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Detecting Change: Observations of Temperature and Precipitation Across Virginia's Climate Divisions

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ABSTRACT

Modern global climate change is primarily attributable to human activities and the release of greenhouse gases into the atmosphere. Climate change impacts span a range of sectors, including agriculture, forestry, public health, and water resource management. The Commonwealth of Virginia has already and will continue to deal with many of these impacts, yet lacks concentrated effort to detect, document, and adapt to local climate changes. This study documents observed changes in temperature and precipitation across Virginia's six climate divisions. Mean seasonal anomalies of minimum temperature, maximum temperature, and precipitation from 1986 to 2016 are examined relative to a long-term 1895-2000 baseline. Additionally, the study assesses and reports full-record (1895-2016) trends for each climate division. Results demonstrate warming across all climate divisions in Virginia, particularly during the winter season (December, January, and February). Precipitation changes vary across the Commonwealth and seasons. Drying conditions, particularly in the Eastern and Western Piedmont, are noteworthy during the summer, while wetter conditions prevail in the spring and autumn. Former Governor Kaine's 2008 Climate Action Plan and subsequent 2016 update by Governor McAuliffe's administration called for a Virginia climate information clearinghouse where the public and decision-makers could efficiently access valuable weather and climate information. This paper represents a first step in this yet unrealized plan.

INTRODUCTION

Observed warming of the climate system since the mid-20th century is indisputable and has been shown to be driven dominantly by human activities, primarily the emission of greenhouse gases from the combustion of fossil fuels (IPCC, 2014; USGCRP, 2018). Numerous observable impacts relevant to human experience are already underway, including those related to public health (Watts et al., 2018), reductions in crop yields (Zhao et al., 2017), diminished benefits to humans from natural ecosystems (Nelson et al., 2013), sea level rise (Boon et al., 2018), global changes in plant and animal phenology (Buitenwerf et al., 2015), and increased risk of heat waves (Mora et al., 2017). Many of these impacts are generally expected to worsen and/or intensify into the future under emissions scenarios with large anthropogenic inputs of heat-trapping gases like carbon dioxide and methane (USGCRP, 2018).

Much of the climate change and resilience conversation in Virginia, however, has generally relied on data such as central estimates of end-of-century (~2100) conditions as simulated in global climate models (e.g., Virginia Climate Fever by Steve Nash and former Governor Tim Kaine's Climate Action Plan) or observational datasets averaged over the entire Southeastern climate region (e.g. USGCRP, 2017) instead of focusing on present-day and historical information from within the Commonwealth. While this is not necessarily problematic in and of itself, a baseline estimate of the amount of climate change that has already happened in our state could set metrics for better communication of the climate impacts that are occurring in the Commonwealth, such as public health burdens, invasive and pest species expansions, and agricultural yields trends. Furthermore, these datasets may lack the location-specific details needed to develop effective and efficient climate resilience policy at the city or county level. While dynamically downscaled, regional climate models can improve our understanding of possible future climate change scenarios, decision makers require place-based information to design interventions to cope with the consequences of global warming (e.g., Portland, Oregon's *Climate Change Preparation Strategy*, available at: https://www.portlandoregon.gov/bps/article/503193). Ultimately, aggregation of climate observations onto a global or even regional scale hinders progress toward the goals set forth by the Governor's Commission on Climate Change in the 2008 Climate Action Plan for the Commonwealth (available at: http://www.sealevelrisevirginia.net/docs/homepage/CCC_Final_Report-Final_12152008.pdf) that stated:

a. *Inventory the amount of and contributors to Virginia's greenhouse gas emissions, and projections through 2025.*
b. *Evaluate expected impacts of climate change on Virginia's natural resources, the health of its citizens, and the economy, including the industries of agriculture, forestry, tourism, and insurance.*
c. *Identify what Virginia needs to do to prepare for the likely consequences of climate change.*
d. *Identify the actions (beyond those identified in the Energy Plan) that need to be taken to achieve the 30% reduction goal.*
e. *Identify climate change approaches being pursued by other states, regions, and the federal government.*

In 2016, the McAuliffe administration issued an update to this original Climate Action Plan with the recommendation that a Virginia climate information clearinghouse be established. This paper represents a foundational step in that process, which to date has yet to be realized (as well as several of the other stated goals).

Limited work has been done to detect large-scale changes in Virginia's climate, restricting municipalities' ability to investigate hazards as they exist at present. Additionally, up-to-date, Virginia specific weather- and climate-related data and interpretations are not easily available to public or policymaker audiences without investing time and resources into understanding how to access, download, and analyze data gathered from the National Centers for Environmental Information (NCEI).

Using Virginia's 6 climate divisions as scales of analysis, this paper evaluates observed changes across maximum (Tmax) and minimum (Tmin) temperatures as well as precipitation (Prcp). The authors then also address some of the climate change impacts specific to the Commonwealth of Virginia and suggest areas for further work.

DATA AND METHODS

Climate divisional data for the Commonwealth of Virginia were obtained through the NCEI Climate at a Glance database portal. Across the continental United States, there are 344 divisions that aggregate station temperature and precipitation data. Divisional values are weighed and computed by area (Karl and Koss, 1984). Aggregation at this scale is primarily intended for agricultural and hydrologic applications.

We analyze average meteorological seasonal (winter, December-February, "DJF"; spring, March-May, "MAM"; summer, June-August, "JJA"; fall, September-November, "SON") anomalies for 1986-2016 (the most recent climatology) relative to a long-term baseline (1895-2000) for minimum temperature (Tmin), maximum temperature (Tmax), and precipitation (Prcp) for each climate division in Virginia. This baseline and period of analysis were chosen to detect and contextualize recent change in temperature and precipitation in relation to the entire 20th century. We also analyze the entire period of record (1895-2016) of each climate variable in each division for statistically significant long-term trends using ordinary least squares regressions (Appendix). Other studies have utilized station-level data to assess how precipitation has changed across the Commonwealth across the 20th century and present (Smirnov et al., 2018; Allen and Allen, under review).

RESULTS

Temperature

Results indicate positive Tmax anomalies across the Commonwealth, irrespective of season or division (Figure 2; Appendix A). The largest anomalies were observed during the winter season with a statewide mean value of +1.42°F. Additionally, five climate divisions showed a significant long-term positive (warming) trend during the winter. After winter, the largest shifts occurred in springtime (statewide anomaly +0.87°F). Across all seasons, Climate Division 4 (Northern) experienced the largest anomalies over the time period.

Tmin anomalies showed a similar pattern when compared to Tmax (Figure 3; Appendix B). Across all seasons, climate divisions indicate positive Tmin anomalies relative to the long-term average. Winter anomalies are again the largest (+1.46°F) when compared to other seasons, and Climate Division 4 (Northern) showed the largest anomalies. Three divisions (Tidewater, Eastern Piedmont, Northern) experienced significant long-term shifts across all seasons with respect to Tmin. After winter, the largest Tmin anomalies were observed for the summer season. This differs from the Tmax results.

<u>Precipitation</u>

Across all climate divisions, negative precipitation anomalies were found for the summer season (Figure 4; Appendix C). The Piedmont divisions showed the largest changes. Unlike summer, positive anomalies were found during the spring and autumn seasons. The largest changes were found during the autumn season with the mean statewide 1986-2016 anomaly exceeding +0.4" relative to 1895-2000. In addition to being the largest, autumn anomalies were the only significant long-term trends detected. Tidewater experienced a +0.59" change across the autumn season. Wintertime precipitation varied the most with only minor differences across the divisions. Spatio-temporal variability in precipitation is also noteworthy as the observed changes in Western Piedmont were the largest for the summer (-0.16), but the region showed one of the smallest changes in the winter. Changes to precipitation not captured by this analysis (e.g., sub-daily extremes) are relevant as wintertime precipitation may play a role in flood-related impacts during springtime melt season and tropical systems can deliver significant percentages of our total annual rainfall in a matter of hours.

DISCUSSION AND RECOMMENDATIONS

In all seasons and across all climate divisions, positive temperature anomalies were observed for both Tmax and Tmin, characteristic of an already warming climate in the Commonwealth. However, as expected, regional variations exist. On average, southwestern regions showed a smaller change than the other divisions. The winter season and Climate Division 4 (Northern) showed the largest shifts relative to the long-term average. Some of the long-term warming signal in minimum temperatures (especially in Climate Division 4) is likely linked to increased urbanization during the analysis period. At present, it is beyond the scope of this manuscript to deduce how much of the detected signal is attributable to urbanization and/or greenhouse gas-driven warming, though this is a considerable area of interest as Virginia's urban areas continue to grow into the midcentury (Nowack and Greenfield, 2018). Unlike temperature, precipitation anomalies showed more seasonal variability. Significant, positive trends were observed for the autumn season, but non-significant decreases were found for the summer season (Appendix C). Recent storminess and slowing tropical systems over the last several decades (Kossin, 2018) may be a contributing factor to the autumn results.

While spatio-temporal variability exists and sub-seasonal trends are not analyzed in the present study, our findings ultimately support several other studies that show trends in aggregated weather variables associated with a global climate change. Since the Industrial Revolution and more dramatically over the last 60 years, the Earth has warmed (IPCC, 2014). Since 1901, the planet has warmed 1.3 - 1.6°F per century but this rate has nearly doubled since 1975 (Blunden et al., 2018). Recent assessments have stated that over the last century, *there is no convincing evidence that natural variability can account for the amount and pattern of global warming observed* (USGCRP, 2017).

Climate change poses a significant medical danger for populations in the US as well as around the world (Watts et al., 2018), and the Department of Defense highlights the impacts of climate change as a *threat multiplier* for military assets (DOD, 2014). A wide-range of ecological and human impacts stem from such environmental change (Rudd et al., 2018). A warmer atmosphere can hold more water vapor, increasing evaporation rates and modifying the hydrologic cycle toward flashier and less consistent rainfall patterns (Kundzewicz et al., 2008). Such changes are relevant to farmers in Virginia who utilize groundwater resources for irrigation or experience increased runoff and soil erosion associated with heavy rain events. Changes in precipitation intensity, duration, and seasonal timing plays an important role in groundwater recharge (e.g. Meixner et al., 2016), transportation (Suarez et al. 2005), school closures, and longer-term implications such as vector habitat or mold and respiratory issues (Chew et al., 2006; Fisk et al., 2007; Institute of Medicine, 2011; Rochlin et al., 2013). According to the Fourth National Climate Assessment (USGCRP, 2018), metropolitan areas, like Norfolk and Virginia Beach, are vulnerable to more frequent flooding and sea level rise, impacting communities, economies, and our national security. As temperatures warm, Appalachian forest communities will experience complex interactions between drought, disease, and wildfire (USGCRP, 2018). In a warmer world, heat-related health issues, which already account for more deaths than any other weather disaster category on average (National Weather Service, 2017), may increase. Longer-lasting, earlier-occurring, and more frequent heat waves play a major role in adverse health outcomes (Sheridan and Allen, 2015). The recent IPCC Special Report on Global Warming of 1.5°C highlights the urgency required to address climate-related impacts (IPCC, 2018). The rapid (e.g., by 2030) decarbonization of nearly all aspects of our society is required to avoid "severe, widespread, and irreversible impacts," as well as concentrated efforts to build climate resilience to the changes already underway and expected in the Commonwealth. Future work on climate-related stressors in Virginia should further our understanding of the effect of urbanization on short-term extreme weather events such as heat waves, interactions between climate and health-related outcomes at least the ZIP Code level, and modeling "what if" scenarios for guided redevelopment of our cities and possible mitigation strategies that achieve the greatest amount of energy efficiency, equitable public health outcomes, and reduction of climate vulnerability in the future of a hotter and wetter Virginia.

The present study is a foundational step toward better informing stakeholders as to the recent changes in our climate system across the Commonwealth of Virginia. Decision-makers must rely on updated, easily-understandable weather and climate-related information.

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Hoffman conducted the analysis for seasonal anomalies, generated maps, and wrote the manuscript. Allen contextualized the findings in the narrative and helped format the manuscript. Labosier modified manuscript framework and format. The authors thank Dr. Eugene G. Maurakis for guidance and inspiration.

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Figure 1. Virginia Climate Divisions.

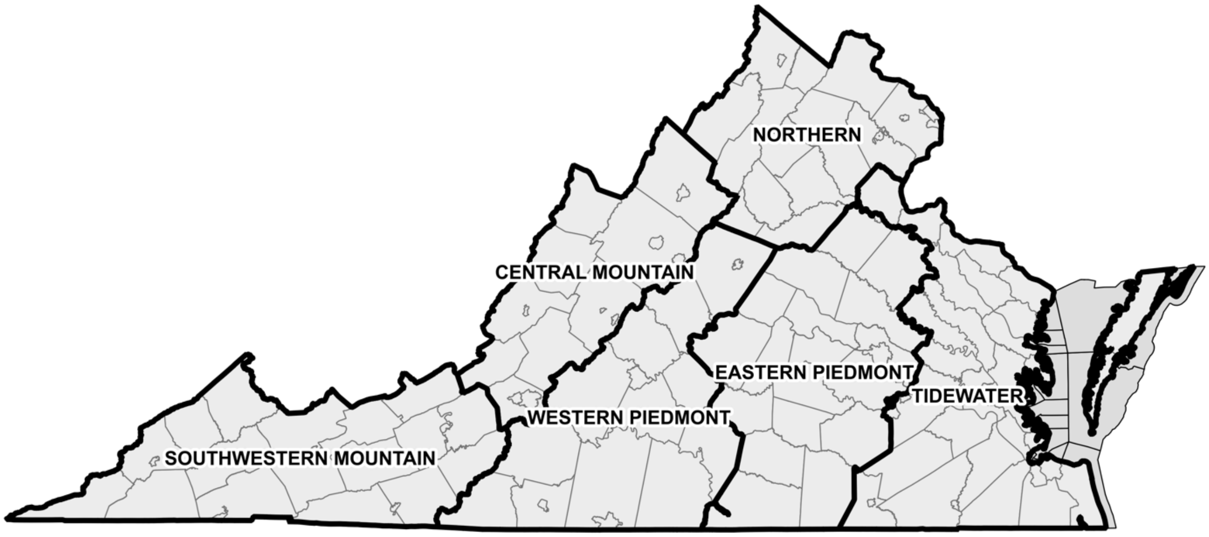


Figure 2. Seasonal maximum temperature anomalies.

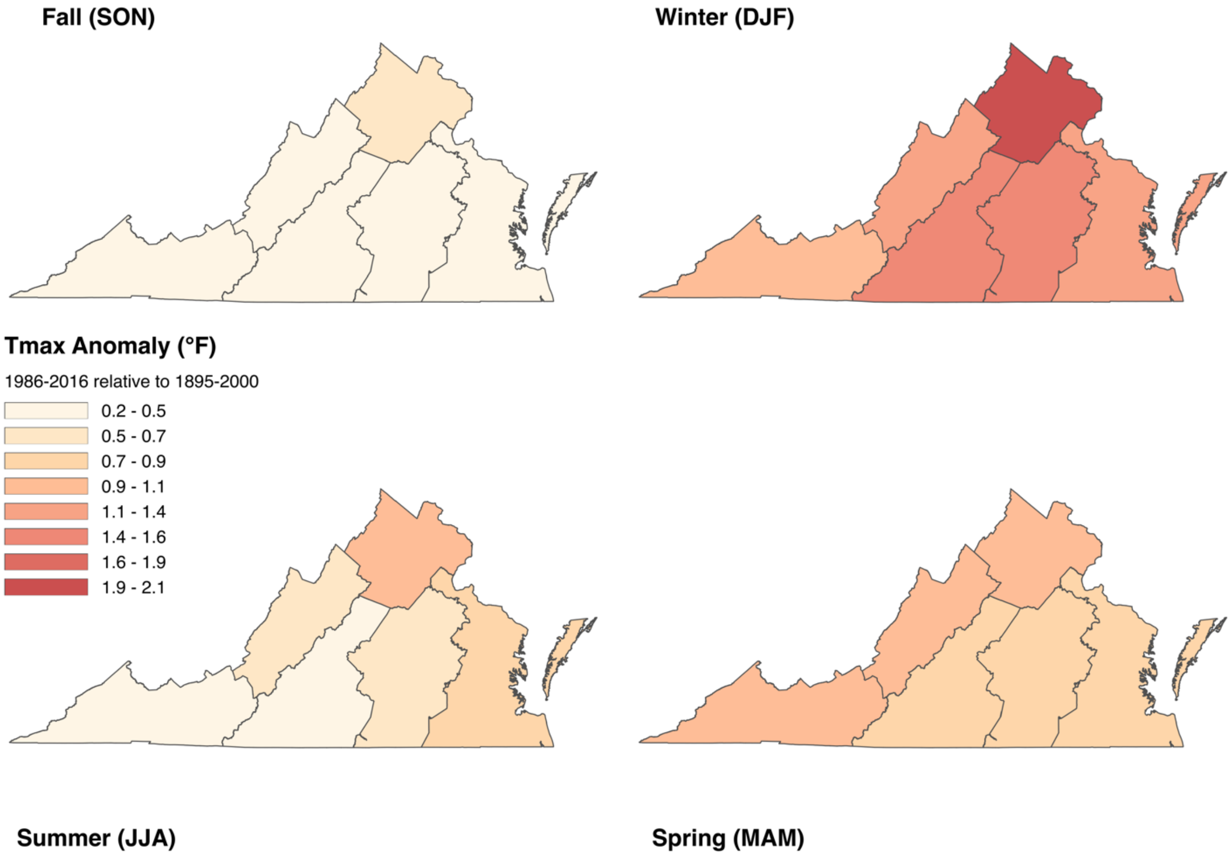


Figure 3. Seasonal minimum temperature anomalies.

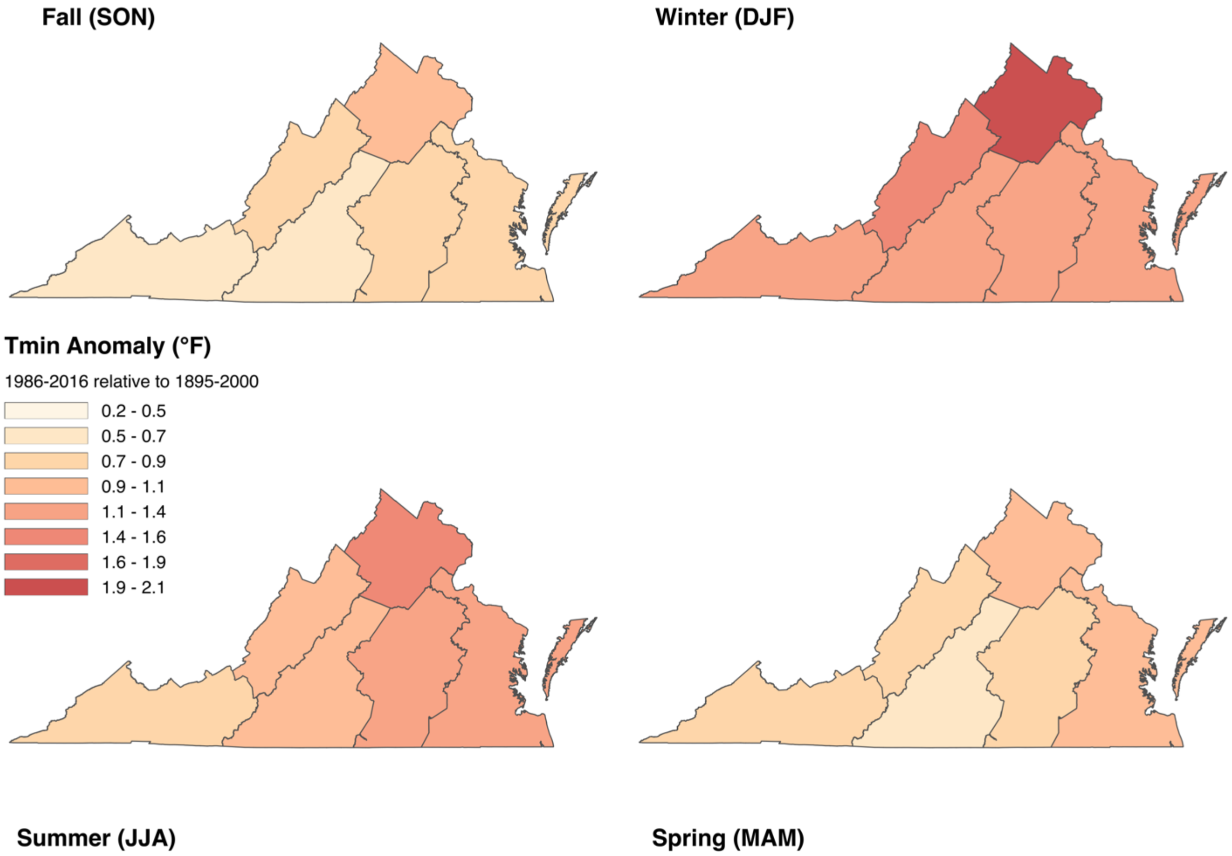
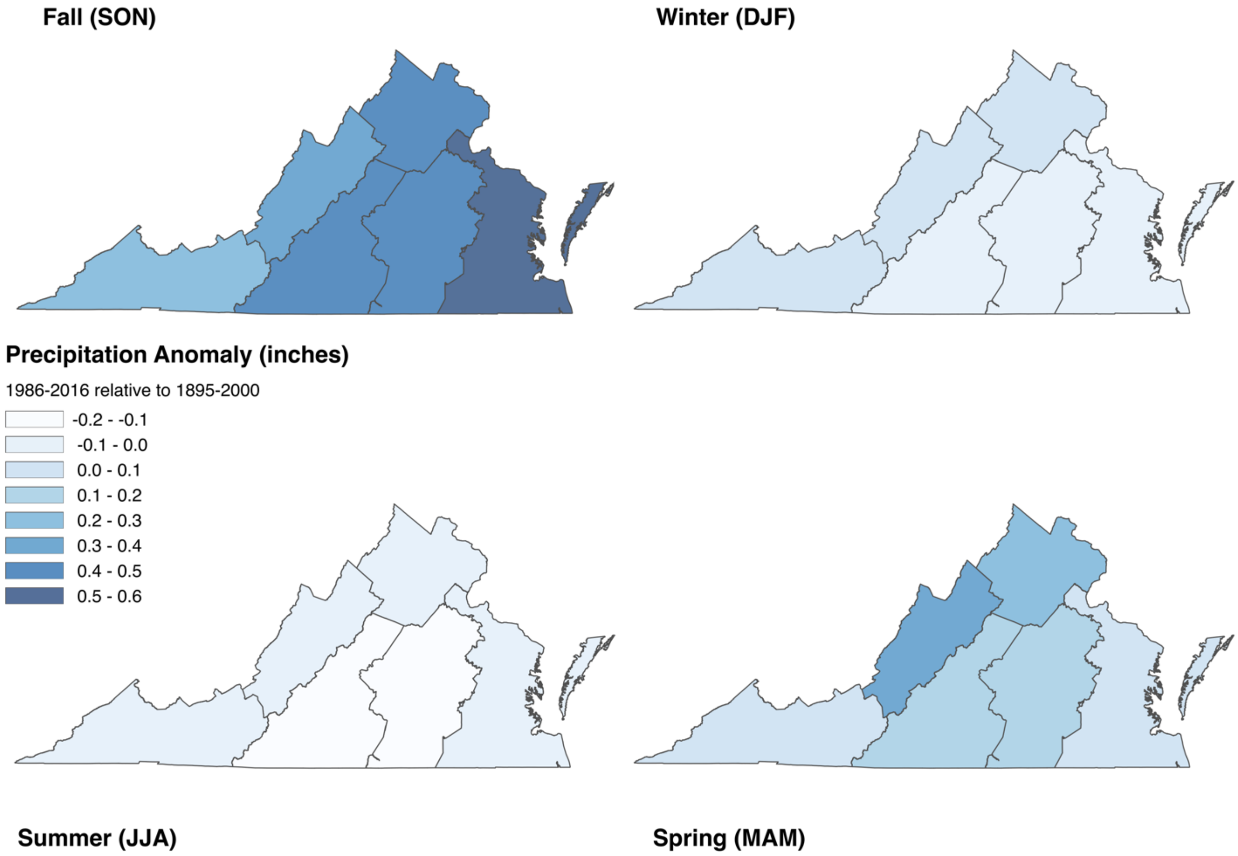


Figure 4. Seasonal precipitation anomalies.



Appendix A. Seasonal Tmax anomalies. Bold italics indicate significant long-term trends (1895-2016) as assessed by ordinary least squares analysis.

Seasonal Tmax (°F) Anomaly (1986-2016 relative to 1895-2000)					
VA Climate Division	Autumn (SON)	Winter (DJF)	Spring (MAM)	Summer (JJA)	Annual
1 - Tidewater	0.44	***1.40***	0.73	0.77	0.83
2 - Eastern Piedmont	0.32	***1.44***	0.69	0.52	0.74
3 - Western Piedmont	0.23	***1.51***	***0.83***	0.40	0.74
4 - Northern	0.60	***1.91***	***1.05***	***0.92***	1.12
5 - Central Mountain	0.30	***1.23***	***0.93***	0.61	0.77
6 - Southwestern Mountain	0.26	1.06	***0.99***	0.36	0.67
Virginia	0.36	1.42	0.87	0.59	0.81

Appendix B. Seasonal Tmin anomalies. Bold italics indicate significant long-term trends (1895-2016) as assessed by ordinary least squares analysis.

Seasonal Tmin (°F) Anomaly (1986-2016 relative to 1895-2000)					
VA Climate Division	Autumn (SON)	Winter (DJF)	Spring (MAM)	Summer (JJA)	Annual
1 - Tidewater	***0.84***	***1.39***	***0.99***	***1.18***	1.10
2 - Eastern Piedmont	***0.85***	***1.38***	***0.84***	***1.24***	1.08
3 - Western Piedmont	0.60	***1.32***	0.65	1.12	0.92
4 - Northern	***1.05***	***2.05***	***1.10***	***1.45***	1.41
5 - Central Mountain	0.67	1.47	0.74	0.97	0.96
6 - Southwestern Mountain	0.52	1.17	0.69	0.76	0.78
Virginia	0.76	1.46	0.83	1.12	1.04

Appendix C. Seasonal precipitation anomalies. Bold italics indicate significant long-term trends (1895-2016) as assessed by ordinary least squares analysis.

Seasonal Precipitation (in) Anomaly (1986-2016 relative to 1895-2000)					
VA Climate Division	Autumn (SON)	Winter (DJF)	Spring (MAM)	Summer (JJA)	Annual
1 - Tidewater	***0.59***	-0.02	0.09	-0.01	0.16
2 - Eastern Piedmont	***0.48***	0.00	0.14	-0.15	0.11
3 - Western Piedmont	***0.46***	-0.01	0.19	-0.16	0.12
4 - Northern	***0.49***	0.05	0.24	-0.09	0.17
5 - Central Mountain	***0.31***	0.09	0.32	-0.07	0.16
6 - Southwestern Mountain	0.21	0.05	0.07	-0.03	0.07
Virginia	0.42	0.03	0.18	-0.09	0.13