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Kansas Trends and Changes in Temperature, Precipitation, Drought, and Frost-Free Days from the 1890s to 2015

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Abstract: Kansas extends 660 km from the moderate elevations and semi-humid conditions of the Lower Missouri Basin to the High Plains lying above the Ogallala Aquifer and along the Rockies' eastern slope. Such characteristics result in significant climate variability across the state, making timely and accurate climate trend and change information valuable for water resources management and crop production. Here we used high-quality daily and monthly climate observations spanning a long-term period of 121 years (1895-2015) to assess trends and changes in air temperature, precipitation, drought, and frost-free days across Kansas. We show that a statewide average warming rate of 0.06°C (0.11°F) per decade was mainly driven by trends in daily minimum temperatures. However, there were no statistically significant trends in precipitation in either western, central, or eastern Kansas. Western Kansas tended toward increasing dryness, but central and eastern Kansas trended wetter as indicated by changes in the Palmer Drought Severity Index (PDSI), a trend that was consistent with a weak wetting signal in eastern Kansas. The length of frost-free season increased by 5.2 days in western, 7.2 days in central, and 12.6 days in eastern Kansas, which reflected more warming in the east and less in the west, especially for changing magnitudes of nighttime temperatures. Such increases of frost-free days, especially in moisture-limited areas (e.g., western Kansas), might increase seasonal evapotranspiration loss, thus exacerbating soil moisture stress and associated management challenges.

Keywords: *climate, water resources, drought, climate change, trends*

Nearly seventy years ago, Snowden Flora, a meteorologist of the U.S. Weather Bureau located in Kansas, published the 'Climate of Kansas' (Flora 1948). This book did an excellent job of documenting the weather and climate conditions for Kansas, based on instrumental observations from the late nineteenth century to the 1940s, and putting them into an accurate historical perspective. Following up this work, a few scientists have published research and educational bulletins and/or books detailing aspects of the climate of Kansas. For example, Bark, in 1963, published a Kansas Agricultural Experiment Station Bulletin on precipitation change in Kansas. Later, Feyerherm and Bark (1964) calculated wet and dry days in Kansas, and in the mid-1990s, Goodin et al. (1995) published the Kansas Climate and Weather Atlas. These publications have not only advanced climate science in Kansas, but more importantly, they successfully helped to assist Kansas stakeholders in climate-informed decision-making. However, these publications are constrained by the use of a limited set of climate stations and/or relatively short periods used for data analysis.

The ability to organize a more comprehensive

documentation of Kansas climate now exists. One of the reasons is that climate scientists working on long-term climate data quality and data homogeneity have been making significant progress addressing climate data quality starting from the 1980s (Karl et al. 1986; Karl and Williams 1987; Menne and Williams 2009; Menne et al. 2012). Another reason to provide updated information on Kansas climate trends and changes is that climate change, including detection and attribution, has been vigorously and extensively studied since 1990, the year of the first Intergovernmental Panel on Climate Change (IPCC) Assessment Report in which the challenge of climate change was addressed (IPCC 1990).

This study is designed to foster the growth of climate science information in the areas of long-term climate changes and extreme weather records for Kansas. As the IPCC authors (Field et al. 2012; IPCC 2013) concluded that "it is likely that anthropogenic influences have led to warming of extreme daily minimum and maximum air temperatures at the global scale" and that "there is medium confidence that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale".

While these global scale changes have an influence on the climate of Kansas, other factors help explain the specific conditions across the state. At the local scale, climates are affected by various factors that include topography, elevation, proximity to oceans, water in lakes and rivers, irrigation practices and other land cover changes, and latitude. The borders of Kansas extend 660 km to include the moderate elevations and abundant precipitation conditions (more than 1,000 mm [~40 inches] of annual precipitation) of the Lower Missouri Basin to the drier High Plains lying along the eastern slope of the Rockies (with less than 500 mm [~20 inches] of annual precipitation). The Gulf of Mexico, which extends westward to the 98th meridian, is the source of the vast majority of moisture for precipitation in Kansas. Northward flow of water vapor associated with low-level jets is frequently pushed eastward and this atmospheric moisture flow pattern contributes to three quite distinct precipitation climate zones of Kansas: a semiarid western third, an intermediate central third, and a semi-humid eastern third (Flora 1948).

Given the mid-latitude and mid-continental location of Kansas, pronounced thermal and hydrologic seasonality characterizes the climate of Kansas. The primary objective of this study is to document and analyze trends and changes in air temperature, precipitation, drought, and frost-free days that have occurred from 1895 to 2015, as well as the related extreme climate records for the 1891-2015 period across Kansas.

Data and Methods

Daily climate data were obtained from the Global Historical Climatology Network (GHCNd). The U.S. component of GHCNd is an integrated version of NCEI's (National Centers for Environmental Information) daily surface observations, including the U.S. Cooperative Observer Network, the Automated Surface Observing System (ASOS), and other observing systems, and represents the most complete historical record of daily data for the United States. Thirty long-term climate stations (Fig. 1) were selected across Kansas for January 1, 1891 to December 31, 2015 based on data availability and station continuity. This daily dataset is part of the U.S. Historical Climatology Network (USHCN) program (Menne et al. 2012). This dataset was subjected to high-quality control (Alexander et al. 2006), but there were still erroneous observations for some Kansas stations. We first identified erroneous temperatures by using the fourth standard deviation as a threshold and then visually assessed suspected records by a spatial correlation method (Alexander et al. 2006). For daily precipitation observations, we only used them to assess the climate extreme records (when analyzing monthly and annual precipitation, we used the monthly dataset) for Kansas.

The U.S. Historical Climatology Network (USHCN, version 2.5) consists of 31 high-quality stations in Kansas and the data quality of monthly average temperatures has been rigorously examined (Menne and Williams 2009; Lawrimore et al. 2011; Menne et al. 2012) (Fig. 1). These 31 USHCN stations have long been commonly selected for use in evaluating climate changes on the global, regional, and state scales and these temperatures are considered a high-quality reference base when evaluating climate change from 1895 to 2015.

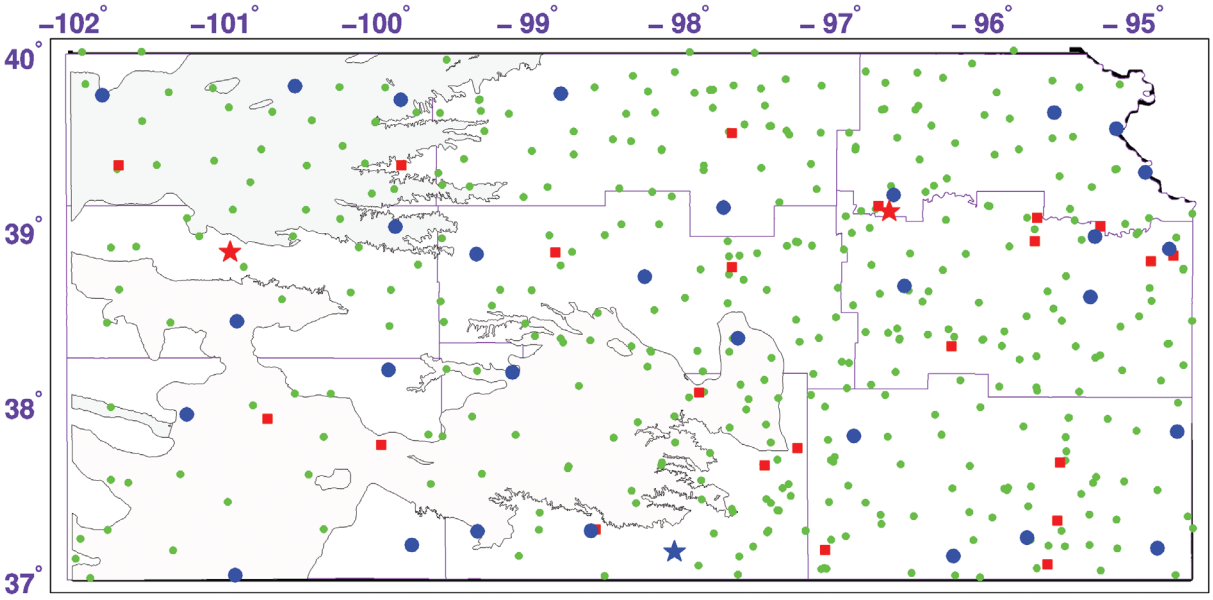


Figure 1. 433 total active daily climate observing stations (green dots) which include 30 long-term (over 1860s to current) high quality daily stations (blue dots) and 31 long-term monthly stations (blue dots plus one blue star) in Kansas selected by the Global Historical Climatology Network (GHCN). Kansas also has 22 federal ASOS stations (red squares) with data from the 1970s to current, and two U.S. Climate Reference Network (USCRN) stations (red stars), from 2002 to current. Aquifers in western Kansas and the nine crop reporting districts are shown. Each third of Kansas contains at least nine high-quality stations analyzed in this report. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

In both daily and monthly datasets that we used in this study, all missing data were retained without any filling or replacement by estimation. Monthly anomalies for maximum, minimum, and average temperatures were departures from a base period of 1981 to 2010 (WMO 1989; WMO 2009). The time series for the state of Kansas was aggregated using an equally weighted station average from each station when the observation was available. It should be noted that the monthly climate data were different from the daily climate data in that there were extensive and high-quality data homogeneity techniques employed in generating the monthly datasets but these procedures were not used for the daily dataset (Menne et al. 2012).

For derived climate variables in this study, the PDSI was selected, an index originally developed and calibrated using western Kansas climate in 1965 (Palmer 1965). The PDSI was calculated from the monthly temperature, monthly precipitation, and Kansas' available water capacity (Guttman 1991). The second climate variable we selected is the frost date, which is defined in this paper as a day with the daily minimum temperature below freezing (0°C). The length of the frost-free season (frost-free days) is defined as the difference between the last-spring freeze and the first-fall freeze dates (Easterling 2002).

To robustly examine the trends, the adjusted standard error and adjusted degree of freedom methods were selected for assessing the statistical significance of temperature trends at 95% confidence levels (von Storch and Zwiers 1999; Santer et al. 2000; Karl et al. 2006; Lin et al. 2016). This approach is a modification of ordinary least squares linear regression, substituting the effective sample size in a regression time series to account for the effect of temporal autocorrelation in the time series or its residual series. The extent of sample number reduction implemented in our linear trend analysis depends upon the strength of the autocorrelation. A strong autocorrelation means that individual values in the sampling series are far from being independent so that the effective number of independent values must be much smaller than the sample size. A trend in a time series significantly different from zero is tested by computing the ratio of the estimated trend and its adjusted standard error,

a stricter test than using standard *p*-values. Note that the 95% confidence intervals used in this paper are adjusted by inverting the Student's *t*-distribution to obtain effective sample size and using the critical value 1- $\alpha/2 = 0.975$ (two-tailed) (Lin et al. 2016).

Results

Temperatures

Over the last decade, temperatures have been among the warmest on record for Kansas, with the only exception being the extreme heat of 1930s "Dust Bowl" era (Figs. 2a and 2b). Statewide annual average temperature varied from a low of 11.3°C (52°F) in 1912 to a high of 14.9°C (59°F) in 2012. Such a swing, 3.6°C (6.5°F), documents an aspect of temperature variability that is one of the reasons that Kansas' agricultural economy is vulnerable to climate change and climate variability. One pronounced result from observations over the last 121 years was the warming of the minimum temperature (nighttime temperatures) much greater than that of maximum temperatures (Figs. 2a and 2b). Maximum temperatures do not have statistically significant trends over the last 121 years but minimum temperatures show a significant warming rate of 0.078 ± 0.03°C per decade (0.14°F per decade). Kansas' average temperature increase, 0.059 ± 0.03°C per decade (0.11°F per decade), was mainly driven by the rise in minimum temperatures (Fig. 2).

When examining seasonal temperature trends, the results indicate that none of four seasons have any statistically significant trend (Fig. 3) except for the winter season, showing significant warming using a 90% confident level (Fig. 3d). In addition, it is clear that this warming trend of winter temperatures was accompanied with larger inter-season variations compared to spring, summer, and fall seasons (Fig. 3d). These results suggest that temperature change impacts on winter wheat are expected to be more

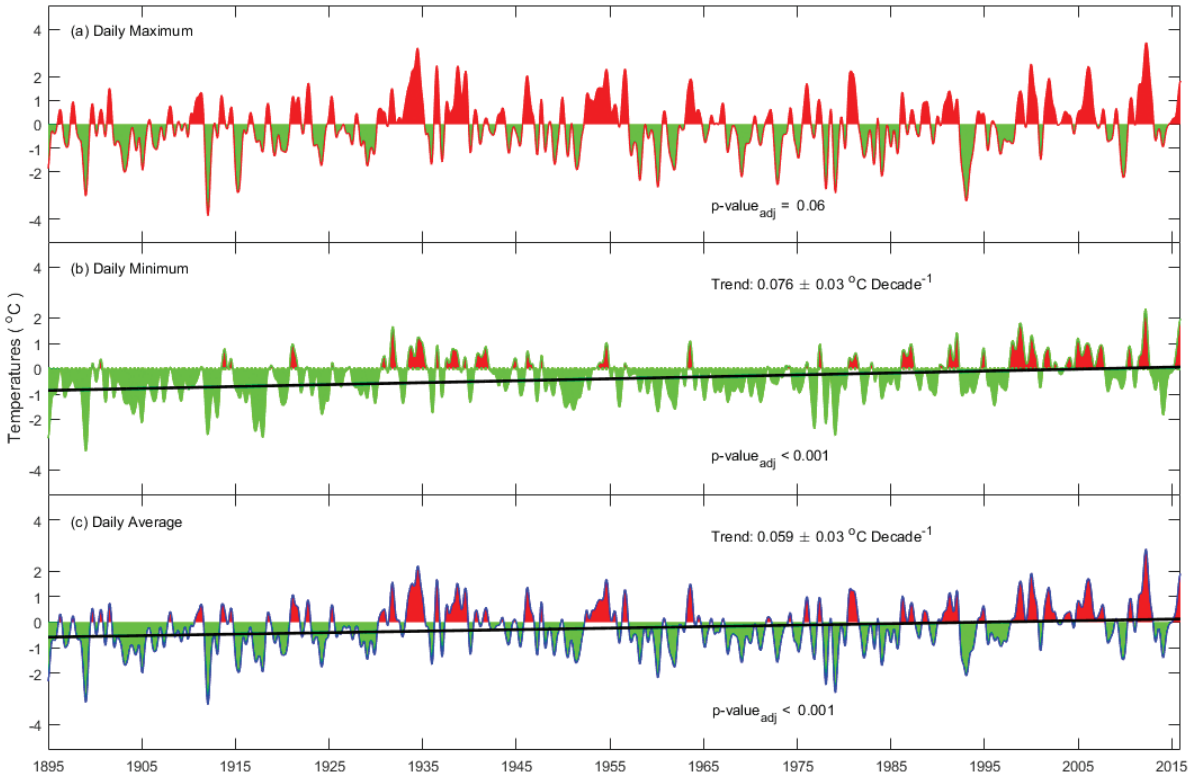


Figure 2. Kansas monthly temperature anomaly time series over 1895 to 2015: (a) daily maximum temperature; (b) daily minimum temperature; and (c) daily average temperature. The base period used is 1981 to 2010 and a 13-point Gaussian filter was used to smooth the data (red line for daily maximum, green line for daily minimum, and blue line for daily average temperatures). When trends (black lines) are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

important than that on other major crops in Kansas (Zhang et al. 2015; Zhang and Lin 2016). It should be noted that this century-scale increase in temperature documented with the analysis of data from stations in Kansas is comparable with the 0.6 to 1.0°C (1.1 to 1.8°F) increases observed across the United States (Karl et al. 2006). Notice that when minimum temperature data are analyzed on a seasonal basis, the data indicate an increase in all four seasons, with the steepest slope in spring (not shown).

Precipitation

Precipitation in Kansas is highly variable from year to year and across the state, with the statewide annual average exhibiting a low of 439 mm (17 inches) in 1956 to a high of 1,110 mm (44 inches) in 1951 (Fig. 4 and Table 1). For the western third, central third, and the eastern third of Kansas, long-term (1895-2015) mean annual precipitation totals were 531 mm (21 inches), 660 mm (26 inches), and 945 mm (37 inches), respectively (Fig. 4). These long-term statistics are slightly larger than those presented by Flora (1948): 474 mm (19 inches) for western, 658 mm (26 inches) for central, and 878 mm (35 inches) for eastern Kansas. Over the last two decades, annual precipitation amounts have increased, but due to large inter-annual (year-to-year) variability the long-term annual precipitation does not show any statistically significant increase or decrease (Fig. 4) at the 95% confidence level for 1895 to 2015. It was clear that if one considers the 90% confidence level, both central and eastern Kansas did present a weak increasing trend (7.08 ± 7.0 mm per decade (0.3 inches per decade) for central and 8.80 ± 9.1 mm per decade (0.4 inches per decade) for eastern, at 95% confidence level) (Fig. 4).

For the state as a whole, the precipitation is 218 mm (9 inches) during spring (March-April-May), 279 mm (11 inches) in summer (June-July-August), 169 mm (7 inches) in fall (September-October-November), and 70 mm (3

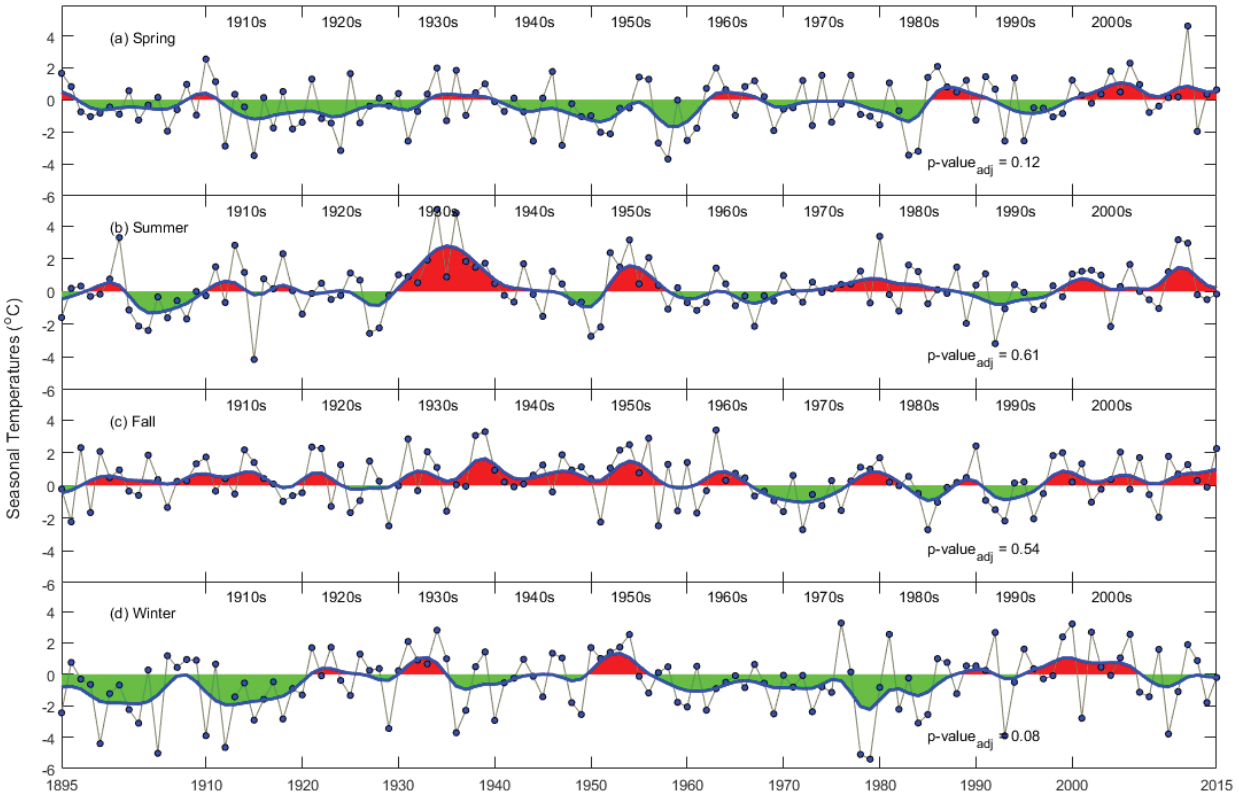


Figure 3. Kansas seasonal temperature anomaly time series over 1895 to 2015: (a) Spring; (b) Summer; (c) Fall; and (d) Winter. The base period used is 1981 to 2010 and a 13-point Gaussian filter was used to smooth the data (blue lines). When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

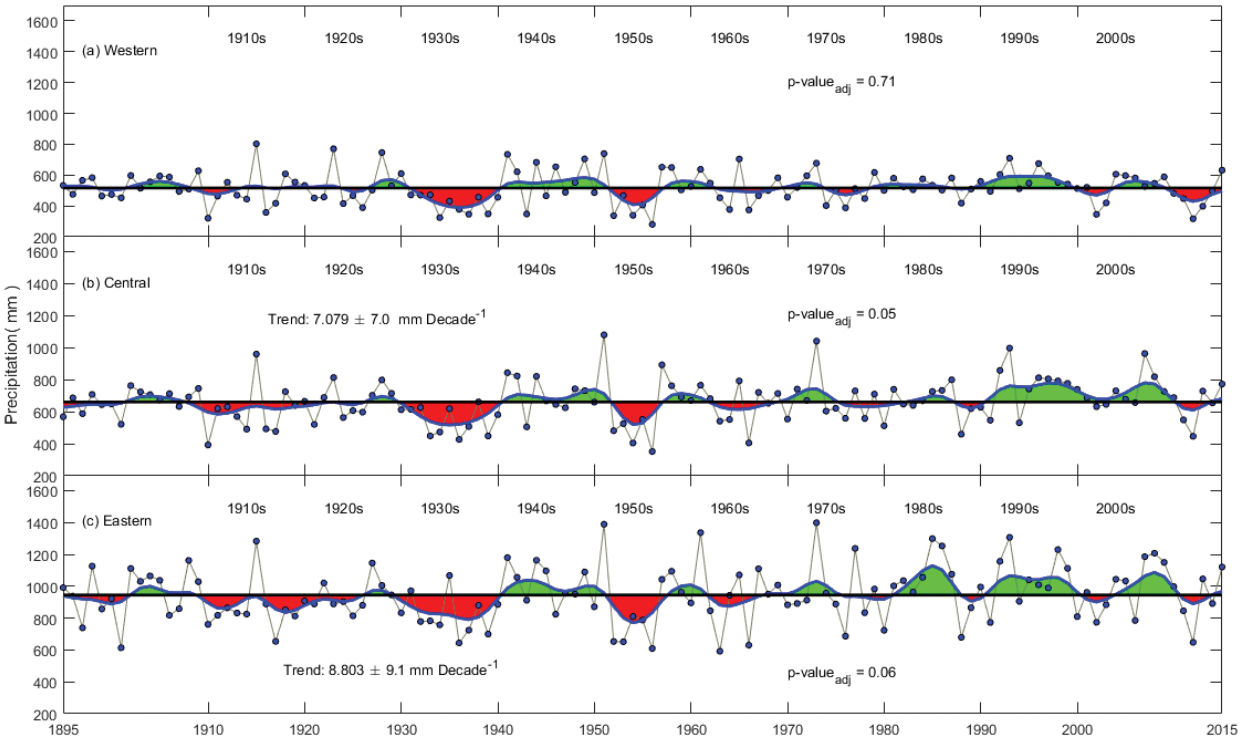


Figure 4. Kansas annual precipitation time series over 1895 to 2015: (a) Western; (b) Central; and (c) Eastern Kansas precipitation variations. The black lines are period-of-observation mean over 1895 to 2015 (inclusive). A 9-point moving average was used as a smoother (blue lines). When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

inches) in winter (December-January-February) seasons (Fig. 5). Winter season precipitation has a comparatively small inter-annual variation. There were no statistically significant trends in seasonal precipitation amount at the 95% confidence level. For the whole U.S., extreme precipitation events are increasing (Karl et al. 2006) and data for Kansas documents a statewide increase in the magnitude of extreme rainfall events, with greater increases in the east (Rahmani et al. 2016). At the 90% confidence level of statistical significance, seasonally, only spring precipitation showed an upward trend.

Drought

Droughts are one of the most devastating natural disasters. Over the course of the time period studied here, the water resources and agricultural economy of Kansas have been considerably effected by drought events. The 1930s drought is often considered the worst drought on record in Kansas (Fig. 6a). This was the driest series of years since instrumental observations began starting in the late 1800s. Sporadic weather observations in the mid-1800s have helped document droughts during that settlement period.

By going over more than 1,000 years of tree-ring data (Cook et al. 2004), it becomes noticeable that the droughts in 1930s were not the worst in history in terms of either drought duration (consecutive years of drought) or drought intensity (the magnitude of drought index) in Kansas. Multiple-year droughts have often occurred in Kansas. The state as a whole has not experienced more frequent or more extreme droughts in recent years compared to either the last 1,000 years (Cook et al. 2004) or the most recent 121-year period (Fig. 6). When the data were subdivided by dividing the most recent 121-year period into two periods (1895 to 1955 and 1956 to 2015) for each of the three regions of Kansas, only western Kansas was dryer on average during the most recent 60-year period when compared to data from 1895 to 1955 (Fig. 7). Both central and eastern Kansas showed

Table 1. Kansas top ten hottest and coldest years (top panel), and driest and wettest years (bottom panel) from 1895 to 2015.

Rank	Hottest Year	°C (°F)	Rank	Coldest Year	°C (°F)
1	2012	14.9 (58.9)	1	1912	11.3 (52.3)
2	1934	14.5 (58.1)	2	1951	11.4 (52.5)
3	1954	14.3 (57.7)	3	1993	11.4 (52.6)
4	2006	14.2 (57.6)	4	1924	11.4 (52.6)
5	1938	14.2 (57.5)	5	1917	11.5 (52.7)
6	1939	14.1 (57.4)	6	1979	11.6 (52.8)
7	1946	14.1 (57.4)	7	1903	11.6 (52.9)
8	1933	14.1 (57.3)	8	1895	11.6 (52.9)
9	1931	13.9 (57.1)	9	1929	11.6 (52.9)
10	1921	13.9 (57.1)	10	1985	11.7 (53.0)

Rank	Driest Year	mm (inches)	Rank	Wettest Year	mm (inches)
1	1956	439 (17.3)	1	1951	1110 (43.7)
2	1966	490 (19.3)	2	1973	1085 (42.7)
3	2012	493 (19.4)	3	1915	1049 (41.3)
4	1936	503 (19.8)	4	1993	1044 (41.1)
5	1952	511 (20.1)	5	1961	968 (38.1)
6	1939	526 (20.7)	6	1941	953 (37.5)
7	1910	526 (20.7)	7	2007	930 (36.6)
8	1917	533 (21.0)	8	1944	925 (36.4)
9	1963	536 (21.1)	9	1985	912 (35.9)
10	1988	541 (21.3)	10	1992	909 (35.8)

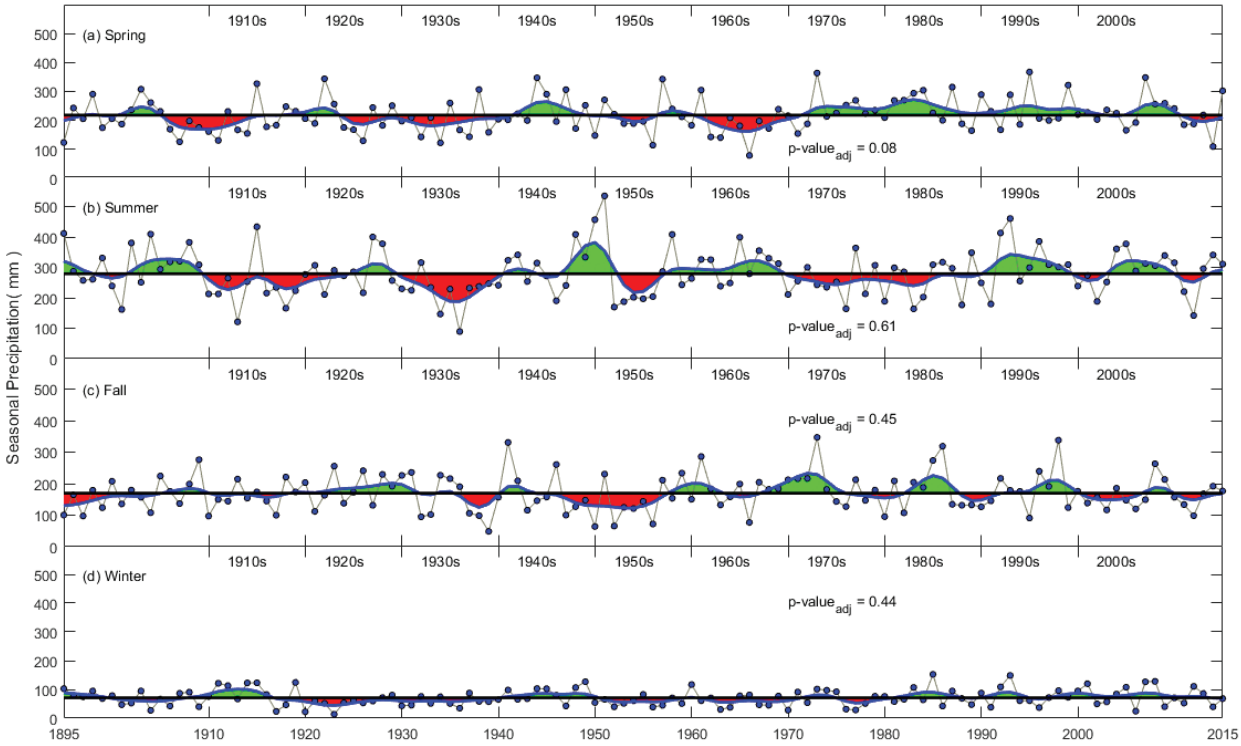


Figure 5. Kansas seasonal precipitation time series over 1895 to 2015: (a) Spring; (b) Summer; (c) Fall; and (d) Winter seasons. The black lines are period-of-observation mean over 1895 to 2015 (inclusive). A 9-point moving average was used as a smoother (blue lines). When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

wetter tendencies in the most recent 60-year period. Recent wetter conditions are challenging summer row crop establishment and final harvest. The drought change information observable in Figure 7 is consistent with precipitation trends for Kansas (Fig. 4).

Frost-free Days

The number of days that the minimum daily temperature falls below freezing is an important indicator for crop production, water management, and ecosystems in Kansas (Lin et al. 2014). Length of the frost-free season and changes in the length of that season have a direct implication for crop production in Kansas. The distinct patterns of first and last frost dates across Kansas result in the shortest growing season occurring in western Kansas (170 days) and longer average growing seasons occurring in central Kansas (182 days) and eastern Kansas (189 days) (Fig. 8). These long-term averages for Kansas are changing (Lin et al. 2014). The frost-free season length in all regions of Kansas exhibits a statistically significant increase from 1901 to 2014 at a rate of 0.99 ± 0.79 days per decade in western Kansas, 0.94 ± 0.90 days per decade in central Kansas, and 1.47 ± 0.74 days per decade in eastern Kansas (Fig. 8). A longer frost-free growing season could give Kansas producers an opportunity to explore cropping alternatives. This longer season could increase yields if other biotic (insects, diseases) and abiotic (heat, drought) stresses do not limit crop growth and development.

Top Ten Hottest, Coldest, Driest, and Wettest Years

Table 1 provides the top ten hottest, coldest, driest, and wettest years, respectively, based on the daily climate data. The hottest year was 2012 and coldest year was 1912. Five of the ten hottest years occurred during the 1930s. Both the driest and wettest years occurred in the 1950s. Perhaps surprisingly, only two of the driest years were during the Dust Bowl decades of the 1930s (Table 1). The temperature

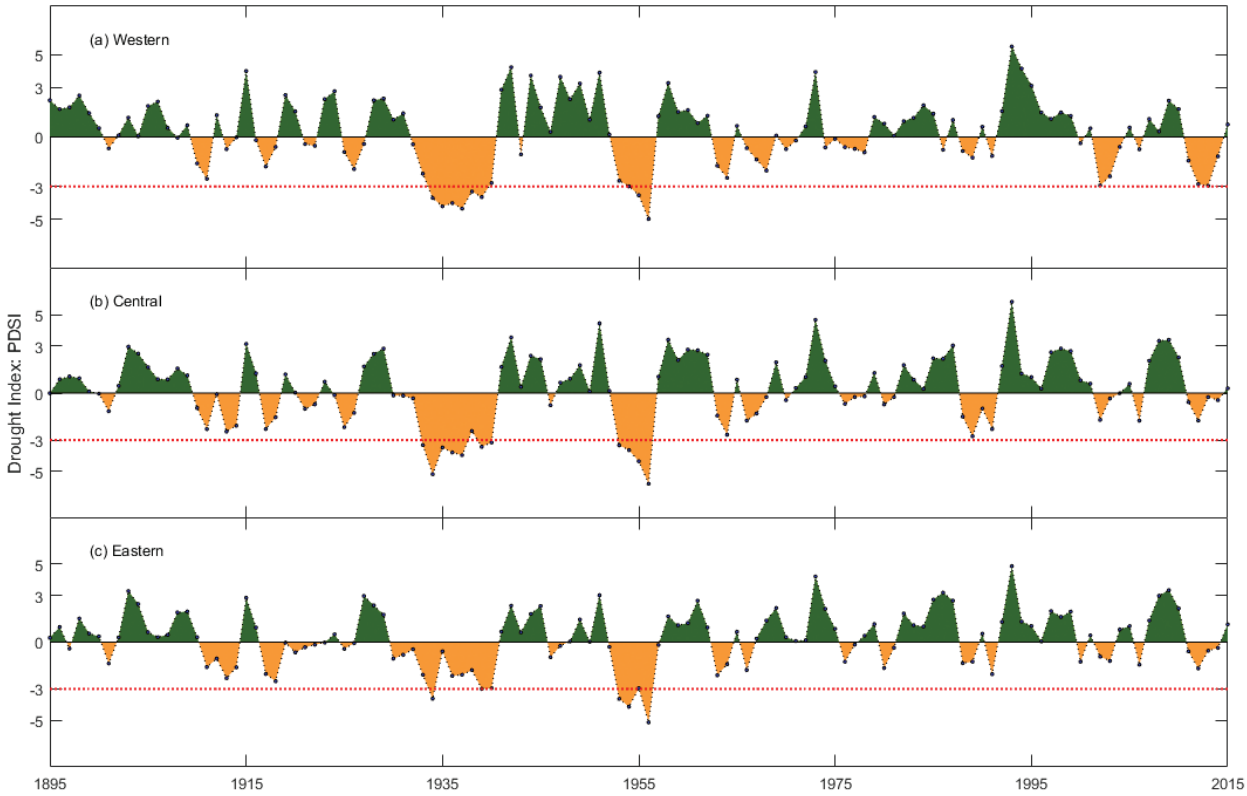


Figure 6. Average annual Palmer Drought Severity Index (PDSI) from 1895 through 2015: (a) Western; (b) Central; and (c) Eastern thirds of Kansas. The more negative the PDSI, the drier (orange). On the opposite side, the more positive the PDSI, the wetter (dark green). The dotted red lines (PDSI = -3) are indicators of severe drought occurrence. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

difference between the hottest year and coldest year is about 2.7°C (5°F) in Kansas. Perhaps more significantly, the precipitation difference is 671 mm (26 inches) between the wettest and driest years, which is more than annual expected precipitation in central Kansas (Fig. 4b). These significant swings of temperature and precipitation make Kansas crop and livestock productions relatively vulnerable to changes of increasing climate extreme events in the short-term and/or longer-term perspectives, which will require that adaptive measures be taken for sustaining Kansas agricultural production.

Summary and Conclusions

Accurate, historical climate information is a key resource for managing Kansas water resources and improving agricultural production. As the climate of Kansas continues to vary over time, information on past conditions and ongoing trends will help those managing other climate-sensitive resources across the state. Average temperatures in Kansas have significantly trended up during the last 121 years, a period in which the daily minimum temperature increased faster than the daily maximum temperature. The warming rate in Kansas, 0.06°C per decade (0.11°F per decade), is comparable with the U.S. as well as global warming rates (approximately 0.07°C per decade, IPCC 2013). This nighttime warming might not directly drive evapotranspiration loss as a whole, but it could have significant impacts on crop production, especially for winter wheat (Lobell and Oritz-Monasterio 2007; Melillo et al. 2014; Zhang et al. 2015).

Both drought and frost-free-days metrics were derived from available temperature and precipitation data. The drought events in 2011, 2012, and 2013 in Kansas were significant but not unprecedented climate phenomena, as they fell within historical variability ranges. Long-term observed precipitation in the state did not exhibit

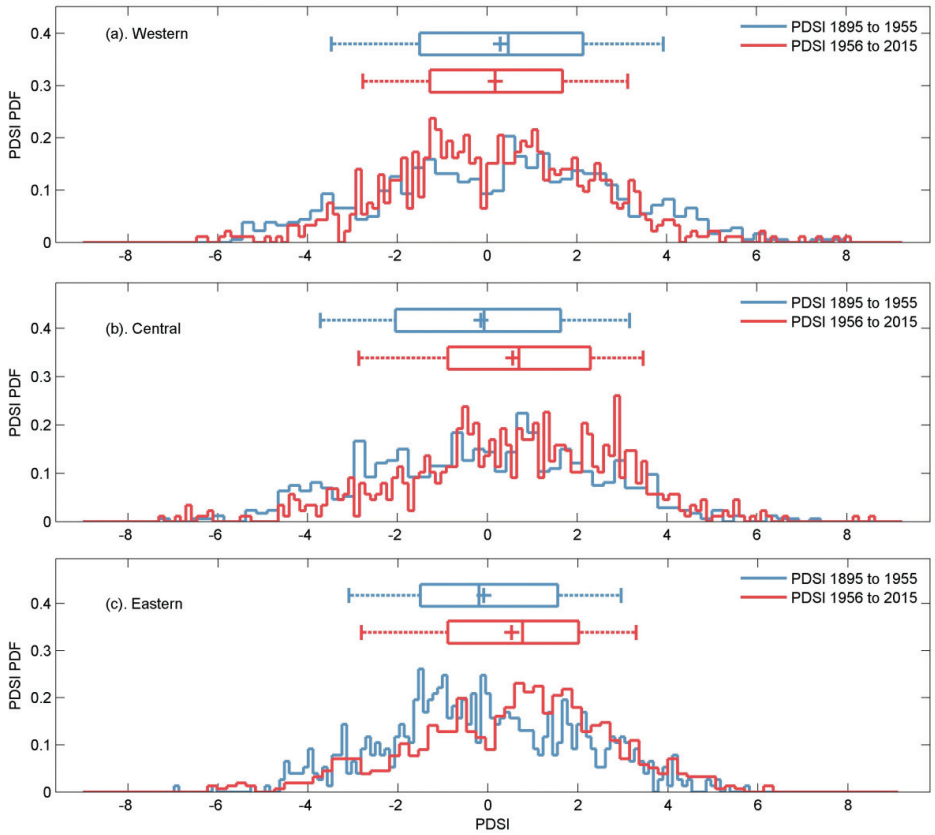


Figure 7. Probability density function (PDF) of Palmer Drought Severity Index (PDSI) during 1895 through 1955 and 1956 through 2015 in (a) Western; (b) Central; and (c) Eastern Kansas, respectively. The negative numbers to the left of "0" on the x axis represent drier-than-average conditions; the positive numbers to the right of "0" represent wetter-than-average conditions. Only in western Kansas is there a slightly drier-than-average pattern in the 1956 to 2015 period (red lines) compared to the 1895 to 1955 period (blue lines). In central and eastern Kansas, the most recent time period has been slightly wetter. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

any significant trends. Only western Kansas tended to be drier in more recent years, while central and eastern Kansas tended to be wetter. The temperature trends across Kansas have no obvious difference although climatology is distinctly different. Additional detail regarding these weak trends towards drier or wetter conditions could be valuable for Kansas water resource management interests. The frost-free season length, in contrast, demonstrated a clear and statistically significant increase across all of Kansas, with increases of 5.2 days in the west and 12.6 days in the east. These differences mirror the overall spatial trends of more warming in eastern Kansas, driven primarily by nighttime temperatures.

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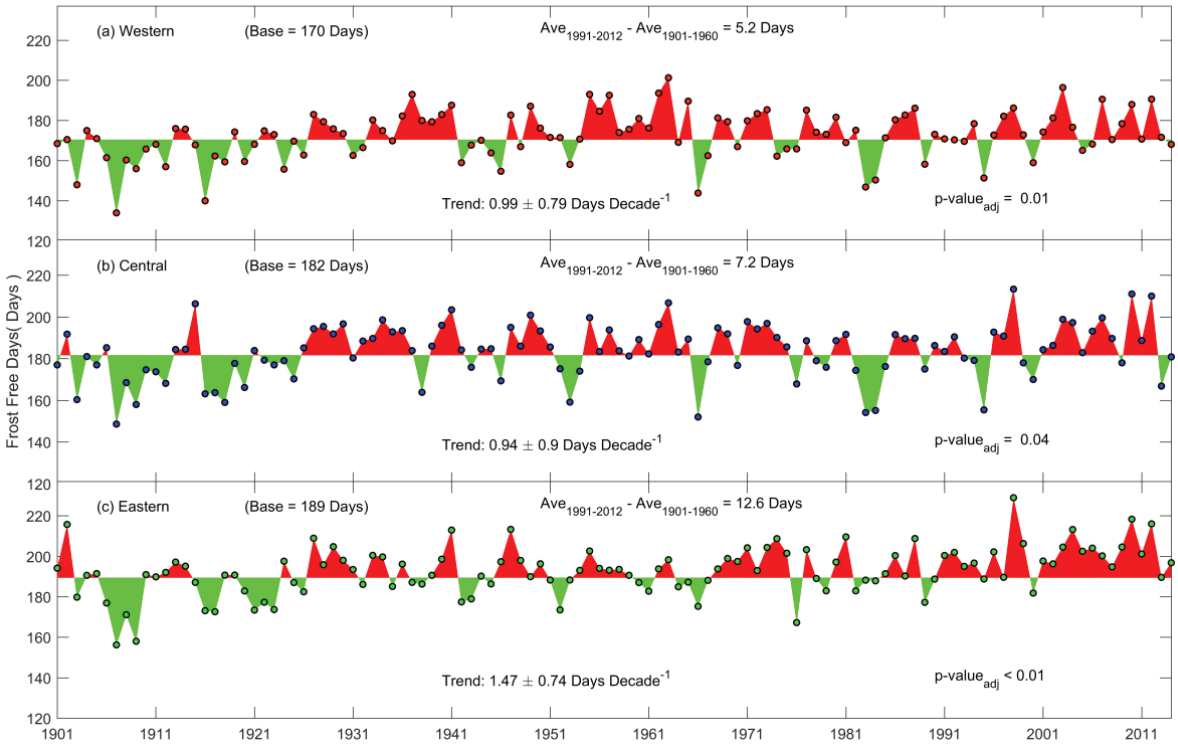


Figure 8. Time series of the frost-free season length in Kansas from 1901 to 2014: (a) Western; (b) Central; and (c) Eastern Kansas. The base indicates average number of frost-free days calculated from 1901 to 1960 (60-year period as a base period). The Ave 1991-2012 – Ave 1901-1960 is the difference of frost-free season length between 1991-2012 and 1901-1960. When trends are statistically significant the trend rates are displayed. All adjusted p values are shown. (View color figure online at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1936-704X.)

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