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Analysis of Climate Change Data across PPL Corporation Service Territories

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Analysis of Climate Change Data across PPL Corporation Service Territories

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Abstract

Climate change is a phenomenon characterized by the long-term shift of global and local weather patterns. This study analyzed 128 years of weather data, including temperature and precipitation, across states served by the PPL Corporation including Pennsylvania, Rhode Island, and Kentucky. Findings indicate that the climate is changing rapidly across the United States but at different rates in each state. Climate patterns in recent decades of 1995 to 2023, are remarkably different compared to a 100-year baseline of 1895 to 1995 with a consistent shift not only towards an overall warmer climate, but towards increased anomalies in extreme weather events. The distribution of the extreme weather events, as shown by the tails of the anomaly's frequency distributions, also show a shift for all parameters in these regions, indicating a heightened risk of extreme weather events. While all three states exhibit clear climate change, Rhode Island shows the most pronounced evidence. Further research is required to better understand how these changing climate patterns could affect future energy needs. Using detrended and long-term historical temperature data to predict future energy needs can lead to underestimating summer energy volumes, over-estimating winter energy volumes, and underestimating peak power requirements in both seasons. This could negatively affect both reliability and affordability of energy services. While further investigation is necessary, this study provides a foundation for recognizing the important role of data-driven decision-making and science-informed awareness of climate change, to support sustainable development in protecting ecosystems, communities, and future generations.

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1. Introduction

In the last century, Earth's climate has experienced significant changes driven by the greenhouse gas effect, which involves substances like water vapor, carbon dioxide, methane, and nitrous oxide trapping heat. The burning of fossil fuels and deforestation have intensified this effect by emitting more greenhouse gases, particularly carbon dioxide. Climate change is visibly affecting every region of the United States, as highlighted in the Fourth National Climate Assessment (NCA4) of the Climate Science Special Report, that reveals 1.2°F rise in annual temperature over the 40-year period since 1986. In the Northeastern region, effects on precipitation are also evident, with a strong upward trend in heavy rainfall events. These trends highlight the urgency of understanding and mitigating climate change's complex processes for current and future generations, especially at regional scales.

1.1 Area of study

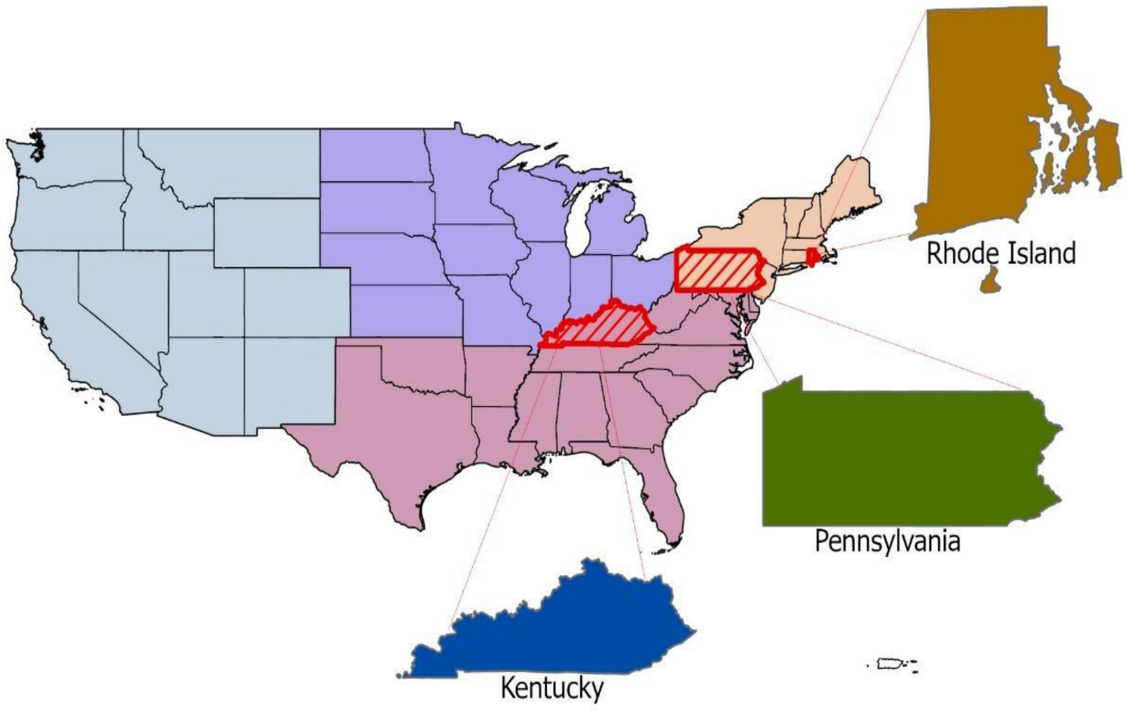


Figure 1. Area of Study (PPL Corporation Territories)

The weather conditions in the northeastern region of the United States are primarily shaped by a strong seasonal cycle, which includes occurrences like ice storms, floods, hurricanes, and droughts. Typically, the annual temperatures in this area are cooler compared to other regions of the US, with average temperatures ranging from 50-60°F in coastal areas and 35-40°F in the higher latitudes and altitudes of the northern part of this region. The climate is significantly influenced by the Atlantic Ocean, Great Lakes, and Lake Champlain, resulting in higher levels of air humidity and precipitation. Due to its proximity to the Gulf of Mexico, the Southeastern region is frequently impacted by subtropical storms originating from the Atlantic Ocean (Marlon et al., 2017). Our analysis centers on three specific regions—Rhode Island, Pennsylvania, and Kentucky—which collectively represent the eastern part of the United States.

Rhode Island. Rhode Island experiences average temperatures between 48 and 51°F, approximately 74°F in July and around 29°F in January. The annual precipitation for the entire state averages about 45 inches (NOAA National Centers for Environmental Information, n.d.).

Pennsylvania. Pennsylvania experiences an average annual temperature of 50.99ºF, which is 2.09% lower than the national average. The average annual precipitation ranges from 28.9 to 64 inches (NOAA National Centers for Environmental Information, 2022).

Kentucky. Kentucky has a relatively warmer climatic profile compared to the Northeast region. The state exhibits an average annual temperature range of 51.4°F to 57.4°F, coupled with annual precipitation variations between 41 and 59 inches.

1.2 Analysis Method

Our investigation utilizes anomaly analysis, a reliable method, to indicate shifts in climate patterns. By examining climate variables such as temperature, wind speed, precipitation, and heating and cooling degree days, we aim to identify shifts in weather events towards extremes. A "degree day" quantifies the heat or cold experienced during a 24-hour period. It's calculated by comparing the average temperature of a day to a baseline of 65 degrees Fahrenheit. Heating and cooling degree days gauge the energy necessary to heat or cool a building to comfort levels based on outdoor temperatures. Using a baseline of 65°F, heating degree days accumulate negative differences from the mean daily temperature, while cooling degree days accumulate positive differences (EPA). Our climate analysis uses publicly available climate data from the National Oceanic and Atmospheric Administration (NOAA), that includes monthly data from January 1895 to July 2023 on 5 distinct facets of climate.

For each variable, we calculated anomalies by comparing observed values between the recent decade (1995-2023) and the base century (1895-1995). An anomaly represents deviations from the typical or expected reading by utilizing a standard score, known as a Z-score, to compare an event at a specific time (such as a month and year) to similar events in the same location (e.g., the state of Pennsylvania) over all comparable time periods (such as all Decembers in Pennsylvania). Z and X measure a specific time (a specific month and year like December 1996), while μ and σ, are across years and unique to months (all Decembers). This reference period allowed us to establish a baseline for what could be considered ordinary or "normal" conditions over the longer time horizon. We chose 1895 – 1995 as the base century. This Z-score calculation is depicted in equation 1 below.

$$Z = X - \frac{\mu}{\sigma} \tag{1}$$

2. Results

Our findings demonstrate consistent evidence of change in the climate variables, not only on a national scale but also remarkably pronounced within the selected regions. Rhode Island emerges as a notable case study, where the shifts are the most significant among the selected regions. Being the smallest state on the Eastern Seaboard, the change in Rhode Island climate patterns is also a reminder of the trends across the New England region. The data underscores a narrative of shifting weather patterns, rising temperatures, and altered environmental conditions that demand attention and further comprehensive analysis.

2.1 Temperature

Temperature is typically the primary and most meaningful indicator of a climate assessment. Our analysis shows a trajectory of rising temperatures against historical norms. The annual and rolling five-year anomaly analyses demonstrate a persistent rise in temperature since 1985 (Fig. 2). From the analysis, the United States exhibited a +0.39 change in standard deviations in comparison to the base century (Fig. 3). Since 1995, the temperature anomalies are consistently increasing by +0.1° F over five-year intervals. The annual average temperature anomalies reached its highest point at +0.88° F in 2012. Furthermore, in 2023, historical temperature records were shattered as October, November, and December marked the warmest months ever recorded for those respective periods.

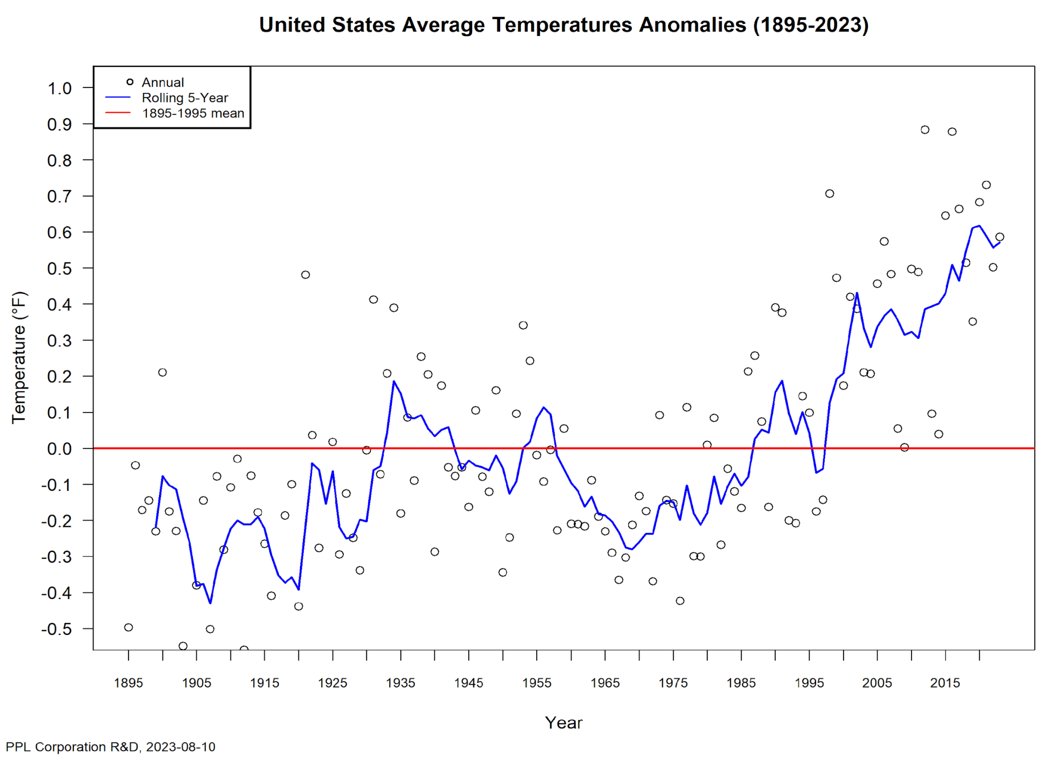


Figure 2. US Temperature Anomalies

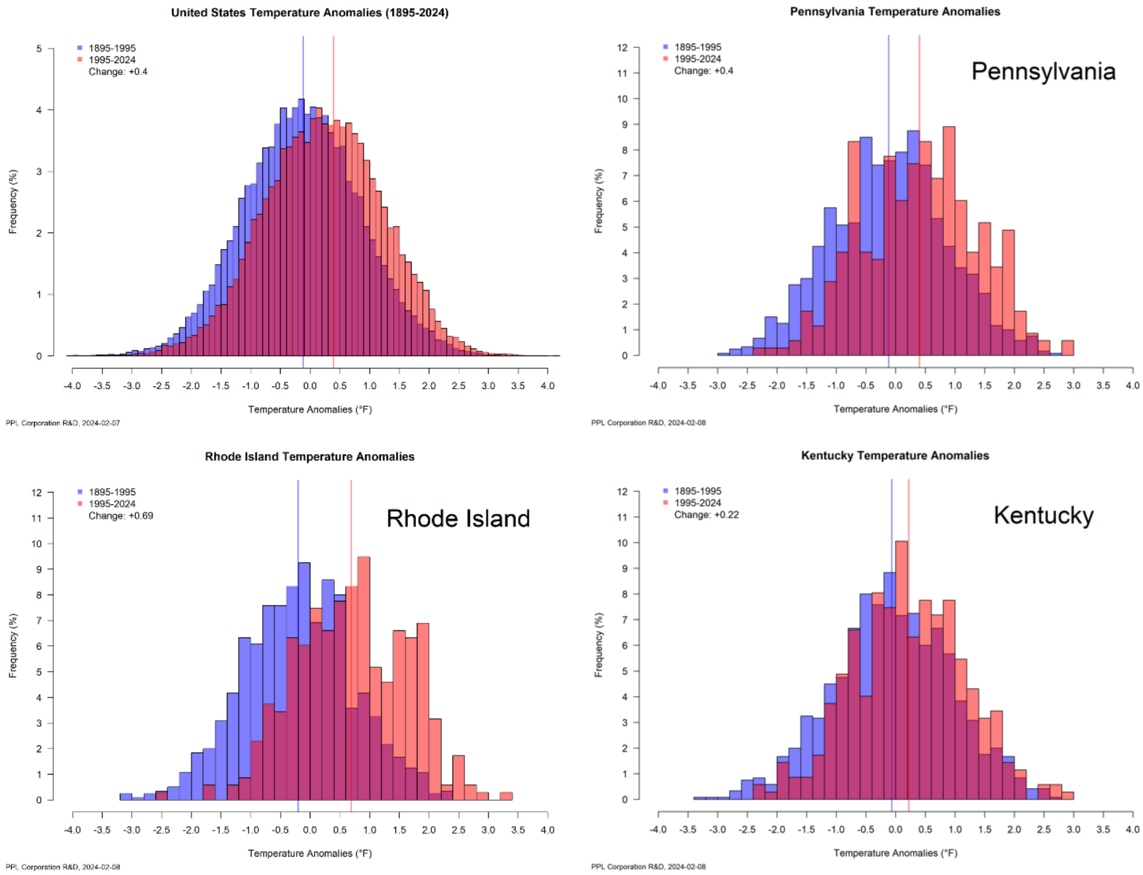


Figure 3. National and Regional Temperature Anomalies

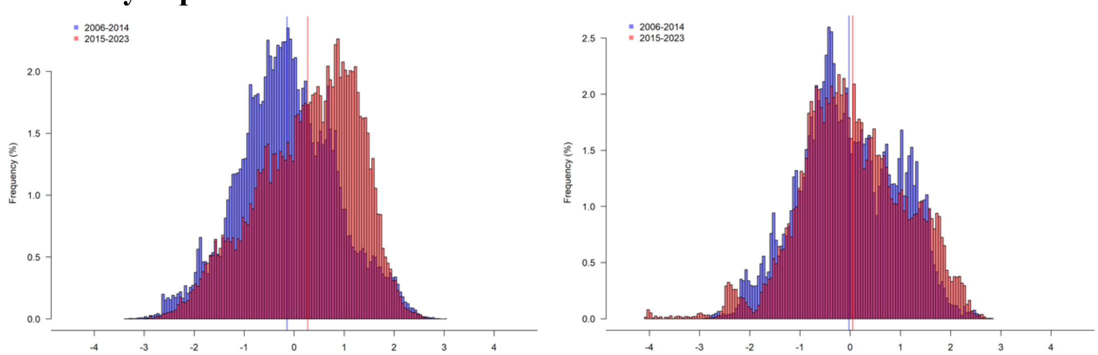
We analyzed the temperature anomaly between the base century period (1895-1995) and the current analysis period (1995-2023). All three regions underwent a shift, exhibiting a frequency bias towards positive anomalies, indicating an overall increase in temperatures in these areas (Fig. 3). Rhode Island, in particular, experienced temperature increases that surpass regional averages with an increase change of +0.69 standard deviations versus 1895-1995 base century. Pennsylvania exhibits the least amount of change amongst the three regions with a calculated change of +0.04.

With the temperature bell curve shifting towards positive anomalies, the data's tail, which indicates extreme events, demonstrates a notable increase in extreme heat. Each region experienced a minimum of +3.0^{o} F rise in the tail, with Rhode Island at +3.5^{o} F, Pennsylvania at +3.2^{o} F, and Kentucky reaching +3.0^{o} F. In addition, when these three regions are combined, an extreme cold anomaly of -3.5^{o} F was observed. This highlights that climate change not only anticipates extreme heat due to rising temperatures but also entails anomalies of extreme cold.

We conducted a monthly anomaly analysis to examine potential seasonality shifts using the data from periods 2006-2014 and 2015-2023 (Fig. 4). Specifically, we compared winter to the end of summer and the beginning of fall for Kentucky and Rhode Island. In the recent period, we observed a higher frequency of warm days during the summer, resulting in an average temperature anomaly shift from -0.2^{o} F to +0.3^{o} F for Kentucky and -0.1^{o} F to +0.15^{o} F for the beginning of fall in Rhode Island. Notably, there were more extreme cold events identified at the negative tail of the distribution.

During winter, Kentucky experienced warmer anomalies in the recent period, but with a notable increase in extreme cold events, reaching as low as -4.1^{o} F below the normal. Conversely, Rhode Island's winter appeared slightly colder in the recent period, accompanied by a significant rise in extreme cold events.

Kentucky Sep-Dec



RI Oct-Dec

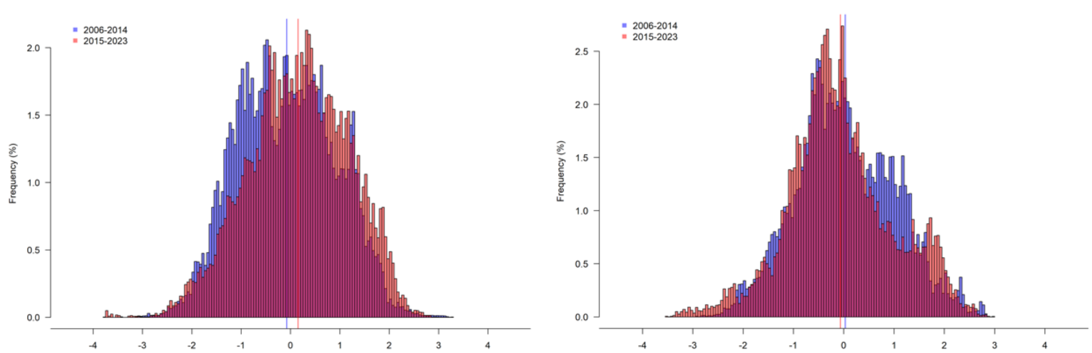


Figure 4. Fall vs Winter Temperature Anomalies

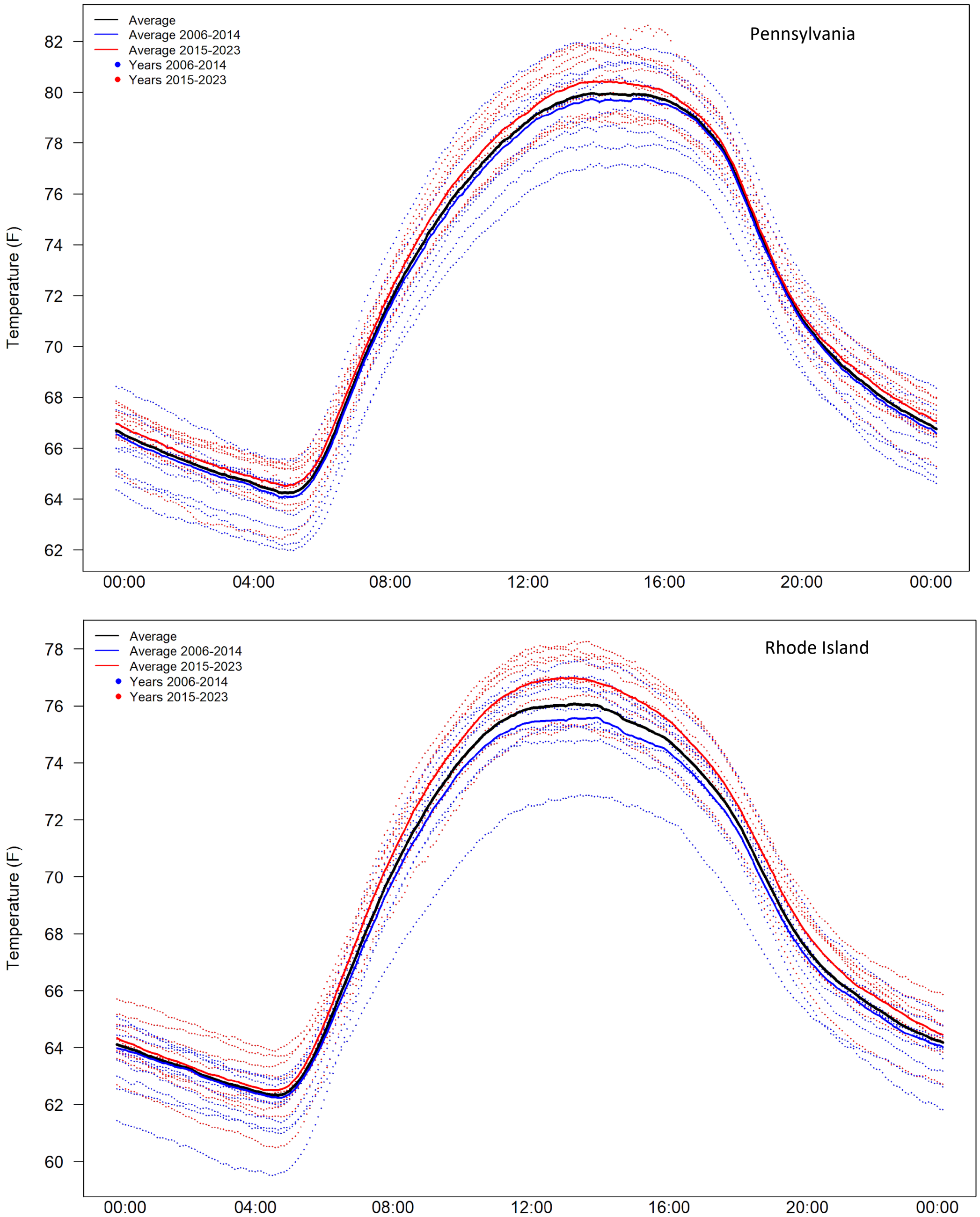


Figure 5. Minutely Temperature Anomalies for PA and RI

We examined the minute fluctuations in temperature during summer across two periods: 2006-2014 and 2015-2023 (Fig. 5). The analysis reveals an upward temperature trend in the recent period for Pennsylvania and Rhode Island. Rhode Island experienced a significant increase of 1.5°F in average summer afternoon temperatures compared to the previous period, while Pennsylvania recorded its highest summer afternoon anomaly of 2.66°F in 2022 during these intervals.

2.2 Heating Degree Days (HDD)

Since 1980, the count of cooling degree days has steadily increased, while that of heating degree days has consistently decreased (Fig. 6). These trends signify a broader shift towards warming rather than cooling. Consequently, these alterations may have influenced energy demand, leading to a nationwide rise in net electricity demand.

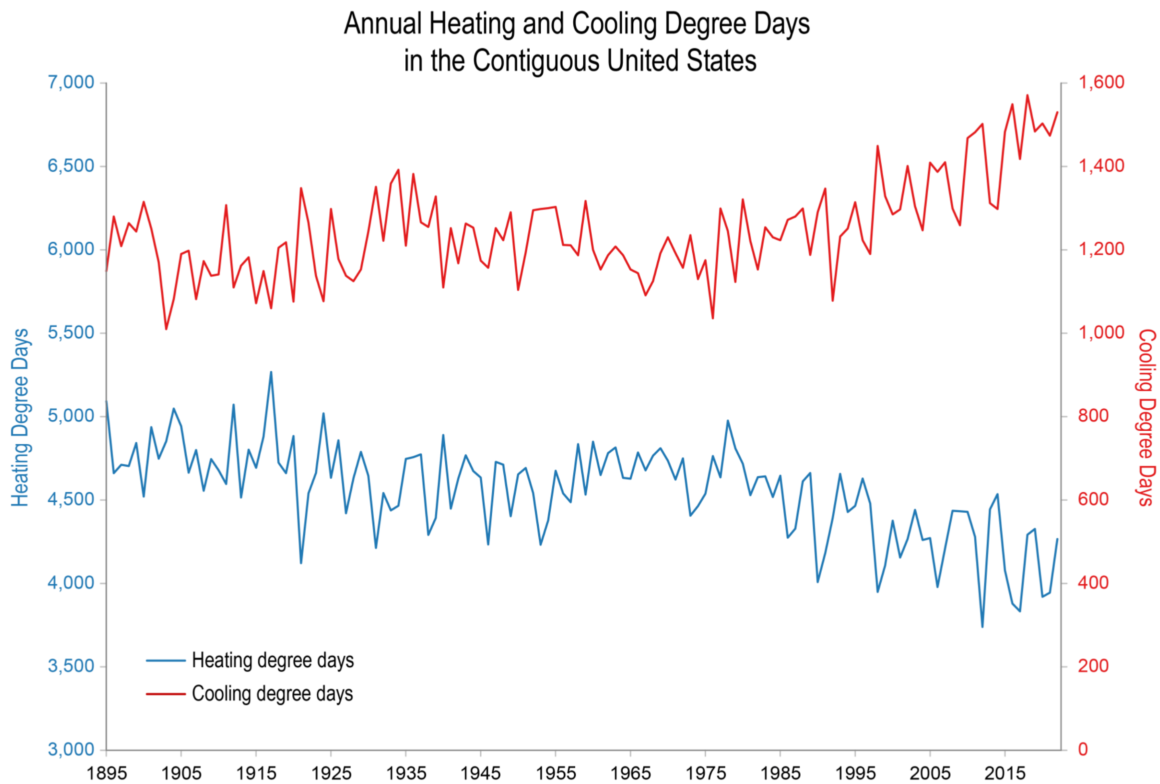


Figure 6. U.S. annual Heating and Cooling Degree Days

(Source: U.S. Global Change Research Program)

Overall, across our focus regions, there has been an 8.91% decrease in heating degree days (HDD), with the state of Rhode Island experiencing the greatest decrease in heating degree days of 12.43%. Hence, winter energy requirements may decrease because of a reduction in winter heating degree days. The pace of change is different across regions, while Rhode Island is experiencing rapid change, Pennsylvania witnesses a moderate decrease of 9.27%, and Kentucky experiences a slower decline of 5.83% (Fig. 7). Although the specific rates per region differ, these findings suggest a consistent trend of rises in temperatures over recent decades. This indicates a shift towards more instances of overall ambient environmental temperatures exceeding 65°F and a transition from heating to cooling degree days.

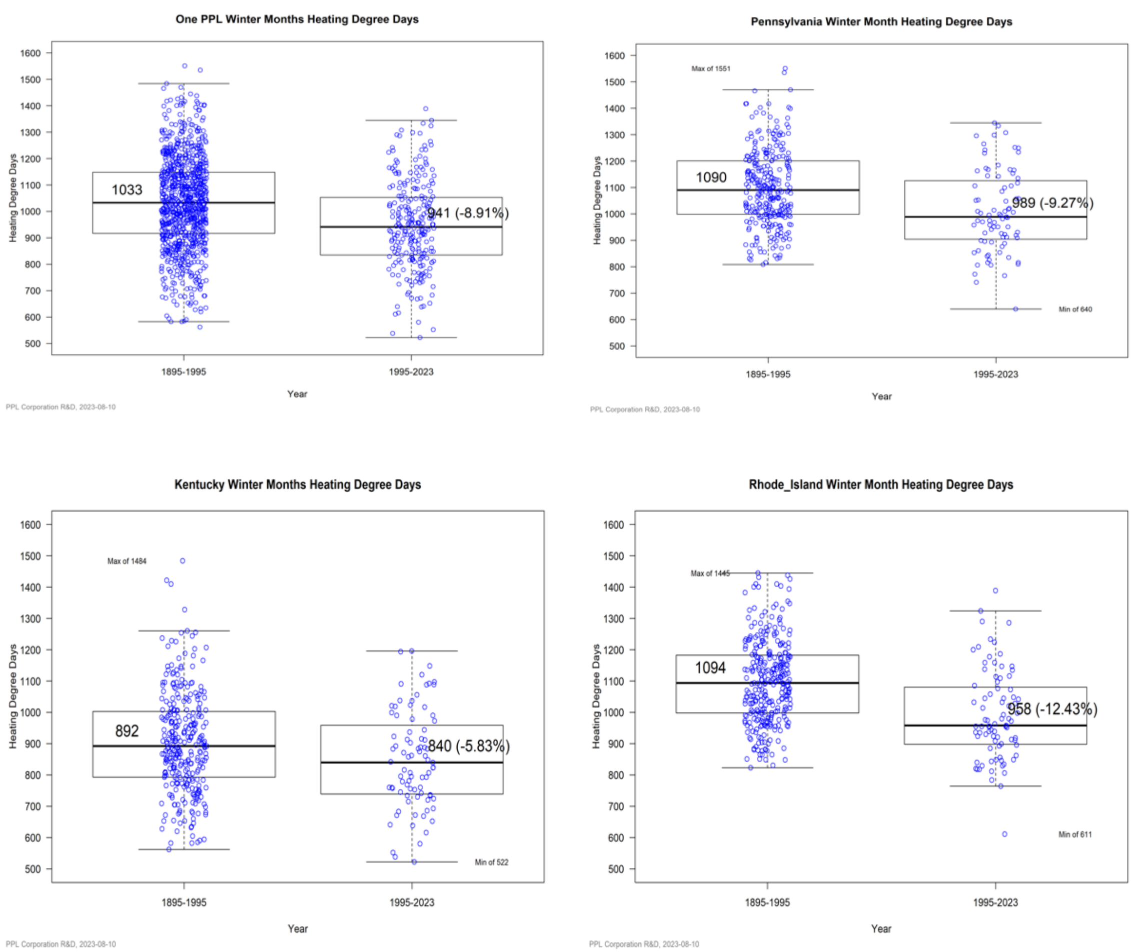


Figure 7. Winter Month Heating Degree Days

2.3 Cooling Degree Days (CDD)

Pennsylvania (PA) typically begins exhibiting Cooling Degree Days (CDD) from May to October, while Rhode Island (RI) shows them from June to September. Kentucky (KY) displays early CDD occurrences starting from March to September, suggesting a warmer climate compared to the other regions. However, there are rare occurrences where CDD events happen even in November, January, and February in KY, which show about 40% increase of this occurrence from the early 20th century to the present period. This trend indicates warming temperatures in Kentucky (KY) during the fall and early spring seasons, in addition to warming winter seasons in between.

Rhode Island saw the most notable increase in CDD values, rising by almost 40%, Pennsylvania rose by 16.87%, while Kentucky remained relatively unchanged. This observation correlates with Figure 3, where Kentucky exhibited the least significant anomalies change. Nonetheless, when considering these three regions together, there was an average increase in cooling degree days by 18.18% (Fig. 8).

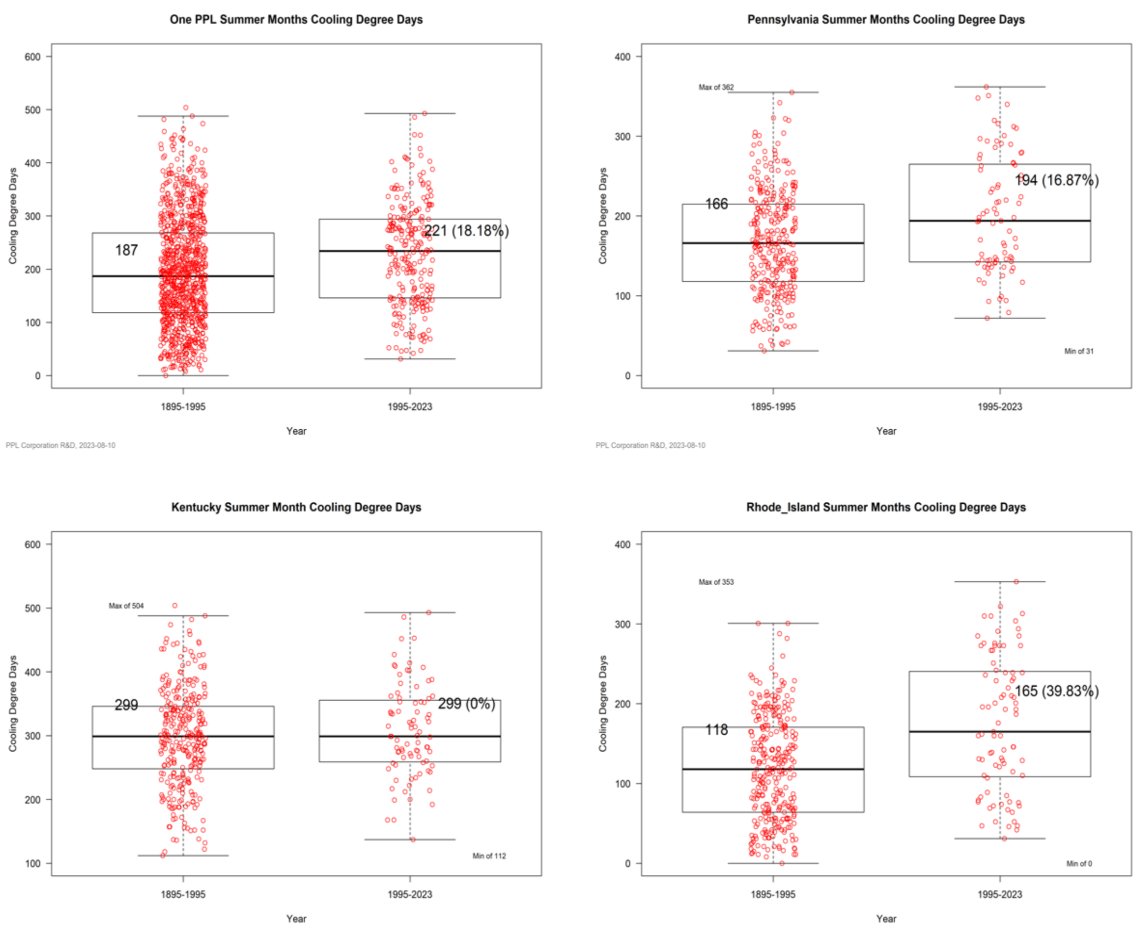


Figure 8. Summer Months Cooling Degree Days

2.4 Precipitation

Across the contiguous United States, the mean annual precipitation stood at 35.87 inches during the period of 1895-1995, exhibiting a subsequent increase of +2.08 inches during 1995-2024. The average precipitation levels within our focus regions markedly surpass the national average, witnessing a notable increase of +4.04 inches to 44.60 inches during the period 1995-2024. In addition, the observed linear trend within these regions shows a steeper progression, with a slope of 0.0432 inches per year, contrasting with the national gradient of 0.026 inches per year (Fig. 9). This finding underscores an accelerated pace of precipitation escalation across the eastern region relative to the national trend. This finding is also strengthened by the rise in the anomalies, as shown in the trend of annual Z-scores comparison between the US and the selected areas (Fig. 10).

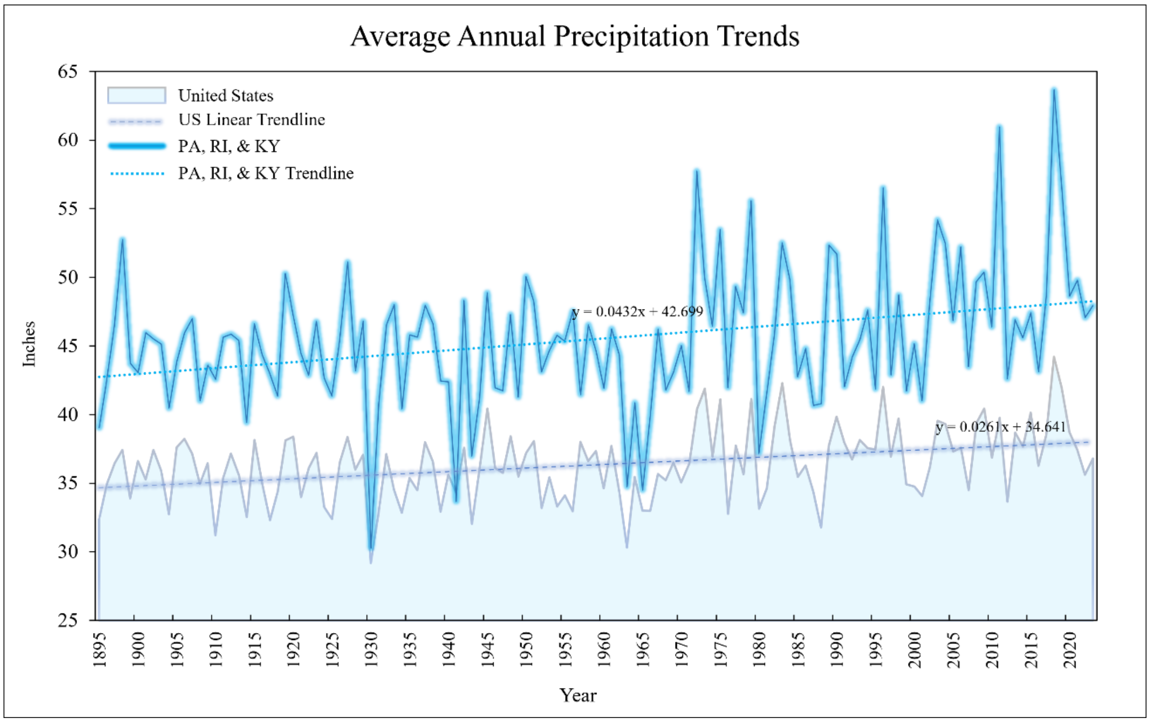


Figure 9. Average Annual Precipitation Trends across US and Focus Area (PA, RI, KY)

Our anomaly analyses have revealed that the United States has witnessed a shift in the median value of precipitation anomalies by 0.12 inches. Interestingly, the peak of the bell curve has shown a reduced value, indicating that the average precipitation across the US during the period of 1995-2024 is only slightly higher than that from 1895-1994. This phenomenon may be attributed to the substantial increase in temperature across the US, which enhances the evaporation of water, subsequent recycling of water vapor, and acceleration of the water cycle (Lehmann et al., 2015). Nonetheless, the recent increase in the maximum tail suggests that the US region will face a heightened risk of more extreme precipitation events (Fig. 11).

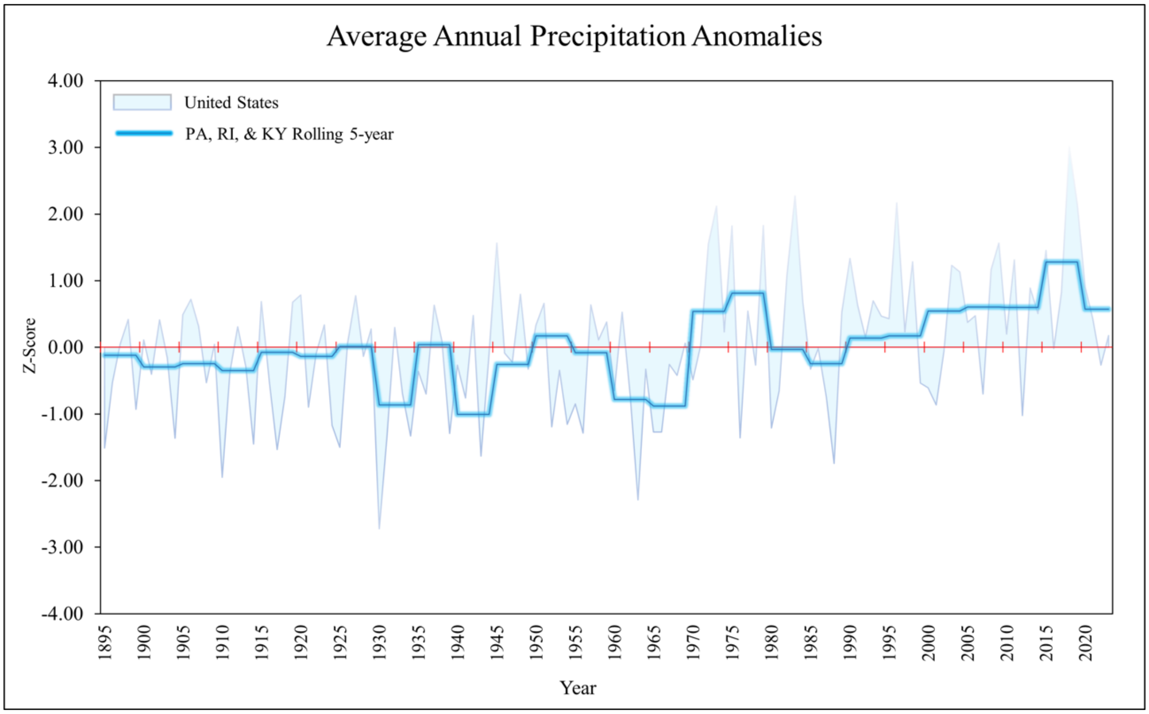


Figure 10. Annual Z-score Trends across US and Focus Area (PA, RI, KY)

Over the past few decades, a notable trend has emerged across PA, RI and KY, characterized by an overall increase in precipitation. This shift is not limited to specific months or seasons but is evident year-round. We analyzed December precipitation anomalies to get a closer look at the changes that are occurring in the selected states. The data suggest that the regions served by PPL have experienced a consistent rise in rainfall and other forms of precipitation during winter months (Fig. 12). This change in precipitation patterns may have important implications for various sectors, including agriculture, infrastructure, and water resource management, necessitating a thorough examination and adaptation to these evolving weather conditions.

In terms of monthly precipitation, the median generally increased in the recent period, particularly in spring and summer across these regions (Fig. 12). The temperature rise likely accelerated the evaporation process, increasing atmospheric moisture and leading to heightened precipitation during warmer seasons. All three regions exhibited significant changes in the upper tail of precipitation anomalies toward the end of summer (September), indicating extreme precipitation events. The overall increase in extreme events and a widening variability envelope are evident in the annual precipitation trends for the United States and the three selected states.

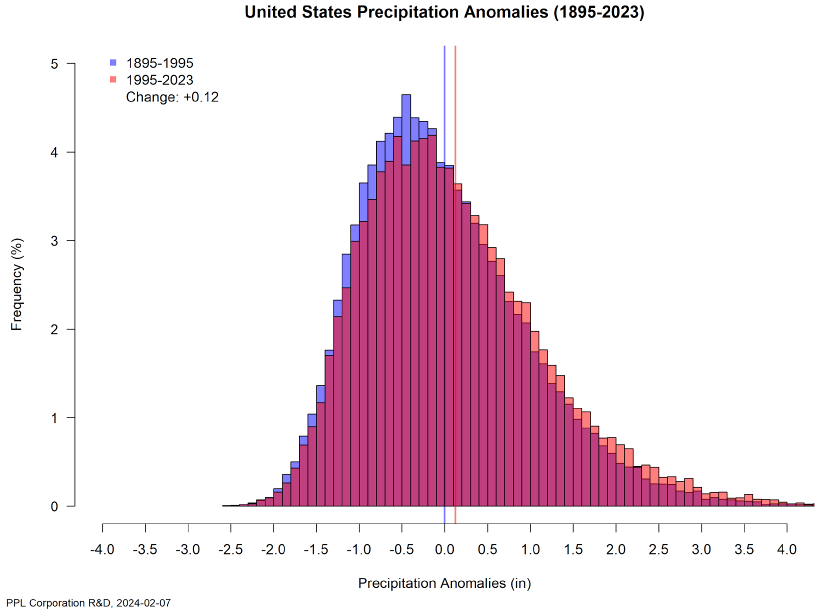


Figure 11. United State Precipitation Anomalies

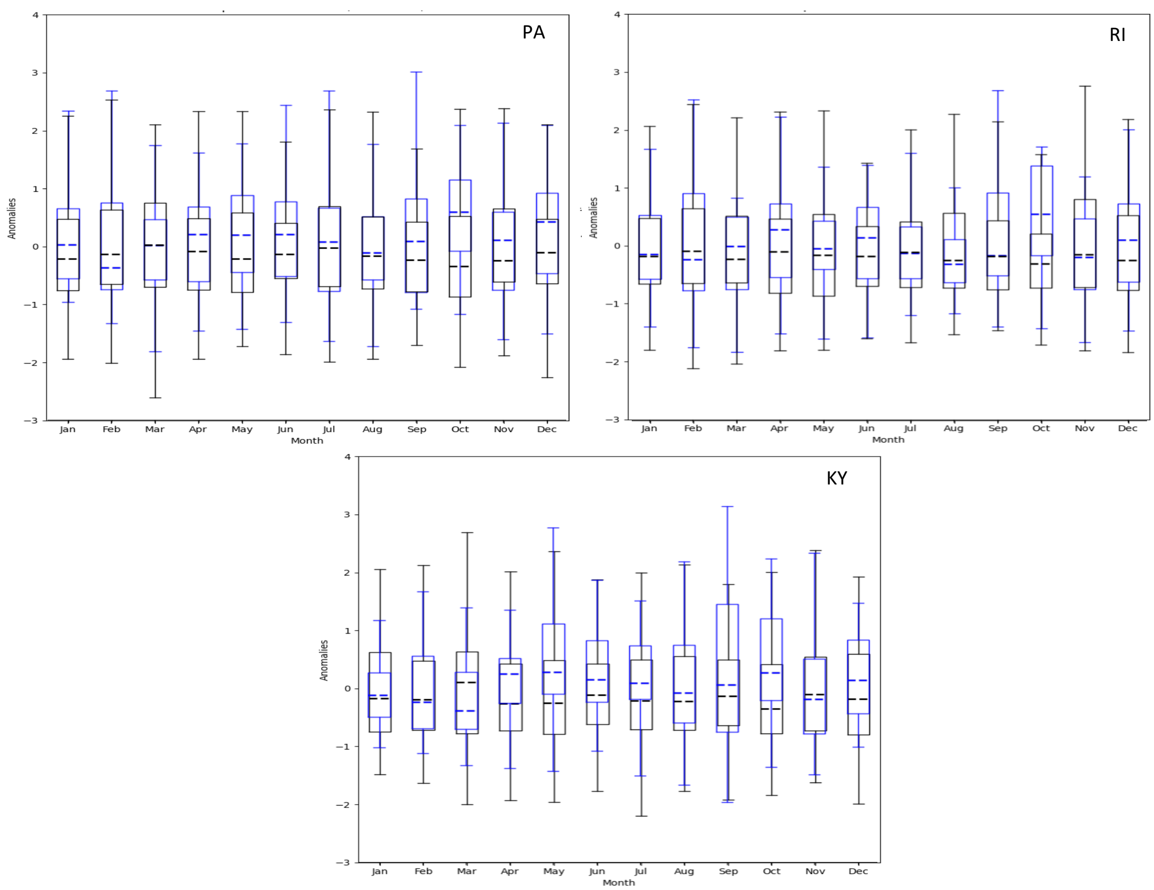


Figure 12. Precipitation Changes Across PA, RI, and KY

During winter (Fig.13), precipitation events have been on the rise in these regions. However, the tail of the whisker displayed lower anomalies in the recent periods compared to the base period, suggesting a reduced likelihood of extreme outlier precipitation events. While further investigation is required, this analysis indicates that the areas served by PPL Corporation are generally experiencing greater rainfall than they did historically.

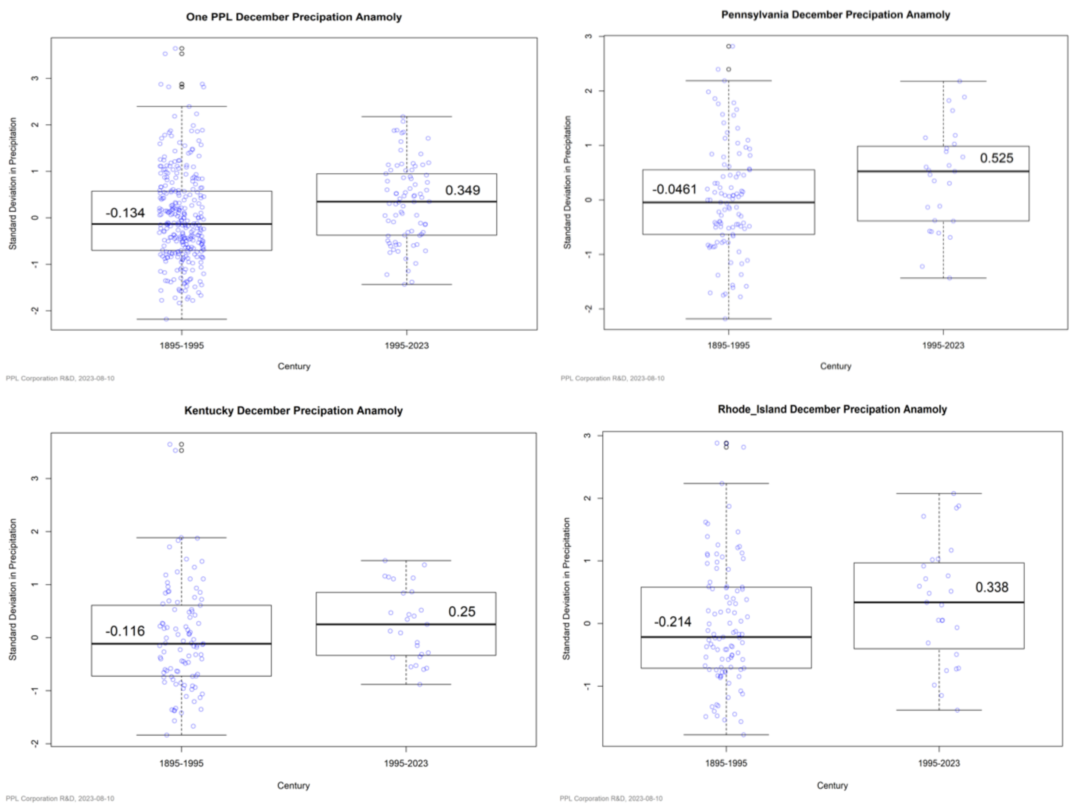


Figure 13. December Precipitation Changes

2.5 Wind Speed

While average wind speeds have remained relatively stable, there is a growing concern regarding the increasing frequency of extremely windy events. In 2023, Kentucky experienced its windiest year on record based on the data available for analysis. Notably, Pennsylvania and Rhode Island also reported windier conditions than usual during this period. Studying these patterns is important for both research and decision-making to assess the challenges posed by more frequent and intense windy conditions. While further analysis of wind data is required, this investigation indicates that wind speeds are increasing and becoming less predictable (Fig. 14).

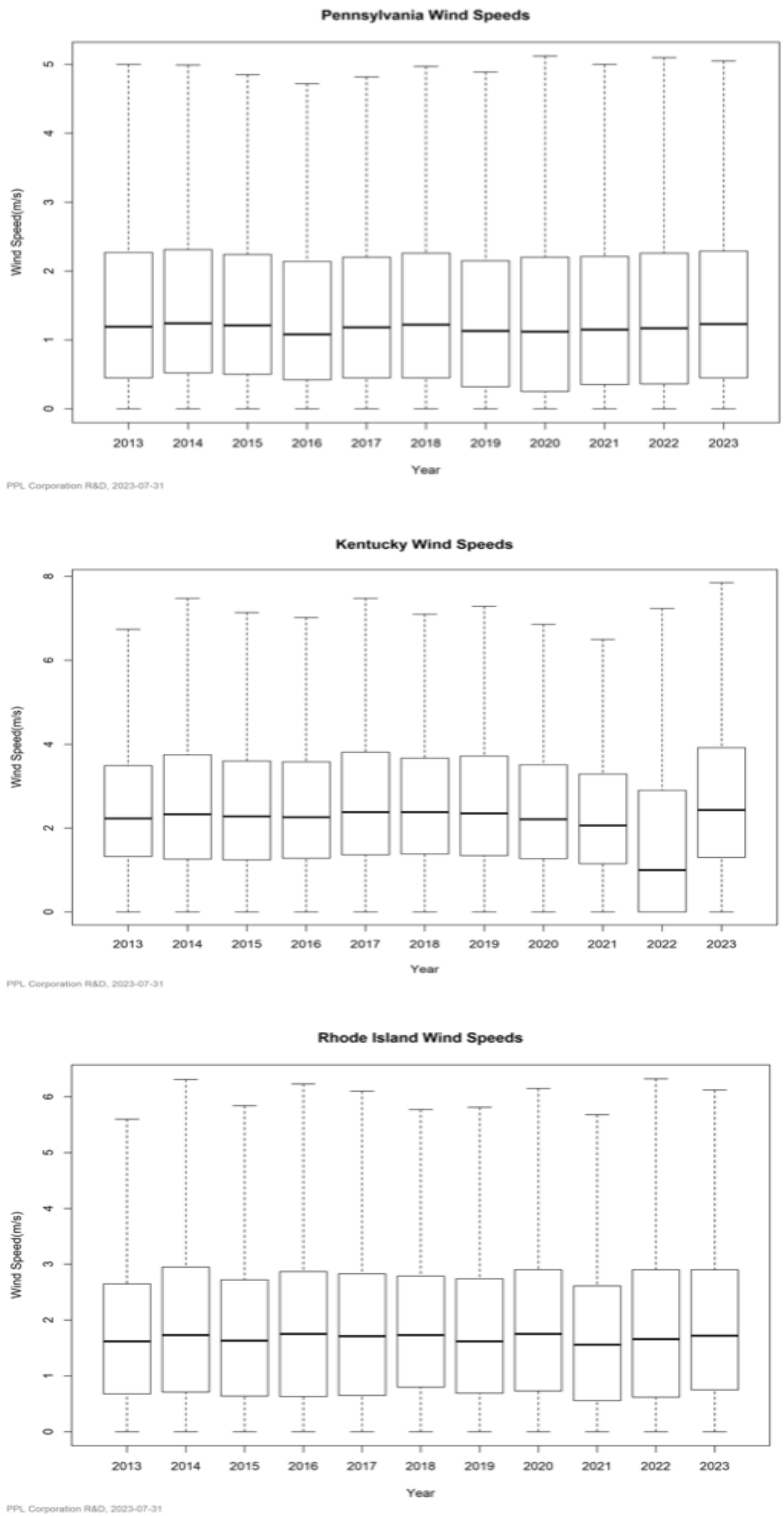


Figure 14. Wind Speed Changes

3. Discussion and Conclusions

Our analysis reveals a notable average value shift across all climate parameters, signaling consistent changes leaning towards warmer temperature in Rhode Island, Pennsylvania, and Kentucky. We evaluated the severity of change across these regions by analyzing the percentage difference for each parameter, comparing data from the base century (1895-1995) to the recent period of 1995-2023.

Additionally, we investigated the average, maximum, and minimum values to discern both general trends and extreme tail changes, which serve as indicators of the likelihood of extreme weather events. Heating Degree Days (HDD) reflect a significant trend towards lower values, indicating a reduction in heating days. Notably, Pennsylvania stands out with a 20% reduction in the maximum tail of CDD, indicating a decrease of extreme hot days (Fig. 15).

Each region experienced an increase in both the minimum and maximum tails for precipitation. Pennsylvania demonstrated the most significant change in the minimum tail, showing a 30% rise, while Rhode Island exhibited the highest shift in the maximum tail with a 35% increase. Conversely, Kentucky showed the least significant change in precipitation anomaly, with a 3% increase on both ends. The rise in the maximum tail indicates an increased risk of extreme precipitation, highlighting Rhode Island as the most vulnerable.

Overall, Rhode Island appears to exhibit the most significant changes when all values are combined, averaging 34% in each parameter tail changes, compared to Kentucky and Pennsylvania that have average tail changes of 19% for each climate parameter (Fig. 15). Our findings can serve as a starting point for further analysis of the impacts of climate change on the three states in the eastern part of the United States (KY, PA, and RI).

In conclusion, the analysis of temperature data shows general warming of the environment across the United States. The climate in the United States, especially the northeastern states, is experiencing a significant increase in average summer and winter temperatures. In addition, the frequency of anomalies is increasing such as the occurrence of peak events, or climate extremes including intense heat days, extreme cold days, warm winter days, etc. Given the evident changing climate across these regions, further investigation is necessary to evaluate how these changes might result in noticeable impacts on the economy and ecosystems of the region, particularly within the context of the power generation industry.

While further research is required, this study suggests that future energy and power requirements are expected to be different than in the past. Total energy volumes should be expected to be higher in the summer, while energy volume requirements in the winter will tend to be lower. Although total winter energy volumes are decreasing with generally warmer and milder winters, extremely cold events are increasing in frequency, causing peak power requirements to increase. Using long-term historical normal temperature data can lead to over-estimating winter energy volumes, underestimating summer energy volumes, and potentially underestimating peak power requirements in both seasons that could lead to poorer reliability. Future energy and power needs across the service territories will require a more robust distribution, transmission, and generation infrastructure that can handle more extreme and less-predictable temperatures than have been observed in the past. To maintain reliability and low cost in the face of climate change, more thorough analysis of climate data and its implications on future energy needs of utility customers is required.

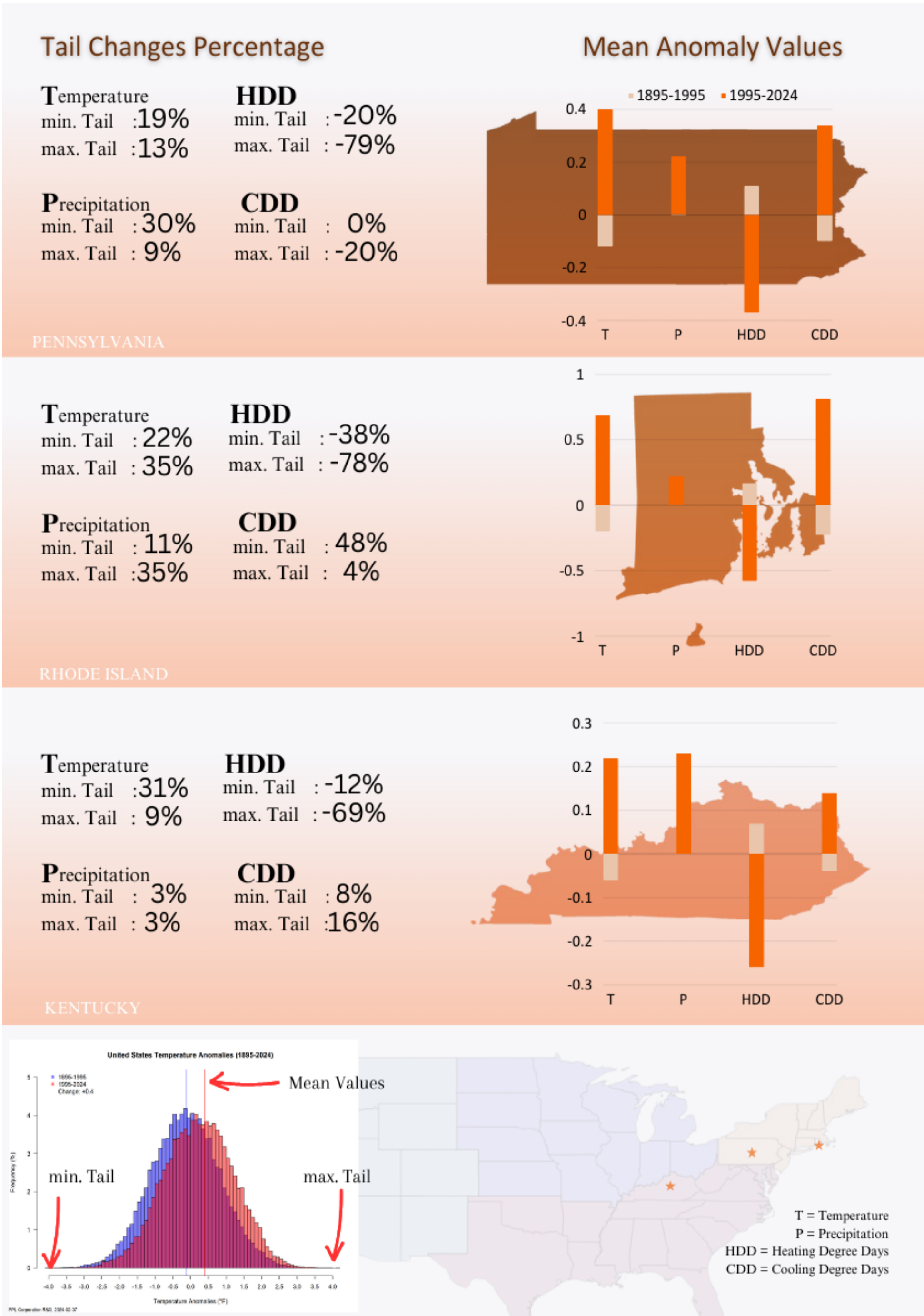


Figure 15. Summary of Anomalies Changes for All Climate Parameters

References

Lehmann, J., Coumou, D., & Frieler, K. (2015). Increased record-breaking precipitation events under global warming. *Climatic Change*, *132*(4), 501–515. https://doi.org/10.1007/s10584-015-1434-y

Marlon, J. R., Pederson, N., Nolan, C., Goring, S., Shuman, B., Robertson, A., Booth, R., Bartlein, P. J., Berke, M. A., Clifford, M., Cook, E., Dieffenbacher-Krall, A., Dietze, M. C., Hessl, A., Bradford Hubeny, J., Jackson, S. T., Marsicek, J., McLachlan, J., Mock, C. J., … Yu, Z. (2017). Climatic history of the northeastern United States during the past 3000 years. *Climate of the Past*, *13*(10), 1355–1379. https://doi.org/10.5194/cp-13-1355-2017

NOAA National Centers for Environmental Information. (n.d.). *State Climate Summaries 2022 149-RI: Rhode Island*. Retrieved February 18, 2024, from https://statesummaries.ncics.org/

NOAA National Centers for Environmental Information. (2022). *State Climate Summaries 2022 150-PA: Pennsylvania*. https://statesummaries.ncics.org/

United States Environmental Protection Agency (US EPA). (n.d.). *Climate Change Indicators - Technical Documentation: Heating and Cooling Degree Days*. Retrieved February 18, 2024, from https://www.epa.gov/sites/default/files/2021-03/documents/heating-cooling_td.pdf