becoming more frequent. [28] Shifting to a related metric, but using a duration of 24 hours and defining extreme precipitation as receiving more than 2 inches within that 24-hour period, the total number of days receiving extreme precipitation has increased over the past 50 years compared to the 1901–2020 average (Figure 7). From 2005–2014, the number of 2-inch precipitation days was generally above average, with 2010–2014 being about 50% greater than the 1900–2020 average of 2.3 days. [28]

The observed increase in extreme precipitation is not unique to New Jersey. Nationally since the 1990s, individual precipitation events exceeding the 5-year return period have occurred 20–40% more frequently, and over 40% more frequently between 2006 and 2016. [42] Looking at this trend another way, the northeastern U.S. saw a 74% increase in 48-hour extreme precipitation over the period 1901–2016. [42] At most U.S. weather stations, increasing extreme precipitation can be directly related to increasing temperatures. [52] Nationally, extreme precipitation events are projected to become more intense and frequent over mid-latitude regions (most of the continental U.S.), where warming is expected to occur at higher rates. [1]

Future projections of extreme rainfall within New Jersey indicate continued intensification of extreme 2-yr, 10-yr, and 100-yr 24-hour rainfall events. [43] The 24-hour event is the amount of rainfall that is accumulated in a 24-hour period. The 2-yr, 10-yr, and 100-yr return periods here represent the frequency at which the accumulated rainfall for a given 24-hour period is expected to occur. Assuming moderate emissions, the median projection for the magnitude of the 100-yr 24-hour rainfall event will increase modestly by 2.5–10% in central and coastal New Jersey and by a larger 20-25% in northern New Jersey by the end of the century. Higher frequency events, such as the 2-year and 10-year 24-hour rainfall events, are projected to have an average increase in rainfall of 7.5–15% by 2100. [43] It should be noted that these increases in rainfall are median estimates of large ranges of possible change. Regardless of the magnitude of the projected changes, the likely trend throughout the rest of the century is for large rainfall events (such as the 100-yr 24-hour rainfall event) in New Jersey to increase in magnitude.

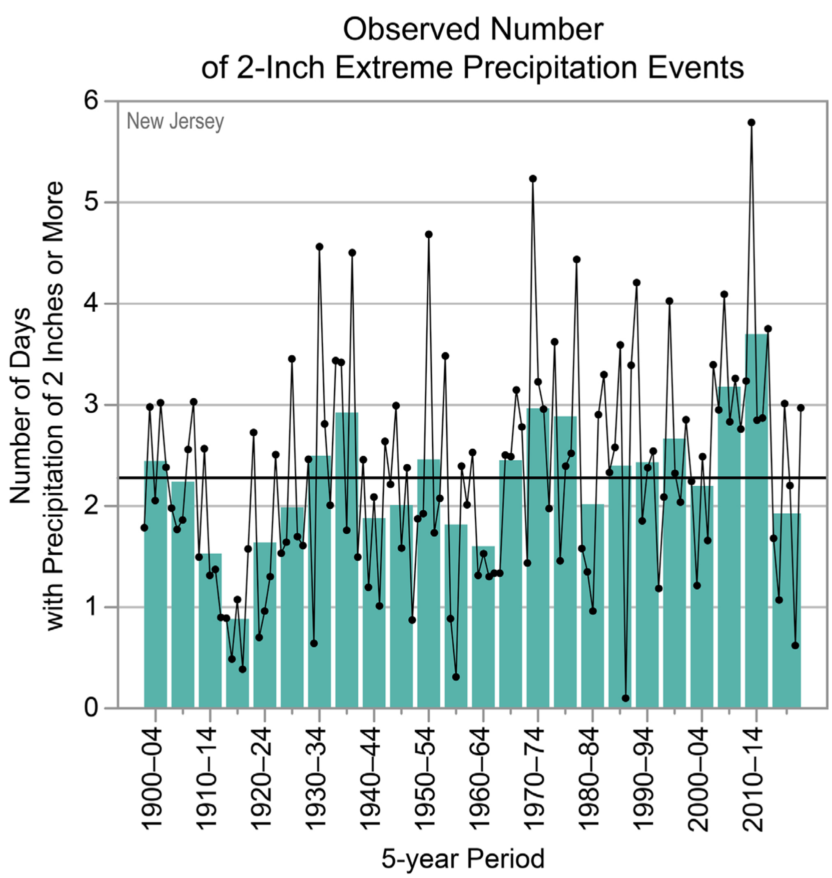


Figure 7. Annual number of days exceeding 2 inches of precipitation for New Jersey from 1900–2020. Bars show 5-year averages of the number of rainfall events, the black dots show the yearly values, and the black horizontal line represents the 1900–2020 average of 2.3 days per year where precipitation exceeds 2 inches. Reproduced from Runkle and others (2022). [28]

Climate Change and an Invasive Blueberry Pest

Insect pest invasions have increased worldwide over the last two centuries [69] and are associated with significant global economic costs, with an estimated increase in global expenditures relating to pest management of more than $1.288 trillion over the last 50 years. [70] Climate change exacerbates this issue by expanding the range of these insects, increasing survival during overwintering, increasing the number of generations, and reducing biological control on pest numbers, especially for natural predators.[71] The spotted-wing drosophila, *Drosophila suzukii* (Figure S2 1), is an invasive pest to North America that has caused yield losses to several crops such as blueberries, raspberries, strawberries, and cherries. [72–75] Farmers have had to increase insecticide usage to manage this new pest. [76,77]

Figure S2 1. Adult spotted-wing drosophila. An invasive pest, the spotted-wing drosophila damages blueberries and other fruits grown commercially in New Jersey. Climate change is likely to increase the insect's population and activity (picture courtesy of Cesar Rodriguez-Saona, Rutgers Department of Entomology and New Jersey Agricultural Experiment Station).

New Jersey is one of the nation's top blueberry-producing states, with a crop valued at $78 million. [78] Historic blueberry pests have been supplanted by spotted-wing drosophila, which is now the primary driver of increased insecticide application in New Jersey's blueberry fields. With climate change, it is likely that the population and activity of spotted-wing drosophila will increase in the near -term throughout much of the U.S., including New Jersey. [79]

The date of spotted-wing drosophila arrival in blueberry fields each year is related to activity: earlier arrival in blueberry fields generally is associated with greater activity and a larger population throughout the growing season. This greater activity results in more damage to the crop. Since 2011, the first arrival of spotted-wing drosophila has generally been earlier each year with small year-to-year variations. Using Oregon State's PRISM database of daily temperatures,[80] Shope et al. *(in press)* found that these trends are affected by climate variables: stronger winter freezing delayed arrival while warmer temperatures of the prior summer advanced the arrival. [81] Spotted-wing drosophila adults can tolerate brief exposures to freezing temperatures, [82–84] but harsh winters serve to lower the population size in New Jersey and reduce spring activity. [85] As our winters warm, we expect greater numbers of overwintering adults, resulting in larger populations in the spring and more damage to blueberry yields. This is likely to be compounded with warmer, more humid summers that further increase the pest activity.

Using projections of winter degree days below freezing and summer growing degree days, Shope et al. *(in press)* modeled how spotted-wing drosophila activity may change by 2030 and 2050. [81] In 2020, the first detection of spotted-wing drosophila was on May 20. With moderate warming under RCP 4.5, it is expected that spotted-wing drosophila will arrive 3.6 (±10.4) days earlier by 2030 and 9.7 (±17.7) days earlier by 2050 (Figure S2 2). With higher emissions under RCP 8.5, arrivals would be 3.9 (±11.7) and 14.5 (±26.3) days earlier by 2030 and 2050 respectively (Figure S2 2). While there will still likely be high year-to-year fluctuations in arrival dates, milder winters and warmer humid summers, will exacerbate spotted-wing drosophila activity in New Jersey blueberry fields and necessitate new integrated pest management practices.

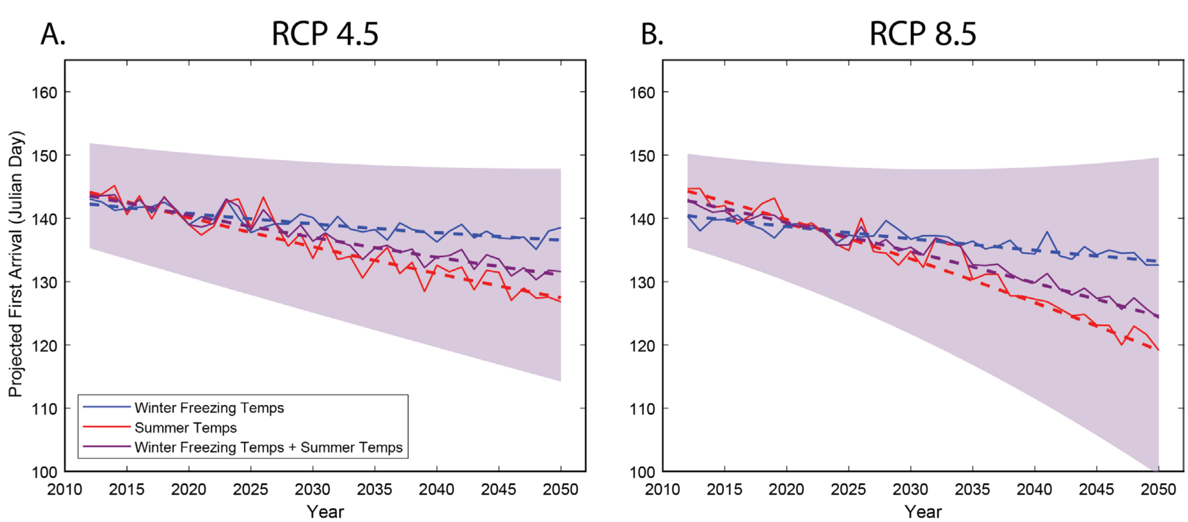


Figure S2 2. Projected spotted-wing drosophila capture date based on models corresponding to winter freezing temperatures (blue), prior summer temperatures (red), and a model incorporating both winter freezing temperatures and prior summer temperatures (purple) for: A. RCP 4.5 and B. RCP 8.5. Dashed lines represent a quadratic fit of each model output. The purple shaded region represents the range of the 95th percentile confidence bounds of the combined model. Data shown are model outputs and may not match observed capture dates exactly. Figure reproduced from Shope et al. *(in press).* [81]

Extreme Events: Focus on the Hot and Dry 2022 Summer

Summer (June–August) 2022 was warmer than normal in New Jersey with an average temperature of 74.9 °F, 1.8 °F above the 1991–2020 normal of 73.1 °F. This ranked as the third warmest summer in New Jersey since statewide records commenced in 1895 with only 2010 and 2020 being warmer. Of note, most of the anomalous warmth occurred during the latter two thirds of the summer. June was 0.4 °F cooler than the 1991–2020 normal and ranked 43rd mildest. However, the July average temperature was 2.4 °F above normal, ranking as the seventh warmest July on record (tied with 2012 and 2013). Finally, the summer rounded out with the hottest August recorded at 77.1 °F, 3.5 °F above normal. In context, the nine warmest summers of the past 128 years (since New Jersey records began in 1895) have occurred since 2005 with only two of the 15 warmest occurring before 1999. Overall, New Jersey has seen increasingly warmer summers as the climate changes, and 2022 was the latest continuation of this trend.

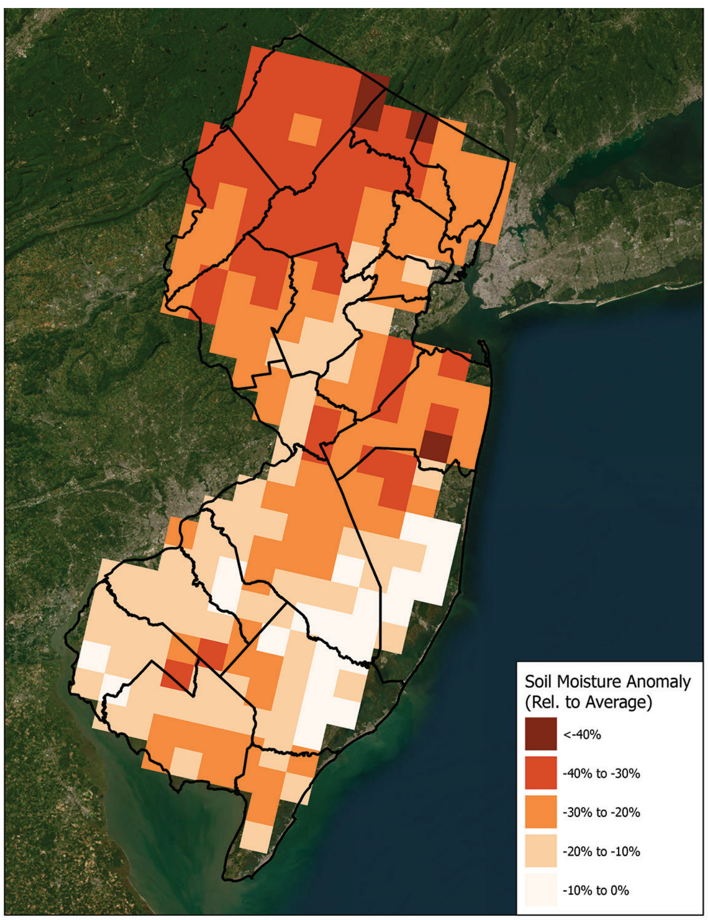
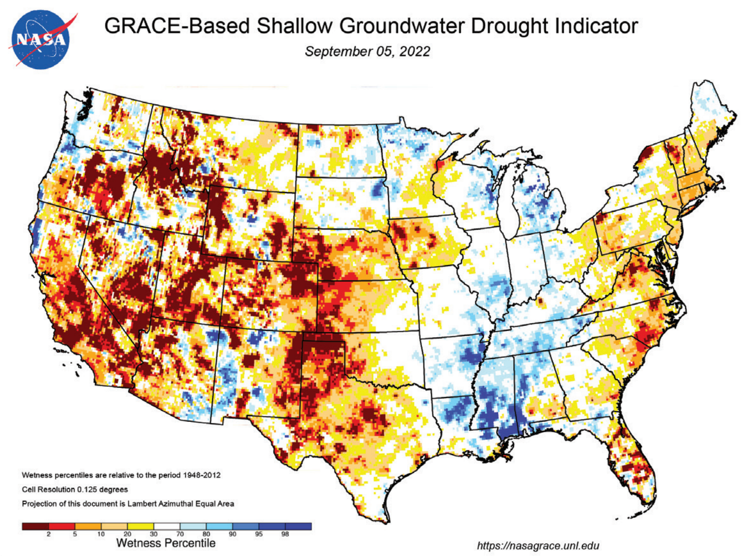


Figure 8. New Jersey top three foot soil moisture anomaly for the week of 29 August 2022 to 4 September 2022 presented as a percent deviation from the historic soil moisture average calculated from 2015 to current (as of September 2022). Data retrieved from the Crop Condition and Soil Moisture Analytics tool [53] and NASA SMAP and MODIS missions.

This summer was also very dry, with precipitation averaging 7.83 inches, 5.75 inches below normal and ranking as the fourth driest on record. This was the driest summer since 1966 when the total precipitation was 5.61 inches. All summer months were drier than

Resources for residents regarding weather emergencies and preparedness information can be found through the New Jersey Office of Emergency Management: https://www.nj.gov/njoem/plan-prepare/current-weather-traffic.shtml



average, with June precipitation being 3.39 inches (0.91 inches below average; 59th driest June), July at 2.09 inches (2.62 inches below average, 12th driest July), and August at 2.35 inches (2.22 inches below average, 18th driest August). This persistent dry pattern led to the New Jersey Department of Environmental Protection issuing a Drought Watch for the entire state on August 9 (https://nj.gov/dep/newsrel/2022/22_0809.htm).

As a result of these dry conditions, statewide root-depth soil moisture levels, the water present within approximately the top 3 feet of soil, were lower than average, with most regions in New Jersey being at least 20% drier than the multiyear average of 2015 to 2022 and many places within central and northern New Jersey being more than 35% drier by the end of the summer (Figure 8, previous page). [53] Combined with the heat, dry conditions reduced yields of many crops such as corn and soybeans, especially in unirrigated fields. [54]

Similarly, groundwater levels were low throughout the northeast, and groundwater drought indicators were in the 10th to 20th percentile (drier than normal) across most of the state during the first week of September (Figure 9). [55] Reduced groundwater is often also coupled with reduced streamflow and reservoir levels. As an example, the stream elevation along the Delaware River at Trenton was

Figure 9. Shallow groundwater indicator for the continental U.S. presented as the percentile of the probability of the 5 September 2022 wetness occurrence within the period of record from 1948 to the 2012. Lower values indicate drier than normal conditions and higher values indicate wetter than normal conditions. Note New Jersey is primarily within the 10th to 20th percentile at the end of the summer 2022 season. [55]

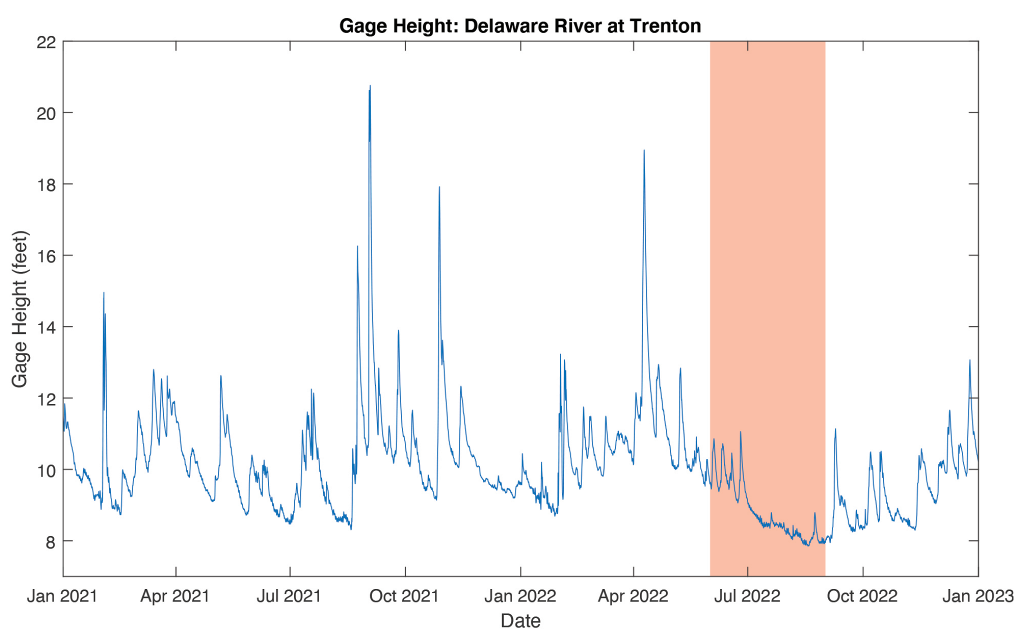


Figure 10. USGS stream gage height in the Delaware River at Trenton, NJ from January 2021 to January 2023. The shaded region indicates the summer (June to August) months of 2022. Note that the recorded river height during the summer and September was much lower than the preceding months. [56]

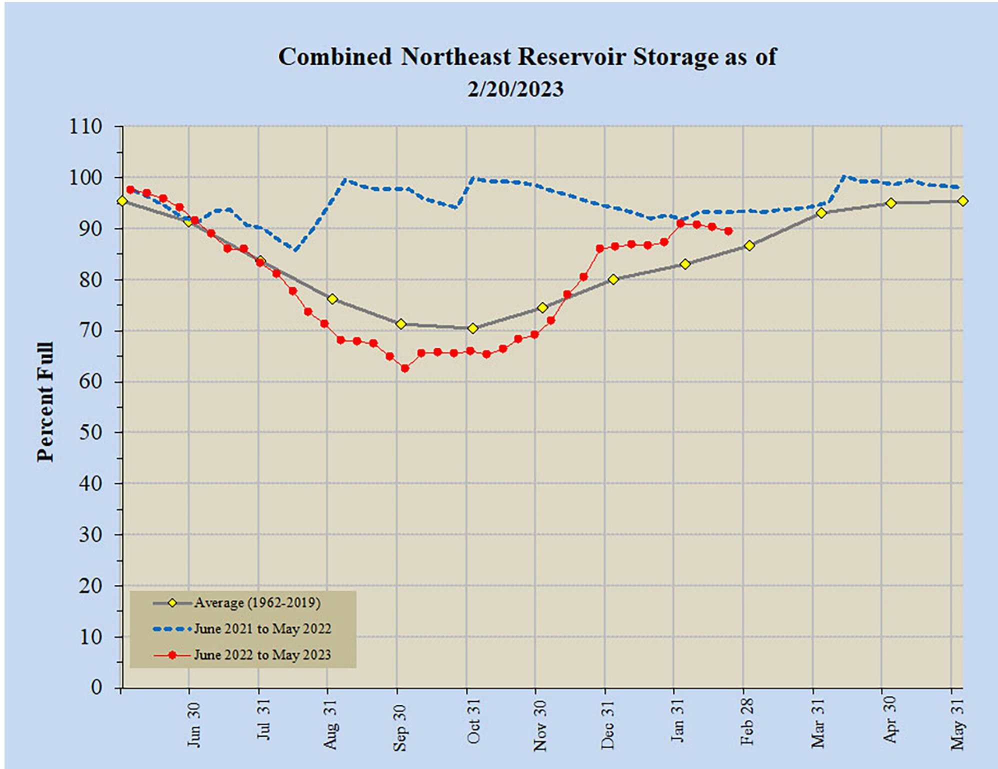


Figure 11. Combined northeast reservoir storage within New Jersey from June 2021 to May 2023 displayed as percentage of the total storage capacity filled. The blue dashed line indicates the June 2021 to May 2022 water year and the red line with circles indicates the June 2022 to May 2023 water year. The grey line with yellow dots represents the long-term average from 1962 to 2019. Note the reservoir volumes were lower than average during the summer to fall in 2022. [57]

below 8 feet in the third week of August after averaging 10.4 feet in the prior year and half (Figure 10, previous page). [56] The combined northeast reservoir storage for New Jersey was also 5% to 10% lower in the second half of summer and leading into October compared to the long-term average and much lower than the storage during the heavy summer and fall rains of 2021 (Figure 11). [57]

High Temperatures Across Months

Unusual weather and climate events are most often defined based on calendar months; for example, August 2022 was the warmest on record averaging 77.1 °F. Although August's warmth was noteworthy, spells of unusual weather are not required to line up neatly with the calendar. For several climate observing stations in central New Jersey, the summer of 2022 featured their warmest 31-day periods on record, but those periods spanned parts of July and August.

At the New Brunswick, Hightstown, and Long Branch-Oakhurst climate stations, the 31-day period from July 13 through August 12 was the warmest on record. At New Brunswick, the average temperature was 81.7 °F. Long Branch-Oakhurst and Hightstown were only slightly cooler, averaging 81.3 °F and 81.2 °F, respectively. The climate station at Freehold-Marlboro also experienced its warmest 31-day period in summer 2022, but during a slightly different period. It averaged 81.2 °F for the period from July 10 through August 9. Each of these stations has been recording temperatures for at least 115 years.

The Newark Liberty International Airport station also saw its warmest 31-day period of all time in 2022, averaging 83.6 °F over the period from July 12 through August 11. The paved surfaces of the airport runways, taxiways, and roadways contributed to the temperatures there being about 2 °F higher than at the other locations. This temperature difference serves as a reminder that densely built urban areas are more susceptible to excessive summer heat, subjecting their residents to potential adverse health impacts.

Summer Heat and Dryness in Context

As summer temperatures throughout the northeast U.S. increase, driving greater potential evapotranspiration, and summer rainfall remains relatively unchanged (DeGaetano et al.; [37] https://climatedashboards.rutgers.edu/), the frequency and magnitude of future summer dry to drought conditions is likely to increase. [58] Additionally, a larger fraction of the rainfall is expected to come in more intense episodes, [43] leading to drier conditions in-between. [44] From a human health perspective, increased summer temperatures will likely drive greater incidences of heat-related morbidity and mortality, [24] especially in dense urban regions. [59]

The summer of 2022 provides insights into some of the hazards and stressors that New Jersey communities will likely face more frequently over the coming century, such as fluctuations in water resources that affect agricultural production and promote higher wildfire risk. While on average New Jersey will likely have a similar amount of annual rainfall through 2100 compared to today, interannual and intra-annual variations in precipitation and extreme heat may contribute to greater variations in dry conditions and produce more summers like 2022.

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Appendix A

Table A1. Publicly Available Datasets used in this Report and the URLs for Access

Data Type	Organization	Data Source URL
Atmospheric Carbon Dioxide Concentrations Measured at Mauna Loa	NOAA Global Monitoring Laboratory	https://gml.noaa.gov/ccgg/trends/
Global Land-Ocean Temperature Index Anomalies	NASA's Goddard Institute for Space Studies; NASA Global Climate Change Vital Signs of the Planet	https://climate.nasa.gov/vital-signs/global-temperature/
New Jersey Climate Data	Office of the New Jersey State Climatologist	http://climate.rutgers.edu/stateclim/
Atlantic City Relative Sea Level Rise Trend	NOAA Tides and Currents	https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8534720
Projected Changes in Extreme 24h Rainfall Events	NJ Department of Environmental Protection; Northeast Regional Climate Center, Cornell University	https://www.nj.gov/dep/dsr/publications/projected-changes-rainfall-model.pdf
Parameter-elevation Regressions on Independent Slopes Model	Oregon State University	https://prism.oregonstate.edu
Soil Moisture - Crop Condition and Soil Moisture Analytics	George Mason University; NASA; USDA–NASS	https://nassgeo.csiss.gmu.edu/CropCASMA/
National Shallow Groundwater Drought Indicator	National Drought Mitigation Center; University of Nebraska-Lincoln; NASA GODDARD Space Flight Center	https://nasagrace.unl.edu/
Delaware River USGS Stream Gage Height at Trenton NJ	U.S. Geological Survey – National Water Information System	https://waterdata.usgs.gov/monitoring-location/01463500/#parameterCode=00065&period=P7D
Combined Northeast Reservoir Storage – NJ	NJ Department of Environmental Protection	https://dep.nj.gov/drought/current-conditions/#reservoir-levels