Spatio-Temporal Analysis of Observed Changes in Seasonal Temperatures in Kentucky, Pennsylvania, and Rhode Island

by Ambarish Karmalkar, Casey Egan, David Beyerle, Larry Holloway, and Aron Patrick

A Joint Research Project Between the University of Rhode Island,
the University of Kentucky, and the PPL Corporation

Executive Summary

Climate change is affecting seasonal temperatures across the United States including in Kentucky, Pennsylvania, and Rhode Island–geographies served by the PPL Corporation family of regulated electric and gas utilities. The rate of change in temperature is, however, not uniform and varies by season, between states, and even by geography within each state. While evidence of warming is apparent in the temperature data we analyzed going back to 1895, the rate of warming has increased significantly since 1995 through 2024.

Rhode Island is experiencing the most-rapid rate of annual warming and climate change. Summer temperatures are, on average, 0.885°F (0.5°C) warmer during just the past decade of 2015 to 2024, than they were in 2006 to 2014. This change in average temperature resulted in Rhode Island having 40 percent more summer cooling degree days on average in 1995 to 2024, than in 1895 to 1995. Although a smaller state, the rate of warming is not uniform in Rhode Island, with eastern and coastal regions, including Providence, warming at a faster rate than more inland western regions of the state. Changes in Rhode Island winter temperatures are less rapid, with heating degree days increasing by 1.9% per decade.

Pennsylvania is experiencing both warmer winters and warmer summers. Summer temperatures are, on average, 0.52°F (0.29°C) warmer during the past decade, and winters are 0.36°F (0.20°C) warmer. Pennsylvania summers had 17% more cooling degree days on average, and 9% fewer winter heating degree days, in 1995 to 2024, than in 1895 to 1995.

Kentucky has experienced a slower rate of warming, with virtually no change in summer temperatures during the past century but significant warming in winters. Winter temperatures in Kentucky are, on average, 3.23°F (1.8°C) warmer during just the past decade of 2015 to 2024, than they were in 2006 to 2014 and this difference is statistically significant ($p < 2.2e-16$). This change in average temperature resulted in Kentucky having 6 percent more winter heating degree days on average in 1995 to 2024, than in 1895 to 1995. Winter in Kentucky is warming at the fastest rate among the states analyzed for this study.

Changing temperatures can be expected to affect utility customer energy requirements. Warming summers can be expected to increase demand for power and energy during hotter summer months, potentially increasing summer peak load and requiring additional capital investments in transmission, distribution, and generation infrastructure. Higher summer temperatures also can result in derating of transmission line capacity during times when demand for electricity for air conditioning is highest, potentially requiring upgrades to certain distribution or transmission infrastructure. Conversely, warming winters can be expected to decrease total winter energy requirements, although we observed no reduction in winter extreme cold events.

Author Information

Ambarish Karmalkar is Assistant Professor of Geosciences at the University of Rhode Island and a climate scientist with expertise in regional climate dynamics and modeling. Professor Karmalkar has previously directed and contributed to various regional climate assessments focusing on states in the northeastern U.S. For this report, Ambarish led the climate analysis, visualized and interpreted the data, and was the principal investigator and primary author of the written report.

Casey Egan is a University of Rhode Island engineering student and student intern at the PPL Corporation focused on environmental conservation and solving green energy challenges. Casey assisted the project with data collection, analysis, and editing.

David Beyerle is a research engineer on the Research & Development team at the PPL Corporation. He holds a master's degree from the Georgia Institute of Technology and a bachelor's degree from the University of Kentucky, both in mechanical engineering. David assisted the project with data collection, analysis, and editing.

Larry Holloway is the endowed Kentucky Utilities Professor of Electrical and Computer Engineering at the University of Kentucky. Professor Holloway has previously served as Vice Provost of the University of Kentucky, Interim Dean of the College of Engineering, Department Chair of Electrical and Computer Engineering, and Director of the Power and Energy Institute of Kentucky (PEIK), all at University of Kentucky. Professor Holloway contributed to this project by helping frame the study, reviewing the analysis, and helping to write and edit the report.

Aron Patrick is the Head of Research & Development for the PPL Corporation, responsible for researching ways to improve how PPL provides safe, affordable, reliable, and sustainable energy to more than 6.5 million energy customers. Aron has been with the PPL Corporation for 8 years with another 8 prior years of civil service including as Assistant Director of the Kentucky Office of Energy Policy. Aron was responsible for managing this project and contributed by building the team, providing funding, framing the analytical questions, analyzing and visualizing data, and helping to write and edit the report.

Acknowledgements

Funding to the University of Rhode Island and University of Kentucky for this study was provided by PPL Corporation Research & Development. The authors attest that this analysis is true to the best of their abilities in the 90-day period of performance provided and declare no conflicts of interest.

Introduction

This report analyzes temperature data to assess changes in mean temperature and its variability over the past century across the three PPL states. These states experience strong seasonal variations in temperature, with hot summers and cold winters. Despite their proximity to the Atlantic Ocean, particularly in RI and PA, all three states have a continental climate influenced by weather systems moving in from the west or southwest. The climate in all these states also exhibits substantial year-to-year (interannual) variations, driven by interactions between regional factors (e.g., topography, vegetation) and continental-scale atmospheric circulation patterns.

Temperature has long been recognized as an important consideration in forecasting for utilities. Outside temperature affects space conditioning needs of buildings and thus the energy use of those buildings. In 2022, HVAC (heating, ventilation, and air conditioning) accounted for over 30% of residential electricity consumption and over 25% of electricity for the commercial sector (EIA, 2022a; EIA, 2022b). Utilities regularly consider weather data when developing daily and hourly load forecasts and consider historical weather data when contemplating longer term resource planning and reserve margins (for example, see LGE-KU, 2021).

Weather affects the power system beyond just the energy demand. For example, the heat from electrical transmission lines must be dissipated to the surrounding air to prevent the lines from overheating or experiencing excessive sagging or changes in material properties. Consequently, the current carrying capacity of such lines are derated based on surface air temperature and wind speed (PJM, 2022). For utilities with summer demand peak, this means that during hot weather, the transmission capacity limit may be reduced at the same time that customer demand for electricity for air conditioning is rising. Other power equipment may also experience performance losses or equipment degradation under excessive heat, so such equipment would have its operation derated when surface air temperature and conditions reduce its ability to dissipate heat. Even thermal power plants such as coal or nuclear may have their power output reduced during excessive heat waves. Thermal power plants that rely on river water for “once-through” cooling will add heat to the river water. Such plants may be required to reduce or stop generation during excessively hot weather to avoid damaging a heat-stressed river ecosystem (Madden et al, 2013; GAO, 2022).

Utilities have long considered average temperatures in planning for generation and considered risks of extreme weather events in planning for infrastructure resiliency. However, until recently, much of this planning assumed decades-long average temperatures and historical weather behaviors. Many utilities are now starting to adjust their forecast methodologies to recognize climate changes that trend to higher temperatures than these long-term averages would indicate. A 2022 survey of 88 utilities representing over 2.3 billion MWh of electricity generation and delivery of a billion cubic feet of natural gas indicates that 22% of respondents are adjusting their normal weather predictions in their energy forecasting models to reflect climate change (Itron, 2022). Approximately half of these are considering climate change by applying trending data to the existing normal weather calculation. Other techniques to consider climate change in energy forecasting are outlined in (Homer et al, 2023). These include basing normal average temperature estimates on shorter time periods, so that more recent weather data dominates in the normal weather calculations.

Climate Data

Climate observations for the last century used in this report are obtained from the National Centers for Environmental Information (NCEI) website of the National Oceanic and Atmospheric Administration (NOAA). We analyze surface air temperature (referred to as temperature in this report), which is the air temperature reported in weather reports and measured by thermometers at 1.5 - 2 meters above the ground. The observed daily minimum, maximum, and average temperatures are part of the *nClimGrid-Daily* dataset (Durre et al., 2022a, 2022b), which is derived from morning and midnight observations from the Global Historical Climatology Network Daily (GHCND) database (Menne et al., 2012; Durre et al., 2010). Additionally, we use the NOAA monthly gridded dataset, *nClimGrid-monthly* (Karl and Koss, 1984; Vose et al., 2014a, 2014b). The nClimGrid datasets provide temperature values on a ~5 km x 5 km latitude-longitude grid for the Continental United States from 1895 to the present. In addition, we also analyze s*ubhourly, 5-minute, data provided by NOAA National Climate Data Center (NCDC) from the U.S. Climate Reference Network / U.S. Regional Climate Reference Network (USCRN/USRCRN) for two weather stations in Kentucky and Rhode Island* (Diamond, et al. 2013).

National Temperature Changes

The observations reveal a clear warming trend between 1901 and 2023 in the contiguous United States including the three PPL states (Fig. 1a). An overall temperature increase has been about 2.2˚F (1.2˚C), which is similar to the rise in global average temperature during this period. The observed warming, however, is not spatially uniform across the three states. The southeastern U.S has experienced less warming than other parts of the U.S. (Fig. 1b). On the other hand, the coastal areas of the northeastern United States, from Maine to New Jersey/Delaware, have experienced enhanced warming compared to the interior parts west of the Appalachians. It is anticipated that land areas will warm more rapidly than the ocean, resulting in greater warming over land compared to the global average.

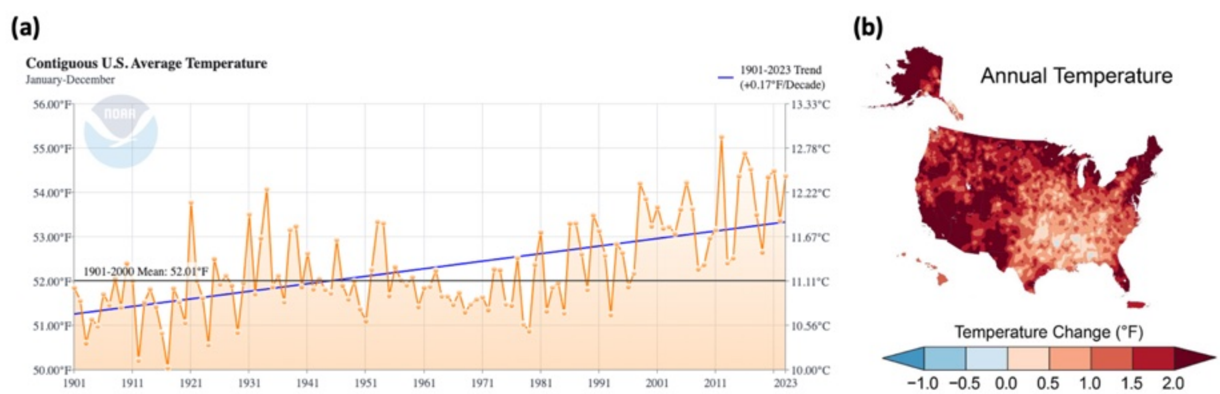

Figure 1: *(a) The annual mean surface air temperature in the contiguous U.S. between 1901 and 2023. The black line shows the twentieth-century average, and the blue line shows the trend over the entire period. (Source: NOAA Climate at a Glance) (b) Temperature change over the historical period across the contiguous U.S. (Source: NCA5; Marvel et al., 2023*)

Consistent with the observed trend in mean temperature, both minimum (TMIN) and maximum (TMAX) temperatures in the contiguous U.S. have risen over the last century (Fig. 2). These changes reflect nation-wide increases in both daytime high and nighttime low temperatures. Minimum temperatures, however, have risen more rapidly (+0.19˚F/decade) than daytime maximum temperatures (+0.15˚F/decade). This asymmetry in warming leads to a decrease in *diurnal temperature range* (DTR), which is the difference between maximum and minimum temperatures.

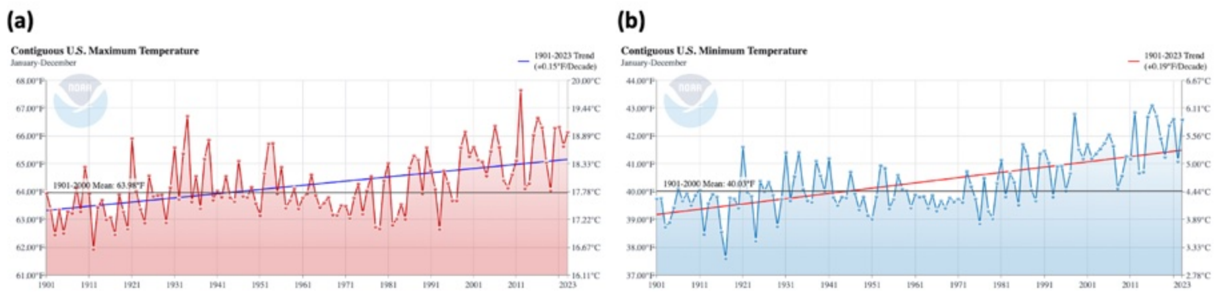

Figure 2: *The mean annual (a) maximum and (b) minimum temperature in the contiguous U.S. between 1901 and 2023. The black line shows the twentieth-century average, and the blue and red lines in a and b, respectively, show trend lines over the entire period. (Source: NOAA)*

<u>Temperature Changes in PPL Territories</u>

Annual and Seasonal Mean Temperature

The evolution of mean annual temperature (Fig. 3) shows a general warming across PPL territories over the last century. Based on a linear trend over the period 1901-2023, the warming rates are approximately 0.34˚F/decade (0.2˚C/decade) in RI, 0.18˚F/decade (0.1˚C/decade) in PA, and 0.07˚F/decade (0.04˚C/decade) in KY. Over the last three decades, however, the rate of warming has increased to 0.8˚F, 0.66˚F, 0.54˚F per decade in RI, PA, and KY, respectively. While Kentucky did not experience a significant long-term rise in temperature throughout the 20^{th} century, it has seen a steady increase in mean annual temperatures since the 1980s. At yearly to decadal timescales, temperature variability may be determined by sea surface temperature variations in the Atlantic and Pacific Oceans and their interactions with the atmosphere (e.g., Meehl et al., 2015). Nonetheless, the overall increase in temperature becomes evident when examining longer, multi-decadal timescales. The total warming over the past 123 years (1901-2023) is 4.2˚F (2.3˚C) in Rhode Island, 2.2˚F (1.2˚C) in Pennsylvania, and 0.83˚F (0.5˚C) in Kentucky.

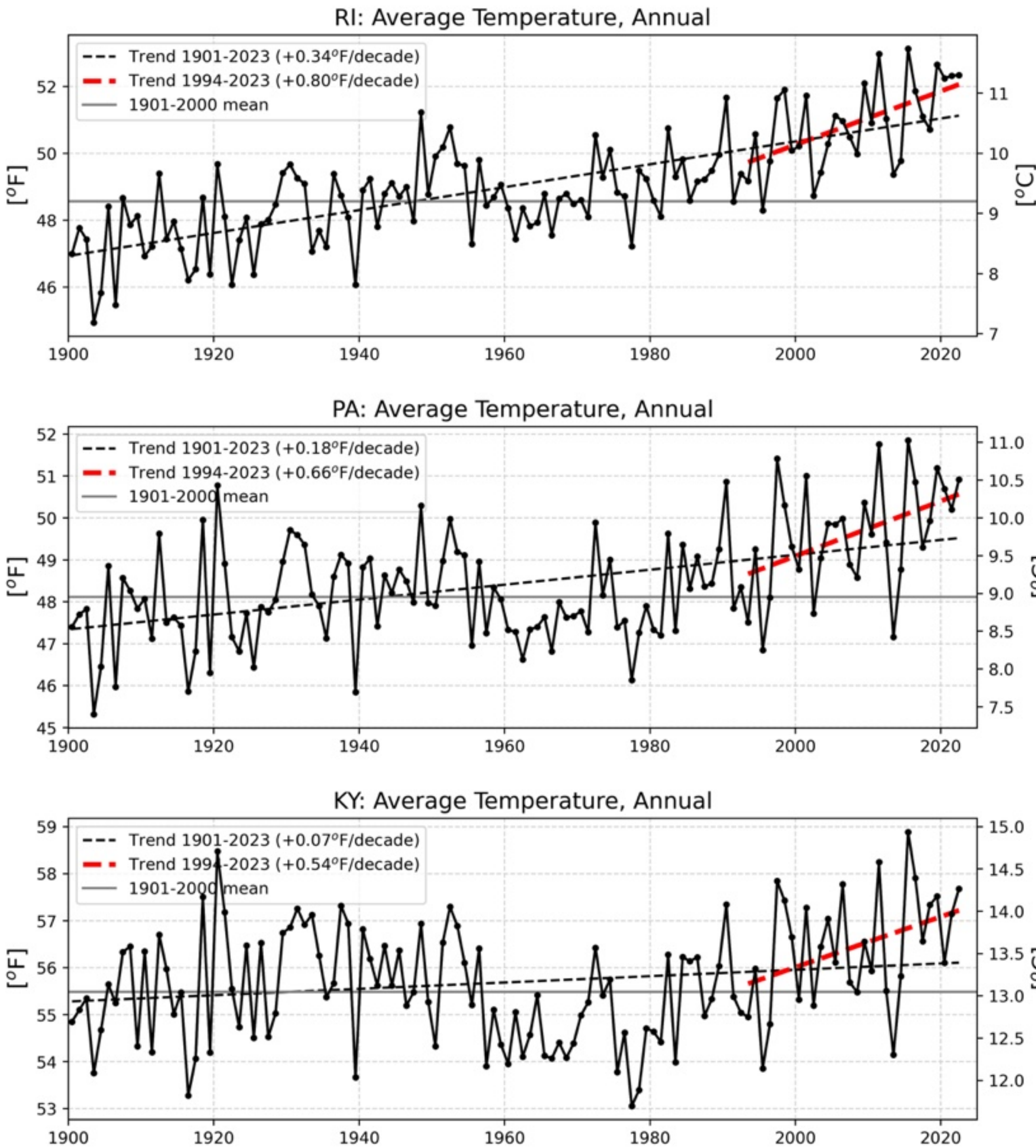

Figure 3: *Annual mean temperature for RI, PA, KY. The dotted lines show linear trends for 1901-2023 (black) and for the last 30 years (1994-2023; red). Dataset: nClimGrid monthly data.*

As noted in Fig. 1, the magnitude of temperature change varies spatially across the PPL territories. Figure 4 shows the spatial patterns of change in annual mean temperature for two periods: the full analysis period of 1901-2023, and the recent three decades (1994-2023). The spatial pattern of observed warming depicted in Fig. 4a underscores the exceptional nature of coastal warming, including in Rhode Island, especially in comparison to other areas of the eastern U.S. For Pennsylvania, the eastern and northwestern parts of the state have experienced higher warming than the central regions of PA. Research into the mechanisms responsible for the observed exceptional long-term coastal warming hints at the interplay between changes in ocean and atmospheric circulation in the North Atlantic region (Karmalkar and Horton, 2021).

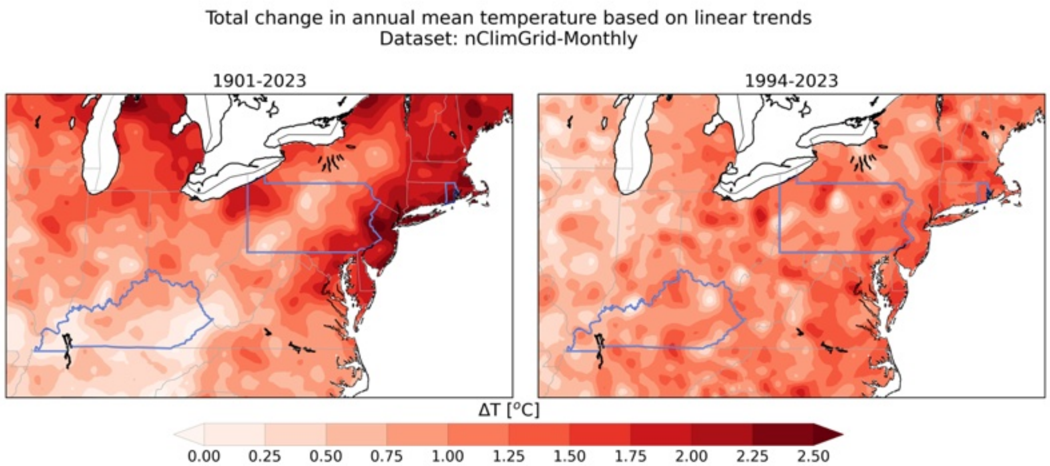

Figure 4: *Changes in annual mean temperature (TAVG) for 1901-2023 (left), and 1994-2023 (right). The total changes in ˚C are calculated based on linear trends over the analysis periods. Dataset: nClimGrid-Monthly data.*

Comparing temperature changes over the whole analysis period (1901-2023) and the recent 30 years (1994-2023) reveals that the rate of warming is higher in the last thirty years in all PPL states. However, the rate of warming varies across the PPL states, with Kentucky warming more slowly than Pennsylvania or Rhode Island. Among PPL states, annual mean temperatures are increasing most rapidly in Rhode Island. This difference is likely due to a number of factors, including natural climate variations influenced by the Atlantic and Pacific Oceans, as well as local factors such as airborne aerosols and land surface feedbacks (Mascioli et al., 2017). Aerosols—tiny particles such as soot and dust suspended in the atmosphere—arise from various human and natural sources (NOAA GFDL; https://www.gfdl.noaa.gov/aerosols-and-climate/). Aerosols emissions caused temporary summertime cooling between early 1950s through mid-1970s, but this trend reversed in the 1970s (Meehl et al., 2015), leading to warming in the eastern U.S., including all three PPL states, over the last four decades.

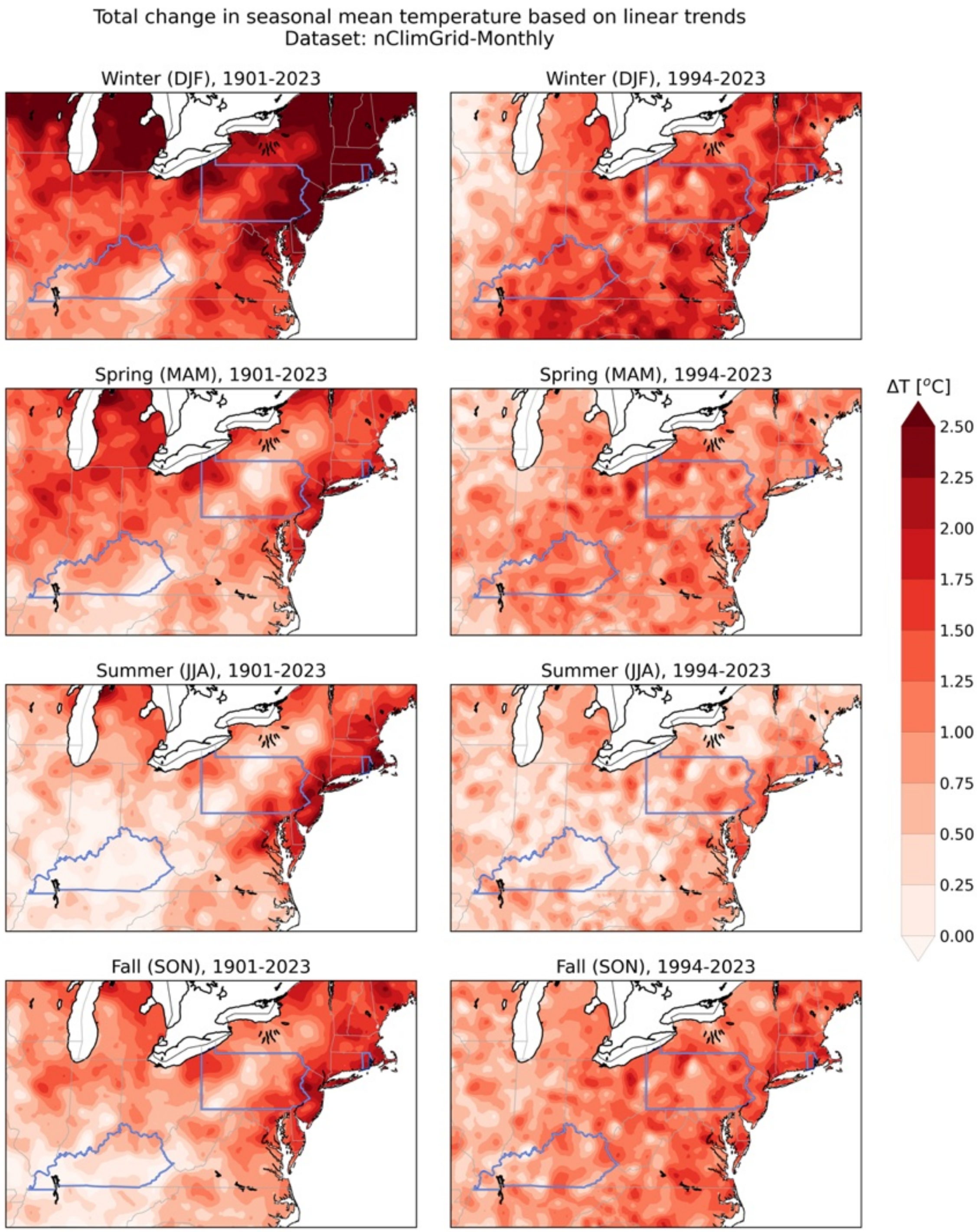

Figure 5: *Changes in season mean temperature (TAVG) for 1901-2023 (left), and 1994-2023 (right). The total change in ˚C are calculated based on linear trends over the analysis periods. Dataset: nClimGrid-Monthly data.*

Next, we consider trends in annual mean temperature aggregate changes occurring over different seasons of the year. The spatial patterns of seasonal mean temperature changes, as shown in Fig.

5, reveal that temperature trends vary by season and region. Winter warming in all three PPL states is more pronounced compared to other seasons. In Kentucky and central Pennsylvania, there is strong winter warming and only slight to moderate warming in summer. Conversely, eastern Pennsylvania and Rhode Island have experienced notable summer warming. In general, the warming pattern for 1901-2023 (Fig 5 left column) indicates relatively lower warming in mountainous areas and greater warming in low-elevation and northern parts of the study region. Over the last thirty years, however, the magnitude of warming is similar across all PPL territories (Fig 5 right column) with the highest warming occurring in winter and the least in summer.

Temperature variability over space and time can be illustrated by plotting temperature distributions and analyzing changes in the mean and width of these distributions. Figure 6 compares average, minimum, and maximum temperature anomalies (relative to the 1901-2000 mean) for two periods, 1901-2000 and 1994-2023, across each PPL state. The blue histograms in Fig. 6 represent spatial variations in temperature anomalies during the 20th century, while the red histograms show variations for the last three decades (1994-2023). Consistent with previous findings on warming trends in the three PPL states, the histograms for recent temperatures shift toward values compared to those of the 20th century. For Rhode Island, in particular, the coldest temperature anomalies of the early 21st are similar to the 20th-century average, underscoring the substantial warming the region has experienced. Despite differing rates of warming, these results highlight that a larger proportion of temperature anomalies now fall outside the range of 20th century variations across all regions.

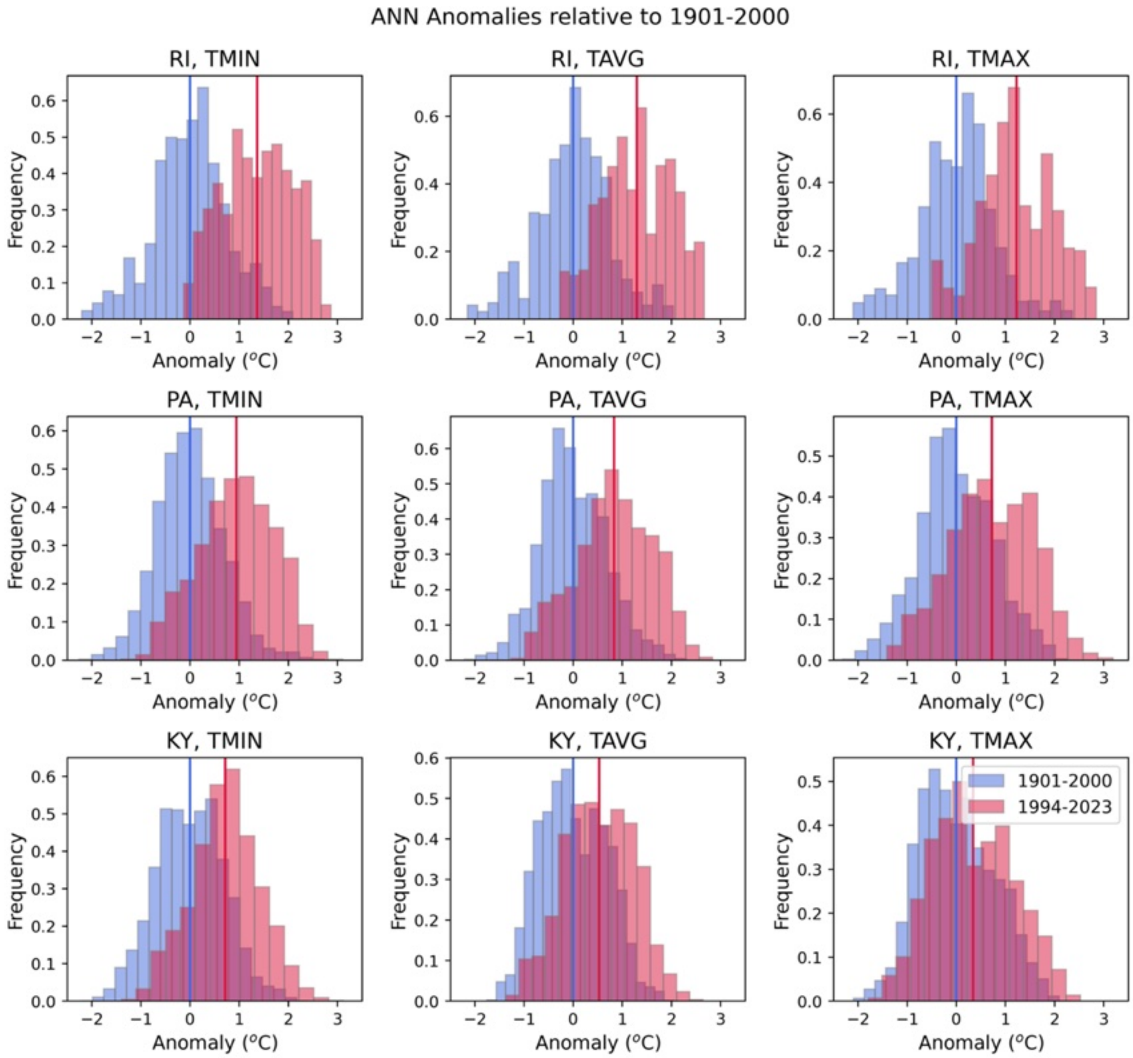

Figure 6: *Spatial variability in temperature anomalies in the three PPL states for 1901-2000 (blue) and 1994-2023 (red). Histograms showing distribution of anomalies in ˚C, at ~4km resolution, in minimum annual (first column), mean annual (second column), and maximum annual (third column) temperatures. Vertical lines indicate averages for the two periods analyzed. Dataset: nClimGrid-Monthly data.*

Cooling and Heating Degree Days

One obvious consequence of a warming climate is the rise in demand for cooling during summer and a decrease in demand for heating in winter. These changes are assessed by calculating cooling and heating degree days using a 65˚F threshold.

Cooling Degree Days (CDD)

To analyze changes in cooling degree days (CDD), we compute the mean CDD for three decades: 1971-1980, 1991-2000, and 2014-2023. Figure 7 shows the decadal mean CDD for the three PPL states. An increase in CDD as time progresses is noted in all three states. There are notable spatial variations, especially in Pennsylvania and Kentucky. Annual CDDs are generally higher in eastern PA and western KY, while they are lower in the higher elevation areas of these states. The increases in CDD since the 1970s are typically higher in low-elevation regions.

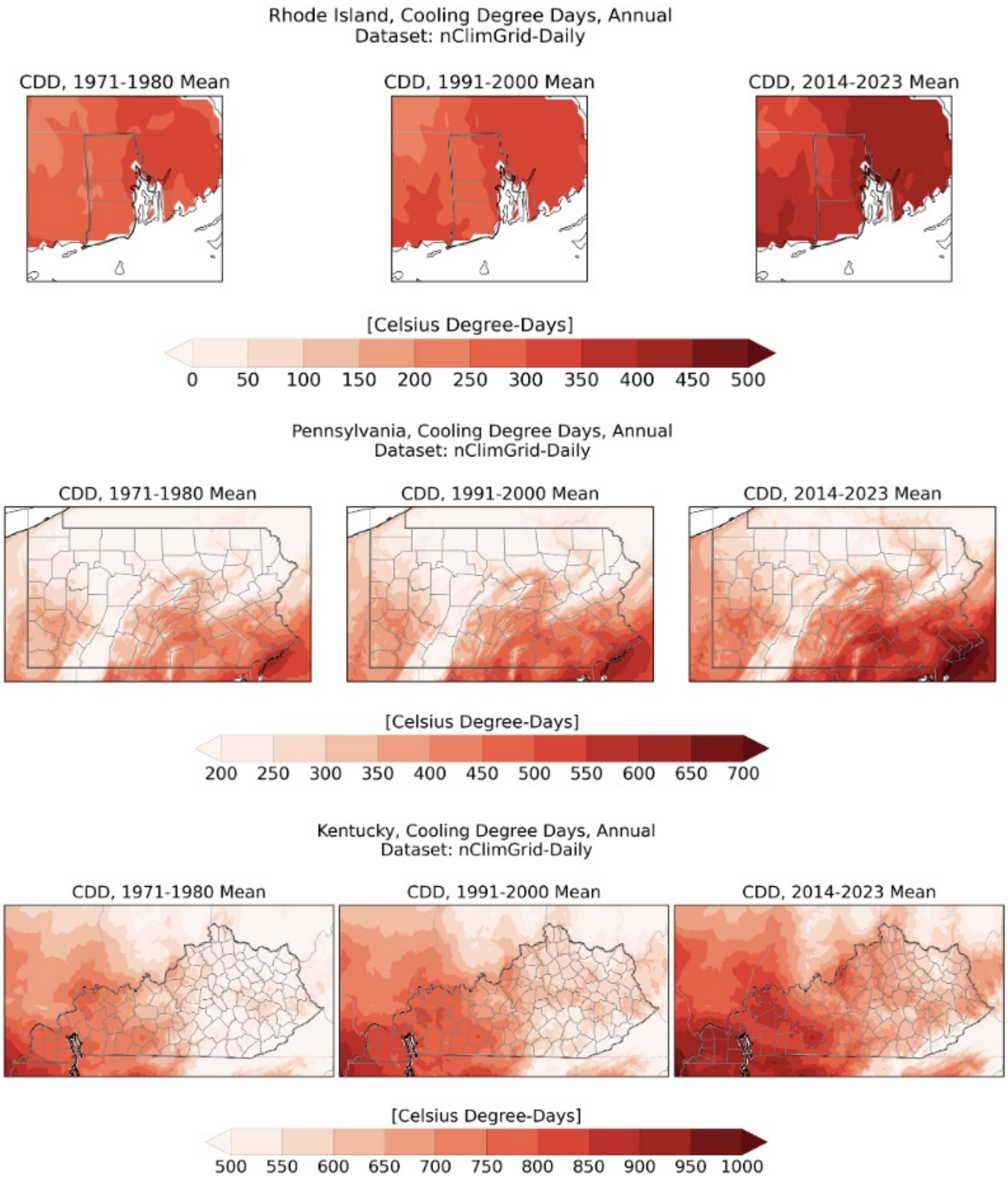

Figure 7: *Annual cooling degree days (threshold: 65˚F) for RI, PA, KY for three periods: 1971-1980, 1991-2000, 2011-2023. For a given state, CDD for three periods are plotted using the same color scale. Dataset: nClimGrid-Daily data.*

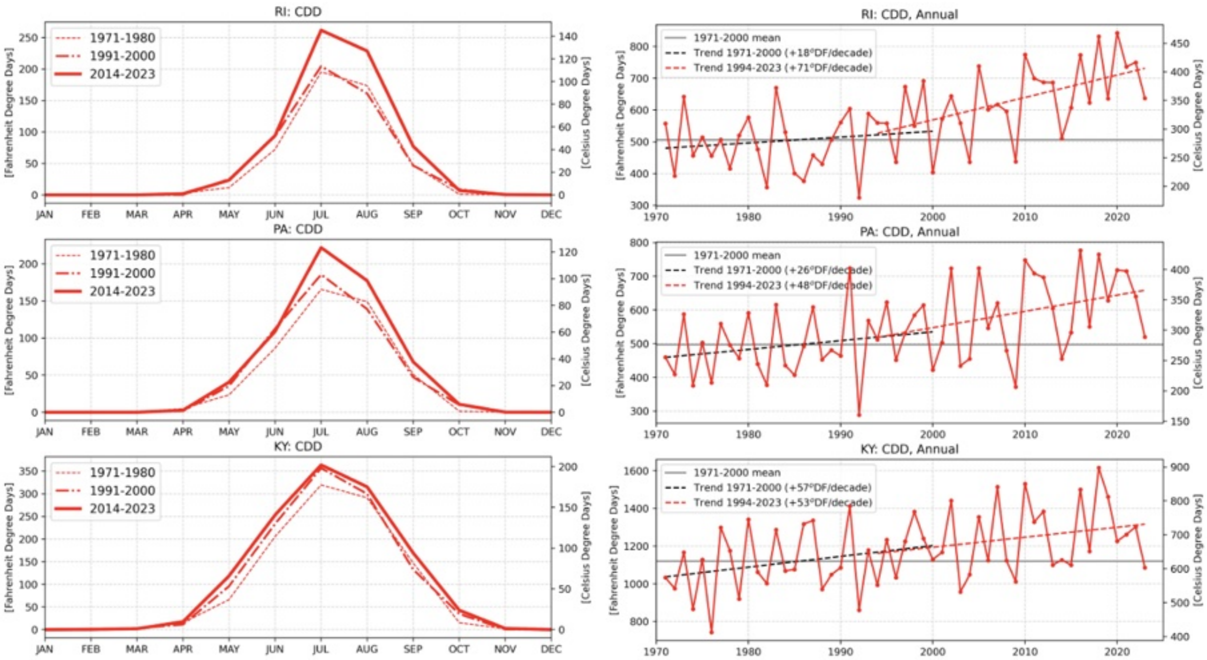

Figure 8: *Left: Annual cycle of cooling degree days (CDD; threshold: 65˚F) for RI, PA, KY for three decades: 19071-1980, 1991-2000, 2014-2023. Right: The dotted lines show linear trends for 1971-2000 (black) and for the last 30 years (1994-2023; red). Dataset: nClimGrid-Daily data.*

The contribution to annual CDD in the three states mainly comes from the months of May through September, as illustrated in the annual cycle of CDD in Fig. 8 (left column). These results describe an increase in CDD during the warm season, with no significant change in the shape of the annual cycle of CDD. The right column in Fig. 8 presents the CDD time series from 1971 to 2023. Recent decades have seen a faster rate of increase in CDD in RI and PA compared to the last 30 years of the 20th century, while KY has experienced an increase at a steady pace of about 55˚DF/decade (˚DF: Fahrenheit degree days).

Heating Degree Days (HDD)

To analyze changes in heating degree days (HDD), we compute the mean HDD for three decades: 1971-1980, 1991-2000, and 2014-2023. Figure 9 shows the decadal mean HDD for the three PPL states. The contribution to annual HDD in the three states mainly comes from the cold season, months of November through March. A decrease in HDD as the time progresses is noted in all three states. There are notable spatial variations in HDD. Annual HDD are generally higher in the mountainous and northern parts of the study region, while they are lower in the low-elevation and coastal regions of the three states. The right column in Fig. 10 presents the HDD time series from 1971 to 2023. A steady decrease in HDD in all three states is expected due to warming in winter months described earlier.

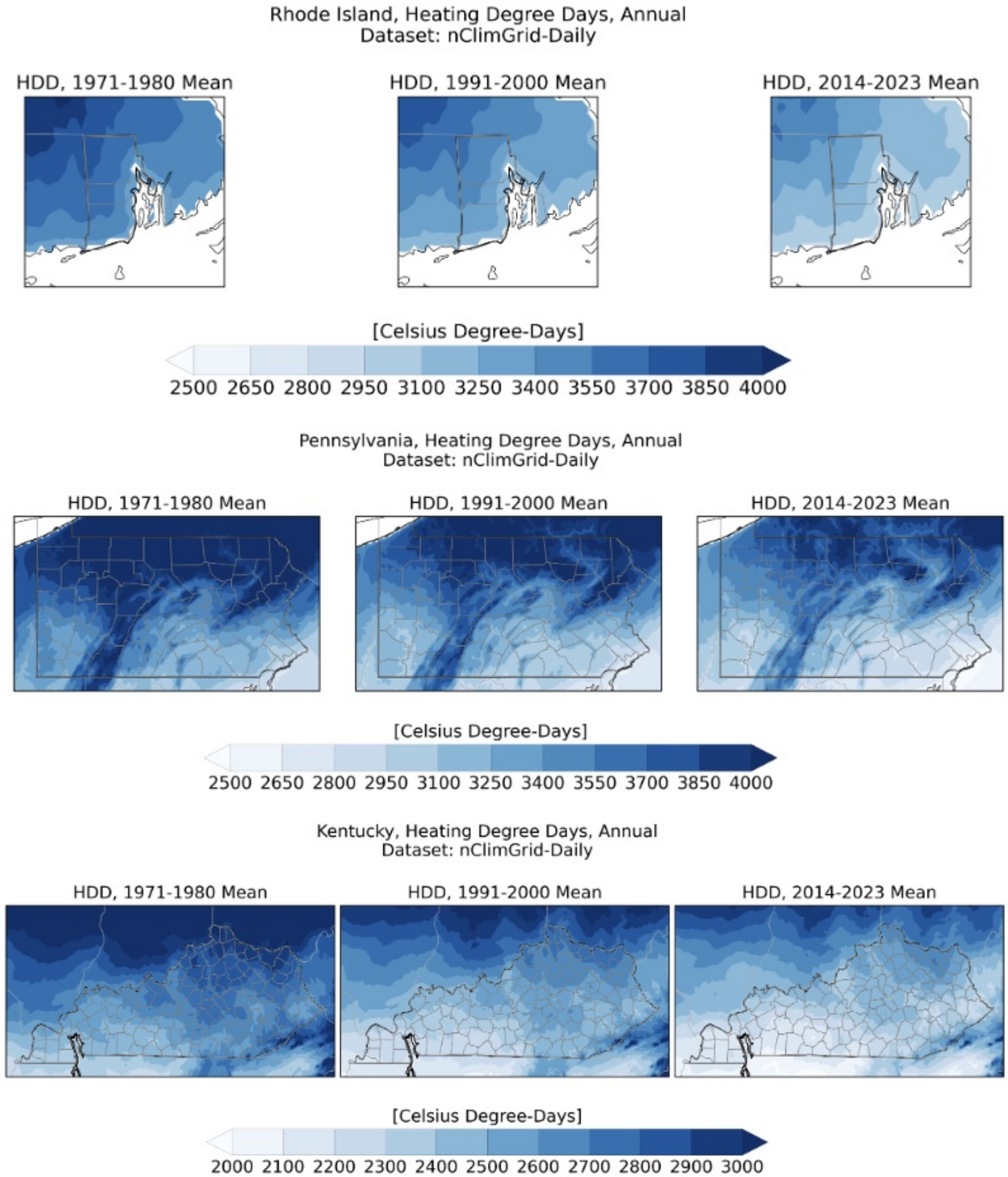

Figure 9: *Annual heating degree days (HDD; threshold: 65˚F) for RI, PA, KY for three periods: 1971-1980, 1991-2000, 2011-2023. For a given state, HDD for three periods are plotted using the same color scale. Dataset: nClimGrid-Daily data.*

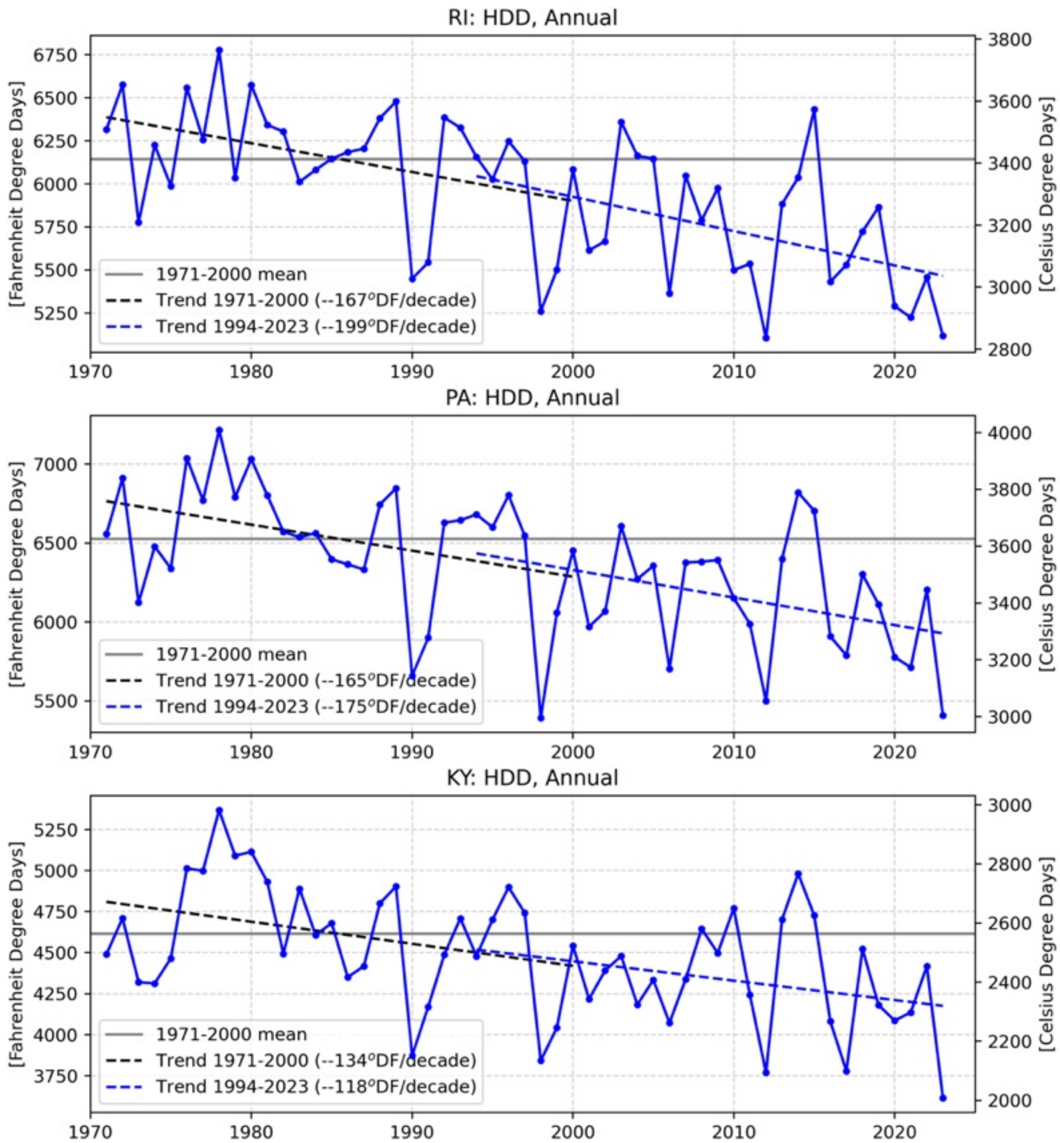

Figure 10: *Annual heating degree days (HDD; threshold: 65˚F) for RI, PA, KY. The dotted lines show linear trends for 1971-2000 (black) and for the last 30 years (1994-2023; red). Dataset: nClimGrid-Daily data.*

<u>Analysis of Minutely Temperature Data by Time of Day</u>

Analysis of higher-granularity, five-minute resolution data provided by NOAA weather stations in Versailles, KY, Kingston, RI, and Avondale, PA show how temperatures are changing not only by season but also by minute of the day. While NOAA's minutely data are only available from 2006 to 2024, and not available for the 1895 to 2024 timeframe that NOAA daily data are, the data nonetheless show significant climate change occurring within the past two decades particularly during winter in Kentucky, as shown in Figure 11 below, and during the summer in Rhode Island as shown in Figure 12 below. While warming during the past decade was apparent in most seasons and in most states, these two showed the most-obvious rate of warming in regions served by the PPL Corporation.

Figure 11 below shows that winter temperatures in Versailles, Kentucky are, on average, 3.23°F (1.79°C) warmer during just the past decade of 2015 to 2024, than they were in 2007 to 2014. A t-test reveals a statistically significant difference in the means at the $p < 2.2e\text{-}16$ level. The probability of observing temperature differences as extreme as these if the null hypothesis, that 2015 to 2023 was not warmer than 2007 to 2014, is less than 0.0000001. The warmest period of the day being just before 16:00 in the afternoon and the coldest period of the day being just before 08:00 in the morning. Both day and night winter temperatures have warmed in Kentucky during the past decade to a degree greater than what is seen in the other states served by the PPL Corporation. These seemingly small differences in temperature multiply by days to become significant reductions in heating degree days across winter seasons in Kentucky.

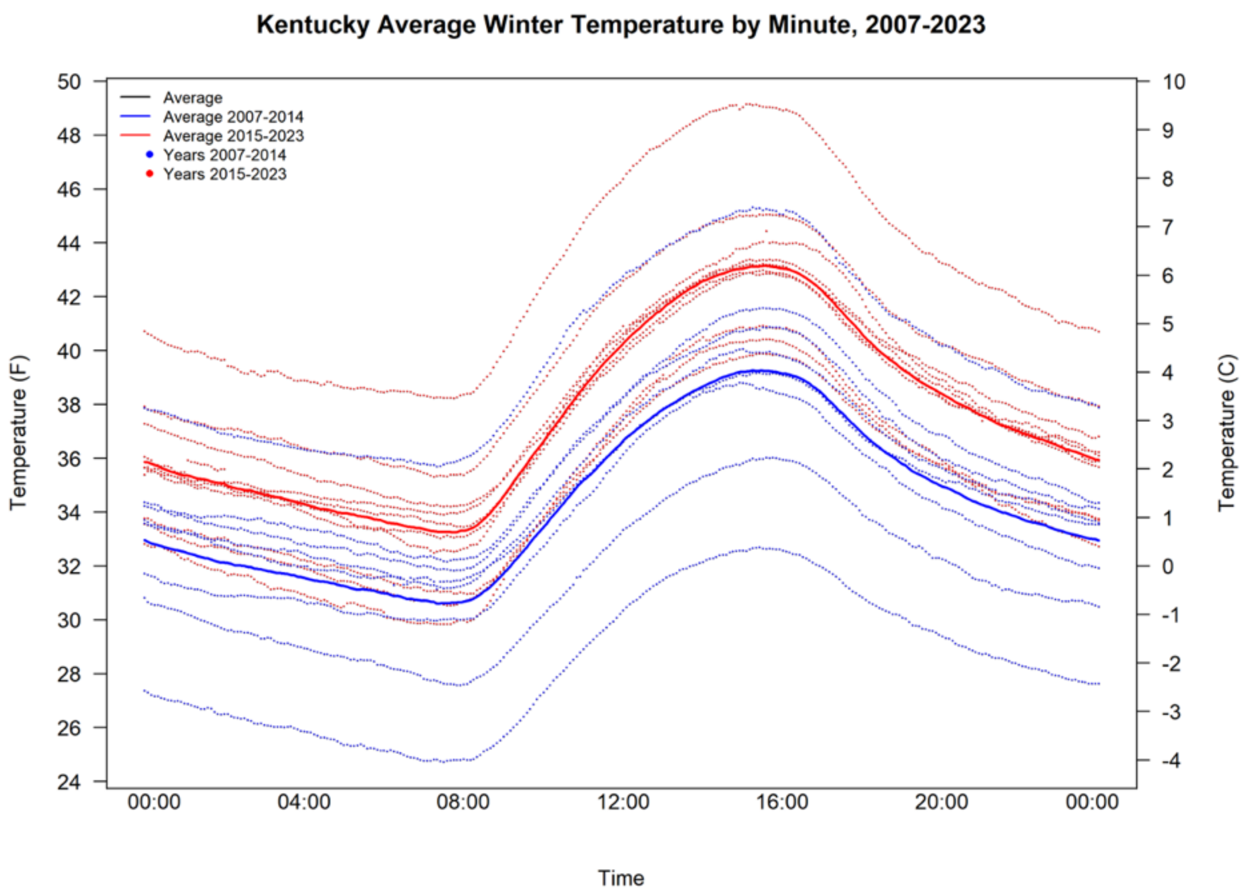

Figure 11: *Average winter (December, January, and February) minutely temperatures by time of day in Kentucky. The dotted blue lines show average annual minutely winter temperatures for years 2007-2014 in Kentucky and the dotted red lines show average annual minutely winter temperatures for 2015 to 2023 in Kentucky. The solid red line shows the average minutely winter temperature for the past decade, from 2015 to 2023, and the solid blue line shows the average minutely winter temperatures in Kentucky from 2007 to 2014.* All times are in Eastern Standard Time (EST). *Subhourly, 5-minute, data provided by NOAA National Climate Data Center*

(NCDC) from the U.S. Climate Reference Network / U.S. Regional Climate Reference Network (USCRN/USRCRN) weather station in Versailles, Kentucky, weather station number 63838, available online at: https://www1.ncdc.noaa.gov/pub/data/uscrn/products/subhourly01/

Figure 12 below shows that the average summer temperatures in Kingston, Rhode Island are, on average, 0.885°F (0.5°C) warmer during just the past decade of 2015 to 2023, than they were in 2006 to 2014 with the warmest period of the day being at 14:00 in the afternoon and the coldest period of the day being just before 05:00 in the morning. Both day and night summer temperatures in Rhode Island have warmed in the past decade. This small difference in temperature multiplies by days to become significant increases in cooling degree days each summer in Rhode Island.

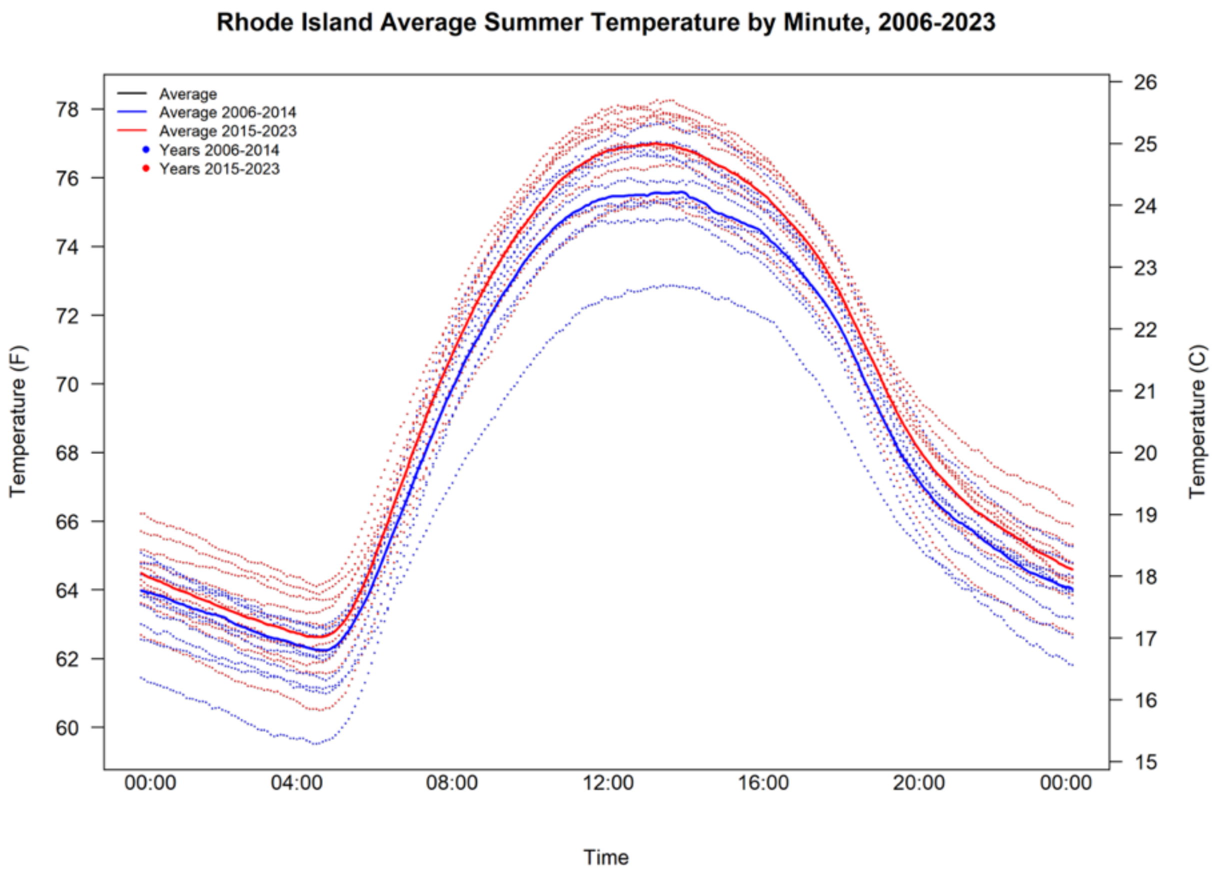

Figure 12: *Average winter (June, July, and August) minutely temperatures by time of day in Rhode Island. The dotted blue lines show average annual minutely summer temperatures for years 2007-2014 in Rhode Island and the dotted red lines show average annual minutely summer temperatures for 2015 to 2023 in Rhode Island. The solid red line shows the average minutely summer temperature for the past decade, from 2015 to 2023, and the solid blue line shows the average minutely summer temperatures in Rhode Island from 2007 to 2014.* All times are in Eastern Standard Time (EST). *Subhourly, 5-minute, data provided by NOAA National Climate Data Center (NCDC) from the U.S. Climate Reference Network / U.S. Regional Climate Reference Network (USCRN/USRCRN) weather station in Kingston, Rhode Island, weather*

station number 54796, available online at:
https://www1.ncdc.noaa.gov/pub/data/uscrn/products/subhourly01/

The histogram in Figure 13 below shows the difference between Kentucky the distribution of September minutely temperatures in 2006 to 2014 versus the distribution in 2015 to 2023. These data suggest that Septembers in Kentucky are becoming warmer and this once traditionally autumn month is becoming more like summer.

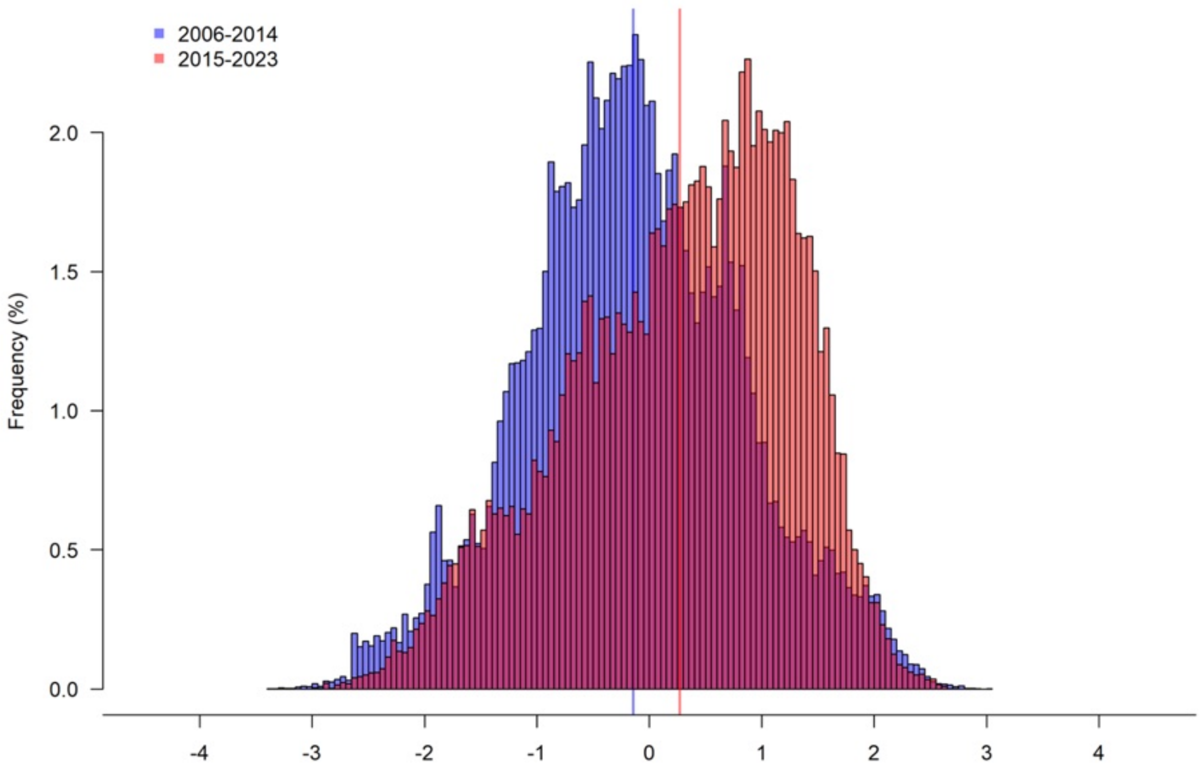

Figure 13: *Histogram showing distribution of minutely temperature anomalies in standard deviations from the mean for Versailles, Kentucky, with blue columns showing data collected from 2006 to 2014 and red columns showing data observed from 2015 to 2023. Subhourly, 5-minute, data provided by NOAA National Climate Data Center (NCDC) from the U.S. Climate Reference Network / U.S. Regional Climate Reference Network (USCRN/USRCRN) weather station in Versailles, Kentucky, weather station number 63838, available online at: https://www1.ncdc.noaa.gov/pub/data/uscrn/products/subhourly01/*

Key Findings

1. Average annual temperatures across all PPL states (KY, PA, RI) have increased since 1901. The magnitude of change differs among states, among geographical regions within each state, and across different seasons. In general, the total warming since 1901 is highest in Rhode Island at 4.2˚F (2.3˚C), followed by Pennsylvania at 2.2˚F (1.2˚C), and then Kentucky at 0.83˚F (0.5˚C).

2. The *rate* of increase in average annual temperature across all PPL states is higher over the last three decades compared to the period since 1901. This suggests an accelerating rate of climate change.
3. The warming of PPL states in general is greatest in the winter and smallest in the summer, but with wide variations based on geographical regions within the states.
4. Distributions of average temperatures show significant warming shifts. For Rhode Island, in particular, the coldest temperature anomalies of the early 21st century are similar to the 20th-century average, underscoring the substantial warming the region has experienced. Despite differing rates of warming, these results highlight that a larger proportion of temperature anomalies now fall outside the range of 20th century variations across all regions.
5. Analyses show an increase in average annual cooling degree days (CDD) across all territories, with the most growth outside the mountainous regions. Recent decades have seen a faster rate of increase in CDD in RI and PA compared to the last 30 years of the 20th century, while KY has experienced an increase at a steady pace of increase.
6. There is a decrease in average annual heating degree days (HDD) for each territory.

Potential Implications for Public Utilities

Changing temperatures can be expected to affect utility customer energy requirements. Warming summers can be expected to increase demand for power and energy during hotter summer months, potentially increasing summer peak power and energy requirements and potentially requiring additional capital investments in transmission, distribution, and generation infrastructure. Higher summer temperatures also can result in derating of transmission line capacity during times when demand for electricity for air conditioning is highest, potentially requiring upgrades to certain distribution or transmission infrastructure. Conversely, warming winters can be expected to decrease total winter energy requirements, although we observed no reduction in winter extreme cold events.

One common practice in the utility industry is to use long-term, multi-decadal. historical temperature data to estimate normal average temperature for both near-term and long-term energy forecasting and integrated resource planning. However, by pooling all past years, this methodology could miss more recent trends of increasing temperature within the data, and thus, risks overestimating winter energy volumes and underestimating summer energy volumes. To address this limitation, some utilities have begun considering climate change within their forecasts, either through considering weather trend data directly in their forecasting or by using shorter and more recent time horizons that reflect the more recent higher average normal temperatures. Future research should consider how best to estimate future temperatures and future energy demand resulting from changing temperature trends.

Numerous factors besides temperature are also compounding energy demand in response to changes in temperature trends, including technological improvements in customer-sited appliances and buildings that change the energy intensity of customer responses to weather. Heating and air conditioning systems are dramatically more energy efficient today than they were in decades prior and customer buildings are also more energy efficient. The cost to customers of deploying more efficient technologies is also improving while the cost of energy has generally increased, which can be expected to increase energy price elasticity and change consumer energy demand. Further research is required to more fully evaluate these trends.

Conclusion and Need for Further Research

This report summarizes the historical temperature changes across states served by the PPL Corporation; including Kentucky, Pennsylvania, and Rhode Island. Since 1895, average annual temperature has risen in all PPL states, though the magnitude of this increase varies by states, region, and season. The rate of change is higher in recent decades for most temperature metrics relative to the twentieth century. The findings in this report and existing research on the subject point to the need for further research.

Future research should include a comprehensive regional analysis of weather and climate extremes, including the evaluation of a full suite of key variables—temperature, precipitation, humidity, wind speed. Climate science offers rich datasets, both observed and model-based, to assess how these variables evolve under various future conditions. Additional analysis is also required to analyze the implications of these changing climate trends on customer energy use and reliability of utility services.

References

Diamond, H. J., T. R. Karl, M. A. Palecki, C. B. Baker, J. E. Bell, R. D. Leeper, D. R. Easterling, J. H. Lawrimore, T. P. Meyers, M. R. Helfert, G. Goodge, and P. W. Thorne, 2013: U.S. Climate Reference Network after one decade of operations: status and assessment. Bull. Amer. Meteor. Soc., 94, 489-498. doi: 10.1175/BAMS-D-12-00170.1

Durre, I., A. Arguez, C. J. Schreck III, M. F. Squires, and R. S. Vose, 2022a: Daily high-resolution temperature and precipitation fields for the Contiguous United States from 1951 to Present. Journal of Atmospheric and Oceanic Technology, doi:10.1175/JTECH-D-22-0024.1

Durre, I., M. F. Squires, R. S. Vose, A. Arguez, W. S. Gross, J. R. Rennie, and C. J. Schreck, 2022b: NOAA's nClimGrid-Daily Version 1 – Daily gridded temperature and precipitation for the Contiguous United States since 1951. NOAA National Centers for Environmental Information, since 6 May 2022, doi:10.25921/c4gt-r169

Energy Information Administration (EIA) (2022a), Annual Energy Outlook 2022: Table 4. Residential Sector Key Indicators and Consumption. Accessed August 9 2024 from https://www.eia.gov/outlooks/aeo/data/browser/

Energy Information Administration (2022b). Annual Energy Outlook 2022: Table 5. Commercial Sector Key Indicators and Consumption. Accessed August 9 2024 from https://www.eia.gov/outlooks/aeo/data/browser/

Government Accountability Office (2022). Tennessee Valley Authority: Additional Steps are needed to better manage climate-related risks, GAO-23-105375, December 2022. https://www.gao.gov/products/gao-23-105375

Hansen, J., Sato, M., & Ruedy, R. (2012). Perception of climate change. *Proceedings of the National Academy of Sciences*, *109*(37), E2415-E2423. https://www.pnas.org/doi/abs/10.1073/pnas.1205276109

Homer, Juliet, Alan Cooke, Kamila Kazimierczuk, Rebecca Tapio, Julie Peacock, Abigail King (2023). Emerging Best Practices for Electric Utility Planning with Climate Variability: A Resource for Utilities and Regulators, Pacific Northwest National Laboratory PNNL-34304, May 2023.

Itron, (2022). 2022 Forecasting Benchmark Survey, October 27, 2022. https://na.itron.com/documents/d/asset-library-120736/itron2022annualenergysurvey

Karl, T., & Koss, W. J. (1984). Regional and national monthly, seasonal, and annual temperature weighted by area, 1895-1983.

LG&E and KU (2021). 2021 Integrated Resource Plan Volume III., accessed August 7 2024 from https://psc.ky.gov/pscecf/2021-00393/rick.lovekamp%40lge-ku.com/10192021013101/5-LGE_KU_2021_IRP_Volume_III.pdf

Madden, N, A Lewis, and M Davis (2013). Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature, *Environmental Research Letters*, vol. 8(3), July 2013. https://iopscience.iop.org/article/10.1088/1748-9326/8/3/035006

Mascioli, N. R., Previdi, M., Fiore, A. M., & Ting, M. (2017). Timing and seasonality of the United States 'warming hole'. Environmental Research Letters, 12(3), 034008.

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

Meehl, G. A., Arblaster, J. M., & Chung, C. T. (2015). Disappearance of the southeast US "warming hole" with the late 1990s transition of the Interdecadal Pacific Oscillation. Geophysical Research Letters, 42(13), 5564-5570.

Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: An overview of the Global Historical Climatology Network-Daily Database. Journal of Atmospheric and Oceanic Technology, 29, 897-910, doi:10.1175/JTECH-D-11-00103.1

Patrick Sullivan, Jesse Colman, Eric Kalendra (2015). Predicting the Response of Electricity Load to Climate Change, National Renewable Energy Laboratory, NREL/TP-6A20-64297, July 2015. https://www.nrel.gov/docs/fy15osti/64297.pdf

PJM Interconnection (2022). Guide for Determination of Bare Overhead Transmission Conductors", DMS #590159, December 2022. https://www.pjm.com/~/media/planning/design-engineering/maac-standards/bare-overhead-transmission-conductor-ratings.ashx

Sailor, David J., and J.R. Munoz (1997). Sensitivity of Electricity and Natural Gas Consumption to Climate in the U.S.A.—methodology and results for eight states. Energy 22:987–998. https://doi.org/10.1016/S0360-5442(97)00034-0

Septiani, R. W., Egan, C., Alkire, C., Patrick, A., Craver, V., & Akanda, A. S. Analysis of Climate Change Data across PPL Corporation Service Territories. https://web.uri.edu/akanda-lab/wp-content/uploads/sites/2184/PPL_URI_Climate_Change_Study_FINAL-1.pdf

USGCRP (2023). Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://nca2023.globalchange.gov/

Vose, R.S., Applequist, S., Durre, I., Menne, M.J., Williams, C.N., Fenimore, C., Gleason, K., Arndt, D. 2014a: Improved Historical Temperature and Precipitation Time Series For U.S. Climate Divisions Journal of Applied Meteorology and Climatology. DOI: 10.1175/JAMC-D-13-0248.1

Vose, R.S., Applequist, S., Squires, M., Durre, I., Menne, M.J., Williams, C.N., Fenimore, C., Gleason, K., and Arndt, D. 2014b: NOAA Monthly U.S. Climate Gridded Dataset (NClimGrid), Version 1. Continental United States. NOAA National Centers for Environmental Information. DOI: 10.7289/V5SX6B56

Supplementary Figures:

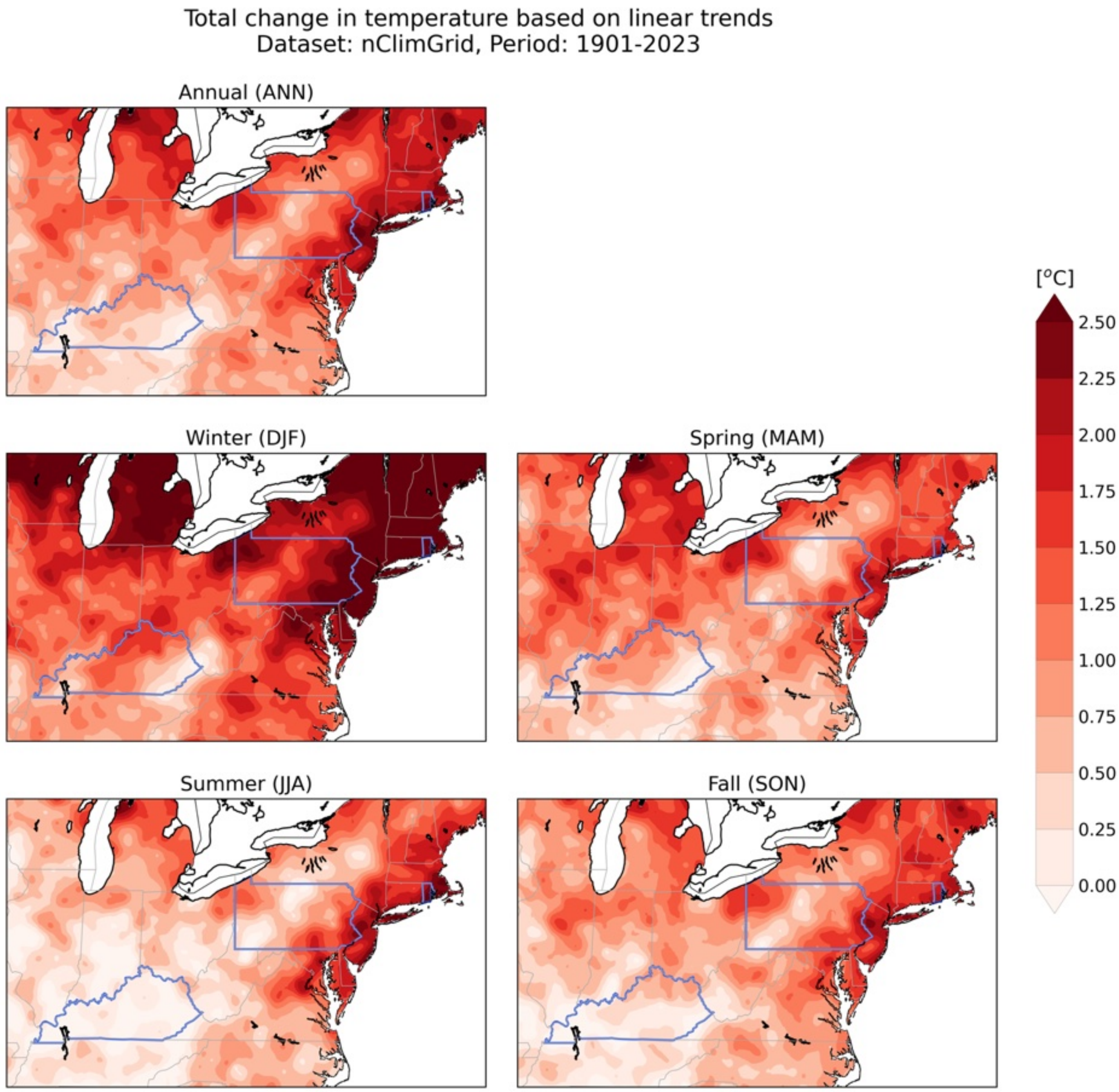

Figure caption: Changes in annual mean and seasonal mean surface air temperature (TAVG) for the period 1901-2023. The total change in ˚C are calculated based on linear trends. Dataset: nClimGrid monthly data.

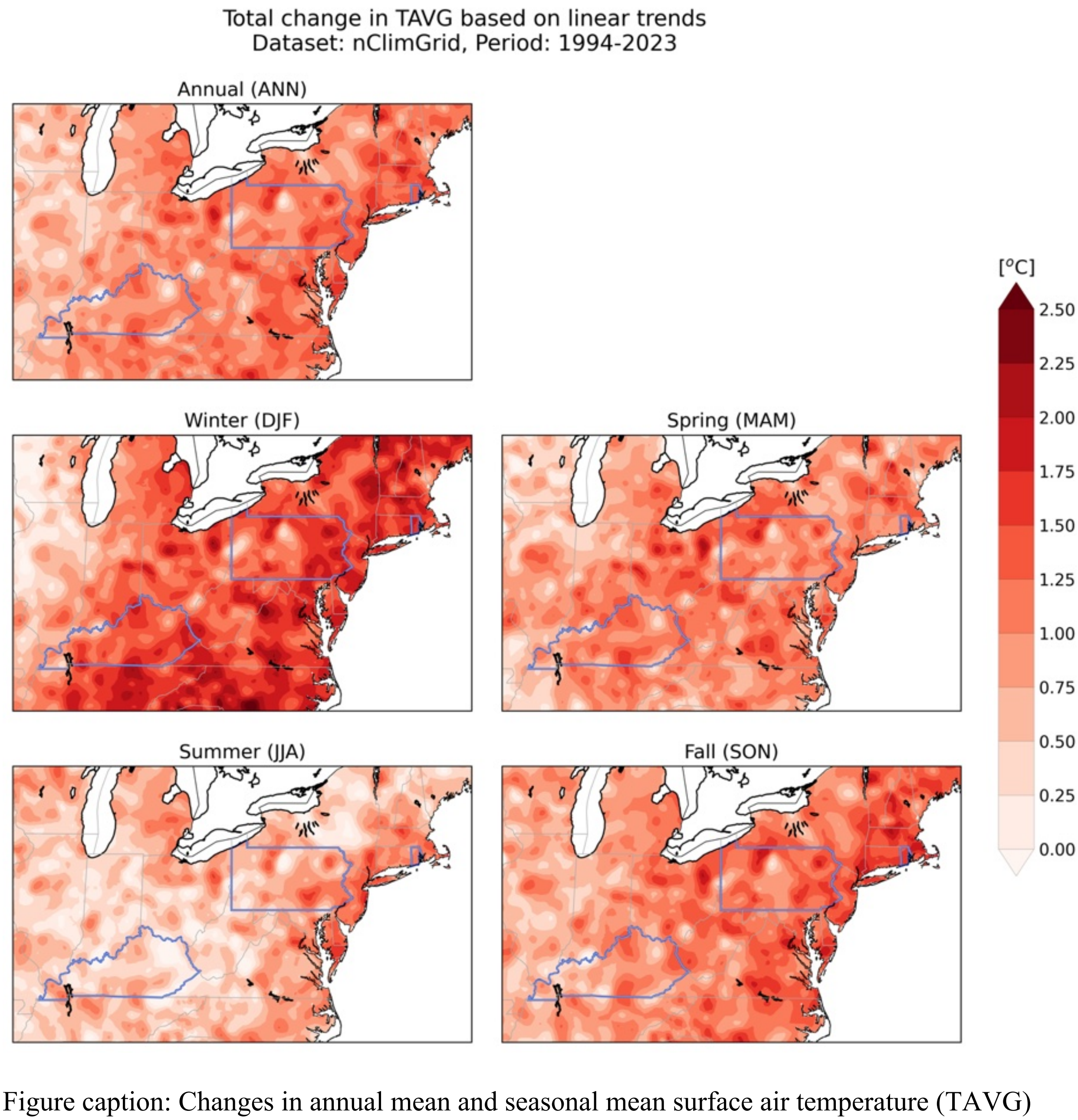

Figure caption: Changes in annual mean and seasonal mean surface air temperature (TAVG) over the last 30 years (1994-2023). The total change in ˚C are calculated based on linear trends. Dataset: nClimGrid monthly data.

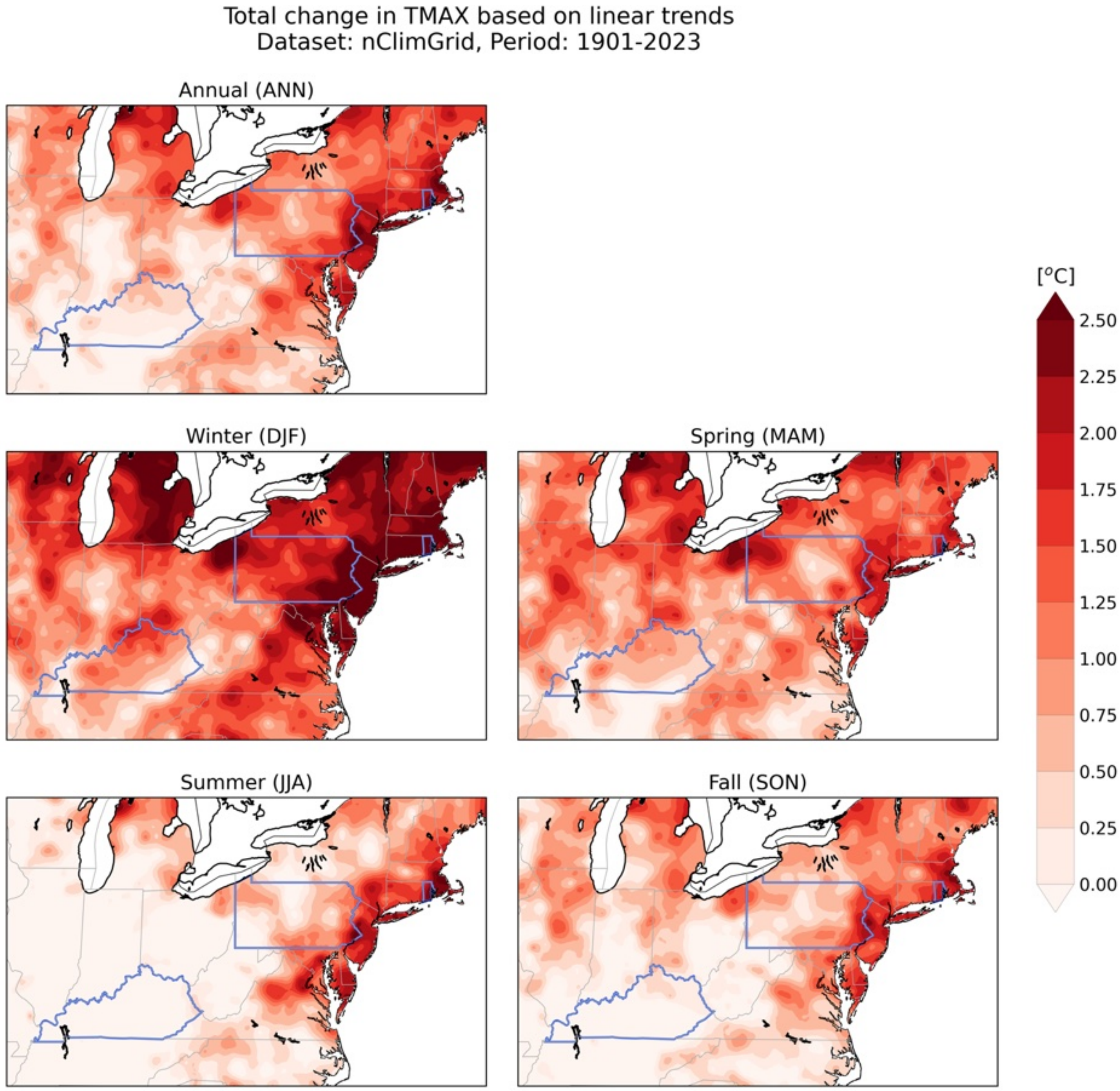

Figure caption: Changes in annual mean and seasonal maximum temperature (TMAX) for the period 1901-2023. The total change in ˚C are calculated based on linear trends. Dataset: nClimGrid monthly data.

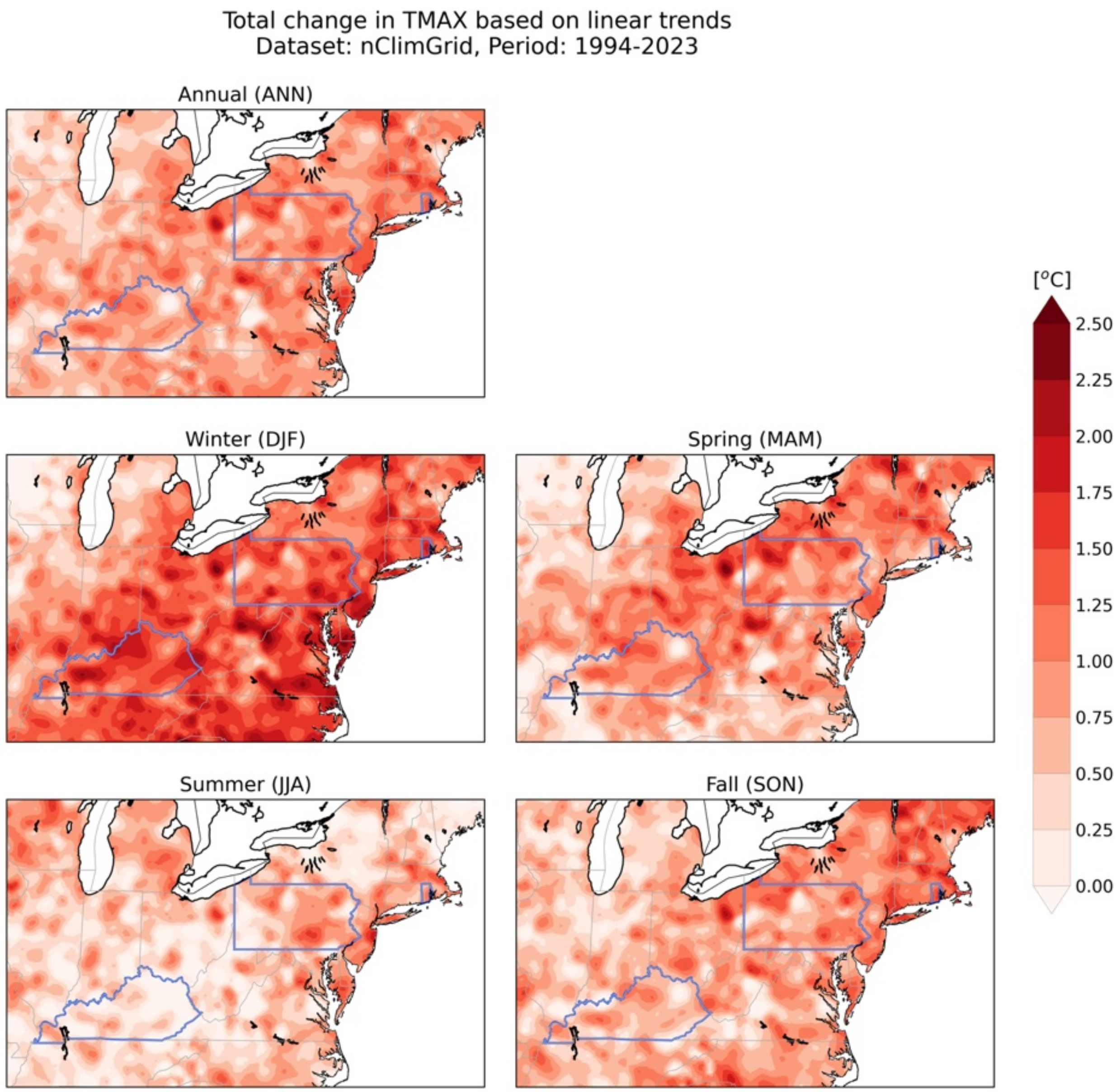

Figure caption: Changes in mean annual and seasonal maximum temperature (TMAX) over the last 30 years (1994-2023). The total change in ˚C are calculated based on linear trends. Dataset: nClimGrid monthly data.

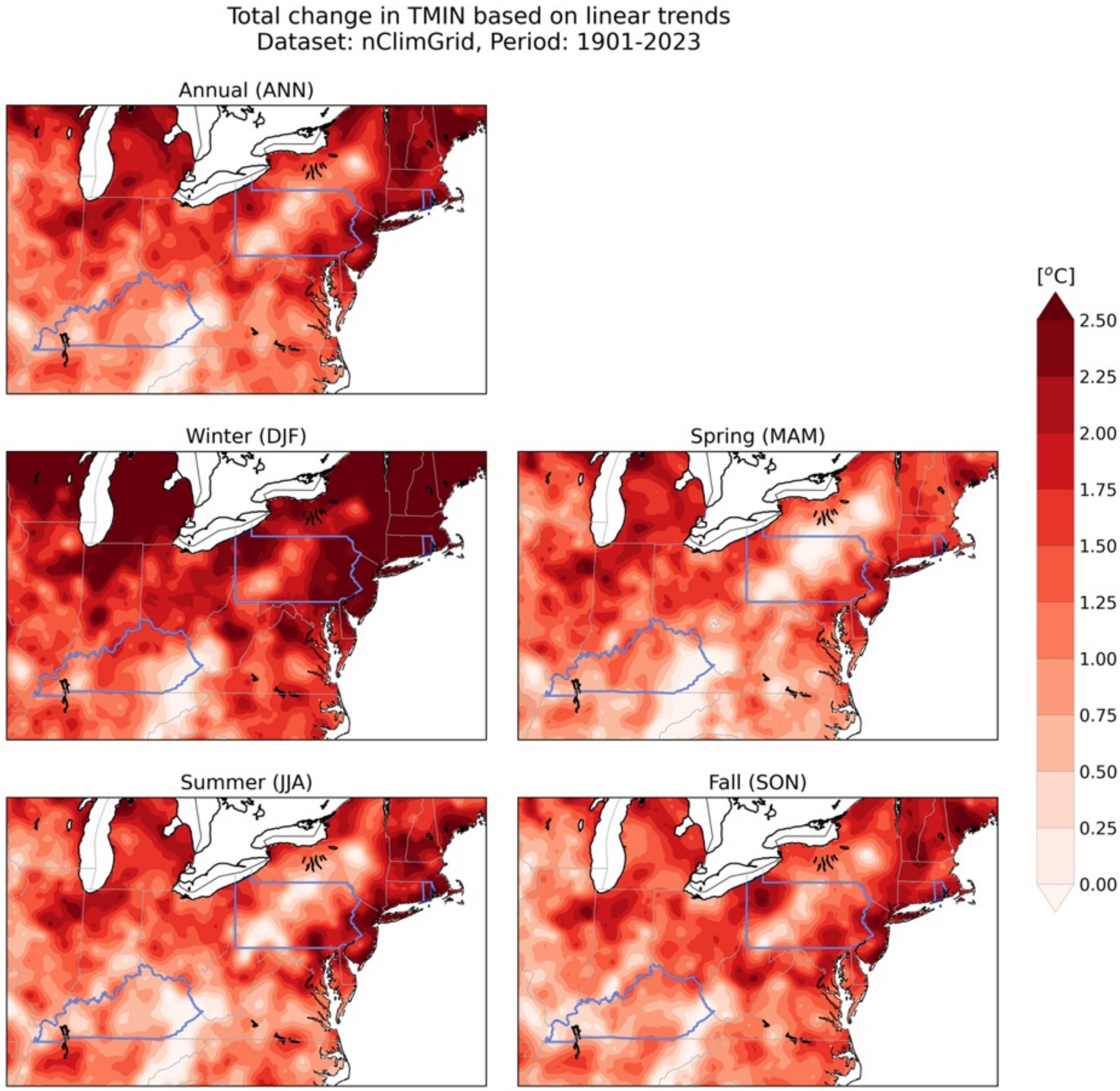

Figure caption: Changes in annual mean and seasonal minimum temperature (TMIN) for the period 1901-2023. The total change in ˚C are calculated based on linear trends. Dataset: nClimGrid monthly data.

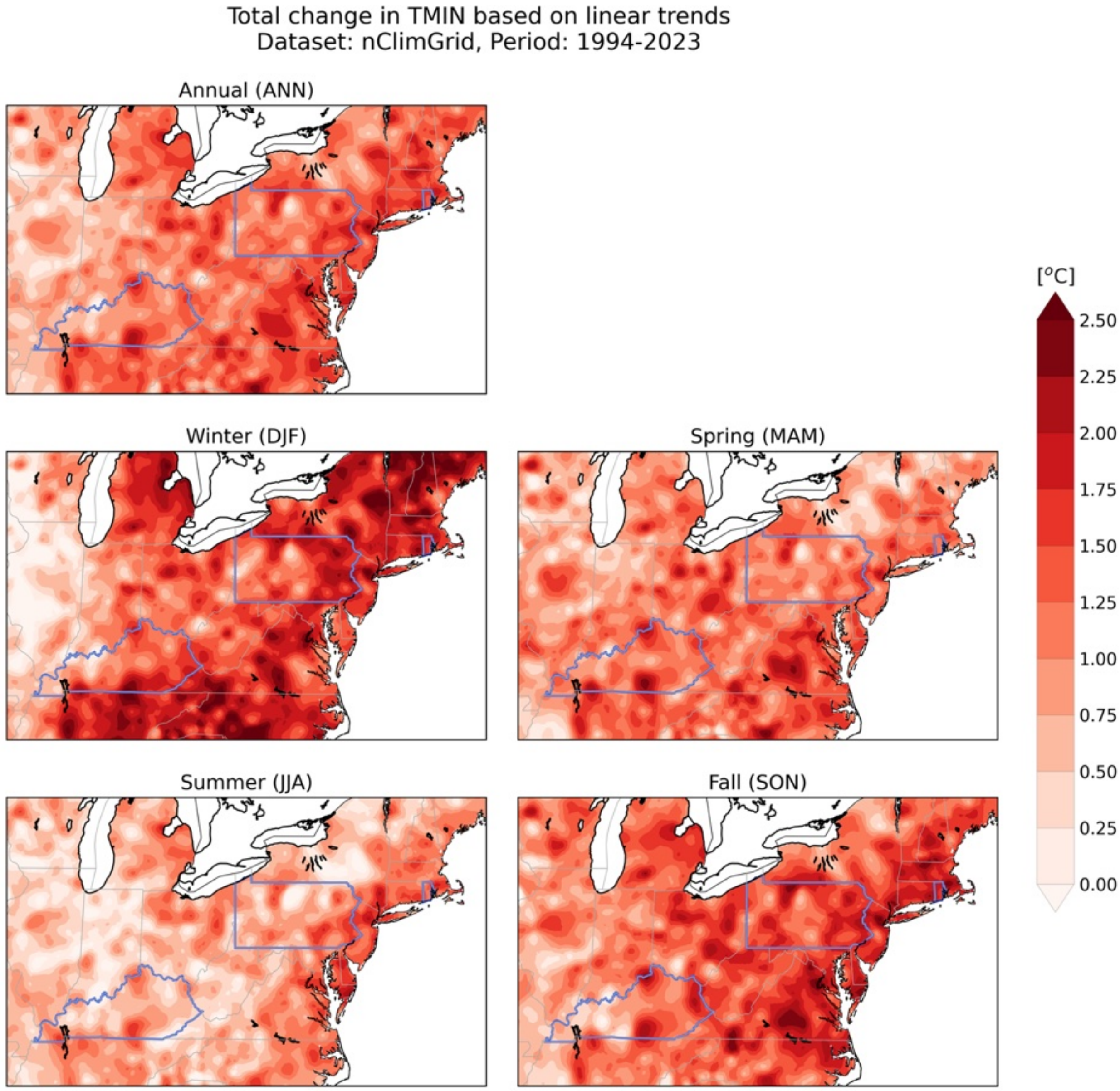

Figure caption: Changes in annual mean and seasonal minimum temperature (TMIN) over the last 30 years (1994-2023). The total change in ˚C are calculated based on linear trends. Dataset: nClimGrid monthly data.