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New Jersey Climate Change
Resource Center

State of the Climate
New Jersey 2021

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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 2021 and climate projections through 2100.

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

3. A synopsis of outstanding 2021 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 flooding and other impacts from Post Tropical Cyclone Ida, providing examples of how changes in extreme rainfall may continue to impact 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. The mid-Atlantic region is one of the most rapidly warming locations in the conterminous U.S., and New Jersey's annual temperatures have risen by about 4 °F, roughly twice the global (over land and ocean surface) average since 1900 and about 1.4 times the global overland average. This 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 be 5–8 °F or 8–14 °F above preindustrial levels with moderate and high greenhouse gas emissions, respectively.

Sea level – Sea level has been perennially increasing along New Jersey at about 0.2 inches/yr (about 18 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, sea levels in New Jersey are projected to be as much as 4.0–6.3 ft above the year 2000 mean sea level.

Precipitation – The total annual rainfall within the state has increased by about 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 5–8% by the end of the century and extreme 24-hour rainfall by 5–15%.

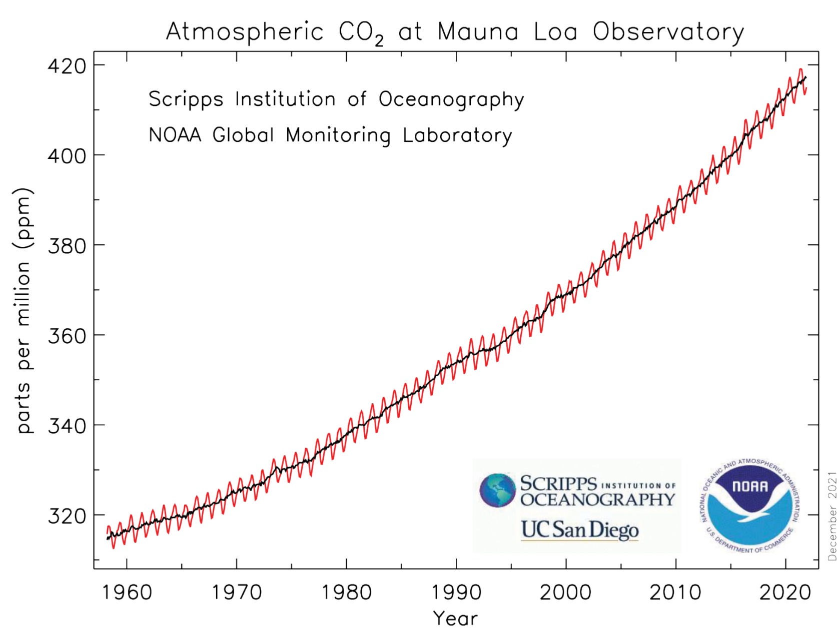
Extreme events – Post Tropical Cyclone Ida in September of 2021 delivered extreme rainfall that brought flash flooding and severe storm conditions throughout central and northern New Jersey that took 30 lives. Ida offers a glimpse of the intense rainfall New Jersey can expect in the future and highlights the challenges such extreme conditions pose to infrastructure and emergency preparedness.

Global Climate

The increased atmospheric concentration of greenhouse gases (e.g., carbon dioxide [CO_2] and 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 415 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 accelerating since the 1970s (Figure 2, next page). 2021 was tied with 2018 as the sixth warmest year on record, and the period of 2014–2021 represents the warmest eight years on record (Figure 2). Since the turn of the century, 19 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 to the present to an average rate of 0.32 °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 measured at Mauna Loa. Red: monthly values; Black: 12-month running average (NOAA Earth System Research Laboratory).[4]



According to the IPCC, it is unequivocal that human activity is the primary cause of increased greenhouse gas concentrations and observed warming.

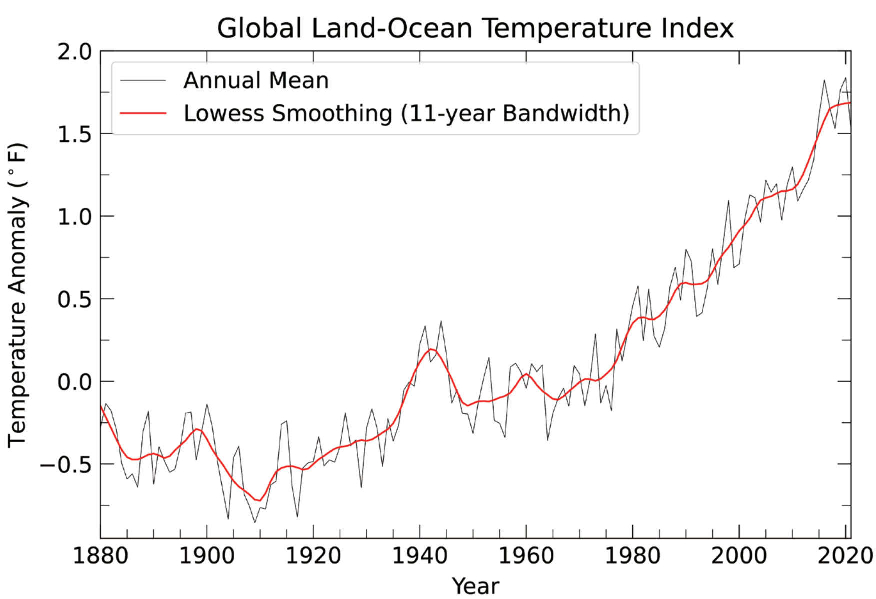
While global temperatures have consistently increased since the 1970s, year-to-year temperature changes are variable. For example, two recent strong El Niño years, 2016 and 1998, exhibited significantly warmer global temperatures relative to surrounding years (Figure 2). Additionally, temperature change 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 overland areas generally warm more than regions over the ocean, 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, 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, unabated 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, throughout the remainder of this document, discussion of emission scenarios and analyses are in reference to the prior IPCC AR5 report[11] unless otherwise noted. Projected climate change effects related to emission scenarios from the current IPCC AR6 report[1] have not yet been fully computed for New Jersey and are expected to be available later in 2022 for full analysis.]

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[12] and the Greenland Ice Sheet loss has caused approximately 0.54 inches of sea-level rise since 1972.[13] The rate of sea level rise is accelerating. Global sea level has risen about 7.6 inches since the early 20th century,[14] about 3.2 inches in the last 21 years alone.[15,16]

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

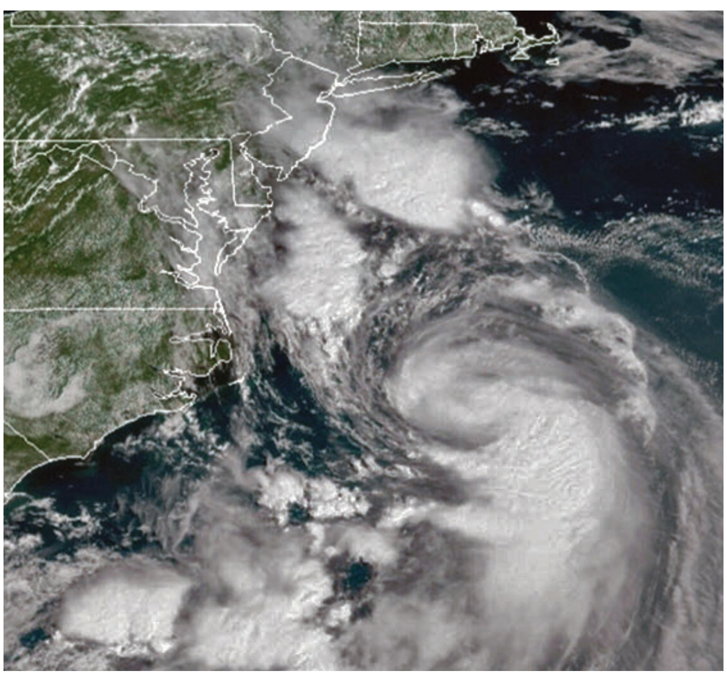


New Jersey Climate

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).

2021 Weather Summary

Climate change has generally brought warming years for New Jersey, and 2021 was no exception, being the third warmest on record (since 1895). The summer and fall were some of the warmest, being the sixth and ninth warmest of their respective season, associated with the latest first fall freeze on record, November 2nd. The average precipitation throughout the state for 2021 was 47.98 inches, close to the 1991–2020 average of 47.56 inches but over 2 inches above the 1895–2021 average of 45.56 inches. Despite this, November and December were both extremely dry, ranking the seventh and sixth driest on record for their respective months and the driest end of year on record cumulatively with total rainfall of only 2.32 inches.



Tropical Storm Henri, August 21, 2021, prior to making landfall (NOAA).

Much of the rain throughout the year was delivered by a few very large events. On August 21–23, Tropical Storm Henri brought as much as 9.00 inches of rainfall to East Windsor (Mercer County) and at least 5.00 inches to 11 counties throughout the state. Henri drove flash flooding at Long Beach Island and southern Mercer and Middlesex Counties. The Raritan River rose about 13.0 ft in response to the deluge and some streams exceeded their banks in the Passaic River Basin. In the wake of Henri, Post Tropical Cyclone Ida, which was a major hurricane when it struck the Louisiana coast, battered New Jersey a little over a week later.

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, 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.

Ida presented the most severe meteorological event of the year for New Jersey as its remnants crossed the state on the evening of September 1. Ida brought intense rainfall that at the 1-, 2-, 3- and 6-hour time scales met or surpassed the 100- to 2000-year recurrence interval magnitudes for locations in central and northeastern New Jersey. While Henri brought much rainfall to the state, Ida's intensity brought larger amounts within a much shorter time frame. Eight counties had at least one station with an 8.00-inch storm total and Hillsborough (Somerset County) received 9.45 inches. Ida produced significant flash flooding, killing 30 people, displacing more, and generated three tornadoes, one of which, an EF-3 in Gloucester County was the strongest observed in New Jersey since 1990.

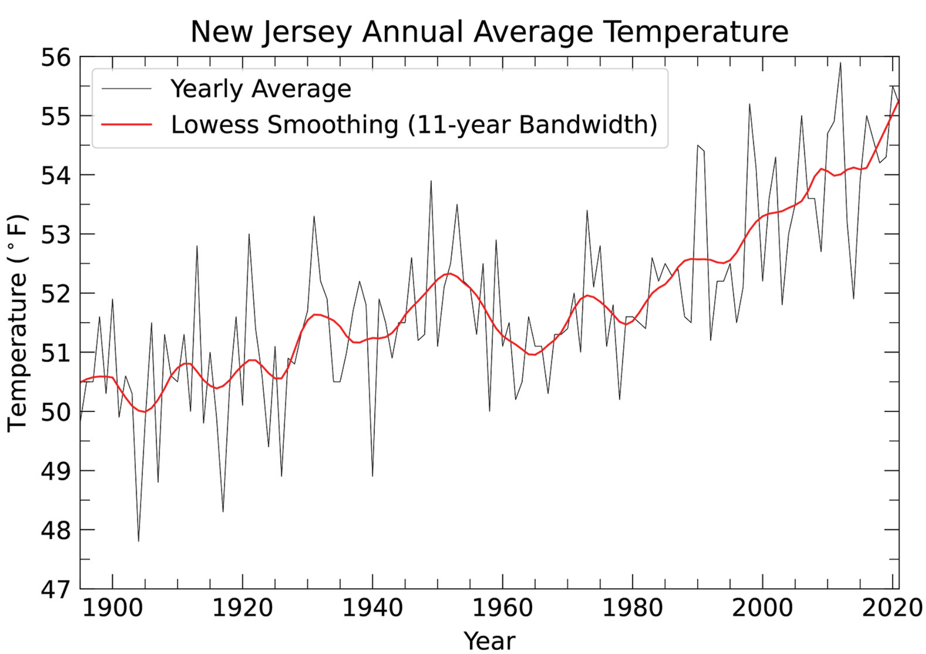
Furthermore, there were 13 tornadoes statewide in 2021, the second highest number on record (1950–present)[17] and a five-fold exceedance of the annual average of about 2.6 per year. In addition to Ida's tornadoes, three more were associated with tropical storms, two with Tropical Storm Elsa in (July 9–10) and one with Tropical Storm Fred (August 19). Of the remaining tornadoes, six occurred on July 29, the second most active day on record, linked to a series of supercells, severe thunderstorms with a deep and persistent rotating updraft.[18,19]

Other noteworthy weather events in 2021 came in the form of large snowfall (January 31–February 3) that left Mine Hill (Morris County) with 32.8 inches of snow and eight counties with at least 20.0 inches. The responsible coastal storm created strong easterly gusts (>50 mph in some locations) that drove minor to moderate coastal flooding at the Sandy Hook tide gauge. October saw multiple episodes of coastal flooding. Earlier in the month (October 8–11), consistent high winds resulted in minor tidal flooding recorded by the Barnegat Lighthouse tide gauge in Ocean County. Later, a nor'easter (October 25–27) generated minor coastal flooding followed by a strong low-pressure system (October 29–30) that caused minor flooding recorded at the Barnegat Lighthouse tide gauge and nine consecutive high tides with minor to moderate tidal flooding at the Burlington gauge on the Delaware River. Finally, while not locally sourced, air quality and visibility were reduced sporadically throughout July due to smoke from western U.S. forest fires.

Temperature

Average annual temperatures in New Jersey have increased by nearly 4 °F since the end of the 1800s (Figure 3), one of the fastest warming regions in the continental U.S.[20] The increase in New Jersey temperatures has been roughly double the global land and ocean average and about 1.4 times the global overland average.[21] Between 1900 and 2021, New Jersey's annual average temperature has increased at a rate of 0.32 ± 0.03 °F/decade, faster than the national rate (0.17 ± 0.02 °F/decade)[22] and the U.S. northeast regional rate (0.23 ± 0.03 °F/decade).[23] 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 Lyme disease and West Nile virus) are also expected to have expanded ranges with increased temperatures (and humidity) as vector species, such as ticks and 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]

Figure 3: Average annual temperatures in New Jersey (°F) [Office of the New Jersey State Climatologist].



Since 1970, New Jersey average temperatures have increased at a rate of 0.66 °F/decade (Figure 3), the equivalent rate of 6.6 °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 on record, 15 have occurred

SEASON	TIME PERIOD			
	1900–2021		1970–2021	
	Linear Rate (°F/ decade)	Calculated Increase (°F)	Linear Rate (°F / decade)	Calculated Increase (°F)
Winter (December–February)	0.42 ± 0.07	5.1 ± 0.9	0.91 ± 0.25	4.7 ± 1.3
Spring (March–May)	0.27 ± 0.05	3.3 ± 0.6	0.51 ± 0.16	2.7 ± 0.8
Summer (June–August)	0.29 ± 0.03	3.5 ± 0.4	0.59 ± 0.11	3.1 ± 0.6
Fall (September–November)	0.26 ± 0.04	3.2 ± 0.5	0.59 ± 0.13	3.1 ± 0.7

Table 1. Average Seasonal Changes in New Jersey Temperatures Calculated by Linear Regression for 1900–2020 and 1960–2020 with Temperature Increases Calculated using the Linear Fit Rate and its Standard Deviation.

since 2000 with 2021 representing the third warmest. Furthermore, none of the top ten 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. Average temperatures during each season rose at higher rates over the past 52 years compared to the 122 years since 1900. Notably, the linear trend in winter temperatures increased by 4.7 ± 1.3 °F since 1970, a rate of 9.1 ± 2.5 °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, summer and fall of 2021 both ranked within the top 10 warmest of each season on record. Summer averaged 74.5 °F (1.4 °F above the 1991–2020 normal) and fall averaged 57.9 °F (2.1 °F above normal).

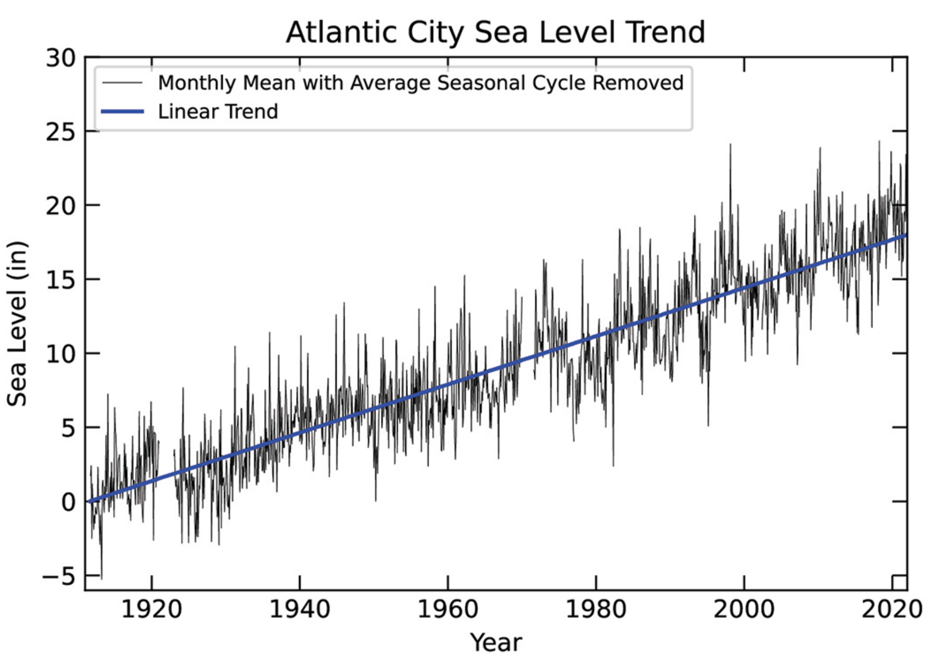
Temperatures in New Jersey are expected to continue increasing as global greenhouse gas concentrations rise. Under a moderate emissions scenario (as detailed under the IPCC AR5 report[11]), average annual temperatures are projected to increase 3–9 °F by the end of the 21st century relative to the 1901–1960 average.[28] Under a high emissions scenario, temperatures are expected to increase 6–13 °F by 2100,[28] 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] and 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] Warming temperatures will increase humidity, which can lead to a higher risk of heat stress because the body's natural cooling from sweating becomes less effective. 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 2021, sea level rose approximately 18.0 inches at Atlantic City (Figure 4), more than double the global average.[14] 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.[14] The average rate of sea-level rise since the early 20th century has been 0.17 inches/yr.[14] 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,[14] a rate of 0.2 inches/yr, indicating that local sea-level rise is accelerating. 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 enhance saltwater contamination of freshwater

Figure 4: Relative sea level trend (inches) at Atlantic City Tide Gauge.[36]



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

resources used for crop irrigation and threaten freshwater ecosystems by pushing salt water farther upstream in estuaries.[35]

Sea-level rise is expected to continue accelerating over the next century. Relative to the 1991–2009 baseline, sea level is projected to increase 0.5–1.1 feet by 2030 and 0.9–2.1 feet by 2050.[14] During this time frame, projections are largely independent of greenhouse gas emission scenarios, but after 2050, projections deviate depending on emission levels. In a low emissions scenario,[14] projected sea-level rise at 2100 is expected to be 1.7–4.0 feet compared to the year 2000. Under a high emissions scenario, sea level is projected to rise 2.3–6.3 feet.[14]

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,

Tidal flooding in Mantoloking, N.J. (Henry Dewing/MyCoast).

Agriculture and Sea-Level Rise Vulnerability in the Garden State

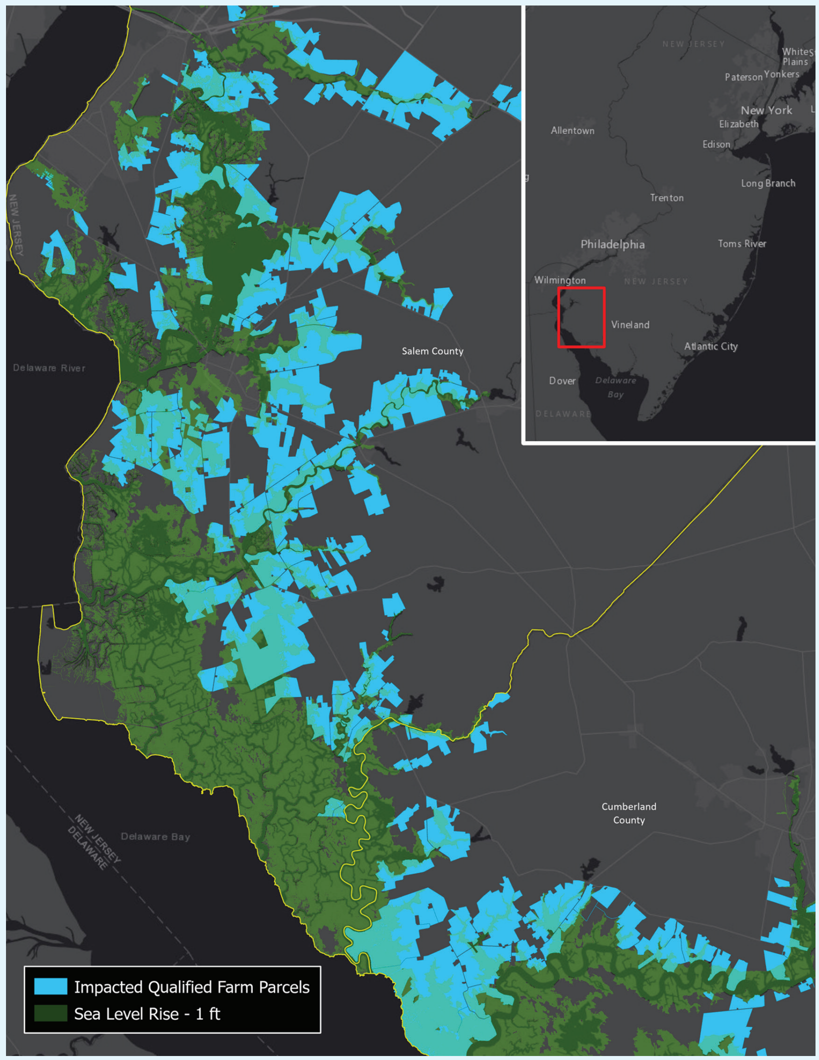
New Jersey's more than 9,000 farms generate more than $1 billion in cash receipts annually.[82] Sea-level rise is a climate change risk to New Jersey's farmers located in coastal regions as it raises the baseline for coastal flooding. Farmland risk can include erosion along tidal waterways (increasing the probability of saltwater intrusion in near-shore freshwater wells), and contamination of soil, farm ponds, crops, and groundwater with saltwater from overwash and tidal flooding.

Salt and Soil

Excessive salt in soil can harm crops by pulling water out of plant roots, resulting in root and plant death.[83,84] Chloride in salt water taken up by plants results in edge and tip burn.[84] Saltwater can temporarily increase soil pH which then interferes with plant nutrient uptake.[83,84] Leaves and branches covered by saltwater are at risk of dying and salt spray can deposit salt on above-ground portions of plants and soil.[84] Saltwater can also mobilize nutrients from fertilizers in farm fields which can have negative impacts for water quality.[85] Also, in some areas of the Northeast, salt tolerant marsh plants that border farm fields are moving inland as marshes migrate, which may affect the ability to farm but could provide an opportunity to create a wetland conservation easement encouraging native plants to prevent the spread of invasive plants.[85]

Elevated Water Table

Sea-level rise can elevate the water table in low-lying coastal areas, potentially rendering low-lying farmland untillable, reducing freshwater



Farm parcels in Salem and Cumberland Counties potentially inundated by 1 foot of sea-level rise in New Jersey. Sea-level rise data are sourced from the National Oceanic and Atmospheric Administration (2018). Qualified farm parcels (2019) from NJ Office of Information Technology, Office of GIS (NJOGIS).

recharge and also result in standing water during or just after heavy rain events.[86] Heavy rain and freshwater flooding on farms can lead to reductions in crop yield from anoxia and spread of plant pathogens or delays in planting due to flooded soils.[87]

Another mechanism by which sea-level rise can impact agriculture is by affecting the water supply necessary for growing crops. Sea-level rise can increase the rate of erosion and/or inundate low-lying coastal land, moving the shoreline and the subsurface freshwater/saltwater interface landward, potentially salinizing wells just inland of this transition zone.[86] Along tidal estuaries with plentiful freshwater flow, 1 foot of sea-level rise is estimated to push saline water thousands of feet upstream.[86] Agricultural groundwater withdrawals from wells close to such tidal streams could pull now-salty water from the estuary into the well.[86,88] Complicating such a scenario could be increasing temperatures from climate change, which would increase agricultural water demands.

Potential Inundation

Over time, sea-level rise can create new wetlands, expand others, change surface drainage, and inundate land.[83,86] An analysis we conducted found that 1 foot of sea-level rise (within the likely projected range by 2030[14]), will inundate approximately 16,600 acres of current agricultural land in coastal New Jersey. The total area of those affected farms is approximately 45,000 acres with a farmland assessed value of almost $18 million. There are strategies farmers can use to address the impacts of saltwater intrusion on their farm and improve soil health, such as irrigation, adding gypsum to impacted soil, planting cover crops to help salt move down through the soil by increasing water flow, and switching to more salt tolerant crops.[85]

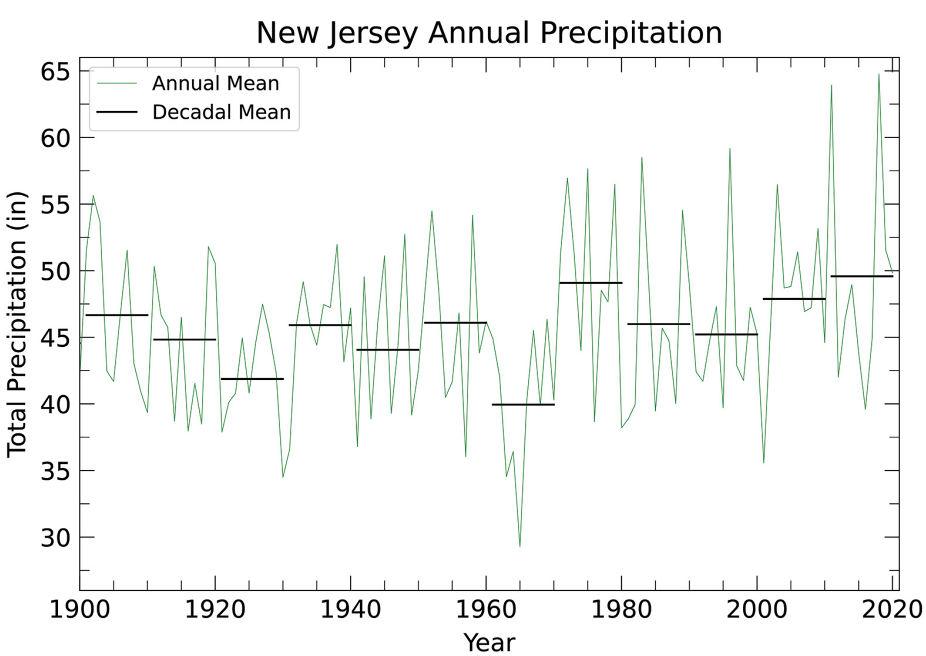
Stow Creek flowing past farm fields, marshes, and woodland at the boundary of Cumberland and Salem Counties (John Gattuso).

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 projected to experience tidal flooding, 85 to 315 days by 2060, and at least 240 days by the end of the 21st century.[14] 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 (about 7%) since the early 1900s (Figure 5). From 1901 to 1960, the average decadal precipitation was constrained between 42–46 inches/yr (Table 2, next page). In the 1960s, the mean fell (coincident with drought conditions) to 40 inches/yr. From 1971 to 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) project New Jersey to experience an increase in mean annual precipitation of 5–8% by the end of the century for moderate to high emissions compared to the 2001–2020 average,[37] consistent with these observed historical changes. The possible range of projected changes in annual rainfall is wide but much smaller than the year-to-year precipitation variability in New Jersey. Therefore, projected changes in future rainfall are illustrative of a small increasing trend, but the exact amounts are uncertain.

Figure 5: New Jersey annual precipitation in inches (Office of the New Jersey State Climatologist).



Observed increased precipitation magnitude has been coupled with an increase in interannual rainfall variability (Figure 5). 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 about 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 U.S. Northeast will become wetter and experience greater precipitation variability by the end of the century.[38] A warming climate intensifies the hydrologic cycle, increasing precipitation variability globally, which can affect regional agricultural production, drought frequency, and flood conditions.[39] 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.

Table 2 (right). Decadal Averages of New Jersey Average Annual Precipitation from 1901 to 2020 (Office of the New Jersey State Climatologist).

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	49.56

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 3.18 ± 6.41 inches/century and 16.15 ± 8.22 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 5). The 1961–1970 period is not included in this analysis due to the large drought early in the decade over-

Table 3 (below). The Top 5 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).

	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	

A flooded neighborhood in Hillsborough, N.J., in the aftermath of Post Tropical Cyclone Ida (Edwin J. Torres/ NJ Governor's Office).

influencing the long-term trend. The top five wettest years 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.

In the Northeast, 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[40] and is expected to continue,[41,42] the periods between such events in the summer are projected to be drier, resulting in more short-term drought conditions.[43] These more frequent dry periods could require increased irrigation and residential water usage, risking saltwater intrusion in New Jersey aquifers due to freshwater pumping.[26,43]

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.[44] 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.[45]

The frequency of extreme precipitation in New Jersey, and the duration of summer dry spells, are expected to increase.

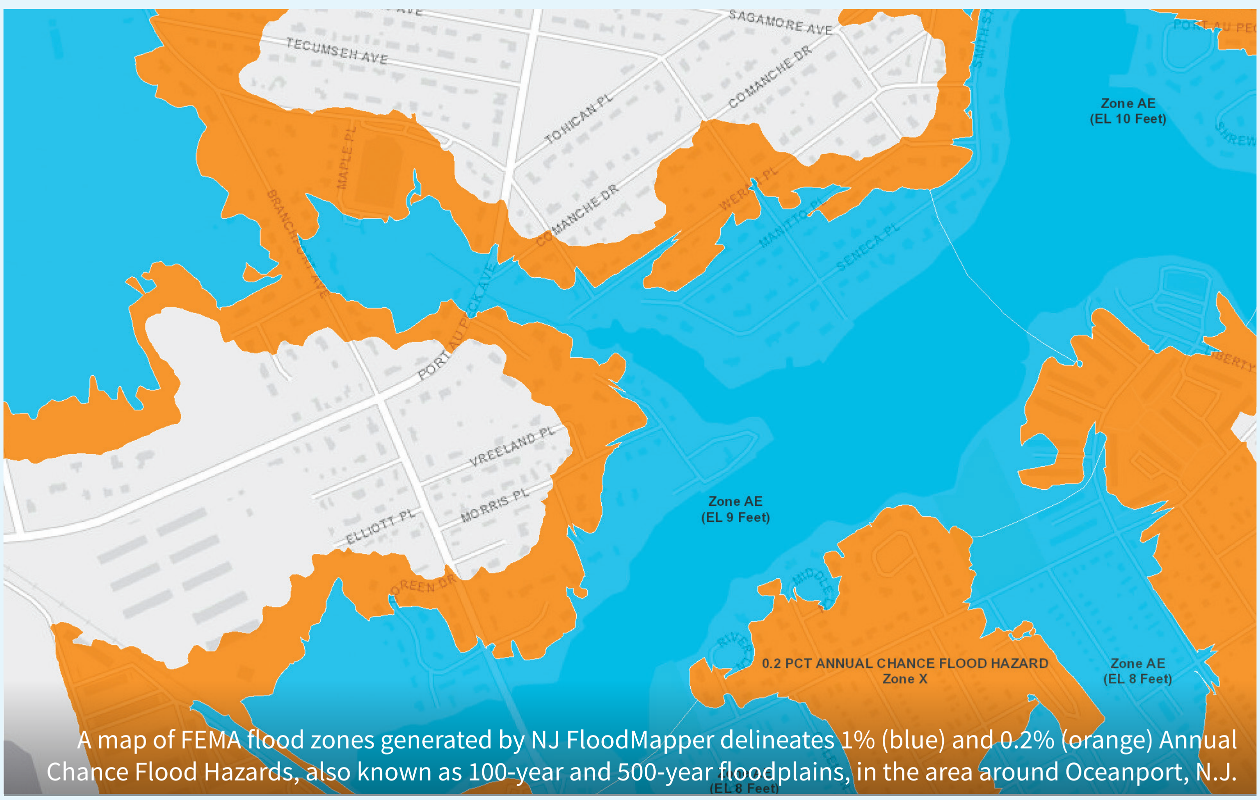
Understanding Return Periods

Extreme events 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.[46]

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-year 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 frequency changes.

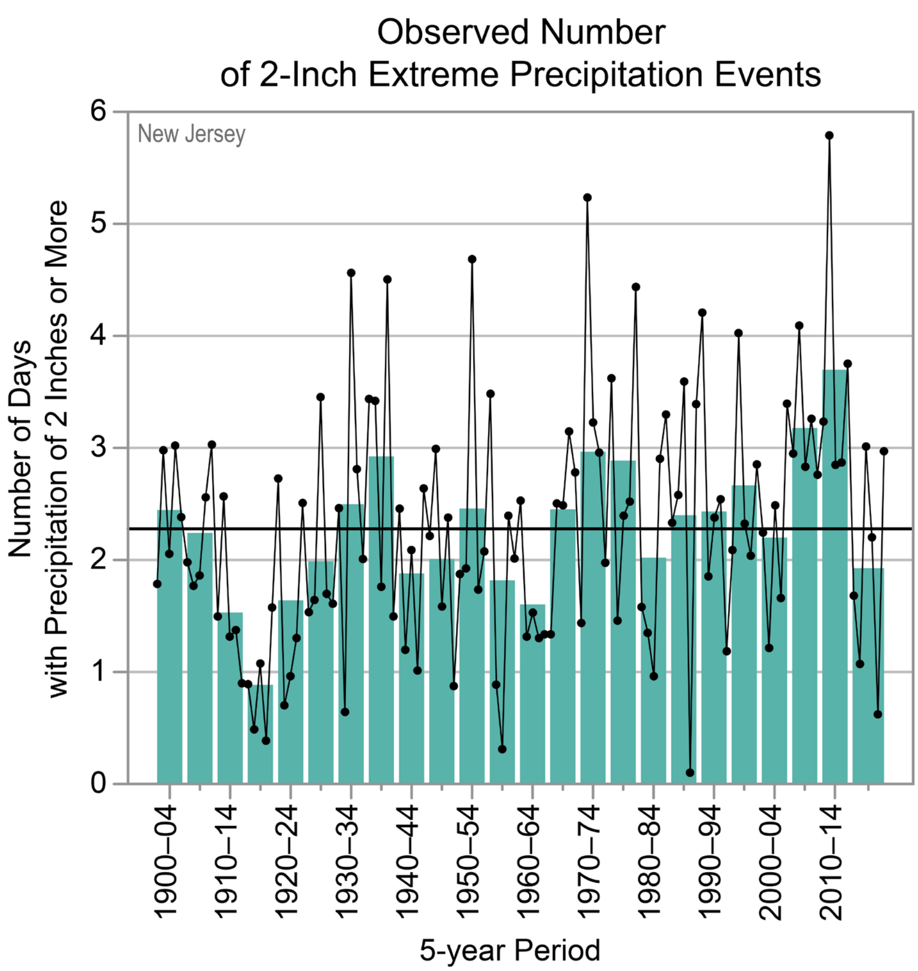
The extreme events described by the return period projection can be singular, such as the return period of a river flood elevation, but they can also include the event duration. For example, the measured rainfall over 24 hours and the rainfall measured over 2 days at a location may both present extreme 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-year return period of the 24-hour rainfall event is distinct from the 10-year 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.

Extreme precipitation events in the northeast U.S. are becoming more frequent and intense.[47,48] Common practice is to use the NOAA Atlas[14] precipitation frequency estimates[49] 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.[40] At most locations, extreme precipitation amounts were found to be more than 2.5% greater than the 2000 dataset estimates.[40] 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.[50] It is therefore necessary that forward-looking metrics of extreme precipitation using historical data be supplemented by model projections to account for future climates.

Figure 6: Annual number of days exceeding 2 inches of precipitation for New Jersey from 1900 to 2020. Bars show 5-year averages of the number of rainfall events. Black dots show the yearly values. 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).[51]



More intense precipitation events will lead to more frequent and larger floods[43] 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 two inches 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 a couple of days. The five-year period with the most extreme precipitation events was 2010–2014, where extreme precipitation is defined as the 5-year rainfall event, 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 6). From 2005 to 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.[51]

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.[41] Looking at this trend another way, now observing extreme precipitation over 48 hours, over the period 1901–2016, the northeastern U.S. saw a 74% increase in 48-hour extreme precipitation events.[41] 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-year, 10-year, and 100-year 24-hour rainfall events.[42] The 24-hour event is the amount of rainfall that is accumulated in a 24-hour period. The 2-year, 10-year, and 100-year 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.[42] 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 that large rainfall events (such as the 100-year 24-hour rainfall event) in New Jersey will become more intense.

Flooded highway in New Brunswick, N.J., after Hurricane Irene, August 2011 (Anthony Adams, CC BY-NC-ND 2.0).

Changes between New Jersey's 1981-2010 and 1991-2020 Climate Normal Periods

Climate normals are 30-year averages of weather observations. Normals are the basis for judging how daily, monthly, and annual weather conditions compare to the average conditions one would expect to see. They are updated every ten years at the turn of the decade replacing the previous 30-year means (e.g., the 1991–2020 period replacing 1981–2010). Updating climate normals provides a necessary reference point for climate impacted stakeholders such as the energy and agricultural sectors, the building design and construction industries, and several governmental organizations such as the U.S. Departments of Agriculture and Health and Human Services. Additionally, because climate normals are updated on a regular basis, comparisons of current weather to "normal" need to recognize that what is "normal" is inherently influenced by climate change and constantly evolving.

Official 1991–2020 normals for the United States have been generated by the National Centers for Environmental Information (NCEI) and are available through the Office of the New Jersey State Climatologist. Included are annual, seasonal, monthly, and daily normals of temperature, precipitation, and other climatological variables available for New Jersey weather stations, counties, climate divisions, and statewide.

The updated climate normals (1991–2020) show a statewide increase in temperature and precipitation compared to the previous 30-year normals (1981–2010). As the years 1991–2010 overlap between these two periods, these changes are driven by the differences between the first and last decades of this overall 40-year period (1981–2020).

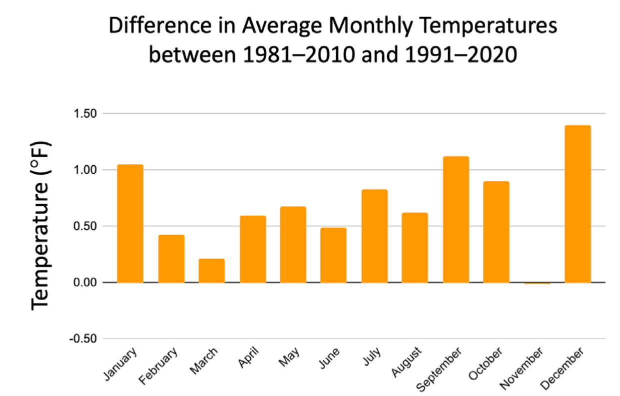
Average Temperature

In New Jersey, the annual average temperature for 1991–2020 was 53.6 °F, 0.7 °F warmer than the 1981–2010 average of 52.9 °F. The monthly average temperature differences between the two normal periods range from zero in November to as much as 1.4 °F in December.

The warm season (May to October) temperatures are consistently warming. Cool season (November to April) temperatures are also warming but show greater month-to-month variation.

Total Precipitation

Mean annual precipitation for 1991–2020 was 47.56 inches while it was 46.36 inches for 1981–2010. The monthly differences between the two periods range from negligible to almost 0.50 inches, and most months have experienced increased precipitation. This increase may be associated with a warming atmosphere that can hold more moisture, which can produce more rainfall. However, precipitation is highly variable, even at decadal scales, so the extent to which climate change affected this recent increase between normal periods is unclear.



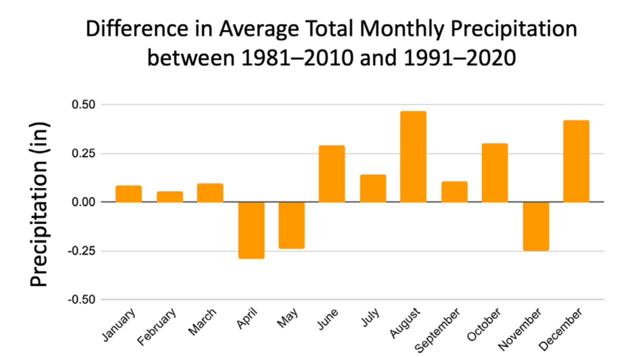


Figure S3. Difference in average temperature (top) and average total precipitation (bottom) by month for the State of New Jersey between the 1991–2020 and 1981–2010 climate normal periods.

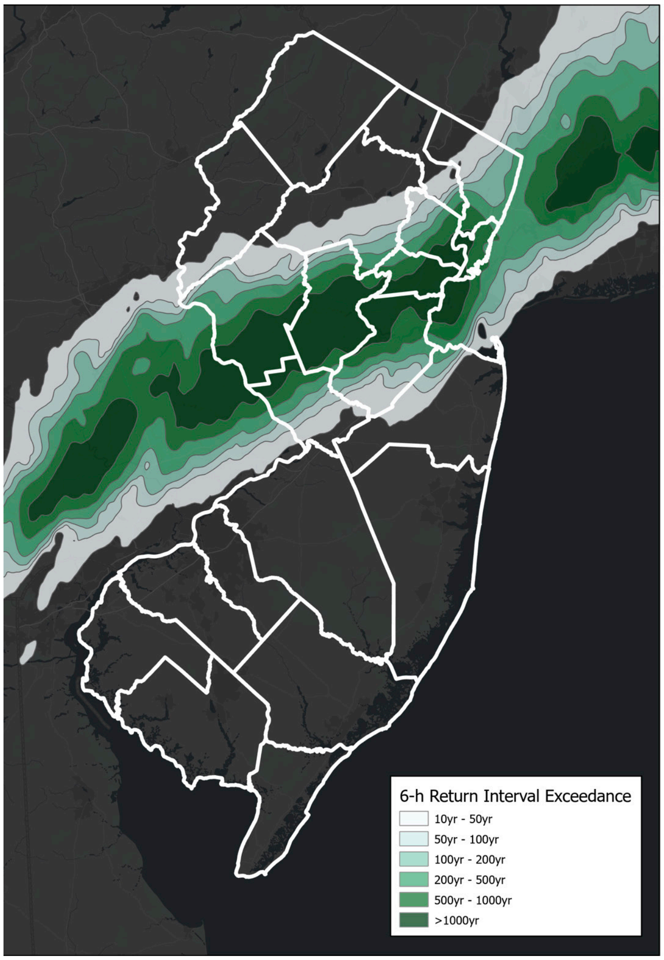
Extreme Events: Focus on Post Tropical Cyclone Ida

On September 1, 2021, the remnants of what had been Major Hurricane Ida (officially Post Tropical Cyclone Ida) arrived in New Jersey after making landfall in Louisiana as a category 4 storm and progressing northeast overland. Its excessive rainfall created flash floods within New Jersey that killed 30 people and displaced many more. Ida caused the second greatest loss of life in New Jersey from a natural event in more than 100 years, only exceeded by Post Tropical Cyclone Sandy in 2012. For the Northeast U.S. as a whole, estimated flood damages from Ida totaled between $16 billion and $24 billion.[53]

The rainfall from Ida was substantial for the whole of the state. Each county received at least 1.98 inches or more except for Cape May (0.98 inches). All regions around and north of US Route 1 received at least 4.00 inches, with the hardest hit regions being northern Mercer and Hunterdon Counties through northern Middlesex and Bergen counties. The heaviest rainfall was measured at 9.25 inches in Hillsborough (Somerset County) and Flemington (Hunterdon County) at 9.20 inches. These large rainfall amounts were greater than twice the normal rainfall for the entire month of September, and most of it came over the span of six hours. When viewed from an average return period perspective, Ida's total rainfall represented the 1,000-year event in Newark, and many stations exceeded their estimated 100-year recurrence interval rainfall amounts. This effect

Gov. Phil Murphy inspects damage caused by Ida in Lambertville, Hunterdon County, N.J.

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



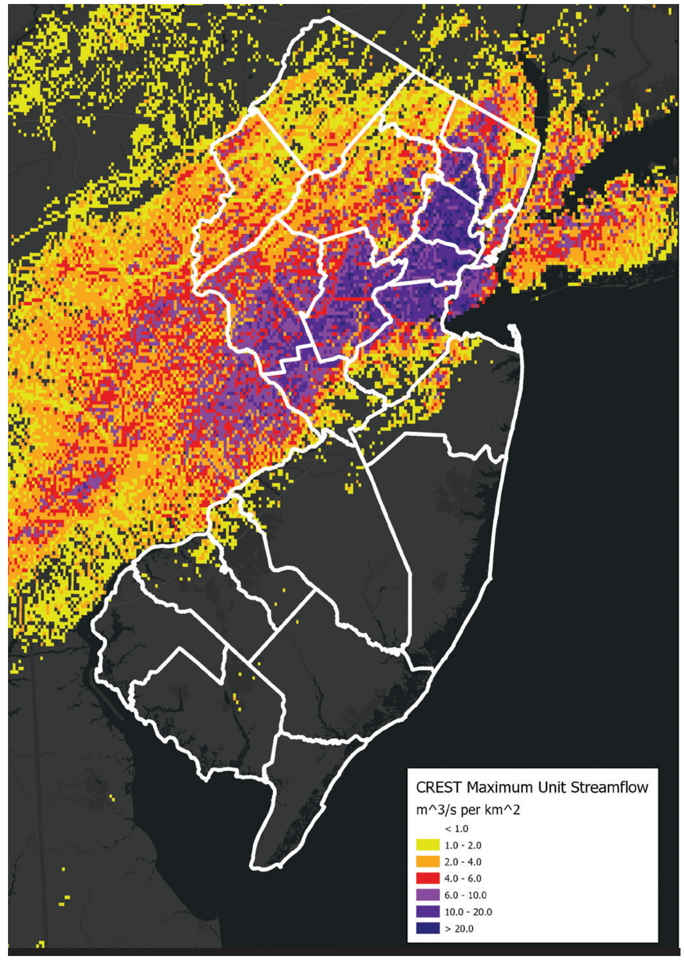


Figure 7 (above left). Post Tropical Cyclone Ida annual rainfall exceedance probabilities for the highest 6-hour rainfall period (Aug 31–Sep 2).[54]

Figure 8 (above right). CREST forecasted maximum unit stream flow (Sep 1, 2021, 1 am) used to monitor flash flooding potential from Post Tropical Cyclone Ida.[56]

was also seen for the peak 2-, 3-, and 6-hour rainfall amounts, where many stations exceeded the threshold for their 100-year event intensity (Figure 7).

Ida Flooding

The extreme rainfall over this short period produced extensive flash floods and riverine flooding that led directly to 30 deaths and property damage. The modeled MRMS CREST maximum unit stream flow is often used by forecasters to issue flash flood warnings. During Ida, the National Weather Service guidance indicated projected stream flow intensities that were 10–20 times the threshold often used to issue flash flood warnings (Figure 8, retrieved 1/8/2021).[55,56] This simple example underscores the intensity of the rainfall and severity of the resultant flash flooding associated with Ida, exceeding warning thresholds multiple times over.

Riverine flooding was widespread, but the Raritan River Basin experienced the greatest amount. Along the main stem of the Raritan, gauges experienced flood stages near or exceeding the record elevation, matched only by Hurricane Floyd in 1999 and Tropical Storm Irene in 2011. Raritan flooding was especially intense in Manville (Somerset County), where the measured water elevation exceeded 27 feet (Figure 9), surpassing Floyd for the greatest flood on record at this location. Hundreds were displaced, and the locally flooded areas experienced gas explosions at homes and a business after evacuation.

Insight into Possible Future Storms

Federally declared as a disaster for New Jersey and New York, Ida offers a glimpse into possible climate-change-driven future storm events in New Jersey. As a hurricane in the Gulf of Mexico, Ida rapidly gained strength due to warm waters of about 86 °F.[58] Warmer waters generate warm moist air, fueling a stronger low-pressure tropical cyclone core, and intensify hurricane winds. With a warming atmosphere and ocean, it is expected that tropical storms may become more energetic,[1,59] may intensify in category more rapidly,[60] and that a larger proportion of hurricanes will reach category 4 and 5 levels.[59,61] And it is virtually certain that they will bring much more rainfall.[1,52]

It is uncertain how the frequency of larger, more severe tropical storms making landfall on New Jersey shores will change. However, the precipitation associated with these storms will likely become more intense with climate change.[1,42] With moderate emissions, the rainfall from a present day 100-year return period (1% annual chance) 24-hour event for most counties in New Jersey is expected to exhibit a return period closer to 50 years (2% annual chance) by the end of the century.[42]

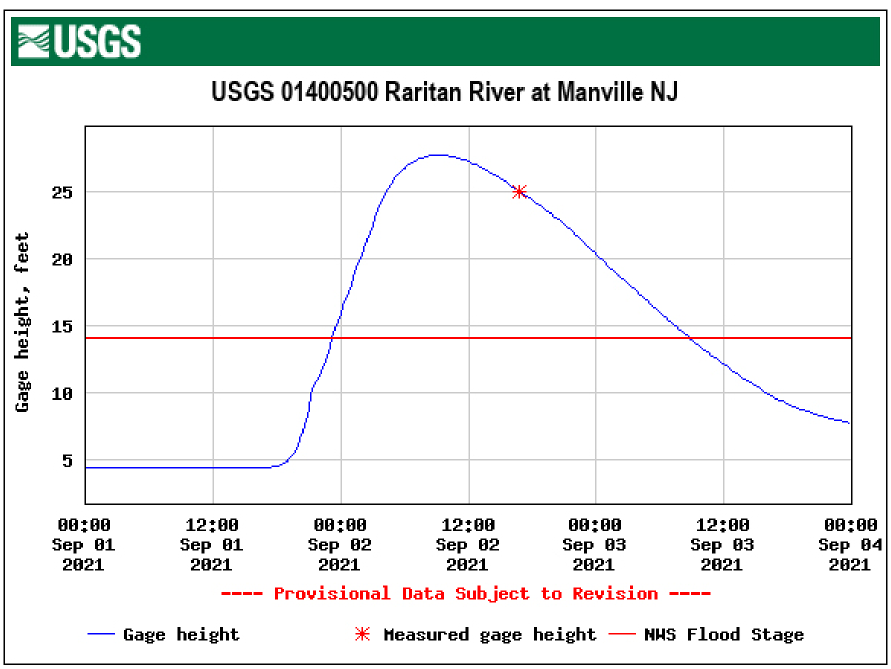


Figure 9. Raritan River measured stream gauge height at Manville, N.J., September 1–4. The red line indicates the first flood stage elevation at 14 feet. [57]

Ida provides insights into the hazards that our communities in New Jersey will face over the next century with the potential for more intense storms that bring increased flooding and severe weather like tornadoes. It once again exemplifies that the state of New Jersey is highly susceptible to flash flooding and riverine flooding caused by extreme rainfall. Finally, Ida unscores that climate change will have wide, unique, and sustained impacts throughout New Jersey in a wetter future.

Climate Change and Vulnerable Populations

Vulnerability is characterized as being prone to harm by climatic change. Climate vulnerability assessments are widely used to identify key factors that explain why particular households, sectors, and groups are more prone to harm or less able to respond to climatic shocks and stresses.[62] Demographic and economic factors such as age, health and disability status, educational attainment, income, and wealth have been found to influence both sensitivity to climate stresses and the ability to respond to or plan for climate extremes.[63]

Children and Older Adults

Children and older adults are particularly vulnerable to climate-sensitive exposures. For children, key factors include immature physiology and metabolism; windows of vulnerability in utero and early childhood; higher exposure per unit body weight to air, food, and water; differences in diet and behavior from adults (e.g., more time out of doors); and their dependence on caregivers.[64] Child-specific climate-sensitive health risks today include decreased air quality (e.g., increases in emergency department asthma visits during the warm weather season in New Jersey); heat-related illness; and psychological and emotional trauma from extreme storms, observed in children whose homes suffered damage from Hurricane Sandy.[64–67] Older adults (age 65+) are at high risk from heat-related illness or death because of pre-existing diseases, reduced ability to thermoregulate, and limited mobility.[68] Senior citizens make up a greater portion of heat-related hospitalizations in New Jersey.[24] Older adults can have difficulty responding to, evacuating, and recovering from extreme events if they have mobility issues and/or cognitive impairment.[68] Additionally, fifty percent or more of senior populations in Atlantic, Burlington, Cape May, Monmouth, and Salem Counties are in areas of high coastal flood exposure.[69]

Intersectionalities

Vulnerability is also shaped by inequalities associated with race, immigration status, gender, and ethnicity. It is important to recognize intersectionalities between different forms of discrimination and economic disadvantage that contribute to disproportionate climate change vulnerabilities among racially or ethnically marginalized populations. Vulnerabilities among marginalized groups may be exacerbated by limited social networks, weak representation in governmental civic and decision-making processes, limited access to health care, and lack of insurance.[63] Structural racism, resulting in discriminatory beliefs, values, and distribution of resources has been identified as a root cause and key determination of the vulnerability of marginalized groups including population health and health inequities.[70–72]

Excacerbating inequalities

The COVID-19 pandemic has revealed disparate occurrences of cases, hospitalizations, and deaths among minority populations across the country. In a study of COVID-19 patients in a Newark, New Jersey hospital, one in three minority patients were at risk for death, noting that underserved minority populations stand to suffer disproportionately from the pandemic and its aftermath due to their lack of access to health care, living in densely

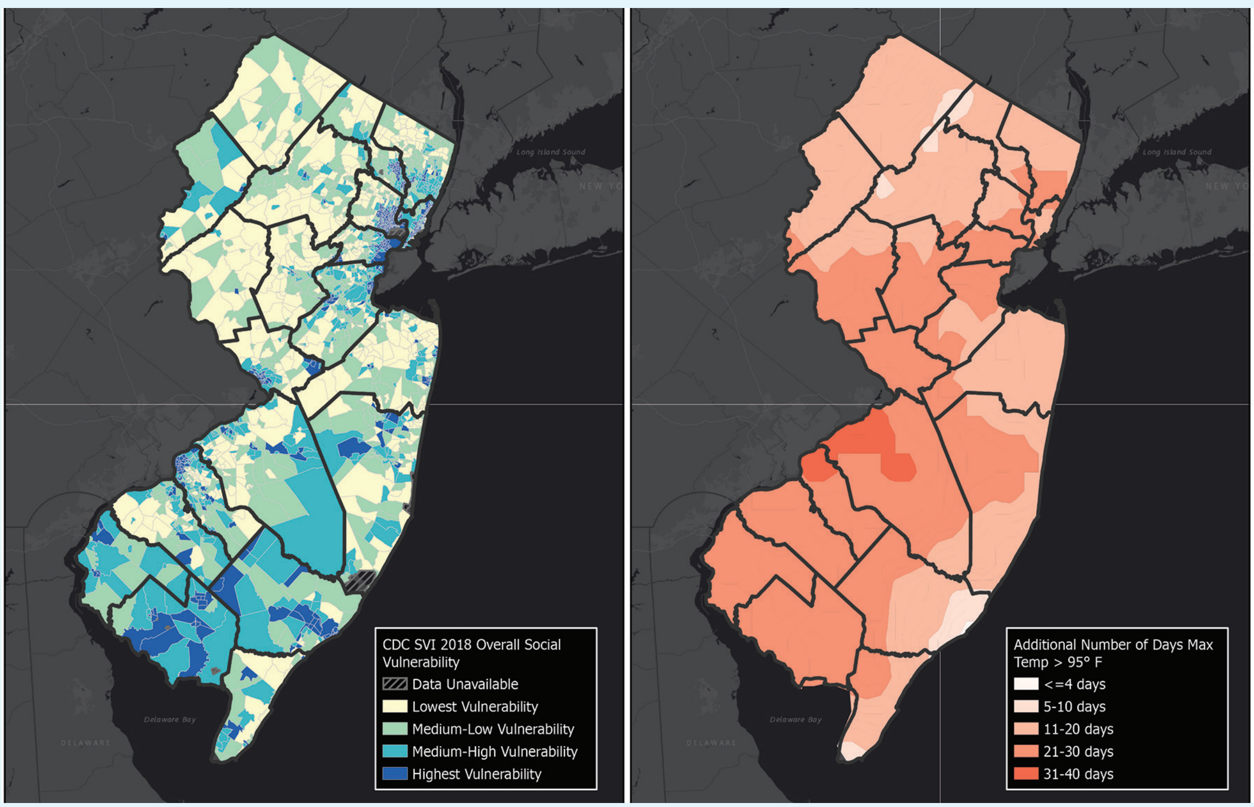
Residents of Union Beach, N.J., stock up on supplies at the police station following Hurricane Sandy.

populated areas, low income, and fewer employment opportunities.[73,74]

While climate change affects all citizens it may amplify and exacerbate inequalities among populations that already have high social vulnerability. Residents in lower-income communities, communities of color, and communities that are linguistically isolated already face social and economic inequities. Climate change magnifies these inequalities, further affecting socially vulnerable residents' health and well-being.[75] In New Jersey, 15% of census tracts are classified as having high social vulnerability populations. Of these areas, almost 70% lie within the current 100-year floodplain, a population of more than 675,000 persons with an average density of approximately 9,500 persons per square mile.[76]

Community-based Planning

Prioritizing adaptation actions within marginalized populations may prove more equitable, improve social cohesion and community resilience, and lead to expanded participation of these populations in climate planning.[77] Community-based planning for climate adaptation involves the wider community including a proactive participatory process that engages socially vulnerable populations to ensure that plans and programs involve all residents.[78–81] The images below indicate the location of vulnerable populations within New Jersey and the projected increase in the annual average number of days where maximum temperature is projected to be above 95°F in 2060 compared to the baseline period of 1981–2010, under a high greenhouse gas emissions scenario. These types of data can provide guideposts in planning for climate change with respect to vulnerable populations.



Above left: The CDC/ATSDR Social Vulnerability Index ranks the social vulnerability of communities to hazardous events and disasters. The data are at a census tract level and include 15 social factors that address four themes: socioeconomic status; household composition and disability; minority status and language; and housing type and transportation (U.S. Department of Health & Human Services, Agency for Toxic Substances and Disease Registry, atsdr.cdc.gov/placeandhealth/svi/index.html). **Above right:** Projected annual number of additional days when the maximum temperature is above 95 °F in New Jersey compared to the 1981–2010 baseline under a high greenhouse gas emissions scenario by 2060. (Data from Applied Climate Information System, Northeast Regional Climate Center). County boundaries are delineated by dark lines.

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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
Post Tropical Storm Ida Annual Rainfall exceedance probabilities	NOAA	https://www.weather.gov/owp/hdsc_aep
CREST Forecasted Maximum Unit Streamflow	University of Oklahoma	http://flash.ou.edu/
Raritan River Measured Stream Gauge Height at Manville NJ	U.S. Geological Survey	https://nwis.waterdata.usgs.gov/nj/v/?cb_00060=on&cb_00065=on&format=gif_default&site_no=01400500&period=&begin_date=2021-09-01&end_date=2021-09-03