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Temperature and Economic Development in New Jersey, USA

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Abstract: *Long-term changes in regional temperature reflect the interaction of multiple natural and anthropogenic processes operating at different temporal and spatial scales. This study examines the historical association between annual average temperature in New Jersey, USA and changes in socioeconomic development, energy consumption, atmospheric emissions, regional sulfate aerosol loading, and Atlantic Multidecadal Variability (AMV) from 1895 through 2025. New Jersey provides a useful regional case study because its economic development can be divided into three historically distinct stages characterized by substantial changes in population, urbanization, industrial activity, and dominant energy sources.*

Background*: The U.S. state of New Jersey is well suited to serve as a prognostic tool in the study of regional and local climate stimuli. New Jersey's coastal location makes it susceptible to more broadly related climate-induced ocean phenomena. In addition, the state's economic and cultural development can be divided into three stages or phases each associated with the dominance of a specific fossil fuel. Finally, New Jersey's diverse, highly educated, and economically well-off and healthy population allows for a political setting that is accepting of the reality of climate change and the need to plan for and implement mitigative measures.*

Materials and Methods*: New Jersey's 130-year temperature record was divided into three periods: an early twentieth-century warming period (1895–1940), a mid-century temperature plateau (1940–1980), and a renewed warming period (1980–2025). Multiple linear regression models were developed for each stage using annual temperature as the dependent variable and climate, atmospheric, energy-use, emissions, demographic, and urbanization variables as predictors. Because historical environmental time series are subject to multicollinearity, temporal dependence, interpolation uncertainty, and common long-term trends, additional robustness analyses were conducted. These included regression diagnostics, first-difference models, reduced-variable analyses, running-average sensitivity tests, explicit lag testing, and heteroscedasticity- and autocorrelation-consistent (HAC) statistical inference.*

Results*: The full multivariable models were statistically significant for all three stages, with coefficients of determination ranging from $r^2 = 0.428$ to 0.674. However, substantial multicollinearity limited interpretation of individual regression coefficients. Robustness analyses identified different dominant statistical relationships among the historical periods. During Stage 1, New Jersey temperature exhibited its strongest and most consistent association with AMV, with explicit lag testing indicating that the relationship was most vigorous contemporaneously. During Stage 2, AMV and regional sulfate aerosol optical depth (AOD) were associated with the decadal-scale temperature plateau, but their individual contributions could not be reliably separated. The strongest individual relationship was observed during Stage 3, when declining regional sulfate AOD was strongly inversely associated with the long-term warming trajectory. This relationship remained statistically significant following autocorrelation-robust correction, while AMV provided little additional explanatory power.*

Key Word*: Temperature trends, New Jersey, regression modeling, AMD, AOD*

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I. INTRODUCTION

The burning of biomass and fossil fuels is inexorably linked to rising atmospheric carbon dioxide levels and thus climate change. The consumption of these fuels can, in turn, be correlated with economic development, especially throughout the 19th and 20th centuries. As U.S. industrial capacity grew and matured, so also did the types of fuels used to power its economy. Beginning with biomass (i.e., wood), fuel usage in the United States moved to coal, followed in close order by petroleum, natural gas, some nuclear, and now is slowly and painfully marching towards renewables.

Atmospheric temperatures are a fundamental measurement for describing climate (USEPA, 2020) and numerous credible studies have used that metric along with others to examine the effects of fossil fuels on global, national and regional climatic patterns, examples include Jay et al., 2023; IPCC, 2026; and NOAA, 2026. This paper, however, seeks to evaluate whether these culturally and economically driven shifts in fuel usage, and the concomitant changes in carbon dioxide emissions, have influenced atmospheric temperatures at less than country-wide or super regional scales.

The U.S. state of New Jersey is well suited to serve as a prognostic tool in the study of regional and local climate stimuli. New Jersey's coastal location makes it susceptible to more broadly related climate-induced ocean phenomena. In addition, the state's economic and cultural development can be divided into three stages or phases each associated with the dominance of a specific fossil fuel. Finally, New Jersey's diverse, highly educated, and economically well-off and healthy population allows for a political setting that is accepting of the reality of climate change and the need to plan for and implement mitigative measures.

Demographic and Physiographic Settings

New Jersey is in the mid-Atlantic Region of the United States (Figure 1) and is 166 miles (267 km) long, and 65 miles (105 km) wide. It had a 2025 estimated population of 9.5 million residents crammed into an area of approximately 8,700 square miles (22,500 square kilometers).

Figure 1. New Jersey's location relative to other Mid-Atlantic and Northeastern U.S. states

Sandwiched between the major metropolitan areas of New York City and Philadelphia, New Jersey is the 11th most populated state although ranking only 47th (out of 50) in total land area. It is home to 1,300 people per square mile (490 people per square km) and is the most densely populated state in the nation. Almost all residents live in areas meeting the definition of urban.

New Jersey's Climate

Cold and sometimes snowy winters and warm, humid summers characterize New Jersey's climate. However, despite its small size, New Jersey's weather and subsequent climate can be quite variable. This is related to three factors:

<u>Mid-latitude position</u>: The solar budget – the amount of energy the Earth receives from the sun versus the energy it loses to space – is the key determinant in the type of climate for a given area. The Earth's curvature controls this energy balance, with solar radiation concentrated at the equator and dispersed at the poles (Hsiang and Kopp, 2018). Because of this accident of geography, New Jersey's mid-latitude position (40º north) experiences significant seasonally induced peak energy changes which in turn drive temperature and precipitation patterns.

<u>Ocean Proximity</u>: Per unit area, ocean water absorbs and loses heat more slowly than an equivalent area of dry land (Colin and Mankin, 2019). This produces cooler summers and warmer winters in coastal regions. Ninety

percent of New Jersey is within 65 miles (105 km) of the Atlantic Ocean. This ocean proximity moderates seasonal temperatures, but it comes with an increased exposure risk to more frequent and intense storms (hurricanes and nor'easters).

Upland Physiography: The decrease in temperature with altitude – the atmospheric lapse rate – is dependent upon water vapor content, air pressure, and localized thermal warming. The temperature changes vary by region, but for dry air can be in the range of 5.4 °F per 1,000 feet (9.8 °C/km). The saturated or moist air lapse rate is location dependent and correlated with temperature and air pressure but often is in the range of 2° to 5 °F/1000 feet (3.6° to 9.2 °C/km) (ICAO, 1993). New Jersey surface elevations vary from sea level (zero feet or meters) along its 130 mile (209 km) long Atlantic Ocean coastline to a modest 1,803 feet (550 m) at High Point, the state's highest elevation along its western border.

Impacts of Climate Change on New Jersey

Wherever the northeastern region of the United States is going in terms of climate change, New Jersey will get there first. Its mid-latitude position, variable topography, long, highly developed low-lying coastline, and densely populated, small, and locally governed urban and suburban areas, many with antiquated infrastructure, make the Garden State particularly susceptible to potential climate change impacts.

Between 1896 and 2021, New Jersey's average annual temperature has risen by 3.8ºF (2.1ºC). This is higher than the northeastern U.S. average of 2.7ºF (1.5ºC) and notably more than the global average of 2.1ºF (1.1ºC) (NJDEP, 2023) Since 1999 these increasing temperatures have been accompanied by an almost 10 percent rise in precipitation, which is occurring mostly in autumn and winter while New Jersey's summers are becoming hotter and drier. Sea level in New Jersey is projected to rise by more than double the global average to 1.1 feet (0.34 m) by 2030 and possibly as much as 5.1 feet (1.6 m) by 2100 (Liou and Madsen, 2007).

Possible climate change impacts have been studied extensively at global, national, and regional scales (Horton et al., 2014; UNWMO, 2023; and Jay et al., 2023). For New Jersey, the potential societal and economic can be summarized as follows (USEPA, 2016):

- Continued rises in sea level will inundate the infrastructure of coastal communities (roads, sewage and water treatment plants, ports, and harbors) and impact New Jersey's $16 billion Atlantic shoreline tourism economy.
- Rising ocean acidity will adversely affect the viability and sustainability of commercial fishing and critical ecological and coastal habitats.
- New Jersey's $300 million agricultural markets will be at risk from from alterations of growing cycles (i.e., precipitation and temperature patterns).
- With the advent of hotter, drier summers and warmer, wetter winters comes increases in public and community health effects including heat related illnesses and deaths, longer and more intense allergies seasons, poorer air quality due to intensification of ground level ozone, and the spread of diseases carried by insects (e.g., West Nile Virus, Lime Disease).
- More frequent and intense storms will drive higher insurance deductibles and premiums related to flooding and wind, especially in those areas of the state that previously have infrequently been subject to extreme meteorological conditions.

New Jersey is working proactively to mitigate climate change impacts, publishing its first global warming response plan in 2007. Since then, 16 governors of both political parties have signed executive orders addressing climate change. In 2023 the state published a comprehensive climate action plan describing near and mid-term governmental actions, deliverables, and milestones (NJDEP, 2023).

Socioeconomic Growth, Cultural Development, and Energy Usage

Three overlapping stages: Agricultural, Industrial, and Nonindustrial can divide New Jersey's economic and cultural development. Associated with each of these stages is the use of different energy sources starting with biomass and renewables (water and wind), then moving to fossil fuels (coal, oil, natural gas, along with some nuclear), and finally the state's current ongoing transition back to renewables (solar and wind).

Stage 1 – Agricultural (1600s through the early 1800s): During this time New Jersey's economy was primarily agrarian-based with an artesian class (e.g., blacksmiths, masons) operating near the state's nascent villages and towns. New Jersey's transition to a pre-industrial society would not begin in earnest until the late 1700s (Gowaskie, 1996). Biomass (i.e., wood) was the primary energy source during most of this stage until coal began to displace it (IHA 2026).

Stage 2 – Industrial (late 1800s through until early 1980s): Its flat-lying topography, long accessible coastline, plentiful surface and groundwater resources, and location between two major markets (New York City and Philadelphia) led to the rapid industrialization of New Jersey over the next 180 years. Supported by business-friendly legislatures, an extensive railroad and canal infrastructure, and proximity to the capital markets of New York City, the industrialization of New Jersey escalated throughout the first half of the 20th century and would remake the state from an agricultural and mineral backwater into a commercial powerhouse. Textiles, pharmaceuticals, petroleum refining, ceramics & glass, and other types of manufacturing would come to dominant New Jersey's economy, work force, and urban development.

Energy use in New Jersey during this period, the pinnacle of the state's industrial prowess, began with coal. While energy source information specific to New Jersey is not available prior to 1960, other U.S. data sets can be used as proxies to help estimate the impact of this important economic metric.

U.S. total primary energy consumption has been estimated for the years 1800 to 1960 (USEIA, 2026) and data on U.S. and New Jersey populations have been well established (Wu, 2010). Not surprisingly, U.S. total and per capita energy consumption between 1800 and 1980 is well correlated with its population (r^2 greater than 0.8). For this same period, New Jersey's population also correlates with U.S. population (r^2 greater than 0.8).

Given the relative strengths of these relationships, it is reasonable to assume that New Jerseyians used about the same about of per capita energy as the rest of the United States. On this basis, Figure 2 estimates New Jersey's total and per capita energy usage between 1800 and 1960.

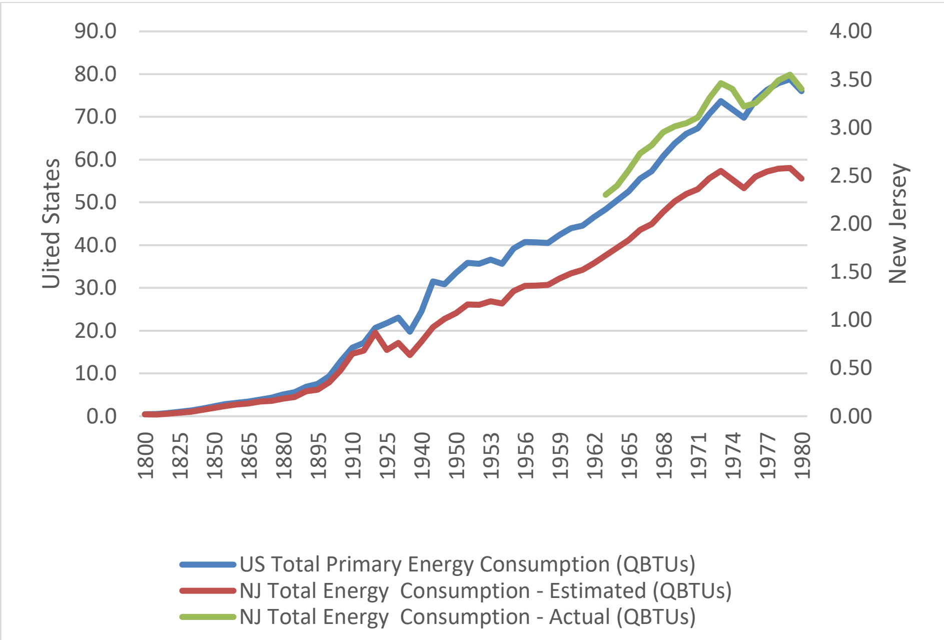

Figure 2. U.S. and New Jersey Energy Consumption 1890-1980

After 1960 information is available for New Jersey's energy use (USEIA, 2026). Note that calculated (estimated) energy use for New Jersey after 1960 is lower than actual energy use, but within about one QBtu. Shortly after World War I petroleum (oil) would supplant coal as America's primary energy source (Sovacool, 2016). Oil, in turn, would start to be pushed aside by natural gas and supplemental nuclear sources around 1970 (Yergin, 2022) Finally, spurred on by the oil embargos of the early 1970s, the current U.S. transition to renewable energy sources (wind, solar, geothermal, etc.) would slowly and haltingly begin (Rose, 2004).

Stage 3 – Nonindustrial (early 1980s through the 2020s): The worldwide economic downturn of the late 1930s in combination with the geopolitical disruptions of World War II began to fundamentally alter New Jersey's business landscape, shifting it from an industrial base to one more industry focused on such business and consumer activities as pharmaceuticals/life science research and development, financial services, technology, and tourism (Schwartz, 1998).

Figure 3 illustrates fossil fuel consumption in New Jersey between 1981 and 2023, which parallels U.S. usage for the same period. New Jersey's fossil fuel consumption was, on average, three to four percent of total U.S. usage. Note the downtown in 2020 related to the COVID pandemic.

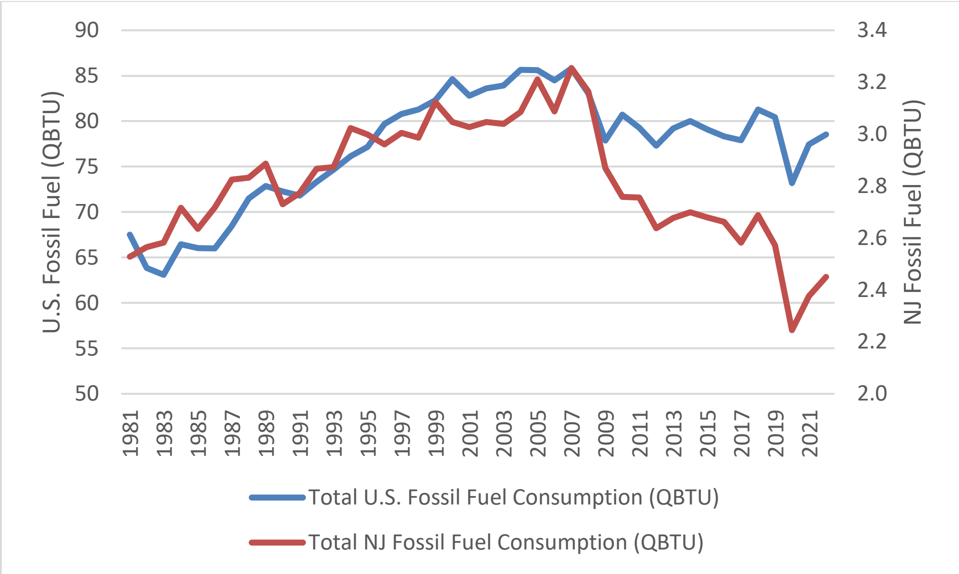

Figure 3. New Jersey and
U.S. Fossil Fuel Consumption: 1981-2023 (USEIA, 2026)

New Jersey's fossil fuel usage reached an inflection point in the early 2000s when it began to decline, even though the state's gross state product – a measure of the total value of goods and services produced by labor and property – continued to grow annually at rates ranging from two to over four percent (IBIS, 2026). This change in energy usage is related to New Jersey's shift to less energy intensive industries as well as the incorporation of renewables, conservation, and efficiency measures in response to utility prices, which began to rise precipitously at about the same time (BLS, 2026).

By the early 1980s New Jersey's primary energy sources were petroleum and natural gas (64 percent and 29 percent of total energy usage, respectively), augmented by two nuclear power plants and renewables which combined added to about four percent of total usage. Coal still had a role in New Jersey's energy market, with total usage of about three percent (USEIA, 2026).

Throughout the 2020s even though natural gas usage had increased to over 40 percent, petroleum (fuel oil) still dominated making up just under 50 percent of New Jersey's total energy supplies. With the closure of the state's last two coal fired power plants in 2022, coal usage slipped to almost zero with renewables and nuclear now making up about ten percent of the New Jersey's power pool.

II. Material And Methods

New Jersey's State Climatologist in association with Rutgers University and the National Weather Service (NJSC, 2025) compiles and maintains current and prior temperature, precipitation, and other meteorological information. Records date to 1896 and statewide annual average temperatures confirm an overall increasing trend over this period of about 0.03ºF (0.02ºC) per year (Figure 4).

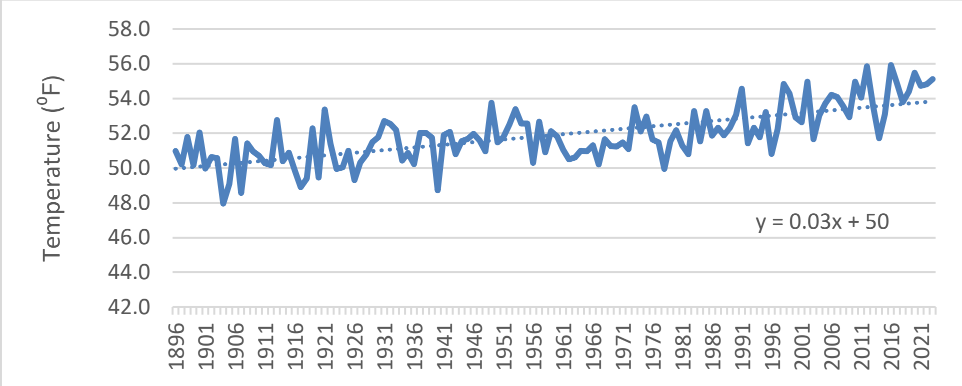

Figure 4. New Jersey Statewide Annual Average Temps (1896-2023)

However, changes in statewide thermal patterns are less uniform when temperature data are divided into those time periods or stages associated with the New Jersey's economic development.

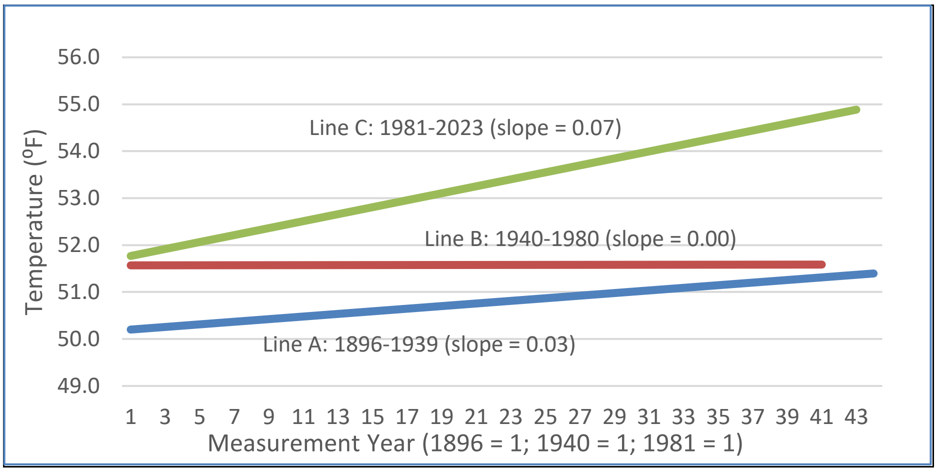

Figure 5. Annual Average Temperature Trends in New Jersey, USA (ºF)
by Economic Development Phases

Figure 5 illustrates that between 1896 and 1939 (Line A) statewide average annual temperatures increase by 0.03ºF/yr or 0.016ºC/yr. Between 1940 through 1980, despite New Jersey's development into a manufacturing powerhouse, a distinct pause in the rate of temperature increases becomes evident (Line B). This pause is followed by a seven-fold increase in the rate of temperature increase between 1981 and 2025 (Line C).

New Jersey's Changing Temperatures

A multiple linear regression model suggests how temperatures in New Jersey could be influenced by its fuel usage and history of industrial and commercial development. This model also includes other possible contributors which may be operating outside the state. Within this model, the dependent variable is New Jersey annual average temperatures which have been recorded since 1896. A data set of eight independent variables (Table 1) incorporated societal metrics (e.g., population, urbanization) in addition to those related to energy usage (e.g., natural gas consumption, sulfate discharges).

Table 1
Multiple Linear Regression Model Data Sets

No.	Name	Status	Description & Source
1	Annual average state-wide temperatures	Dependent variable	1895-2025. Rutgers University and State of New Jersey Climate Office (NJSC, 2025)
2	New Jersey SO_2 emissions (ktons)	Independent variable	Primary data sources include CEDS (CEDS, 2025) which incorporates data from Hoesly et al., 2018; PNNL, 2004; and Feng et al., 2020 as well as EPA National Emissions Inventory (EPA, 2025)). Data have been linearly interpolated between anchor years.

Table 1 Multiple Linear Regression Model Data Sets			
No.	Name	Status	Description & Source
3	New Jersey Coal Usage (TBtu)	Independent variable	EIA State Energy Data System (SEDS) (USEIA, 2025). Pre-1960 data have been estimated and linearly interpolated from historical census data.
4	New Jersey Oil Usage (TBtu)	Independent Variable	EIA SEDS (USEIA, 2025) total petroleum products for New Jersey. Pre-1960 values estimated and linearly interpolated from nationwide petroleum consumption trends.
5	New Jersey Gas Usage (TBtu)	Independent Variable	EIA SEDS natural gas consumption for New Jersey (USEIA, 2025). Pre-1960 values estimated and linearly interpolated from American Gas Association historical records (AGA, 2025).
6	New Jersey Population (1,000s)	Independent Variable	Federal Reserve Economic Data as compiled by U.S. Census Bureau (FRED, 2025). Recorded during decennial census anchor years (1900,1910, etc.). Intercensal years are estimated by linear interpolation.
7	New Jersey Urbanization (percentage of land area)	Independent Variable	U.S. Census Bureau (USCB, 2010) and New Jersey Department of Workforce & Development (NJDLWD, 2025). Intercensal or non-anchor years are estimated by linear interpolation.
8	Mid-Atlantic Sulfate Aerosol Optical Depth (AOD) (dimensionless)	Independent Variable	Published research (Smith et al., 2011) and NASA data post 2005 (NASA, 2025). Non-anchor years are estimated by linear interpolation.
9	Atlantic Multidecadal Variability Index (AMV Index) (^{o}C)	Independent Variable	Published research (Enfield, 2001) and NOAA data (NOAA, 2025). Non-anchor years are estimated by linear interpolation.

Appendix A contains the data sets used in regression modelling. While the variables listed in Table 1 are mostly self-explanatory, three require further description.

Urbanization: In the censuses of 1880, 1890, and 1900, places were deemed urban based on minimum population sizes of at least 2,500 inhabitants. The first time when over 50 percent of the U.S. population met the definition of urban was in the 1920 census. Today, about 80 percent of the U.S. population and over 95 percent of New Jersey residents live in places classified as urban.

Mid-Atlantic Sulfate Aerosol Optical Depth (AOD): This is a dimensionless measure of sunlight blocking by sulfate particles in the atmosphere over the eastern United States. Elevated sulfate AOD reduces atmospheric visibility and results in a local negative radiative forcing (cooling effect) by reflecting incoming solar radiation back into space.

Atlantic Multidecadal Variability Index (AMV Index): Also called the AMO Index (Atlantic Multidecadal Oscillation), this independent variable measures long-term changes in North Atlantic sea surface temperatures. It tracks multi-decadal warm and cold phases across the ocean basin that last 60 to 80 years which influence global weather patterns (including temperature), rainfall, and the frequency of hurricanes.

Regression Modeling Methodology, Findings, and Limitations

Table 2 summarizes the results of the multivariable regression models for each of New Jersey's three developmental stages. Stage 1 included an annual model plus a 10-year running average sensitivity approach with explicit five-year lag test. Stage 2 incorporated an annual model with a 10-year running average decadal analysis plus HAC correction. Stage 3 data was processed using an annual model with a 10-year running average sensitivity analysis plus HAC correction.

Note that several historical data series used in this study were not available as complete annual records. Rather, they were estimated between documented anchor years using linear interpolation. This was necessary to construct temporally consistent datasets across the 130-year study period. This approach may reduce apparent year-to-year variability and increase common low-frequency structure among variables. Accordingly, regression results involving interpolated variables need to be interpreted primarily in terms of broad, multi-year associations rather than precise annual responses. First-difference, reduced-variable, lag-sensitivity, and smoothed-series analyses were done in part to evaluate whether the principal findings were dependent upon a single representation of the historical data. As indicated in Table 2, severe multicollinearity was detected among independent variables, and the study acknowledges the inability of regression alone to establish causation within the relatively small sample sizes of each stage's data set. Most of these limitations have been addressed through robustness testing, but common, long-term temporal changes may still be influencing findings.

Table 2. Regression Results Summary

Analysis	**Stage 1 (1895–1940)**	**Stage 2 (1940–1980)**	**Stage 3 (1980–2025)**
Observations (n)	46	41	46
r^2	0.551	0.428	0.674
Adjusted r^2	0.438	0.262	0.592
Model significance (p)	0.0003	0.0241	0.000
Residual autocorrelation (D.W. score)	2.19	2.00	1.99
Heteroscedasticity (B.P. test score)	Not significant ($p = 0.535$)	Borderline, but not significant ($p = 0.066$)	Not significant ($p = 0.475$)
Residual normality (S.W. test score)	Acceptable ($p = 0.696$)	Acceptable ($p = 0.256$)	Acceptable ($p = 0.667$)
Multicollinearity	Severe (VIF>20)	Severe (VIF>20)	Severe (VIF>20)
Full first-difference model	$r^2 = 0.311$; $p = 0.114$	$r^2 = 0.117$; $p = 0.900$	$r^2 = 0.122$; $p = 0.833$
First-difference signal	AMV and AOD individually significant	None	None
Most robust annual-scale climate association	AMV	AOD and AMV	AOD
Reduced climate model	AOD + AMV: $r^2 = 0.329$	AOD + AMV: annual relationship modest; stronger at decadal scale	AOD + AMV: $r^2 = 0.517$
Smoothed-temperature sensitivity	10-year average used in primary analysis	Strong AOD and AMV associations	Strong AOD association
Autocorrelation-robust smoothed results	Not separately required [1]	AOD and AMV significant individually	AOD highly significant; AMV not significant
Explicit lag sensitivity (0–5 years)	AMV is strongest at zero lag. No evidence that lag improves primary relationship.	Lag/smoothing sensitivity supports multi-year climatic relationships.	Lag/smoothing sensitivity supports strong long-term AOD relationship.
Primary robust climate finding	AMV strongest contemporaneous association.	Both AMV and AOD are associated with decadal temperature pattern; effects not separable.	AOD strongly and consistently associated with warming trajectory.

Notes:

1. Stage 1 data incorporated a 10-year running average. The zero-to-five-year lag sensitivity analysis did not identify an improved AMV relationship.

2. Abbreviations: AOD: sulfate aerosol optical depth; AMV: Atlantic Multidecadal Variability; BP: Breusch-Pagan test; DW: Durbin-Watson statistic; HAC: Heteroscedasticity and autocorrelation consistent; SW: Shapiro-Wilk test.

III. RESULTS

Modeling identified shared, overall relationships between the independent variables and New Jersey's temperature trends, but these need to be considered as collective historical associations, not precise independent causal contributors to individual predictors. Only two independent variables – AMV and AOD – would emerge as exhibiting the strongest relationship with New Jersey temperatures.

Stage 1: 1895-1940
The most consistent and statistically robust association with AMV is seen in this first stage of New Jersey's economic development. AMV is clearly associated with annual temperature changes in the first-difference analysis and continued to act as a predictor across alternative model specifications.

In addition, a time-lag sensitivity analysis (zero through five years) found that the AMV-temperature relationship during this period was strongest year to year and weakened with increasing lag. There was no evidence that introducing other, multi-year lag intervals improved the Stage 1 AMV relationship.

Sulfate aerosol optical depth (AOD) also exhibited statistically meaningful associations with Stage 1 temperature. AOD did display a modest improvement in bivariate explanatory power at approximately four to five years of lag time. However, this improvement was not significant enough to establish a unique optimal lag or alter the finding that AMV represented the most robust Stage 1 climate association.

Stage 2: 1940-1980
New Jersey second stage of economic development (1940 through 1980) was characterized by an interruption in its earlier warming trend. Unlike Stage 1, statistical relationships became more pronounced when examined at multi-year and decadal time scales. AMV and sulfate AOD are clearly linked with the smoothed Stage 2 temperature record.

Heteroscedasticity and autocorrelation consistent standard errors were applied to the smoothed regressions given that overlapping running averages can introduce serial dependence to the data set. After autocorrelation correction, individual AMV and AOD relationships remained statistically significant. However, when examined simultaneously, neither variable could be reliably distinguished statistically as an independent contributor. This indicates that substantial overlaps in their explanatory information may be present inhibiting reliable statistical partitioning of each variable's relative contribution.

Results from Stage 2 modeling are in line with a multi-factor explanation for New Jersey's mid-century temperature plateau. Atlantic climate variability and changes in atmospheric aerosol conditions were important associated factors related to changes in New Jersey temperatures. However, the available data do not allow for the individual contributions or effects of these mechanisms to be quantified reliably.

Stage 3: 1980-2025
New Jersey's third and final stage of economic development produced the strongest and most consistent statistical associations. In the annual regression, reduced-variable models, and associated smoothed sensitivity analyses, AOD has a strong inverse relationship with temperature (ten-year running average r^2 of 0.851). This relationship remained statistically robust even after application of HAC/Newey-West corrections across multiple lag conditions. In contrast, AMV clarified little of the Stage 3 decadal temperature variability and did not provide significant additional explanatory power when included with AOD.

These results provide consistent statistical support for an association between declining regional sulfate aerosol loading and the long-term warming trajectory observed in New Jersey after approximately 1980. They do not, however, establish the numerical magnitude of a causal aerosol contribution.

There is a notable progression in the dominant statistical relationships across New Jersey's three historical periods. Stage 1 had the clearest association with AMV, suggesting an important role for internal Atlantic climate variability during this early twentieth-century warming period. During Stage 2, both AMV and AOD were strongly related to the decadal temperature pattern even though their statistical effects could not be separated. Declining AOD noted during Stage 3 exhibited the strongest and most meaningful connection with the renewed late 20th and early 21st century warming, while the explanatory contribution of AMV became less important.

This progression illustrates that the relative importance of internal climate variability and external atmospheric forcing has changed during New Jersey's temperature history. However, the statistical analyses presented here should be interpreted as evidence of temporal association and consistency with proposed mechanisms and not as definitive attribution of causation.

These findings further demonstrate that New Jersey's long-term temperature history cannot be characterized by a single, uniform relationship between temperature and environmental forcing variables (e.g., fuel usage or population growth). Rather, the statistical relationships differ substantially among the three historical stages. The early twentieth-century warming period (Stage 1) was most strongly associated with Atlantic climate variability; the mid-century temperature plateau (Stage 2) with Atlantic variability and aerosol conditions; and the modern warming period (Stage 3) having a particularly strong inverse association with declining regional sulfate aerosol optical depth.

Extensive robustness analyses give confidence to the conclusion that these broad patterns are not artifacts of a single regression specification. At the same time, the persistence of multicollinearity and common long-term temporal structure among the historical environmental and climatic variables limits the observational regression analysis ability to assign independent causal responsibility. Statistical findings should therefore be viewed as identifying historically coherent and statistically robust associations that are consistent with changing climatic and atmospheric influences on New Jersey temperature over the past 130 years.

IV. Conclusion

These results support the finding that regional temperature change over long historically distinct periods reflects the interaction of multiple processes operating at different temporal scales. Ocean-atmosphere variability is particularly relevant to the early twentieth-century warming period. Changes in atmospheric aerosol conditions are associated with the transition from the mid-century temperature plateau to the renewed warming observed after 1980. This stage-dependent pattern provides a framework for interpreting long-term regional climate change that complements, rather than replaces, broader assessments of global climate forcing.

Disclosures

The author used OpenAI's ChatGPT (GPT-5.6 Luna) as an analytical and editorial assistance tool during the preparation of this manuscript. The tool was used to assist with statistical analyses and helped in organizing, refining and evaluating the presentation of statistical results. Analyses, interpretations, conclusions, and final manuscript content were reviewed and finalized by the author, who assumes full responsibility for the accuracy and interpretation of the work. The author further declares that he has no known competing financial interests or personal relationships that could have influenced the work described in this paper.

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Appendix A
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Year	NJ Temp_F	NJ SO2 Emissionskton	Sulfate AOD	NJ Coal TBtu	NJ Oil TBtu	NJ Oil S Pct	NJ Gas TBtu	NJ Population thousands	NJ UrbanPct	AMVIndex
1895	50.2	12.00	0.010	320.0	50.0	1.80	2.0	1664.5	71.0	-0.025
1896	51.8	12.60	0.011	326.0	54.0	1.80	2.4	1708.4	71.0	-0.041
1897	51.4	13.20	0.011	332.0	58.0	1.80	2.8	1752.3	71.0	-0.032
1898	52.1	13.80	0.012	338.0	62.0	1.80	3.2	1796.2	70.9	-0.018
1899	50.9	14.40	0.012	344.0	66.0	1.80	3.6	1840.1	70.9	-0.055
1900	51.5	15.00	0.013	350.0	70.0	1.80	4.0	1884.0	70.9	-0.062
1901	51.0	15.70	0.013	358.0	75.0	1.79	4.6	1949.3	71.1	-0.078
1902	50.8	16.40	0.014	366.0	80.0	1.78	5.2	2014.6	71.3	-0.091
1903	50.3	17.10	0.014	374.0	85.0	1.77	5.8	2079.9	71.5	-0.102
1904	49.7	17.80	0.015	382.0	90.0	1.76	6.4	2145.2	71.7	-0.115
1905	50.1	18.50	0.015	390.0	95.0	1.75	7.0	2210.5	72.0	-0.097
1906	51.3	19.20	0.016	396.0	102.0	1.74	8.0	2275.8	72.2	-0.083
1907	50.0	19.90	0.016	402.0	109.0	1.73	9.0	2341.1	72.4	-0.071
1908	51.6	20.60	0.017	408.0	116.0	1.72	10.0	2406.4	72.6	-0.059
1909	50.4	21.30	0.017	414.0	123.0	1.71	11.0	2471.7	72.8	-0.043
1910	52.2	22.00	0.018	420.0	130.0	1.70	12.0	2537.0	73.0	-0.038
1911	52.5	22.80	0.019	418.0	140.0	1.69	13.6	2598.9	73.5	-0.052
1912	50.1	23.60	0.019	416.0	150.0	1.68	15.2	2660.8	74.1	-0.067
1913	52.0	24.40	0.020	414.0	160.0	1.67	16.8	2722.7	74.6	-0.048
1914	51.2	25.20	0.021	412.0	170.0	1.66	18.4	2784.6	75.1	-0.036
1915	50.8	26.00	0.021	410.0	180.0	1.65	20.0	2846.5	75.7	-0.024
1916	51.1	26.80	0.022	408.0	192.0	1.64	22.0	2908.4	76.2	-0.033
1917	49.3	27.60	0.023	406.0	204.0	1.63	24.0	2970.3	76.7	-0.021
1918	51.4	28.40	0.024	404.0	216.0	1.62	26.0	3032.2	77.2	-0.008
1919	51.9	29.20	0.024	402.0	228.0	1.61	28.0	3094.1	77.8	0.004
1920	51.0	30.00	0.025	400.0	240.0	1.60	30.0	3156.0	78.3	0.015
1921	53.1	30.80	0.026	396.0	256.0	1.59	33.0	3244.5	78.7	0.027
1922	52.0	31.60	0.026	392.0	272.0	1.58	36.0	3333.0	79.1	0.039
1923	51.5	32.40	0.027	388.0	288.0	1.57	39.0	3421.5	79.6	0.048
1924	50.2	33.20	0.028	384.0	304.0	1.56	42.0	3510.0	80.0	0.032
1925	51.8	34.00	0.029	380.0	320.0	1.55	45.0	3598.5	80.4	0.055
1926	51.3	34.80	0.029	372.0	342.0	1.54	48.0	3687.0	80.8	0.069
1927	52.1	35.60	0.030	364.0	364.0	1.53	51.0	3775.5	81.2	0.081
1928	52.0	36.40	0.031	356.0	386.0	1.52	54.0	3864.0	81.7	0.074
1929	50.6	37.20	0.031	348.0	408.0	1.51	57.0	3952.5	82.1	0.062
1930	53.2	38.00	0.032	340.0	430.0	1.50	60.0	4041.0	82.5	0.085
1931	54.3	38.40	0.033	330.0	446.0	1.49	62.0	4052.9	82.5	0.093

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1932	52.1	38.80	0.033	320.0	462.0	1.48	64.0	4064.8	82.5	0.107
1933	53.0	39.20	0.034	310.0	478.0	1.47	66.0	4076.7	82.5	0.115
1934	52.8	39.60	0.034	300.0	494.0	1.46	68.0	4088.6	82.5	0.098
1935	51.5	40.00	0.035	290.0	510.0	1.45	70.0	4100.5	82.5	0.112
1936	51.0	40.40	0.036	288.0	528.0	1.44	73.0	4112.4	82.5	0.124
1937	51.8	40.80	0.036	286.0	546.0	1.43	76.0	4124.3	82.5	0.138
1938	52.9	41.20	0.037	284.0	564.0	1.42	79.0	4136.2	82.5	0.151
1939	53.2	41.60	0.037	282.0	582.0	1.41	82.0	4148.1	82.5	0.163
1940	51.4	42.00	0.038	280.0	600.0	1.40	85.0	4160.0	82.5	0.172
1941	52.8	43.30	0.039	278.0	610.0	1.39	87.0	4227.5	82.9	0.185
1942	51.9	44.60	0.041	276.0	620.0	1.38	89.0	4295.0	83.3	0.178
1943	51.6	45.90	0.042	274.0	630.0	1.37	91.0	4362.5	83.7	0.165
1944	52.1	47.20	0.044	272.0	640.0	1.36	93.0	4430.0	84.1	0.192
1945	52.5	48.50	0.045	270.0	650.0	1.35	95.0	4497.5	84.5	0.204
1946	53.0	49.80	0.046	262.0	664.0	1.34	98.0	4565.0	85.0	0.218
1947	51.8	51.10	0.048	254.0	678.0	1.33	101.0	4632.5	85.4	0.195
1948	52.2	52.40	0.049	246.0	692.0	1.32	104.0	4700.0	85.8	0.181
1949	53.1	53.70	0.051	238.0	706.0	1.31	107.0	4767.5	86.2	0.167
1950	51.6	55.00	0.052	230.0	720.0	1.30	110.0	4835.0	86.6	0.153
1951	52.3	59.00	0.055	222.0	744.0	1.29	113.0	4958.2	86.8	0.139
1952	52.5	63.00	0.059	214.0	768.0	1.28	116.0	5081.4	87.0	0.126
1953	53.4	67.00	0.062	206.0	792.0	1.27	119.0	5204.6	87.2	0.112
1954	53.2	71.00	0.065	198.0	816.0	1.26	122.0	5327.8	87.4	0.098
1955	52.0	75.00	0.069	190.0	840.0	1.25	125.0	5451.0	87.6	0.084
1956	51.8	79.00	0.072	185.8	863.1	1.24	128.8	5574.2	87.8	0.071
1957	52.7	83.00	0.075	181.5	886.2	1.23	132.6	5697.4	88.0	0.057
1958	51.5	87.00	0.078	177.3	909.4	1.22	136.5	5820.6	88.2	0.043
1959	53.0	91.00	0.082	173.0	932.5	1.21	140.3	5943.8	88.4	0.029
1960	51.9	95.00	0.085	168.8	955.6	1.20	144.1	6067.0	88.6	0.015
1961	52.4	103.00	0.091	182.4	978.9	1.19	159.1	6177.1	88.6	0.001
1962	51.2	111.00	0.096	195.9	1002.2	1.18	174.1	6287.2	88.7	-0.013
1963	51.5	119.00	0.102	209.5	1025.6	1.17	189.2	6397.3	88.7	-0.027
1964	51.8	127.00	0.107	223.0	1048.9	1.16	204.2	6507.4	88.7	-0.041
1965	51.5	135.00	0.113	236.6	1072.2	1.15	219.2	6617.5	88.8	-0.055
1966	51.0	144.00	0.118	213.9	1107.8	1.14	241.6	6727.6	88.8	-0.069
1967	51.6	153.00	0.123	191.3	1143.3	1.13	264.0	6837.7	88.8	-0.083
1968	52.1	162.00	0.129	168.6	1178.9	1.12	286.4	6947.8	88.8	-0.097
1969	51.3	171.00	0.135	146.0	1214.4	1.11	308.8	7057.9	88.9	-0.111

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1970	51.7	180.00	0.140	123.3	1250.0	1.10	331.2	7168.0	88.9	-0.125
1971	51.2	175.00	0.136	105.6	1220.0	1.08	321.0	7187.7	88.9	-0.138
1972	51.8	170.00	0.132	87.8	1190.0	1.06	310.7	7207.4	88.9	-0.152
1973	53.0	165.00	0.128	70.1	1160.0	1.04	300.5	7227.1	88.9	-0.166
1974	52.5	160.00	0.124	52.3	1130.0	1.02	290.2	7246.8	88.9	-0.153
1975	52.3	155.00	0.120	34.6	1100.0	1.00	280.0	7266.5	89.0	-0.141
1976	51.5	146.00	0.114	29.3	1050.0	0.97	284.0	7286.2	89.0	-0.128
1977	51.0	137.00	0.108	24.0	1000.0	0.94	288.0	7305.9	89.0	-0.116
1978	50.3	128.00	0.102	18.6	950.0	0.91	292.0	7325.6	89.0	-0.103
1979	50.1	119.00	0.096	13.3	900.0	0.88	296.0	7345.3	89.0	-0.091
1980	51.8	110.00	0.090	8.0	850.0	0.85	300.0	7365.0	89.0	-0.078
1981	53.0	105.00	0.086	7.4	846.0	0.82	306.0	7401.5	89.0	-0.065
1982	51.2	100.00	0.081	6.8	842.0	0.79	312.0	7438.0	89.1	-0.052
1983	52.7	95.00	0.077	6.2	838.0	0.76	318.0	7474.5	89.1	-0.038
1984	52.1	90.00	0.072	5.6	834.0	0.73	324.0	7511.0	89.2	-0.025
1985	51.3	85.00	0.068	5.0	830.0	0.70	330.0	7547.5	89.2	-0.012
1986	53.2	80.40	0.064	4.8	822.8	0.67	340.0	7584.0	89.2	0.001
1987	53.5	75.80	0.060	4.6	815.6	0.64	350.0	7620.5	89.3	0.015
1988	52.2	71.20	0.056	4.4	808.4	0.61	360.0	7657.0	89.3	0.028
1989	51.6	66.60	0.052	4.2	801.2	0.58	370.0	7693.5	89.4	0.042
1990	54.1	62.00	0.048	4.0	794.0	0.55	380.0	7730.0	89.4	0.056
1991	54.0	57.20	0.044	3.8	803.0	0.52	384.0	7798.4	89.9	0.071
1992	52.5	52.40	0.041	3.6	812.0	0.49	388.0	7866.8	90.4	0.085
1993	52.3	47.60	0.037	3.4	821.0	0.46	392.0	7935.2	90.9	0.099
1994	53.2	42.80	0.034	3.2	830.0	0.43	396.0	8003.6	91.4	0.113
1995	53.5	38.00	0.030	3.0	839.0	0.40	400.0	8072.0	91.9	0.127
1996	52.1	36.00	0.028	2.8	835.2	0.38	414.0	8140.4	92.4	0.141
1997	52.8	34.00	0.027	2.6	831.4	0.36	428.0	8208.8	92.9	0.155
1998	55.0	32.00	0.025	2.4	827.6	0.34	442.0	8277.2	93.4	0.169
1999	54.6	30.00	0.024	2.2	823.8	0.32	456.0	8345.6	93.9	0.183
2000	53.4	28.00	0.022	2.0	820.0	0.30	470.0	8414.0	94.4	0.197
2001	54.2	26.00	0.021	1.9	812.0	0.28	462.0	8451.8	94.4	0.212
2002	54.5	24.00	0.019	1.8	804.0	0.26	454.0	8489.6	94.5	0.226
2003	53.1	22.00	0.018	1.7	796.0	0.24	446.0	8527.4	94.5	0.214
2004	53.0	20.00	0.016	1.6	788.0	0.22	438.0	8565.2	94.5	0.201
2005	54.1	18.00	0.015	1.5	780.0	0.20	430.0	8603.0	94.6	0.188
2006	55.2	16.20	0.014	1.4	764.0	0.18	430.0	8640.8	94.6	0.175
2007	54.3	14.40	0.012	1.3	748.0	0.16	430.0	8678.6	94.6	0.162

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2008	53.5	12.60	0.011	1.2	732.0	0.14	430.0	8716.4	94.6	0.149
2009	53.0	10.80	0.009	1.1	716.0	0.12	430.0	8754.2	94.7	0.136
2010	53.8	9.00	0.008	1.0	700.0	0.10	430.0	8792.0	94.7	0.123
2011	54.2	8.00	0.007	0.9	690.0	0.09	436.0	8841.7	94.7	0.110
2012	55.8	7.00	0.007	0.8	680.0	0.08	442.0	8891.4	94.7	0.097
2013	53.4	6.00	0.006	0.7	670.0	0.07	448.0	8941.1	94.8	0.084
2014	52.6	5.00	0.006	0.6	660.0	0.06	454.0	8990.8	94.8	0.072
2015	55.1	4.00	0.005	0.5	650.0	0.05	460.0	9040.5	94.8	0.059
2016	56.0	3.60	0.005	0.4	626.0	0.04	466.0	9090.2	94.8	0.046
2017	54.9	3.20	0.004	0.4	602.0	0.04	472.0	9139.9	94.8	0.033
2018	54.2	2.80	0.004	0.3	578.0	0.03	478.0	9189.6	94.9	0.020
2019	54.5	2.40	0.003	0.3	554.0	0.03	484.0	9239.3	94.9	0.007
2020	55.7	2.00	0.003	0.2	530.0	0.02	490.0	9289.0	94.9	-0.006
2021	55.0	1.75	0.003	0.2	555.0	0.02	495.0	9289.7	94.9	-0.019
2022	55.3	1.50	0.003	0.1	580.0	0.02	500.0	9290.3	94.9	0.050
2023	56.1	1.40	0.002	0.1	590.0	0.01	510.0	9291.0	95.0	0.120
2024	56.4	1.30	0.002	0.1	595.0	0.01	515.0	9342.0	95.0	0.150
2025	56.2	1.20	0.002	0.1	600.0	0.01	520.0	9548.0	95.0	0.180