Changes in spatial and temporal trends in wet, dry, warm and cold spell length or duration indices in Kansas, USA

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ABSTRACT: Extended periods with excessive or no rainfall or high or low temperatures have important implications on the water cycle, can stress ecosystems and can be detrimental to the economy of a region. These periods are generally studied using spell length indicators or duration indices (SDIs). Fourteen SDIs are calculated to study the changes in wet/dry/warm/cold spells using daily precipitation and maximum and minimum air temperature from 23 centennial weather stations spread across Kansas during four time periods (through 1920, 1921–1950, 1951–1980 and 1981–2009) and two temporal scales (annual and seasonal). Among the SDIs, 3 represent wet spells [wet spell length (WetSL); AvWetSL; MaxWetSL]; 3 for dry spells [dry spell length (DrySL); AvDrySL; MaxDrySL]; 4 for warm spells [warm spell length (WarmSL); average warm spell length (AvWarmSL); maximum warm spell length (MaxWarmSL); WarmSDI] and 4 for cold spells [cold spell length (ColdSL); average cold spell length (AvColdSL); maximum cold spell length (MaxColdSL); ColdSDI]. In general, we observe that Kansas has 57–64 days year⁻¹ in a wet spell; 302–309 days year⁻¹ in a dry spell; ∼ 47 days year⁻¹ in each warm and cold spells. The average length of a wet/dryspell is ∼ 1.5 days, while the warm/cold spells are for 2 days. The maximum length of a wet spell is ∼ 4.4 days, a dry spell is ∼ 35 days and warm/cold spells is ∼ 6 days. We found the number of wet days increasing annually. Interestingly, the warm days during winter are increasing with an overall decrease in the days in warm and cold spells across both temporal scales.

KEY WORDS climate impact indices; wet spell length indices; dry spell length indices; warm spell duration indices; cold spell duration indices; Kansas

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1. Introduction

Ecosystems and water resources sectors are directly affected by climate (PaiMazumder and Mölders, 2009). Therefore the provision of adequate climate information at a regional/local scale is of paramount importance and climate impact indices are being increasingly used in different sectors to transfer information about climate change impacts to stakeholders (Pan et al., 2004). These indices representing periods of excessive warmth, cold, wetness or dryness are also known as duration indices (Alexander et al., 2006) or spell length indicators (Usman and Reason, 2004). In this study, we refer to them as spell length or duration indices (SDIs).

Extended periods with excessive or no rainfall or high or low temperatures cause stress on plants (Gray et al., 2006; Anandhi et al., 2013), animals (Alho and Silva, 2012) and humans (Smith et al., 2013). Such periods also have many ecological and hydrological consequences (Regonda et al., 2005; Gray et al., 2006; Anandhi et al., 2013). They affect plant growth, development and crop yield; milk production in livestock, reproductive capabilities of dairy bulls and conception in cows; changes in growing season and implications on the water cycle (Sivakumar, 1992; Kirschbaum, 2000; Barron et al., 2003; Anandhi, 2016) and can be detrimental to the economy of a region. Detailed geographical and temporal variations of the SDI are useful (1) as a key to watershed and agricultural modeling for water planning and management (Apipattanavis et al., 2007), (2) to compare how well-simulated precipitation is representing the observed record (Sharma and Lall, 1999), (3) to represent the precipitation occurrence process in statistical downscaling models, which are useful in projecting urban drainage (Willems and Vrac, 2011), (4) as a guide in breeding plant varieties of various maturity durations for different locations (Sivakumar, 1992), (5) to assess the climatic effect on agricultural commodities, (6) to manage the water resources throughout the world (Deni et al., 2010) and (7) to evaluate the changes in drought and wet periods (Usman and Reason, 2004).
Figure 1. Location map of the meteorological stations used within the nine climate divisions of Kansas.

The cold spell duration index (ColdSDI), warm spell duration index (WarmSDI), average wet spell length (AvWetSL), average dry spell length (AvDrySL), maximum consecutive wet days (MaxWetSL) and maximum consecutive dry days (MaxDrySL) are some of the common indices defined in the literature (Alexander et al., 2006). Changes in SDI can be indicative of regional changes in extreme weather and climate events over time. A number of studies have examined some of these indices for larger regions encompassing Kansas (Alexander et al., 2006; Tebaldi et al., 2006; Peterson et al., 2008; Zhang et al., 2009; Fodor et al., 2010). Conflicting trends are also observed in these studies. Also, less attention has been paid so far to the analysis of long-term variability of the spells (Zolina et al., 2012), and no studies have focused on the changes in SDI and compared the long-term trends in SDI for different time periods in Kansas.

Therefore, the main objective of this study was to examine long- (~100 years) and short-term (~30 years) variation and trends in Kansas for wet, dry and warm spells using 14 indices at four different time periods using 23 centennial weather stations at annual and seasonal scales. We hypothesize that this would explain previous conflicting trends observed in the region. Among the 14 indices, 3 indices are for wet spells [wet spell length (WetSL); AvWetSL; MaxWetSL]; 3 for dry spells [dry spell length (DrySL); AvDrySL; MaxDrySL]; 4 indices for warm spells [warm spell length (WarmSL); average warm spell length (AvWarmSL); maximum Warm spell length (MaxWarmSL); WarmSDI] and 4 indices are for cold spells [cold spell length (ColdSL); average cold spell length (AvColdSL); maximum cold spell length (MaxColdSL); ColdSDI].

2. Methodology

2.1. Data

Daily precipitation (RF) and maximum ($T_{max}$) and minimum ($T_{min}$) air temperature data were downloaded from the High Plains Regional Climate Center’s (HPRCC’s) website for 23 centennial weather stations across Kansas. The locations and periods of records are provided in Figure 1(a) and Table 1. The records extended to the late 1800s for a few stations and to the early 1900s for the rest; consequently, the start dates of the records are different, but the end dates are the same (2009).

2.2. Data quality and homogeneity

Weather stations are selected for their long-term quality based on criteria such as consistent observation times, low potential for heat-island bias and other quality assessments (Easterling et al., 1999; Robeson, 2002). The centennial stations had 95% of the data and the missing observations were handled in three ways. First the missing data were recovered from the original B91 forms with observed data. Second, if no observation was available, for a single missing observation the value was interpolated from prior and subsequent observations. Finally, if neither step one or two was applicable, an average of the three nearest neighbors was used to estimate missing values. The data were tested for 5/10 bias and undercount below 1.27 mm (0.05 inches)
Table 1. Details of the 23 meteorological stations used in Kansas.

| SN | COOPIDa | Station name | County | Climate division | Latitude | Longitude | Elevation | Record length |
|----|---------|--------------|--------|------------------|----------|-----------|-----------|---------------|
| 1  | 140365  | ASHLAND      | CLARK  | 7                | 37:11    | −99:45    | 1970      | 1900–2009     |
| 2  | 140405  | ATCHISON     | ATCHISON| 3                | 39:34    | −95:06    | 945       | 1893–2009     |
| 3  | 141699  | COLBY        | THOMAS | 9                | 37:10    | −101:04   | 3170      | 1900–2009     |
| 4  | 142432  | COLUMBUS     | CHEROKEE| 7                | 37:00    | −101:53   | 3599      | 1900–2009     |
| 5  | 142835  | ELKHART      | MORTON | 9                | 37:50    | −94:42    | 845       | 1895–2009     |
| 6  | 143527  | HAYS 1 S    | ELLIS  | 5                | 38:51    | −99:20    | 2010      | 1892–2009     |
| 7  | 143810  | HORTON       | BROWN  | 3                | 39:40    | −95:31    | 1030      | 1890–2009     |
| 8  | 143954  | INDEPENDENCE | MONTGOMERY| 9              | 37:14    | −95:42    | 805       | 1893–2009     |
| 9  | 144464  | LAKIN        | KEARNY | 7                | 37:56    | −101:14   | 2998      | 1893–2009     |
| 10 | 144531  | LARNED NO. 2 | PAWNEE | 8                | 38:11    | −99:05    | 2015      | 1903–2009     |
| 11 | 144972  | MANHATTAN    | RILEY  | 3                | 39:11    | −96:34    | 1065      | 1890–2009     |
| 12 | 145152  | MCPHERSON    | MCPHERSON| 5              | 38:22    | −97:36    | 1520      | 1890–2009     |
| 13 | 145175  | MEDICINE LODGE | BARBER | 8                | 37:17    | −98:33    | 1535      | 1891–2009     |
| 14 | 145363  | MINNEAPOLIS  | OTTAWA | 2                | 39:07    | −97:42    | 1322      | 1892–2009     |
| 15 | 145906  | OBERLIN      | DECATOR| 6                | 39:49    | −100:31   | 2610      | 1893–2009     |
| 16 | 146128  | OTTAWA       | FRANKLIN| 8              | 38:36    | −95:16    | 919       | 1900–2009     |
| 17 | 146378  | PHILLIPSBURG #2 | PHILLIPS | 9                | 39:44    | −99:18    | 1889      | 1891–2009     |
| 18 | 147093  | SAINT FRANCIS | CHEYENNE| 1              | 39:46    | −101:48   | 3362      | 1908–2009     |
| 19 | 147305  | SEDAN        | CHAUTAUQUA| 7              | 37:07    | −96:11    | 900       | 1890–2009     |
| 20 | 148235  | TRIBUNE 1 W | GREELEY| 4                | 38:27    | −101:46   | 3636      | 1900–2009     |
| 21 | 148495  | WAKEENY     | TREGO  | 4                | 39:01    | −99:52    | 2460      | 1893–2009     |
| 22 | 148964  | WINFIELD 3NE | COWLEY | 9                | 37:17    | −96:56    | 1235      | 1900–2009     |

aStation identification number. The first two digits designate a US state code, and the last four digits are assigned to stations within a state in general accordance with the alphabetical order of the station name.

by plotting the histogram (Daly et al., 2007). We observed almost negligible 5/10 bias and undercount after 1920 and they decreased further in later years (figure not shown).

Homogeneity assessment in the 23 stations and three variables (RF, \( T_{\text{max}} \) and \( T_{\text{min}} \)) was done (Table 2(a) and (b)). For this purpose we used two change point tests namely: CUSUM and Pettitt methods (Rahmani et al., 2015). In addition, mean and variance of July diurnal temperatures were plotted. We first identified the stations and year in which both the two change point detection methods indicated significant non-homogeneity. This resulted in fewer stations identified as non-homogenous compared to using just one method. Next, the years in which a change point was detected were studied. The stations with only change points in the 1930s and 1950s were removed from the non-homogenous group because the Great Plains are known for dramatic extremes in weather and climate such as the Dust Bowl droughts in the 1930s and back to back droughts in the 1950s (Burnette et al., 2010; Burnette and Stahle, 2013). Many stations observed change points before 1920, and, to have uniformity in the start dates, periods before 1920 were eliminated from our analysis of long-term trends. July diurnal temperatures, its mean and variance were plotted (figure not provided). The results from these figures were also cross checked with the results in table and additional in-homogeneities were identified (e.g. Medicine Lodge’s trend values during the 1981–2009 were removed from the trend plots due to higher variance during 1998 July). Stations having change points after 1920, other than the 1930s and 1950s, were removed from the long-term trend analysis but were included in certain short-term trend periods by considering the trends before and after the change points. For example, a change point in 1970 in station A was excluded from long-term trend analysis and 1951–1980 short-term trend analysis, but the station was included in short-term trend analysis during 1921–1950 and 1981–2009 time periods.

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2.3. Definitions of spell length duration indices (SDIs)

Fourteen SDIs are estimated in this study and defined in Table 3. The World Meteorological Organization Commission on Climatology (CCl) and the Climate Variability and Prediction (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDIs) jointly developed a core set of indices (Karl et al., 1999; Peterson and Manton, 2008). Among the 14 SDIs, 4 are from this core set relating to SDI (ColdSDI, WarmSDI, MaxDrySL and MaxWetSL). In this analysis, the spells ended in each year and did not continue into the next year at the annual scale, and spells ended in each season and did not continue into the next season at the seasonal scale. The thresholds of 90th and 10th percentiles of $T_{\text{max}}$ and $T_{\text{min}}$ are calculated for each day of the year using the procedure described in Zhang et al. (2009), 2009).

2.4. Steps in calculating SDI

Step 1: Obtain the daily $T_{\text{max}}$, $T_{\text{min}}$ and RF for 23 stations in Kansas (more details in Section 2.1).

Step 2: For each station, at annual and seasonal scales, calculate the number of days in the spells and the number of spells for SDI indices using Matlab codes developed in this study.

Step 3: Calculate the average number of days in the spells for each of the four time periods (through 1920, 1921–1950, 1951–1980 and 1981–2009) by summing the days in spells or the number of spells for each year or a season in a year then calculating the time-period averages.

Step 4: Fit least squares linear trends on each of the 14 SDIs (predictands $[T_i]$) using linear regression. Linear trends provide the simplest and most convenient way to describe the overall change over time in a data set and are widely used (Vincent et al., 2002). However, linear trends may be deceptive if the trend number is given in isolation and removed from the original data. The 14 predictands $[T_i]$ are the 3 wet spells [wet spell length (WetSL); Average wet spell length (AvWetSL); Maximum consecutive wet spell days (MaxWetSL)]; the 3 dry spells [dry spell length (DrySL); Average dry spell length (AvDrySL); Maximum consecutive dry spell days (MaxDrySL)]; the 4 warm spells [warm spell length (WarmSL); Average warm spell length (AvWarmSL); Maximum consecutive warm spell days (MaxWarmSL)]; the 3 cold spells [ColdSDI]; and the 4 cold spells [ColdSL; Average cold spell length (AvColdSL); Consecutive cold spell days (MaxColdSL); Cold spell duration index (ColdSDI)]. The predictands are evenly spaced time index ($t = 1, 2, 3, \ldots, n$) representing (1) the number of days in the spells and (2) the number of spells for SDI. Linear regression lines are fitted to each of these time series. The slope of the fitted line (b) or the linear trend value is in Equation (1).

$$b = \frac{\sum (t-\bar{t}) T_t}{\sum (t-\bar{t})^2}$$

Step 5: Test significance of trends. A variant of the t-test calculated the significance of the trend and accounted for the serial auto-correlation in the time series. In this study, each time series has one value in each year, so the series are considered as evenly spaced time points. So the denominator in Equation (1) is estimated using Equation (2). In Equation (2), n represent the number of data points (e.g. n = 30; for the 30-year time period, say 1920–1949).

$$\sum (t-\bar{t})^2 = \frac{n(n^2 - 1)}{12}$$

To test if the trend in $T_t$ is significantly different from zero, the ratio between the estimated trend and its standard
error \[ S_b \] is calculated (Equation (3)):

\[ t' = \frac{b}{S_b} \tag{3} \]

In Equation (3), \[ S_b \] is calculated using Equations (4) and (5) representing the variance of the residuals, with equivalent sample size \( n_e \) to account for lag 1 serial autocorrelation \( (r_1) \) in the time series.

\[ S_b = \frac{1}{n_e - 2} \sum (T_i - \bar{T})^2 \tag{4} \]

\[ n_e \approx n \frac{1 - r_1}{1 + r_1} \tag{5} \]

For large samples \( (n \geq 30) \), the calculated \[ t \] ratio \( (t') \) followed the \( t \)-distribution \( (Brown \text{ and } Kipfmueller, 2011) \) and was compared from a \( t \)-table with a critical \[ t \] value \( (t_{crit}) \) for a significance level at \( n-2 \) degrees of freedom. The detailed information can be obtained from Anandhi \textit{et al.} (2013a, 2013b), Wigley \textit{et al.} (2006) and Santer \textit{et al.} (2000). In this article, a trend is considered to be statistically significant if it is significant at the 5% level.

Step 6: Document spatio-temporal changes in the SDI for Kansas. Annual and seasonal times are the two temporal scales used in this study. Long term refers to the entire time period of record (start of records 1890s–1900s to 2009). Short term refers to the \( \sim30 \text{-year} \) time periods (through 1920, 1921–1950, 1951–1980 and 1981–2009); however, short-term linear trends were estimated for 1921–1950, 1951–1980 and 1981–2009 only.

3. Results

Results from the 14 SDIs across four time periods at 23 centennial stations in Kansas are provided in boxplots and time-series plots. Annual and seasonal SDI averages and trends are shown in boxplots (Figures 2–4), with each boxplot obtained from 14 to 23 values (one value from each homogenous station) for each period. The spread of the boxplot represents spatial variability across the stations. The four boxplots in each subplot and the subplots at annual and seasonal scales represent the temporal variability across the stations in the four periods. The median values from these boxplots are discussed in sections below.

3.1. Average days in annual and seasonal wet and dry spells

The results of six SDIs relating to wet and dry spells (WetSL; AvWetSL; MaxWetSL; DrySL; AvDrySL; MaxDrySL) are given in Figure 2. These numbers were obtained first by estimating the six SDIs for each year, and then they were averaged for the long- and short- time periods (100 and \( \sim30 \text{ year} \)) at two temporal scales (annual and seasonal).

During the past 100 years, by counting the total days in wet/dry spells in a year, we observed that, in general, annually Kansas has a wet spell for \( \sim57–64 \text{ days year}^{-1} \) (dry spell 302 to \( \sim309 \text{ days year}^{-1} \) – days in DrySL).

The annual average wet spells are of much shorter duration (AvWetSL: 1.5–1.6 days year\(^{-1}\)) than the dry spells (AvDrySL: 7–8 days year\(^{-1}\)). The annual maximum wet spells (MaxWetSL) last about 4.4 days year\(^{-1}\), while the maximum dry spell duration (MaxDrySL) is longer and lasts about 35–40 days year\(^{-1}\). The number of dry spell days is lowest during the latest time period (1981–2009) when compared to the remaining three time periods; however, these differences are not observed with AvDrySL.

There are seasonal differences in the wet/dry spells (columns 2–4 in Figure 2). Among seasons, summer (JJA) had the highest number of days in wet spells (20–21 days year\(^{-1}\)) and had the least variability among the 18 stations in the state. Although spring (MAM) too has similar high wet days, the variability among the stations was more here (17–21 days year\(^{-1}\)) during spring and summer, followed by fall (SON) with 12–14 days year\(^{-1}\) and winter (DJF) having the least number of days with 8–9 days year\(^{-1}\). The maximum duration of wet spells, MaxWetSL, is \( \sim3.5 \text{ days year}^{-1} \) during spring and summer, followed by fall (\( \sim3 \text{ days year}^{-1} \)) and winter (\( \sim2 \text{ days year}^{-1} \)). The most recent time period has the least variability among stations and lower WetSL and MaxWetSL than the other short-term time periods.

Winter had the highest DrySL (80–82 days year\(^{-1}\), followed by fall with 77–79 days year\(^{-1}\), spring with 71–75 days year\(^{-1}\) and summer with 71–72 days year\(^{-1}\). Summer had the least variability among the 23 stations in the state. AvDrySL was lowest in spring and summer (\( \sim6 \text{ days year}^{-1}\)). Fall had 8–10 days year\(^{-1}\) and winter had 12–13 days year\(^{-1}\). MaxDrySL was highest in the winter (29–33 days year\(^{-1}\)), followed by fall (25–29 days year\(^{-1}\)), spring (17–21 days year\(^{-1}\)) and summer (17–21 days year\(^{-1}\)). MaxDrySL was lowest in the most recent period compared to the others.

3.2. Average days in annual and seasonal warm and cold spells

The annual and seasonal results of eight SDIs relating to warm and cold spells are discussed here (Figure 3). Similar to the earlier section, these numbers are also obtained first by estimating the SDIs for each year and then averaging them for the long- and short- time periods (100 and \( \sim30 \text{ year} \)) at two temporal scales (annual and seasonal).

In Kansas, the Dust Bowl period (1930s) still stands out as the warmest period until 2009 (except spring season). This can be observed from higher values of all the warm spell indicators at the annual scale (Figure 3, column 1) during 1921–1950 [days in WarmSL, AvWarmSL, MaxWarmSL, WarmSDI]. However, the spatial variability in the warm spells in Kansas is the least during 1981–2009 (shorter boxplots represent less variability among stations). The average days in a warm or cold spell are \( \sim2 \text{ days year}^{-1} \).

There are seasonal differences in Kansas in the warm/cold spells (columns 2–4 in Figure 3) with summer having the higher days in warmer spells (\( \sim12 \text{ days year}^{-1}\))
and least spatial variability (≈12 days year$^{-1}$); spring has similar days but with a higher spatial variability. These are followed by fall and winter (≈10 days year$^{-1}$). The duration of maximum warm/cold spells is ≈4 days [MaxWarmSL, MaxColdSL] with winter MaxColdSL lowest during 1981–2009 winters.

3.3. Number of wet, dry, warm and cold spells – season and annual

The number of spells during annual and four seasons in Kansas is provided in Figure 4 for six SDIs [WetSL, DrySL, WarmSL, WarmSDI, ColdSL and ColdSDI]. Kansas had a similar number of wet and dry spells in a year (40–42 wet dry spells year$^{-1}$) in the last century. However, the number of days in the spell is different for wet and dry (provided in Section 3.1). Similar seasonal patterns are also observed. Summer had the highest number of spells (each has 13–14 spells year$^{-1}$), followed by spring (12–13 spells year$^{-1}$), fall (8–10 spells year$^{-1}$) and winter (6–8 spells year$^{-1}$). The summer season has the least spatial variability in the number of wet and dry spells.

The numbers of warm and cold spells year$^{-1}$ in Kansas in the last century are ≈22 spells year$^{-1}$ (Figure 4). The state had 5–6 warm spells each season. The Dust Bowl
Figure 3. Boxplots of average warm and cold SDIs across three time periods. Each boxplot is for a time period and temporal scale. Boxes show range of 25th–75th percentile, whiskers show extent of data up to 10th and 90th percentiles. Outliers represent data values beyond the maximum whisker extent. For each station, the SDI for all years during the time period and temporal scale are averaged to get a single value. Average values from each homogenous station, at a particular time period and temporal scale are used to create a boxplot. The acronyms in figure: The annual (A) averages are in column 1 and the four seasonal averages (winter-DJF, spring-MAM, summer-JJA, fall-SON) are in columns 2–5.

had a slightly higher WarmSDI than the other periods. In general, the number of warm spells (WarmSL) in winter is increasing, while the number of cold spells (ColdSL, ColdSDI) is decreasing annually and across all seasons.

3.4. Trends in wet and dry spells – seasonal and annual

Trends in annual and seasonal results of SDI relating to wet and dry spells combined for all 23 stations can be observed from boxplots (Figure 5), and individual station time-series plots are provided (Figure 6(a) and (b)). Differences in long- and short-term linear trends in WetSL, AvWetSL and MaxWetSL are observed at all 23 stations at both seasonal and annual scales and time periods (Figure 5). Among the stations, 14 exhibited a significant increase of 0.1–1.2 days decade$^{-1}$, three showed a decrease (two significant: Ashland and Saint Francis).
of 0.1–0.5 days decade$^{-1}$ in long-term WetSL values, and one station had no change (Figure 6(a)). The eastern part of Kansas had higher WetSL than the western part. Among the seasons, summer had the highest number of stations with significantly increasing trends in WetSL, followed by spring, with a decreasing trend. Similarly, significantly increasing trends up to 0.1 days decade$^{-1}$ are observed in MaxWetSL for summer at annual and seasonal scales.

DrySL and WetSL are complementary, so DrySL decreases with increases in WetSL (figure not shown). The western part of Kansas had higher DrySL than the eastern part. Nine stations exhibited a significant decrease of 0.1–1.4 days decade$^{-1}$ in long-term MaxDrySL, 6 stations had an increase of 0.1–0.5 days decade$^{-1}$ and two stations had no change. Among the seasons, winter and spring have the highest number of stations with significantly increasing trends in MaxDrySL, followed by fall and summer. Among the stations, Tribune had the highest decrease during winter and fall (1.9 and 1 days decade$^{-1}$, respectively), whereas in spring the highest decrease was 0.9 days decade$^{-1}$ (in Wakeeney) and 0.4 day decade$^{-1}$ (Lakin).

The linear trends in the WetSL indicate that the number of wet days increased annually (Figure 6(a)) and in summer across the three time periods (boxplots Figure 5). The winter and spring WetSL trends shifted from positive
3.5. Trends in warm and cold spells – season and annual

The trends in annual and seasonal results of SDI relating to warm and cold spells combined for all 23 stations can be observed from boxplots (Figure 7) and are to negative trends, and during fall, 1951–1980 had more positive trends. Among seasons, the variability of trends among stations was high in spring during 1921–1950 and 1981–2009 periods. Trends in AvWetSL and MaxWetSL are different and lower in 1951–1980.

Figure 5. Boxplots of linear trends in wet and dry SDI across three time periods. The trend values are estimated for a station and time period. Boxes show range of 25th–75th percentile, whiskers show extent of data up to 10th and 90th percentiles. Outliers represent data values beyond the maximum whisker extent. For each station, the SDI for all years during the time period and temporal scale are averaged to get a single value. Average values from each homogenous station, at a particular time period and temporal scale are used to create a boxplot. The acronyms in figure: The annual (A) averages are in column 1 and the four seasonal averages (winter-DJF, spring-MAM, summer-JJA, fall-SON) are in columns 2–5.
Figure 6. Ten-year moving averages (thin blue lines) and linear trends in (a) WetSL, (b) MaxDrySL, (c) WarmSL, and (d) ColdSL in the 23 centennial stations in Kansas are shown. Long-term trends are calculated for the entire period of record (red line), and multiple trend lines are calculated for three short-term time periods (1921–1950, 1951–1980 and 1981–2009 – short black lines). The subplots in (a)–(d) are arranged in their approximate geographical locations. The numbers in the subplots represent the trend in days decade$^{-1}$ and significant trends are in italics and bold. The long-term trend value is in red (top), and the three values in black (bottom) are the short-term trends for the three time periods. Trend lines and values from non-homogenous stations (listed in Table 2) are not provided for long-term in the figures, while short-term trend lines are plotted provided homogeneity issues do not impact them.
provided for station-selected time-series plots (Figure 6(c) and (d)). WarmSL generally decreased at an annual scale (Figure 7) in the last century, with 11 stations having a decrease of $-2$ to $-0.2$ days decade$^{-1}$ and 3 stations having an increase of $0.1-0.9$ days decade$^{-1}$ (Figure 6(c)). Atchison, in eastern Kansas, had the highest decrease, and Tribune, in western Kansas, had the highest increase. Similar decreasing trends are observed in the length of maximum warm spells (MaxWarmSL); 17 stations had a decrease of $-0.4$ to $-0.1$ days decade$^{-1}$ and 6 stations had no change, with Independence in eastern Kansas having the highest decrease. Decreasing trends were also observed in AvWarmSL. In short-term trends, winter had more decreasing trend in WarmSL (boxplots, Figure 7). Winter had increasing trends in 21 stations (the rest displayed no trend, figure not shown) and Tribune had the highest increase of $0.4$ days decade$^{-1}$. Summer had higher decreases (17 stations with trends of $-1.3$ to
−0.1 days decade⁻¹), followed by fall (17 stations with trends of −0.8 to −0.1 days decade⁻¹) and spring (15 stations with −0.3 to −0.1 days trend⁻¹). Similar decreasing trends in MaxWarmSL were also observed in summer and fall seasons, with trends of −0.4 to −0.1 days decade⁻¹; however, the trends are mixed and lower in winter and fall +/−0.1 day decade⁻¹.

In Kansas, ColdSL also decreased at the annual scale in the last century at 17 stations (−3.6 to −0.1 days decade⁻¹), as observed in Figure 6(d). Elkhart, in western Kansas, had the highest decrease. The length of maximum cold spells also decreased (MaxColdSL, −0.2 to −0.1 days decade⁻¹). All seasons had a decrease in ColdSL, but the decrease was more consistent in winter, with 16 stations reporting a
decrease. The rate of decrease in ColdSL was highest in summer. The highest decrease was in summer (Hays had highest decrease of −1.3 days decade\(^{-1}\)), followed by spring (Elkhart had the highest decrease of −1.0 days decade\(^{-1}\)), winter (Elkhart had the highest decrease of −0.9 days decade\(^{-1}\)) and fall (Elkhart had the highest decrease of −0.7 days decade\(^{-1}\)). Similar decreasing trends of up to −0.2 days decade\(^{-1}\) were observed with MaxColdSL in the four seasons.

The pattern of 30-year trends in the three time periods can be observed from boxplots (Figure 7). In general, for WarmSL, AvWarmSL and maxWarmSL, trends in the 1951–1980 time period are lower than the other two time periods at annual and seasonal scales (except spring). The trends in ColdSL during 1951–1980 are higher than the other two time periods in winter; however, in the summer, the trends in the most recent period are higher, and there was no visible difference during the fall season. AvColdSL trends and their variability across the 23 stations increased across the three time periods, and maxColdSL trends increased in spring.

3.6. Trends in the number of spells – annual

The number of wet spells during the last century (Figure 8) increased at 13 stations (0.02–0.56 spells decade\(^{-1}\)) and decreased in 5 stations (−0.01 to −0.42 spells decade\(^{-1}\)). However these long-term trends contradict the decreases we found during the latest time period (short term 1981–2009) (Figure 9), indicating the decrease is not sufficient to modify the long-term trends. Wakeeny had the highest increase, whereas Colby had the highest decrease in the long-term numbers. Similar to WetSL, decreasing trends in number of dry spells were observed for shorter time periods (Figure 8), and increasing trends were observed in the long term.

The trends in the number of warm spells (WarmSL, WarmSLI) and cold spells (ColdSL, ColdSDI) in 1951–1980 were higher than in the other two periods. From the long-term trends in the last century, 8 stations had decreases (−0.01 to −0.49 spells decade\(^{-1}\)), whereas 6 stations had increases (0.01–0.52 spells decade\(^{-1}\)); however, all 14 stations showed a long-term decrease in the number of WarmSDI spells (0.01–0.16 spells decade\(^{-1}\)). The number of warm spells during the Dust Bowl period was highest in most stations in the state. From the short-term trends in ColdSL and ColdSDI, the trends in 1951–1980 were lower than those of the other two time periods. ColdSL and ColdSDI decreased in the long-term trends at 17 (−0.02 to −1.77 spells decade\(^{-1}\)) and 16 stations (−0.01–0.11 spells decade\(^{-1}\)), respectively.

4. Discussion and conclusion

Both short-term (30-year time periods) and long-term analysis (100-year time periods) of wet, dry and cold spells in Kansas were studied using the 14 SDIs estimated from RF, \(T_{\text{max}}\) and \(T_{\text{min}}\) from 14–23 centennial stations. Based on the linear trends in the long-term records, there was a general increase across Kansas in days in WetSL, MaxWetSL, and number of WarmSL in winter season and a decrease in DrySL, MaxDrySL, WarmSL, AvWarmSL, MaxWarmSL, ColdSL, AvColdSL, MaxColdSL and the number of wet, dry, warm and cold spells in a year. Our data indicated that on average, the state:

1. has WetSL of 57–64 days year\(^{-1}\), with AvWetSL of \(~1.5\) days and MaxWetSL of \(~4.4\) days (summer has the highest WetSL, followed by spring, fall and winter);
2. has DrySL of 302–309 days year\(^{-1}\), with AvDrySL of \(~7.5\) days and MaxDrySL of \(~35\) days (winter season has the highest DrySL, followed by fall, spring and summer seasons);
3. has WarmSL of \(~47\) days year\(^{-1}\), with AvWarmSL of \(~2\) days and MaxWarmSL of \(~6\) days;
4. has ColdSL of \(~47\) days year\(^{-1}\), with AvColdSL of \(~6\) days and MaxColdSL of \(~5.7\) days; and
5. receives \(~41\) wet and dry spells year\(^{-1}\), \(~22\) warm spells year\(^{-1}\) and \(~24\) cold spells year\(^{-1}\).

The trends in SDI are found to vary across stations, time periods and time scales. Based on the long-term records, there was an annual increase in WetSL (0–1.2 days decade\(^{-1}\) at 14 stations) and number of wet spells (0.02–0.56 in 13 stations) and a similar decrease in DrySL. An increase of up to 0.1 days decade\(^{-1}\) was observed in MaxWetSL along with a decrease of −1.4 to −0.1 days decade\(^{-1}\) at 13 stations. The decrease in WarmSL was −2 to −0.2 days decade\(^{-1}\), ColdSL was −3.6 to −0.1 days decade\(^{-1}\) and maxWarmSL and maxColdSL decreased by up to −0.2 days decade\(^{-1}\).

The trends in MaxDrySL from earlier studies are conflicting. Frich et al. (2002) and Tebaldi et al. (2006) found an overall decreasing trend in MaxDrySL for the entire state of Kansas in 1946–1999 and 1960–2000, whereas Kiktev et al. (2003) found an increase of 0–1 wet days decade\(^{-1}\) and an increase in MaxDrySL of 0–2 days decade\(^{-1}\) in 1950–1995. Our results explain this discrepancy because most regions in Kansas showed decreasing MaxDrySL (8 stations with −0.1 to −1.4 days decade\(^{-1}\), and some showed increasing MaxDrySL (6 stations; 0.1–0.5 days decade\(^{-1}\)). Depending on the stations used in the earlier studies, the trends are positive or negative. The higher values of MaxDrySL during the Dust Bowl and in the 1950s at some stations influence the direction of trends in MaxDrySL; furthermore, increases in wet days from our results and other studies (Kiktev et al., 2003; Tebaldi et al., 2006) could be another reason for the decreasing trends in dry spell indicators. The winter and spring seasons had increasing trends in dry spells, however, in 1981–2009.

In Kansas, we found a general decrease in WarmSL (−2 to −0.2 days decade\(^{-1}\) in 11 stations) at an annual scale in the last century, and 3 stations have increases of 0.1–0.9 days decade\(^{-1}\). The decreasing trends occurred because, before 2009, the warmest period in the state was
Figure 8. Ten-year moving averages (thin blue lines) and linear trends in the number of (a) WetSL, (b) WarmSL, (c) WarmSDI and (d) ColdSL in the 23 centennial stations in Kansas are shown. Long-term trends are calculated for the entire period of record (red line), and multiple trend lines are calculated for three short-term time periods (1921–1950, 1951–1980 and 1981–2009 – short black lines). The subplots in (a)–(d) are arranged in their approximate geographical locations. The numbers in the subplots represent the trend in days decade\(^{-1}\), and significant trends are in italics and bold. The long-term trend value is in red (top), and the three values in black (bottom) are the short-term trends for the three time periods. Trend lines and values from non-homogenous stations (listed in Table 2) are not provided for long-term in the figures, while short-term trend lines are plotted provided homogeneity issues do not impact them.
the Dust Bowl in the 1930s, and the analysis did not include the warmer period, 2010–2013. Daily temperature observations constructed since 1828 also indicated that the 19th century was fundamentally cooler than the 20th and early 21st centuries (Burnette et al., 2010); however, studies including data from the 1950s showed an increase in warm spells. For example, Alexander et al. (2006) found an increase of 0–3 and 0–4 days decade$^{-1}$ in the days with warm and cold spells in 1951–2003, and Donat et al. (2013) found a lower increase of 0–1 day 60 years$^{-1}$ in 1951–2010. These increasing trends could be because the WarmSL trends in 1950–1980 are lower and ColdSL are higher than in the 1981–2000 time period. These results could be related to the area of cooling in the central United States termed the ‘warming hole’ (Pan et al., 2004).

Results of our long-term and short-term analysis of wet, dry, warm and cold spells using 14 SDIs on 14–23 centennial stations in Kansas improve our understanding of spells, add local precision to earlier findings for some SDIs that encompassed larger areas and help explain the differences in trends from some earlier studies. Future work can build on this research by exploring the external forces responsible for the changes and comparing the changes with model simulations (past and future).
Figure 9. Distributions of linear trends in the annual average number of wet, dry, warm and cold spells (WetSL, WarmSL, DrySL, WarmSDI, ColdSL, ColdSDI) across three time periods (1921–1950, 1951–1980 and 1981–2009). Boxes show range of 25th–75th percentile, whiskers show extent of data up to 10th and 90th percentiles. Outliers represent data values beyond the maximum whisker extent. For each station, the SDI for all years during the time period and temporal scale are averaged to get a single value. Average values from each homogenous station, at a particular time period and temporal scale are used to create a boxplot. The acronyms in figure: The annual (A) averages are in column 1 and the four seasonal averages (winter-DJF, spring-MAM, summer-JJA, fall-SON) are in columns 2–5.

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References

Alexander L, Zhang X, Peterson T, Caesar J, Gleason B, Klein Tank A, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A. 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res.: Atmos. (1984–2012) 111: D05109.

Alho CJ, Silva JS. 2012. Effects of severe floods and droughts on wildlife of the Pantanal Wetland (Brazil) – a review. Animals 2: 591–610.

Anandhi A. 2016. Growing degree days – ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas. Ecol. Indic. 61: 149–158.

Anandhi A, Perumal S, Gowda PH, Knapp M, Hutchinson S, Harrington J Jr, Murray L, Kirkham MB, Rice CW. 2013a. Long-term spatial and temporal trends in frost indices in Kansas, USA. Clim. Change 120: 169–181.

Anandhi A, Zion MS, Gowda PH, Pierson DC, Lounsberry D, Frei A. 2013b. Past and future changes in frost day indices in Catskill Mountain region of New York. Hydrol. Processes 27: 3094–3104.

Appattanavis S, Pedestal G, Rajagopalan B, Katz RW. 2007. A semi-parametric multivariate and multisite weather generator. Water Resour. Res. 43: W11401.

Barron J, Rockström J, Gichuki F, Hatibu N. 2003. Dry spell analysis and maize yields for two semi-arid locations in East Africa. Agric. For. Meteorol. 117: 23–37.

Brown DP, Kipfmueller KF. 2011. Pacific climate forcing of multidecadal springtime minimum temperature variability in the Western United States. Ann. Assoc. Am. Geogr. 102: 521–530, doi: 10.1080/00045608.2011.627052.

Burnette DJ, Stahle DW. 2013. Historical perspective on the dust bowl drought in the central United States. Clim. Change 116: 479–494.

Burnette DJ, Stahle DW, Mock CJ. 2010. Daily–mean temperature reconstructed for Kansas from early instrumental and modern observations. J. Clim. 23(6): 1308–1333.

Daly C, Gibson WP, Taylor GH, Doggett MK, Smith JL. 2007. Observer bias in daily precipitation measurements at United States cooperative network stations. Bull. Am. Meteorol. Soc. 88: 899–912.

Deni SM, Jemain AA, Ibrahim K. 2010. The best probability models for dry and wet spells in Peninsular Malaysia during monsoon seasons. Int. J. Climatol. 30: 1194–1205, doi: 10.1002/joc.1972.

Donat MG, Alexander LV, Yang H, Durre I, Vose R, Caesar J. 2013. Global land-based datasets for monitoring climatic extremes. Bull. Am. Meteorol. Soc. 94: 997–1006.

Easterling DR, Karl TR, Lawrimore JH, Del Greco SA. 1999. United States historical climatology network daily temperature, precipitation, and snow data for 1871–1997. ORNL/CDIAC-118, NDP-070, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy: Tennessee, 82pp. http://aprs.ornl.gov/~webworks/cppry/200207pt/101454.pdf (accessed 2 February 2016).

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Fodor N, Dobí I, Mika J, Szeidl L. 2010. MV-WG: a new multi-variable weather generator. *Meteorol. Atmos. Phys.* **107**: 91–101.

Frich P, Alexander L, Della-Marta P, Gleason B, Haylock M, Klein Tank A, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Clim. Res.* **19**: 193–212.

Gray ST, Betancourt JL, Jackson ST, Eddy RG. 2006. Role of multi-decadal climate variability in a range extension of pinyon pine. *Ecology* **87**: 1124–1130.

Kiktev D, Sexton DM, Alexander L, Folland CK. 2003. Comparison of modeled and observed trends in indices of daily climate extremes. *J. Clim.* **16**(22): 3560–3571.

Kirschbaum MU. 2000. Forest growth and species distribution in a changing climate. *Tree Physiol.* **20**: 309–322.

Pan Z, Arritt RW, Takle ES, Gutowski WJ Jr, Anderson CJ, Segal M. 2004. Altered hydrologic feedback in a warming climate introduces a ‘warming hole.’. *Geophys. Res. Lett.* **31**: L17109–L17112.

Peterson TC, Zhang X, Brunet-India M, Vázquez-Aguirre JL. 2008. Changes in North American extremes derived from daily weather data. *J. Geophys. Res. Atmos.* **(1984–2012)** **113**: D07113.

Regonda SK, Rajagopalan B, Clark M, Pitlick J. 2005. Seasonal cycle shifts in hydroclimatology over the Western United States. *J. Clim.* **18**: 372–384, doi: 10.1175/jcli-3272.1.

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