A Record of Historical Temperature Change from 1893 to 2021, Southwest Ohio, United States of America

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ABSTRACT. A local record of historical temperature change from 1893 to 2021 was established for a region centered in southwest Ohio, United States. Temperature records were examined from 8 weather stations located in Ohio, Indiana, and Kentucky, all within a radius of 50 miles (approximately 80 km) from Miami University, Oxford, Ohio. Results indicate that annual minimum temperatures increased by approximately 0.11 °F (0.060 °C) per decade between 1893 to 2021, with a total increase of 1.4 °F (0.78 °C) over the 128-year study period ($p < 2 \times 10^{-16}$, $R^2 = 0.74$). Spring and summer minimum temperatures increased by 2.0 °F (1.1 °C) and 1.5 °F (0.83 °C) respectively, whereas fall and winter minimum temperatures increased by 1.1 °F (0.63 °C) and 0.77 °F (0.43 °C), respectively. Annual maximum temperatures increased by approximately 0.071 °F (0.039 °C) per decade, resulting in a total increase of 0.90 °F (0.50 °C) over the study period ($p < 2 \times 10^{-16}$, $R^2 = 0.74$). The largest observed increase in maximum temperatures occurred during the spring (1.7 °F; 0.94 °C), with fall (1.6 °F; 0.88 °C), and winter (1.6 °F; 0.88 °C) maximum temperatures increasing similarly. No change was observed in summer maximum temperatures. Historical temperature trends in the region studied broadly match state and regional temperature compilations for the lower Midwest, with greater warming occurring during spring and negligible warming in summer. This analysis indicates local datasets complement regional climate compilations and models, as well as help to identify geographic variation in temperature trends critical for assessing local vulnerabilities and informing regional mitigation strategies for climate change.

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INTRODUCTION

Global temperatures are increasing at an alarming rate. Since 1880, average global temperatures have increased by approximately 2.0 °F (1.1 °C) and the rate of warming has more than doubled since 1981 (Lindsey and Dahlman 2020). Rising temperatures have widespread impacts on various aspects of the climate system. In general, a warmer planet results in a more vigorous hydrologic cycle and enhanced precipitation globally (Easterling et al. 2017). In many regions this causes increases in extreme precipitation events (Ford et al. 2021) and results in intensified flooding (Mallakpour and Villarini 2015), but can also result in a higher frequency of droughts in other regions (Yuan et al. 2023). A warmer planet also causes an increase in evapotranspiration, which results in decreasing soil moisture (Grillakis 2019), reduced groundwater recharge, and a lowering of global lake levels (Yao et al. 2023). The pattern of global warming is not geographically uniform, with high latitudes and land masses warming at a greater rate than lower latitudes and water bodies (Hansen et al. 2006). For municipalities and organizations to adapt to climate change and mitigate impacts, a thorough understanding of past changes in climate at a local scale is needed.

In the contiguous United States, annual temperatures have increased by approximately 1.8 °F (1.0 °C) between 1895 and 2016 (Vose et al. 2017). This temperature increase displays spatial and seasonal variability, with high latitudes and winter months typically experiencing a higher degree of warming (e.g., Balling et al. 1998). State climate summaries report a wide range in temperature changes since the start of the 20th

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century for midwestern and adjacent states. Temperature increases for the eastern half of the Midwest range from approximately 0.60 °F to 3.0 °F (0.33 °C to 1.7 °C) (Fig. 1) (Frankson et al. 2022a; Frankson et al. 2022b; Frankson et al. 2022c; Frankson et al. 2022d; Frankson et al. 2022e; Runkle et al. 2022a; Runkle et al. 2022b). In general, the upper Midwest has experienced the greatest increase in temperature with Michigan and Wisconsin increasing by 3.0 °F and >2.0 °F (1.7 °C and >1.1 °C) respectively (Frankson et al. 2022b; Frankson et al. 2022e). States at lower latitudes in the eastern Midwest (Ohio, Illinois, and Indiana) experienced temperature increases of approximately 1.5 °F (0.84 °C) or greater (Frankson et al. 2022a; Frankson et al. 2022c; Frankson et al. 2022d). Kentucky has experienced a 0.60 °F (0.33 °C) temperature increase (Runkle et al. 2022b), whereas West Virginia warmed by approximately 1.0 °F (0.56 °C) since the early 20th century (Runkle et al. 2022a). Historical warming also shows spatial variability within individual states, especially in Ohio and Kentucky (Vose et al. 2017; Frankson et al. 2022a; Runkle et al. 2022b). Therefore, more localized climate assessments are needed to identify regional vulnerabilities and inform mitigation strategies.

Global warming, both historical and in the recent geologic past, is often characterized by seasonal variation in warming trends (Carré and Cheddadi 2017; Young and Young 2021). Analysis of historical warming trends have identified that winter temperatures are currently rising at the fastest rate on a global scale (Balling et al. 1998). This non-uniform change decreases seasonality and impacts the nature of precipitation patterns and other hydrologic processes (EPA 2021). On a more local scale, seasonal temperature changes can profoundly influence survival rates of pests and agricultural yields (Bindi and Olesen 2011), the spread of infectious diseases (e.g., Gray et al. 2009), and a wide range of ecosystems and ecosystem services (Scheffers et al. 2016).

Universities, municipalities, and city governments across the United States are developing and adopting climate change resilience plans to minimize the impacts of climate change on stakeholders (Woodruff and Stults 2016; Woodruff et al. 2022). In general, these plans assess threats climate change may pose to communities based on historical data and model predictions of local climates (Davoudi et al. 2009). The United States Climate Resilience Toolkit, an online portal operated by an inter-agency research group

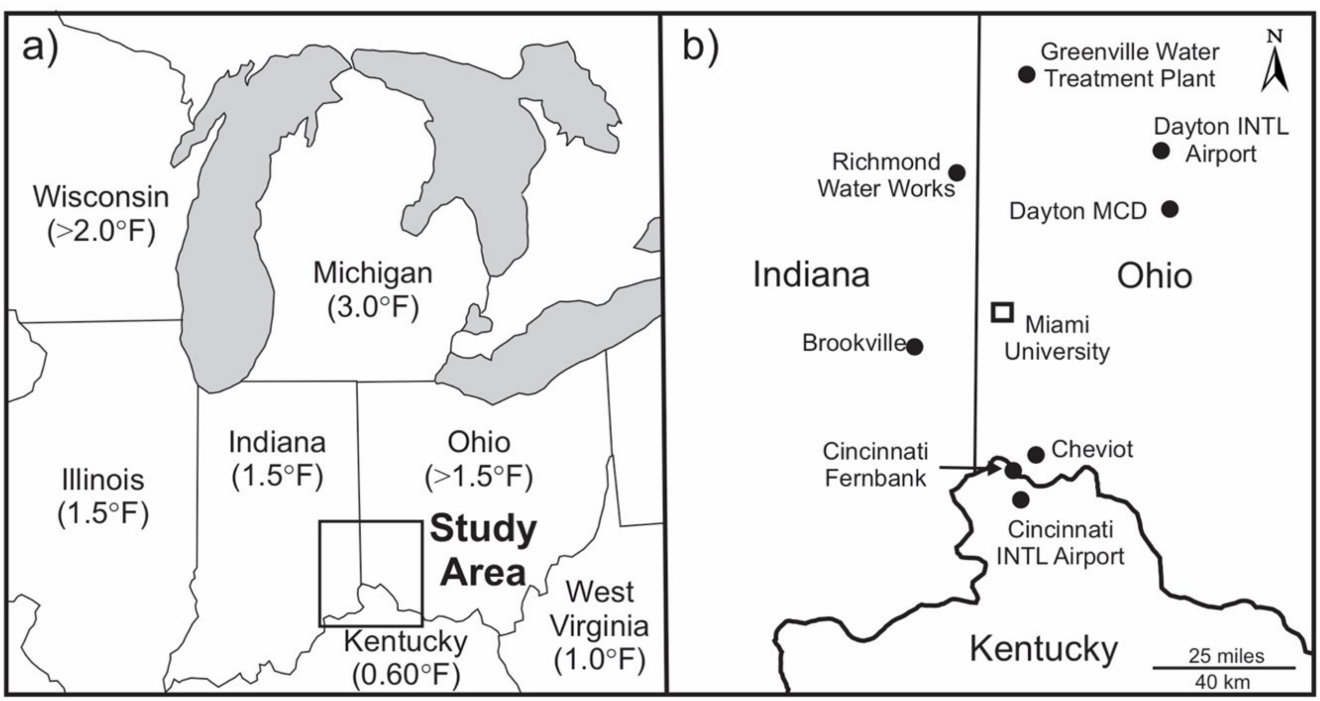

FIGURE 1. Location of the eastern Midwest and study area: a) the midwestern states of Wisconsin, Michigan, Illinois, Indiana, and Ohio, with the adjacent states of West Virginia and Kentucky. Temperature increases are reported by the NOAA State Climate Summaries (Frankson et al. 2022a; Frankson et al. 2022b; Frankson et al. 2022c; Frankson et al. 2022d; Frankson et al. 2022e; Runkle et al. 2022a; Runkle et al. 2022b). b) Study area centered in southwest Ohio and location of weather stations used in analysis.

and maintained by NOAA, includes a variety of resources to help organizations in the United States develop resilience plans (US Government 2014). Miami University's Climate Action Task Force used the Climate Explorer tool to determine if there were any changes in minimum or maximum daily temperatures on an annual and seasonal scale as recorded by local weather stations. Results of the current study are being used as the basis for the Miami University's Climate Resilience Assessment and its Climate Action Plan.

METHODS

Data Collection and Initial Processing

Each of the 8 weather stations selected for the study are within 50 miles (80 km) of Miami University and situated in the states of Ohio (OH), Indiana (IN), and Kentucky (KY), including the Greenville Water Treatment Plant (OH), Dayton International Airport (OH), Dayton Miami Conservancy District (OH), Cheviot (OH), Cincinnati Fernbank (OH), Richmond Water Works (IN), Brookville (IN), and Cincinnati/Northern Kentucky International Airport (CVG) (KY) (Fig. 1). This radius was selected to capture local trends with enough stations to limit bias from any single station. Data collection began at variable dates between 1893 and 1970 (Table 1). This region is referred to hereafter as "southwest Ohio" (Fig. 1).

Data Analyses and Generation of Models

Daily records of minimum and maximum temperatures from each weather station were retrieved from Climate Explorer, a tool in the U.S. Climate Action Toolkit (US Government 2014). The daily maximum and minimum recorded temperatures from each weather station were averaged, resulting in 2 spatially-averaged observations (maximum and minimum) for each day between 1893 and 2021. This analyses used an astronomical definition of season, which uses the timing of solstices and equinoxes to determine the boundaries between seasons. There were 24 days throughout the 128-year study period, all prior to 1914, without temperature records from any of the stations. The largest range in maximum temperatures between stations on a single day is 50 °F (28 °C) and the largest range in minimum temperatures between stations on a single day is 44 °F (24 °C). Days with inter-station variation in minimum or maximum temperatures greater than 20 °F (11 °C) were removed from the dataset as a 20 °F (11 °C) difference in minimum or maximum temperature within 50 mi (80 km) is unlikely. Details regarding the removal of observations are outlined in Appendix A.

Preliminary time series and seasonal and trend decomposition using Loess (STL) analyses were conducted (Appendix B), but this required imputation for days with no temperature observations (Afrifa-Yamoah et al. 2019). As regression analysis does not require imputation for days with missing observations, the decision was made to move forward with this method of analysis. Multiple linear regression models were created to quantify trends in daily minimum and maximum temperatures over the study period. Several

Table 1
Station location

Station	State	Latitude	Longitude	Starting year
Greenville Water Treatment Plant	Ohio	40.1000°	-84.6500°	1893
Dayton MCD	Ohio	39.7633°	-84.1911°	1893
Brookville	Indiana	39.4239°	-85.0144°	1925
Dayton International Airport	Ohio	39.9061°	-84.2186°	1935
CVG International Airport	Kentucky	39.0444°	-84.6724°	1947
Cincinnati Fernbank	Ohio	39.1169°	-84.6961°	1950
Richmond Water Works	Indiana	39.8544°	-84.8779°	1968
Cheviot	Ohio	39.1547°	-84.6233°	1970

regression models were constructed to quantify trends in maximum and minimum temperatures on both an annual and seasonal scale. In each case, models used the year and, separately, the month, of the temperature records as predicator variables. Using the temperature record year as the predictor allowed the determination of trends over time, whereas using the temperature record month as the predictor helped account for natural seasonal variability in temperature. Total temperature changes were calculated for each model by multiplying the slope of the regression equation by the number of years in the study.

RESULTS

Minimum temperatures averaged between weather stations centered in southwest Ohio increased by approximately 0.11 °F (0.060 °C) per decade between 1893 to 2021, with a total increase of 1.4 °F (0.78 °C) ($p < 2 \times 10^{-16}$, $R^2 = 0.74$) (Table 2; Fig. 2). Spring had the largest increase in minimum temperatures with a total increase of 2.0 °F (1.1 °C) over the entire study period, at a rate of 0.16 °F (0.089 °C) per decade ($p = 0.027$, $R^2 = 0.49$) (Table 2; Fig. 3). Summer minimum temperatures increased at a rate of 0.11 °F (0.063 °C) per decade with an overall increase of 1.5 °F (0.83 °C) ($p = 6.9 \times 10^{-13}$, $R^2 = 0.15$)

Table 2
Average minimum temperatures

	Trend		Δ Temp (1893-2021)			
Season	**(°F/decade)**	**(°C/decade)**	**(°F)**	**(°C)**	***p* value**	**R^2**
Annual	0.11	0.060	1.4	0.78	$< 2 \times 10^{-16}$	0.74
Spring	0.16	0.089	2.0	1.1	0.027	0.49
Summer	0.11	0.063	1.5	0.83	6.9×10^{-13}	0.15
Fall	0.089	0.050	1.1	0.63	2.70E-04	0.42
Winter	0.060	0.034	0.77	0.43	0.046	0.07

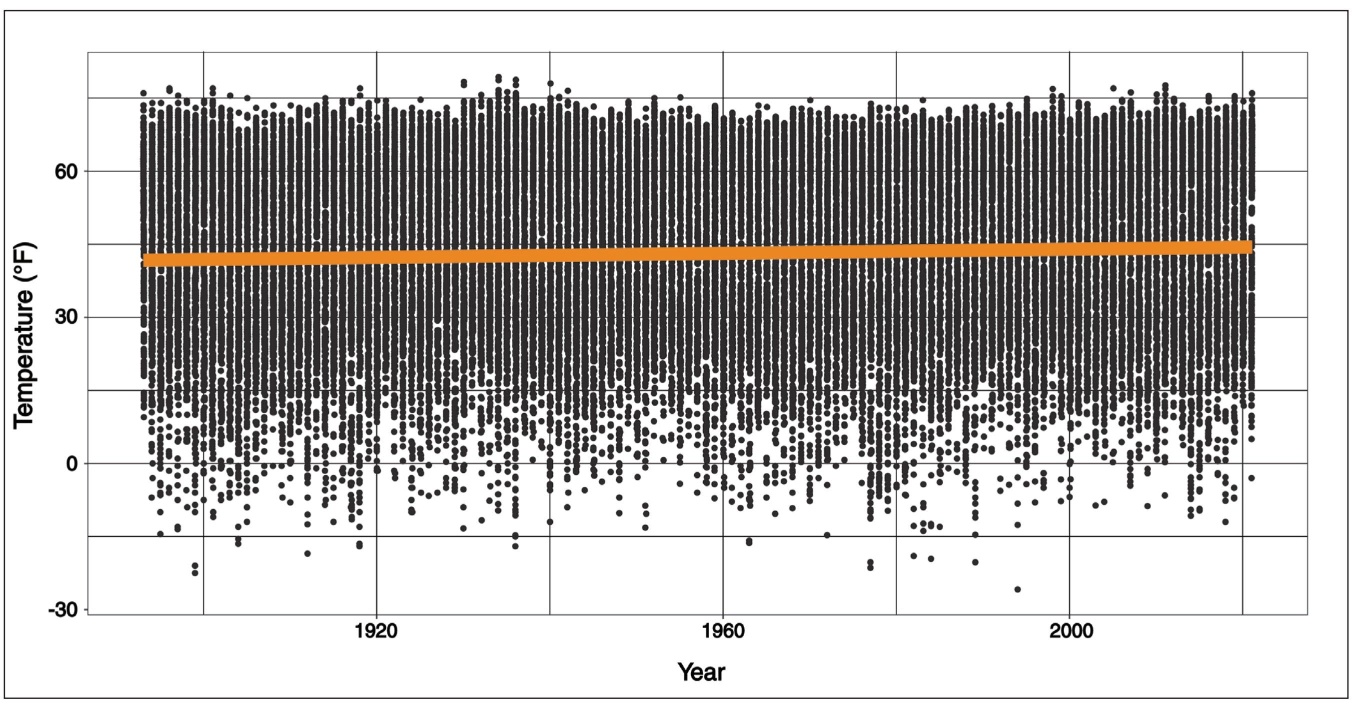

FIGURE 2. Daily average minimum temperature observations with linear regression least-square line (orange) plotted using year as the predictor

(Table 2; Fig. 3). Fall minimum temperatures increased 0.089 °F (0.050 °C) per decade, with an overall increase of 1.1 °F (0.63 °C) between 1893 and 2021 ($p = 2.7 \times 10^{-4}$, $R^2 = 0.42$) (Table 2; Fig. 3). Winter minimum temperatures increased the least, with a rate of change of 0.060 °F (0.034 °C) per decade resulting in a total increase of 0.77 °F (0.43 °C) over the study period ($p = 0.046$, $R^2 = 0.07$) (Table 2; Fig. 3). Over the course of the study, spring and summer minimum temperatures increased more than fall and winter.

Annual maximum temperatures increased less than annual minimum temperatures (Table 3). Annual maximum temperatures increased 0.071 °F (0.039 °C) per decade, resulting in a total increase of 0.90 °F (0.50 °C) over the study period ($p < 2 \times 10^{-16}$, $R^2 = 0.74$) (Table 3; Fig. 4). Spring maximum temperatures increased 1.7 °F (0.94 °C) from 1893 to 2021 at a rate of 0.14 °F (0.075 °C) per decade, the largest observed seasonal increase in maximum temperatures ($p = 2.3 \times 10^{-8}$, $R^2 = 0.44$) (Table 3; Fig. 5). Fall and winter maximum temperatures both increased 0.13 °F (0.071 °C) per decade, resulting in an increase of 1.6 °F (0.88 °C) over the study period for fall ($p = 1.03 \times 10^{-6}$, $R^2 = 0.53$) and winter ($p = 1.41 \times 10^{-5}$, $R^2 = 0.12$) maximum temperatures (Table 3; Fig. 5). There was no statistically significant change in summer maximum temperatures ($p = 0.81$) (Table 3; Fig. 5).

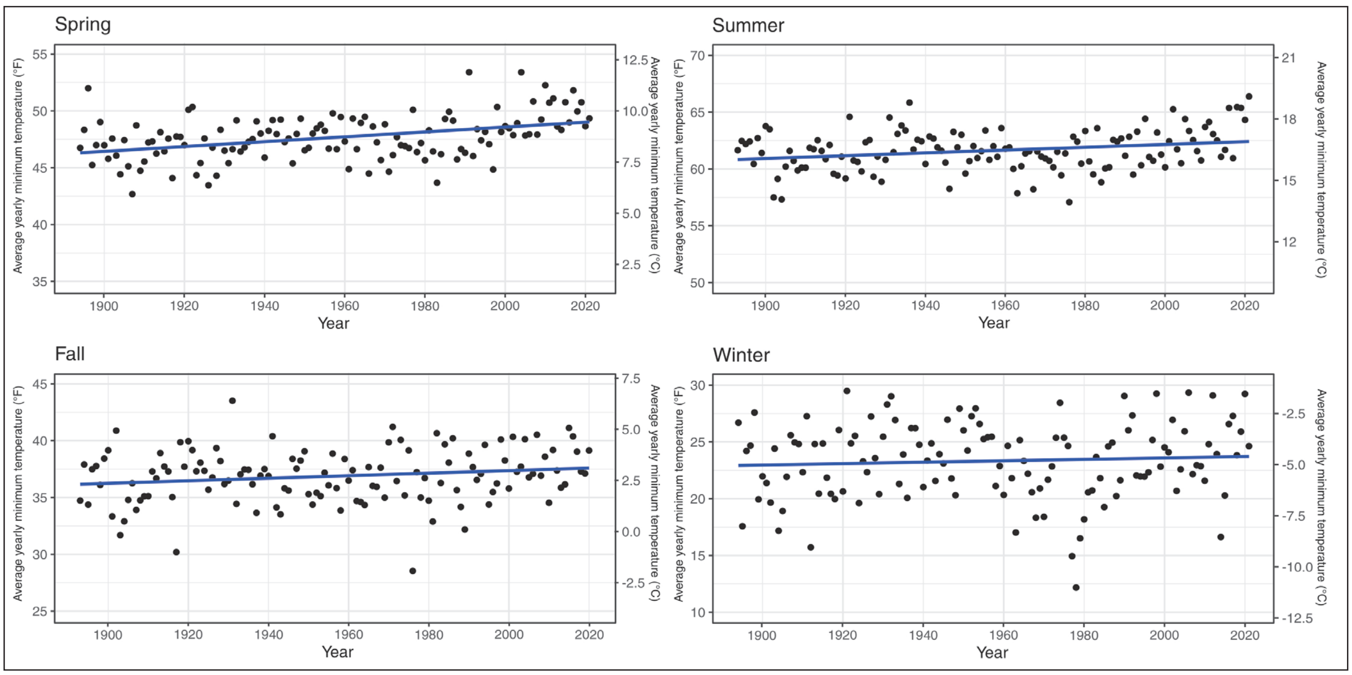

FIGURE 3. Minimum temperatures averaged between weather stations to get a daily spatial average, then averaged temporally to get an annual value for each season with linear regression least-square line plotted (blue)

Table 3
Average maximum temperatures

	Trend		Δ Temp (1893-2021)			
Season	**(°F/decade)**	**(°C/decade)**	**(°F)**	**(°C)**	***p* value**	**R^2**
Annual	0.071	0.039	0.90	0.50	$< 2 \times 10^{-16}$	0.74
Spring	0.14	0.075	1.7	0.94	2.3×10^{-8}	0.44
Summer	NA		NA		0.81	0.11
Fall	0.13	0.071	1.6	0.88	1.03×10^{-6}	0.53
Winter	0.13	0.071	1.6	0.88	1.41×10^{-5}	0.12

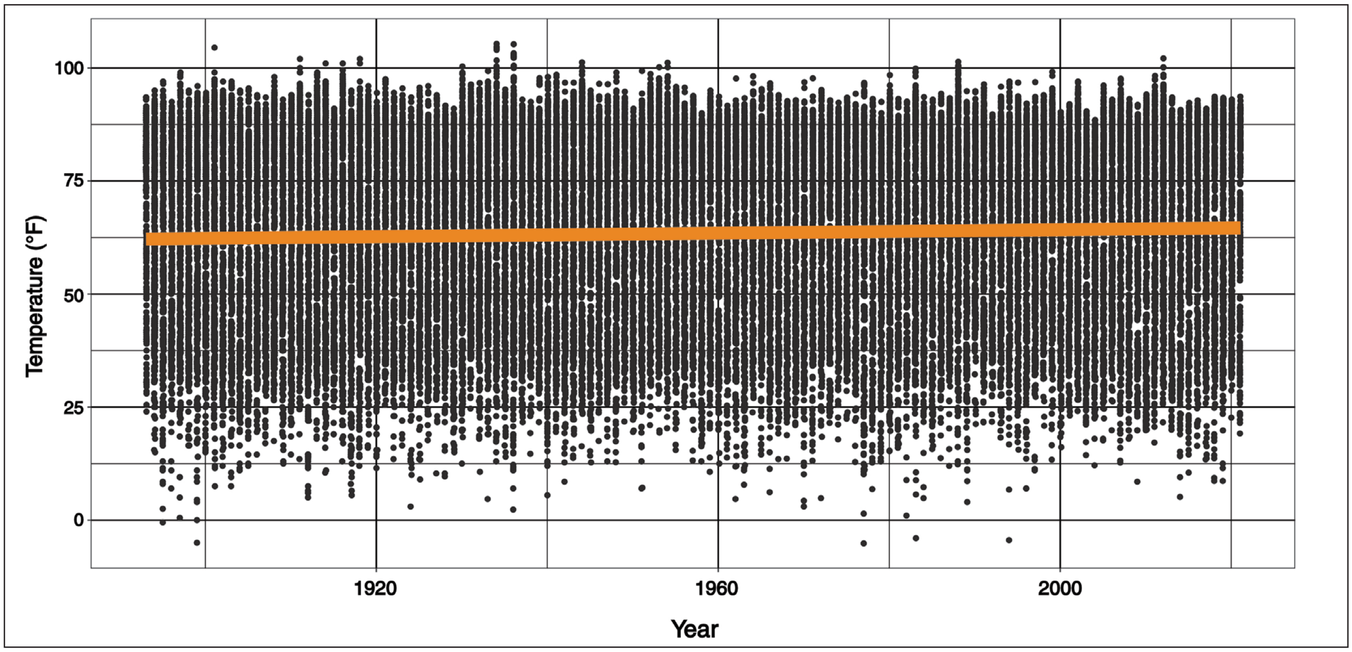

FIGURE 4. Daily average maximum temperature observations with linear least-square regression line (orange) plotted using year as the predictor

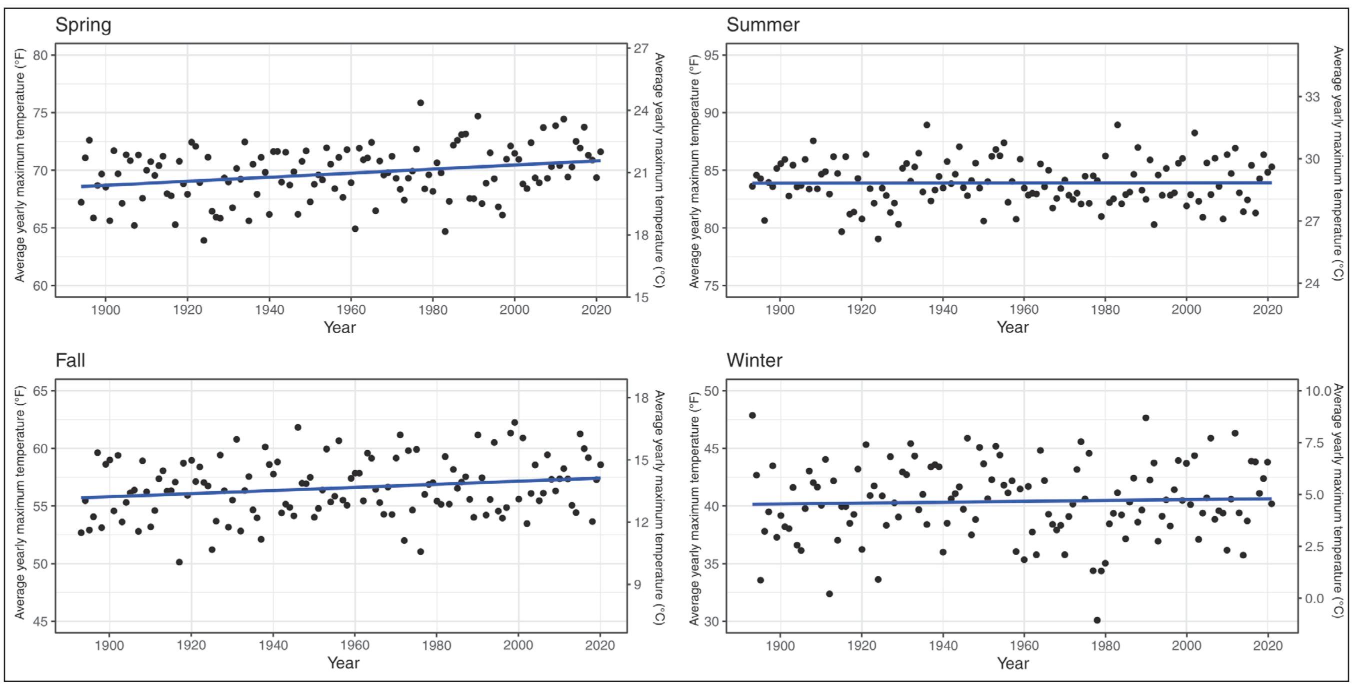

FIGURE 5. Maximum temperatures averaged between weather stations to get a daily spatial average, then averaged temporally to get an annual value for each season with linear regression least-square line plotted (blue)

DISCUSSION

The slope of the regression equations represents trends in temperature change. There is strong evidence ($p < 0.001$) of warming trends in average annual minimum and maximum temperatures in southwest Ohio from 1893 to 2021 (Table 2 and Table 3). There is moderate ($p < 0.05$) to strong ($p < 0.001$) evidence that seasonal minimum temperatures increased in all seasons over the study period, with the greatest rate of increase in spring and the lowest in winter. There is also strong evidence ($p < 0.001$) that seasonal maximum temperatures increased between 1893 and 2021 in spring, fall, and winter, but there is no evidence of an increase in summer. The rate at which the maximum temperatures increased also varied by season, being slightly greater in spring than in fall, and least in winter.

In southwest Ohio between 1893 and 2021, the annual minimum temperatures increased by approximately 0.11 °F (0.060 °C) per decade, a faster rate of change than the annual maximum temperatures, which increased 0.071 °F (0.039 °C) per decade. Similar relationships have been identified across the country. The Midwest has been identified as the region in the contingent United States with the greatest difference between the annual minimum and maximum temperature rates of warming (Vose et al. 2017). In agreement with annual trends identified in the entire Midwest by Vose et al. (2017) and Basso et al. (2021), the summer minimum temperatures in southwest Ohio increased between 1893 and 2021, while the summer maximum temperatures did not significantly change. The lack of a trend in summer maximum temperatures reported here is not in agreement with the regional trend of decreasing summer maximum temperatures in the Midwest identified by Mueller et al. (2016). Our results also show larger increases in winter minimum temperatures compared to winter maximum temperatures, in agreement with relationships identified for annual temperatures for the entire Midwest (Vose et al. 2017). Contrary to annual trends identified for the entire Midwest (Vose et al. 2017), however, results from the current study show that spring and fall maximum temperatures increased more than minimum temperatures. Additionally, rates of warming in the winter in southwest Ohio were not historically faster than in the other seasons, a deviation from the global pattern (Balling et al. 1998). These differences highlight the need to analyze temperature trends on a more local scale when assessing vulnerabilities and informing climate action plans.

Removing days with temperature ranges between stations greater than 20 °F (11 °C) from the dataset had a larger impact on the annual maximum temperature trend compared to the annual minimum temperature trend. Annual maximum temperatures increased 1.2 °F (0.67 °C) between 1893 and 2021 when these days were included and 0.90 °F (0.50 °C) when they were excluded. Annual minimum temperatures increased 1.3 °F (0.72 °C) over the study period when these days were included and 1.4 °F (0.78 °C) when they were excluded.

The analysis of historical changes in temperature at the local level is important for developing climate resilience assessments and climate action plans. Typically, climate forecasts address broad regions and have large uncertainty, making them difficult for local stakeholders to use when creating climate action plans. Analyses of local changes in historical climate are needed to understand and prepare for regional manifestations of climate change, as well as to inform predictions of future climate that often do not include seasonal trends or changes in daily minimum and maximum temperatures.

Seasonal changes in minimum and maximum temperatures are important for many stakeholders, especially in southwest Ohio where crops can be affected by seasonal changes in temperature, temperature extremes, and soil moisture. Analysis of climate trends from locations known to stakeholders can also be a powerful tool for convincing local constituents that climate is changing.

Results from the current study are being used in conjunction with climate projections for the region (Vose et al. 2017) to inform Miami University's Climate Resilience Assessment and its Climate Action Plan. For example, high nighttime temperatures hinder sleep, especially in low-income communities without access to air conditioning (Obradovich et al. 2017). High nighttime temperatures can also lead to an increase in mortality rates (Murage et al. 2017). Thus, an increase in minimum temperatures during the summer may have important health implications and needs to be considered in climate resilience and action plans. High temperatures can also lead to an increase in alcohol and substance use (Hensel et al. 2021), a key concern in a college setting. Longer warm seasons and increases in minimum temperatures can also increase mosquito and tick populations, and subsequently the risk of outbreaks of associated diseases. A detailed analysis of historical climate changes is crucial to formulate climate resilience and action plans, and assess the potential impacts of climate change on human health.

Conclusions

From 1893 to 2021, southwest Ohio experienced patterns of warming similar to broader trends identified across the Midwest. Annual temperatures in the area are higher today than at the start of the 20th century, with larger increases in annual minimum temperatures than annual maximum temperatures. This warming is not equal across all seasons. Measurements taken in spring revealed the largest seasonal increases in both minimum and maximum temperatures.

With temperatures increasing globally, communities and organizations need to plan for associated hazards to infrastructure and human health. Regional studies on historical temperature change can elucidate local variations in trends observed in broader climate models. Characterizing the nature of warming by conducting seasonal analyses, as well as analyzing maximum and minimum temperatures separately, provides additional context to determine the most urgent and serious hazards relevant to communities experiencing a changing climate.

ACKNOWLEDGEMENTS

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APPENDIX A

Removal of days with inter-station variation in minimum or maximum temperatures greater than 20 °F (11 °C) resulted in the removal of 2,472 days from the dataset, or 5.27% of days in the study period. Days without a record from any station were also removed from the dataset. In total, 44,349 days were used in the regression analysis, with limited variation across the decades of observations in the number of days removed from the dataset per decade (Fig. A1).

APPENDIX B

A regular time series was created for minimum and maximum temperatures. Minimum and maximum temperatures were interpolated for days with no recorded temperature by averaging the corresponding values from the temperature record from the previous and following day (all values in the temperature record had previously been averaged across each weather station as described in the methods section) to construct a regular time series for the entire study period. A Seasonal and Trend decomposition using Loess (STL), developed by Cleveland et al. (1990), with a periodic seasonal window, was subsequently conducted to isolate the long-term trends from the seasonal variation in the

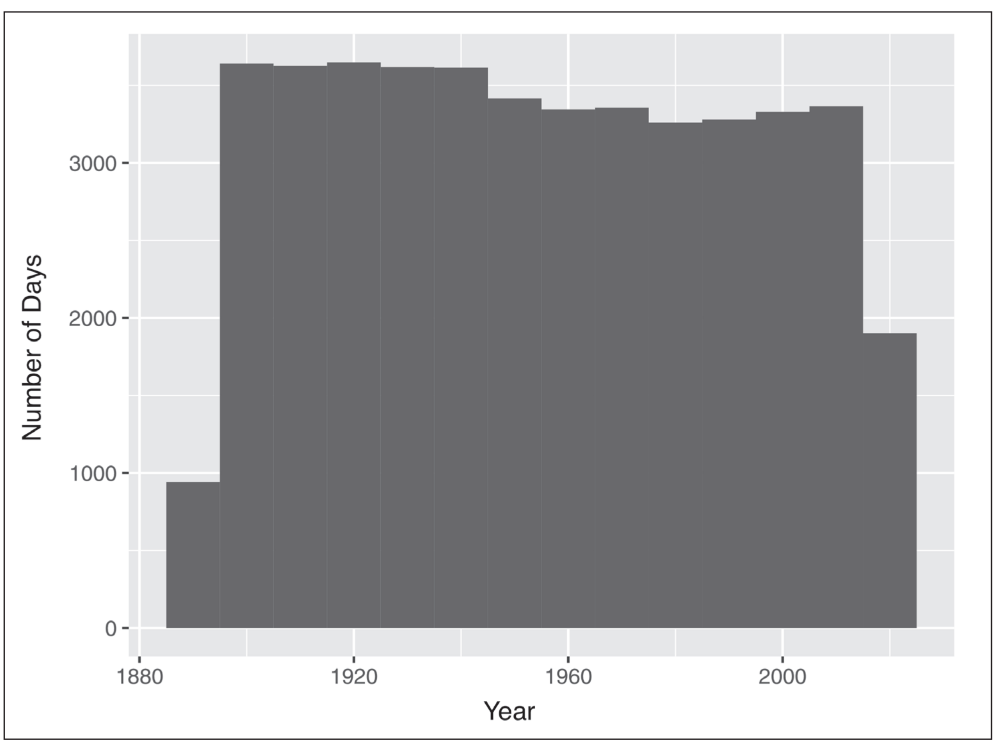

FIGURE A1. Histogram of days used in regression analysis binned by decade, beginning with the first day of observation in 1893 and ending in 2021

data. Time series and STL analysis with a periodic seasonal window showed no clear trend over the entire study period for maximum temperature observations (Fig. B1). Minimum temperature time series analysis also did not show a clear trend for the entire study period, however, STL analysis of minimum temperatures resulted in a general increasing trend in the last third of the record (Fig. B2).

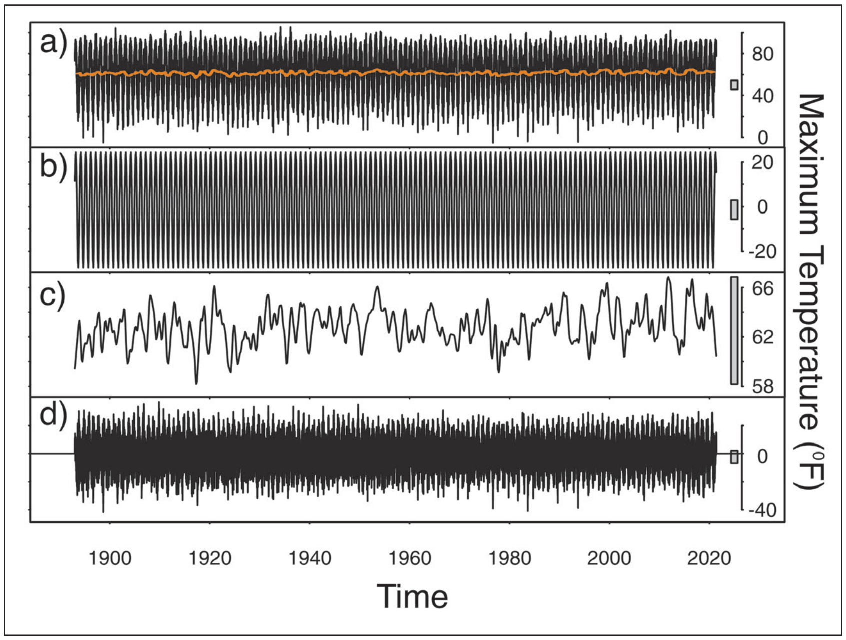

FIGURE B1. Maximum temperature data represented as timeseries showing (a) the complete data, including interpolated observations and an orange line plotting the long-term trend in minimum temperatures; (b) seasonal cyclic variation; (c) long-term trend; and (d) the remaining uncertainty in the data isolated. The grey bars on the right vertical axis cover the same range of values in all panels, highlighting the influence of each component of the decomposition on the variation observed in the data.

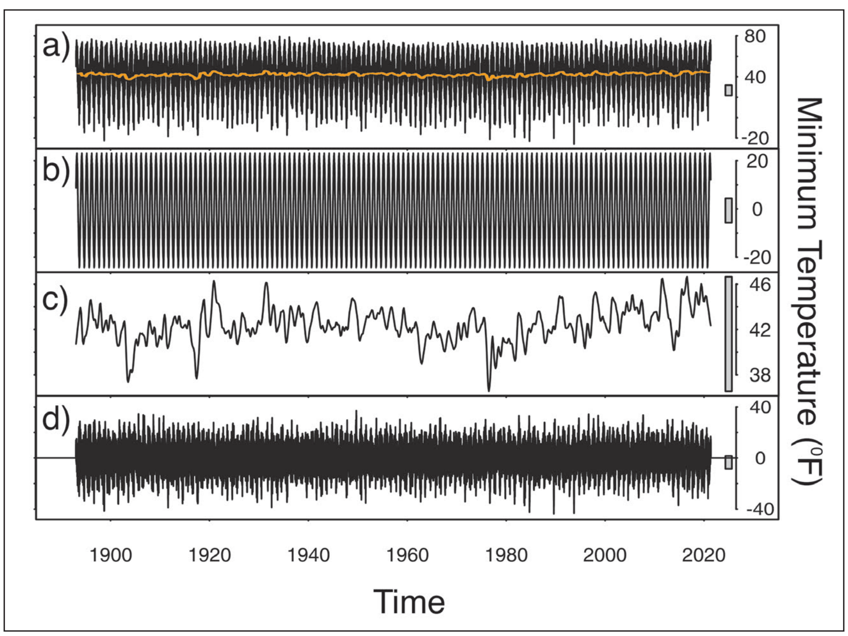

FIGURE B2. Minimum temperature data represented as timeseries showing (a) the complete data, including interpolated observations and an orange line plotting the long-term trend in minimum temperatures; (b) seasonal cyclic variation; (c) long-term trend; and (d) the remaining uncertainty in the data isolated. The grey bars on the right vertical axis cover the same range of values in all panels, highlighting the influence of each component of the decomposition on the variation observed in the data.

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Erratum:

Article was edited to include article title in the running header on every other page.