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Abstract Three new 159-year long reconstructions of spring, summer, and growing season precipitation totals were developed for northeastern Kansas and northwestern Missouri from five station clusters (Lawrence, Leavenworth, and Manhattan, Kansas; Miami and Oregon, Missouri). Nonstandard observation practices are inherent in the early meteorological data, which can induce an undercount in precipitation measurements, particularly during the cool season. Threshold analyses of these five station clusters indicated undercount can be lessened for daily precipitation totals of 0.50 in. and greater during the warm season ("half-inch threshold"). Therefore, "adjusted reconstructions" of total precipitation for the spring (AMJ), summer (JA), and growing season (AMJJA) were derived using the "half-inch threshold" totals and an estimate of the missing amount between 0.00 and 0.50 in. based on an average of the modern observations at each station (or the nearest available station). The new precipitation reconstructions suggest that the most severe spring drought may have occurred during the mid-19th century, although the potential for undercount is likely highest during the spring season. The most severe summer precipitation deficit is estimated during the 1930s Dust Bowl drought, followed by the summer drought of the 1910s. When precipitation is totaled for the entire growing season, the mid-19th century and Dust Bowl droughts were of approximately equal magnitude and duration in this reconstruction. However, the integration of precipitation and temperature into seasonal measures of effective moisture, using a new 19th century temperature reconstruction for northeastern Kansas, indicates that the 1930s growing season moisture deficit was the most severe and sustained since 1855, highlighting the extraordinarily high temperatures recorded during the 1930s Dust Bowl drought.

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1 Introduction

The Dust Bowl drought is the most severe and sustained drought across the central United States during the era of instrumental meteorological observations. The precipitation deficit across the state of Kansas during the decade of the 1930s was −37.20 in., or the equivalent to the normal amount of precipitation that would fall over 1.5 years (Flora 1948). Precipitation deficits were most extreme across the Great Plains in 1934 and 1936, when average Palmer Drought Severity Indices (PDSI) exceeded −5 and −4, 3.5 and 2.8 standard deviations below the 1870–2005 mean, respectively (Dai et al. 2004). Two of the hottest summers in Kansas over the past 180 years also occurred in 1934 and 1936 (Burnette et al. 2010). Daily maximum temperatures of 105–110 °F (40.6–43.3 °C) were common during those summers, and many stations recorded daily maximum temperatures above 120 °F (48.9 °C) in July 1936 during the most intense heat wave to ever strike the United States (Flora 1948; Burt 2004).

The extreme 1930s drought and ecological impacts resulted in one of the worst environmental disasters in American history. Worster (2004) suggested that anthropogenic land degradation aggravated by economic depression caused many of the dust storms and subsequent societal impacts during the Dust Bowl drought, which included farm abandonment and population loss (Warrick and Bowden 1981). However, Cunfer's (2005) analyses indicated that the percentage of plowed farmlands was actually low in the region where most dust storms occurred. Cunfer (2005) argues that spatial anomalies in high temperature, low precipitation, and low soil moisture better explain dust storm geography than do cultivation patterns coupled with drought. Increased saltation associated with drought-blighted sandy soils may have contributed to wind erosion in rangeland ecosystems (Cunfer 2005). Cunfer (2005) suggests that natural forces were as important as human activities in generating the dust storms during the Dust Bowl drought.

In the instrumental climate record of the Great Plains, the Dust Bowl was part of a series of droughts separated by approximately 20 years (Borchert 1971). This observation fueled speculation of a drought "cycle" related to the 22-year double sunspot cycle (Bollinger 1945; Mitchell et al. 1979), the 18.6-year lunar tidal cycle (Currie 1981, 1984a, b), or a complex interaction of both solar and lunar cycles (Bell 1981a, b). These apparent "cycles" have been criticized because no reasonable physical explanation has been able to connect the solar and lunar activity to climate variations in the lower atmosphere (Pittock 1978, 1983; Namias 1983; Cook et al. 1997). Nevertheless, a bidecadal "rhythm" of drought in the Great Plains continues to be found at certain time intervals in some proxy data including tree-ring reconstructions of the PDSI across North America (Cook and Krusic 2004; Herweijer et al. 2007).

Tannehill (1947), Namias (1983), and many others argued that on a broad scale, ocean-atmospheric variability over the Pacific Ocean has a strong influence on drought occurrence across North America. Recent climate modeling experiments provide support for this hypothesis, and indicate that the sea-surface temperature (SST) patterns observed during the 1930s can account for much of the decadal drought variance over North America during the Dust Bowl (Schubert et al. 2004; Seager et al. 2005a, b; Herweijer et al. 2007). Cook et al. (2008, 2009, 2011) concluded that model simulations during the Dust Bowl can be further improved by incorporating changes in vegetation cover and dust emissions into the forcing, which suggests that land-surface feedbacks as well as ocean-atmospheric teleconnections were involved in the spatial pattern of the Dust Bowl drought.

Proxy climate data suggest that the Dust Bowl was exceeded by megadroughts during early colonial and medieval times (Woodhouse and Overpeck 1998; Stahle et al. 2000; Cook et al. 2004; Herweijer et al. 2007). Fye et al. (2003) used tree-ring reconstructed PDSI to suggest that the mid-19th century "Civil War" era drought resembled the severity and persistence of the Dust Bowl drought, although this 1860s era drought extended across the southern Great Plains into northern Mexico and the 1930s drought was concentrated in the central and northern Great Plains and northern Rocky Mountains.

Flora (1948) argued that the 1860s drought in Kansas "ranks with that of the 1930's as one of the two most severe and prolonged periods of dry weather on State's record." However, Flora (1948) used unscreened instrumental precipitation records from Leavenworth and Manhattan, Kansas, that are subject to undercount due to poor gauge observations. The United States Army Surgeon General, Smithsonian Institution, and Signal Service recorded temperature and precipitation on a daily basis in the central United States beginning in the 1820s, but many of these records are hopelessly biased by poor thermometer exposure, poor rain gauge placement, and other primitive observational practices. Nevertheless, careful and highly selective analyses of early rain gauge and thermometer records may recover useful data from a few of these historical observations (e.g., Mock 2000; Mock et al. 2007; Burnette et al. 2010). In this paper, spring, summer, and growing season precipitation records are recovered and reconstructed for 159 years over northeastern Kansas and northwestern Missouri, and are then used with new temperature reconstructions for eastern Kansas (Burnette et al. 2010) to place the decadal Dust Bowl drought into the perspective of 19th century climate variability.

2 Methods

Historical precipitation observations can be impacted by non-climatic biases that must be assessed and minimized. Problems with 19th century precipitation data can include conversion of snowfall to liquid equivalent, high placement of the rain gauge that can cause lower liquid accumulation with higher wind speed, infrequent observation of the precipitation gauge which can allow water loss due to evaporation, changes in the physical environment around the gauge (e.g., tree growth, building construction), and changes in instrumentation (Larson and Peck 1974; Mock 1991, 2000; Daly et al. 2007). These problems can lead to undercounted precipitation, which is commonly found in historical precipitation records. Most of the undercount problem occurs in the cold season (Larson and Peck 1974; Mock 1991, 2000), and therefore, this study was restricted to the warm season (April–August). Poor gauge exposure and observer inattentiveness to small rain events can impact the quality of the precipitation data even in the warm season, but these problems can be minimized by careful screening and selection of the best available records.

a. Reconstruction of seasonal precipitation amounts

The reconstruction of spring, summer, and growing season precipitation totals for northeastern Kansas and northwestern Missouri involved the acquisition of historical and modern instrumental precipitation observations from five clusters of stations that were the most continuous from 19th century to present (Fig. 1). These data were then screened for quality to detect data segments with a probable bias (see electronic supplementary material for details on data screening and integration of historical and modern precipitation). The precipitation record was constructed for each month of the warm season from April 1850 to August 2008 by summing the daily precipitation amounts at all available station clusters per month and dividing by the number of station clusters. The interquartile range was used to approximate the uncertainty for each monthly estimate. Potentially useful precipitation data from Fort Leavenworth do exist prior to 1850, but these data have not been included in this reconstruction because of frequent observer changes and the absence of independent records for comparative

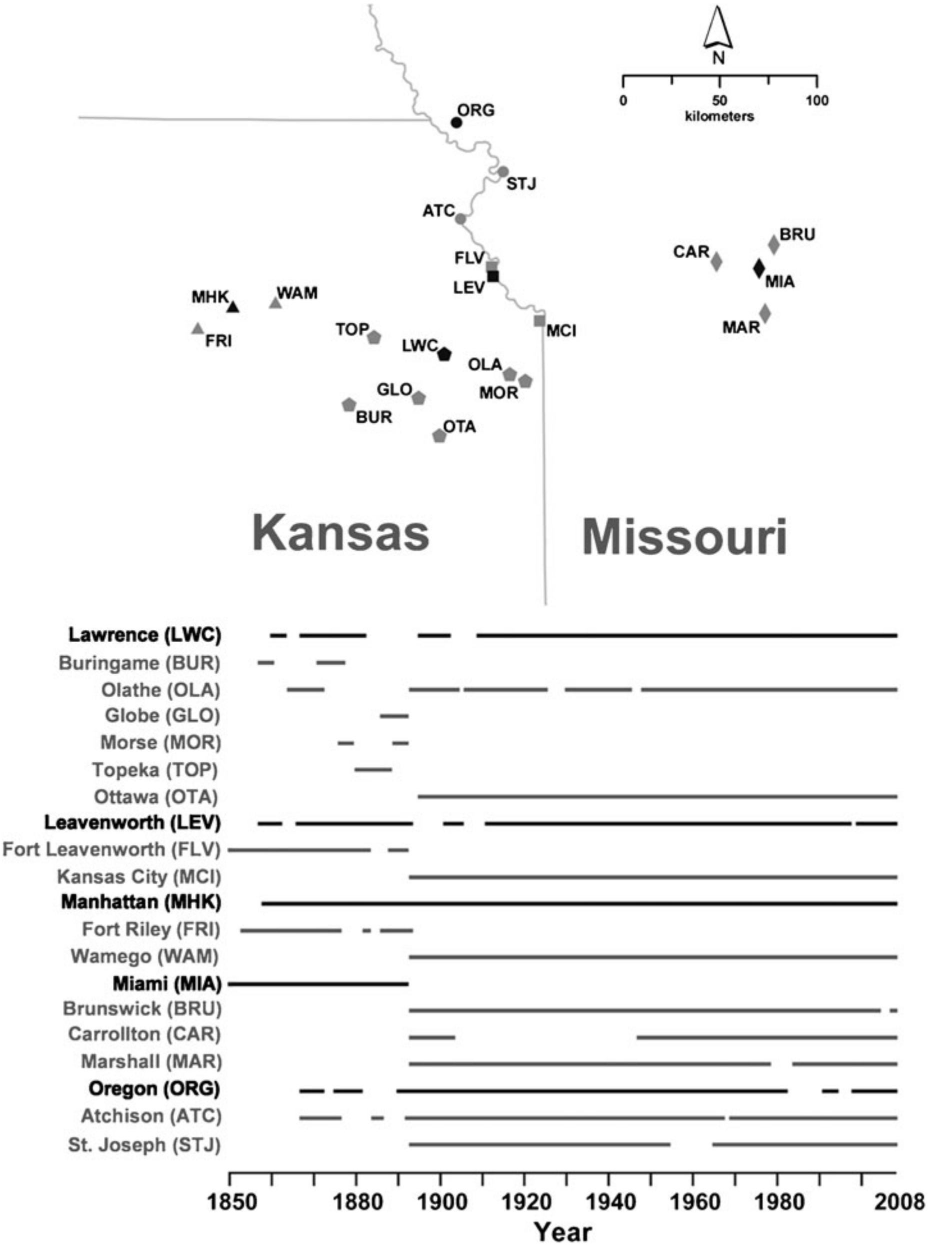

Fig. 1 The 159-year precipitation reconstruction for northeastern Kansas and northwestern Missouri was computed from discontinuous data available from 20 weather stations (symbols denote station clusters, primary stations *black*, secondary stations *gray*; *top*). The time coverage of the historical (pre-1893) and modern (1893–2008) observations is indicated by the *horizontal bars* (*bottom*)

study. There are two or more station clusters involved in the reconstruction from 1850 onward, three or more starting in 1854, and four or more starting in 1857.

Months included in the spring, summer, and growing season reconstructions were chosen to 1) minimize the influence of cold season precipitation on amounts and 2) provide an estimate of total precipitation during the growing season. For the purposes of this paper, spring was defined as April through June, summer as July and August, and the growing season as April through August (cf., Wahl 1968; Mock 1991, 2000). Station average precipitation amounts for each month and their associated interquartile range were summed to produce the regional reconstructions of spring, summer, and growing season precipitation.

b. Adjusting the seasonal reconstructions

Because the undercount bias in 19th century precipitation measurements appears to be most serious for minor rainfall events, analyses were performed on the historical and modern data to identify the minimum daily precipitation threshold where undercounting of low precipitation amounts could be minimized. These threshold analyses were performed on daily precipitation totals and precipitation day counts, and indicated that undercount biases were minimized with daily precipitation events at or above 0.50 in. ("half-inch threshold"; see Burnette 2009). Analyses also indicated that undercount of small precipitation events had impacted the raw precipitation reconstructions prior to 1925 (see Burnette 2009). Therefore, "adjusted" seasonal precipitation reconstructions were developed using the "half-inch threshold" totals and an estimate of the missing amount between 0.00 and 0.50 in. This missing amount was based on the average precipitation below 0.50 in. in the modern instrumental data from 1979 to 2008, and it was assumed that the proportion of small amounts to amounts ≥0.50 in. was the same in the older historical records. The threshold analysis was performed at each of the five station clusters on a monthly basis, and the monthly totals were then averaged to complete the "adjusted" regional reconstruction (Fig. 2, Burnette 2009).

Average rainfall over northeastern Kansas and northwestern Missouri from 1979 to 2008 was 359, 215, and 574 mm in the spring, summer, and growing seasons, respectively. The adjustments performed from 1850 to 1924 resulted in an average increase of 8, 4, and 12 mm, or approximately 2 % of the three seasonal reconstructions. The largest single year adjustments represent 13 % of the rainfall typically observed in each season. Figure 2 illustrates the magnitude of these adjustments relative to the raw data for each season. Adjustments were more positive for the 19th century data, which were much more likely to be biased by undercount. Because precipitation may not have been undercounted during some years, the addition of the average precipitation below 0.50 in. to all years in a problem segment could theoretically lead to some overestimation of precipitation in the historical period.

c. Estimation of the effective moisture index

Time series of effective moisture anomalies were developed from 1855 to 2008 using the monthly "adjusted" precipitation data from this study and the reconstructed daily mean temperature for Manhattan, Kansas (Burnette et al. 2010; temperature data before 1855 have additional uncertainty and were not used). Historical climate data are more restricted to temperature and precipitation farther back in time, and the Thornthwaite method has the advantage of only requiring monthly mean temperature. Thus, this method was used to transform the temperature data into estimates of potential evapotranspiration (Thornthwaite 1948; see supplementary material for details).

Effective moisture was calculated per month by computing the difference between the adjusted precipitation totals and the potential evapotranspiration. These monthly

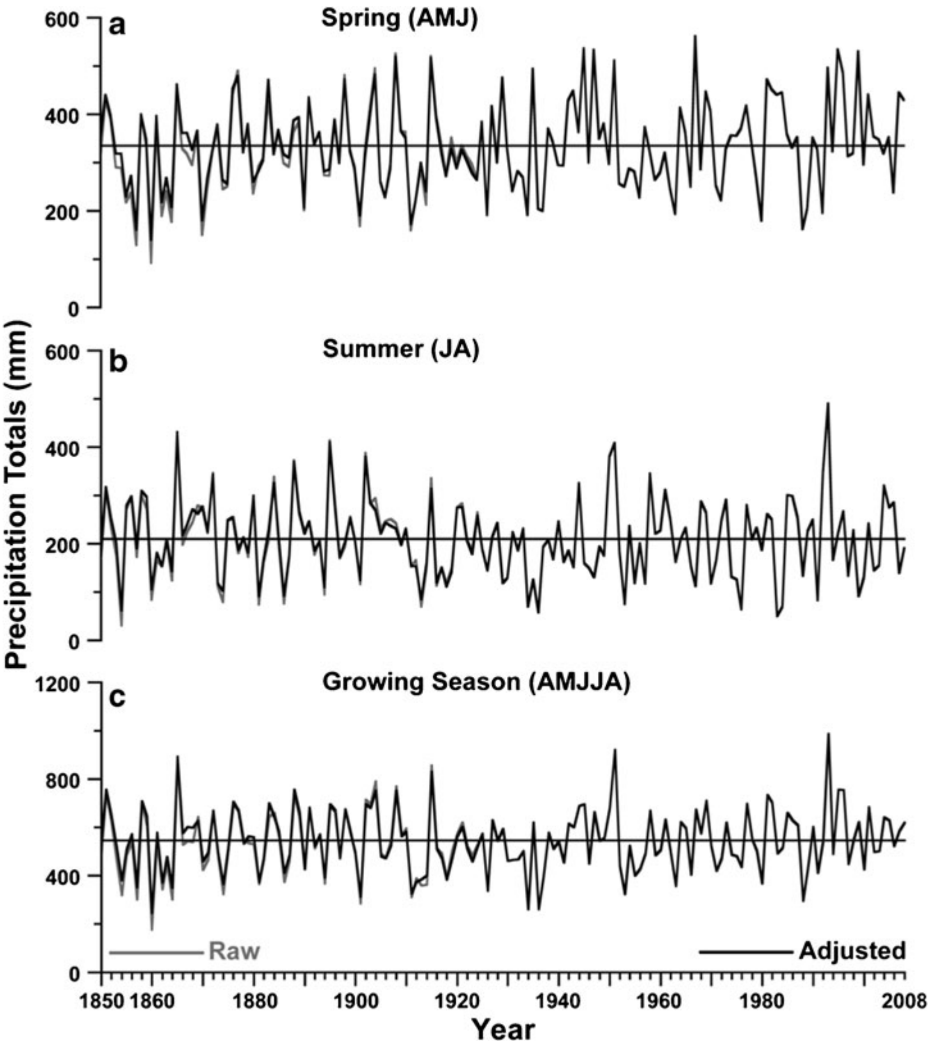

Fig. 2 Comparison of the raw (*gray*) and adjusted (*black*) seasonal precipitation reconstructions from the five station regional average. No corrections were applied after 1924

values were then transformed into anomalies by subtracting the 1855–2008 median and then summed on a seasonal basis. The resulting estimate of the moisture budget is positive when temperatures are low and precipitation amounts are high, and negative when temperatures are high and precipitation amounts are low. This estimate of effective moisture does not account for soil moisture storage or other lag effects.

d. Homogeneity assessment

Despite the efforts to minimize the undercount in these early meteorological records, nonstandard methodology, changes in observers, and other problems that have impacted these observations irregularly through time are difficult to assess. Thus, it is possible that the 19th century precipitation estimates may yet contain hidden biases. There are very few long instrumental precipitation records from elsewhere in the vicinity with which to test the accuracy of these historical precipitation measurements. The spatially discontinuous convective nature of warm season precipitation also complicates homogeneity assessment in these data. Documentary accounts of the weather can provide a critical reality check on precipitation estimation (e.g., Mock et al. 2007), but a compilation and assessment of Kansas documents has not yet been attempted.

Double mass analyses were performed on the growing season precipitation data prior to 1893 between each "adjusted" station cluster during their common data periods (Kohler 1949; Burnette 2009). Five potential breakpoints were detected in the 10 possible comparisons from 1850 to 1892, and these were tested to determine if the slopes of a linear regression fit to the data before and after the breakpoint were significantly different. All five were statistically significant ($P < 0.05$), and three of the five occurred in the early 1870s. This could be due to inhomogeneity remaining in the individual station records. It could also be a function of the localized nature of warm season precipitation, and an average of the five station clusters might be more internally homogeneous.

Precisely dated tree-ring chronologies that are sensitive to growing season precipitation amounts have been used to assess the homogeneity of precipitation and streamflow time series (Cleaveland and Stahle 1989). Tree-ring chronologies developed from old-growth post oak (*Quercus stellata*) trees at four sites in southeastern Kansas (Stahle 1982) were averaged, and then transformed into estimates of April through June precipitation with linear regression to test the homogeneity of the adjusted spring precipitation reconstruction using double mass analysis (Kohler 1949; Burnette 2009). April through June was chosen because that period best corresponds with the growth of post oak tree rings in the southern Great Plains [low order persistence was also removed from the tree-ring time series with autoregressive modeling (Stahle and Cleaveland 1988)]. No potential breakpoints were detected in the double mass analysis (see Burnette 2009), which suggests that a regional average of the five station clusters for April through June might be internally homogenous.

Correlations between the growing season effective moisture index and the Dai et al. (2004) gridded instrumental PDSI data averaged from April to August are presented in Fig. 3, and indicate that the reconstructed moisture index is correlated with instrumental PDSI values across the central United States. However, there are large differences in the size of the area exhibiting strong correlation with the Kansas-Missouri moisture index, when the correlations are segmented into non-overlapping 30-year time periods (Fig. 3). The smallest correlation field is observed for the 1870–99 subperiod (Fig. 3a), which might indicate problems with the temperature or precipitation data used for the reconstructed moisture index. Alternatively, the reduced correlation field in the late-19th century (Fig. 3a) might simply reflect the very sparse network of meteorological observations used by Dai et al. (2004) in the computation of the PDSI grid and/or decadal climate variability. The large spatial pattern of correlation observed from 1930 to 1959 (Fig. 3c) might reflect the prevalence of widespread decadal drought over the central U.S. in the 1930s and 1950s. SSTs have been identified as the primary forcing mechanism behind both droughts, but ocean-atmospheric circulation anomalies in the 1930s are inconsistent with the expected response from SSTs alone and major land-surface feedbacks appear to have been involved (Cook et al. 2011).

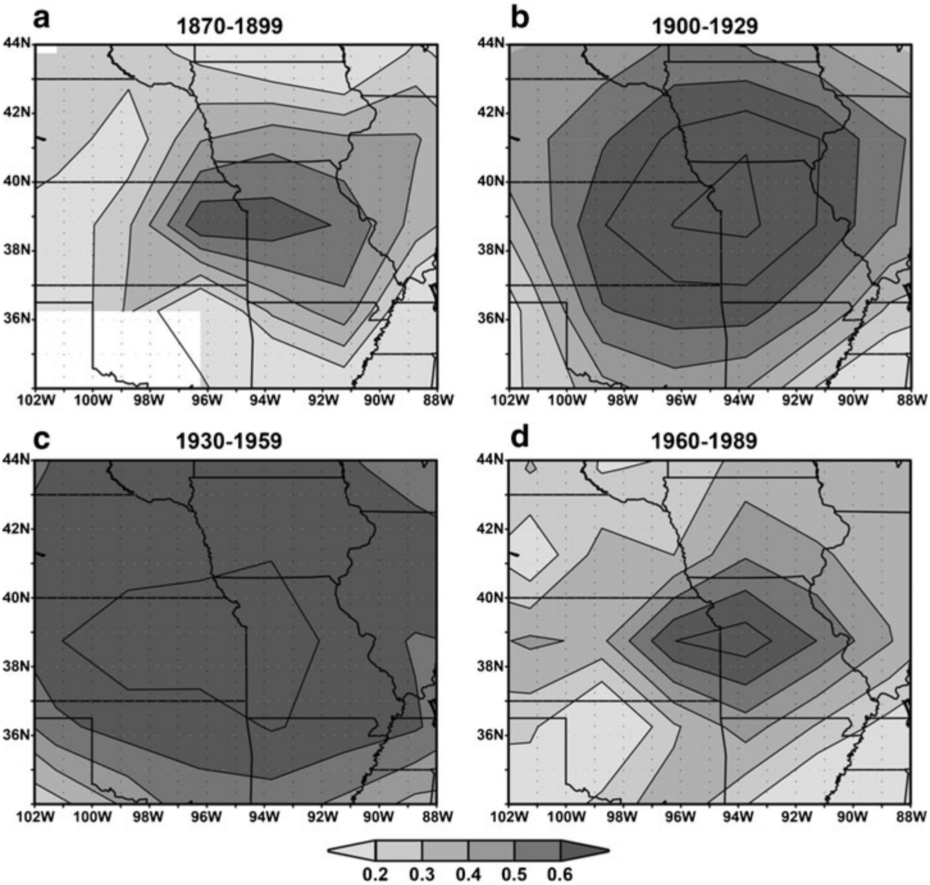

Fig. 3 Positive correlations between the reconstructed effective moisture anomalies (AMJJA) and the gridded April–August instrumental PDSI (Dai et al. 2004) are plotted for the central U.S. during non-overlapping 30-year subperiods [1870–89 (**a**), 1900–29 (**b**), 1930–59, (**c**), and 1960–89 (**d**); the highest correlations exceed 0.6; KNMI Climate Explorer]

3 Results

a. Reconstructed precipitation and drought

The adjusted reconstructions of precipitation totals for the spring, summer, and growing seasons from 1850 to 2008 are illustrated in Fig. 4. Hidden undercount biases may remain in the earliest data, especially before 1880 given the double mass analyses. Most years prior to 1890 were adjusted upward to lessen the undercount bias (Fig. 2), and no significant trend was detected in any of the seasonal time series. Snowfall, which is seriously impacted by undercount, can occur in April over Kansas and Missouri, but analyses of monthly adjusted precipitation totals indicated that dry conditions during the mid-19th century drought were present in all 3 months of spring (i.e., were not limited to April, not shown). The precipitation distributions were compared from 1850–1924 to 1925–2008 (Burnette 2009), and did not indicate major differences for spring, summer, or growing season precipitation between these two periods.

Spring precipitation averaged 335 mm from 1850 to 2008, and exhibits dramatic

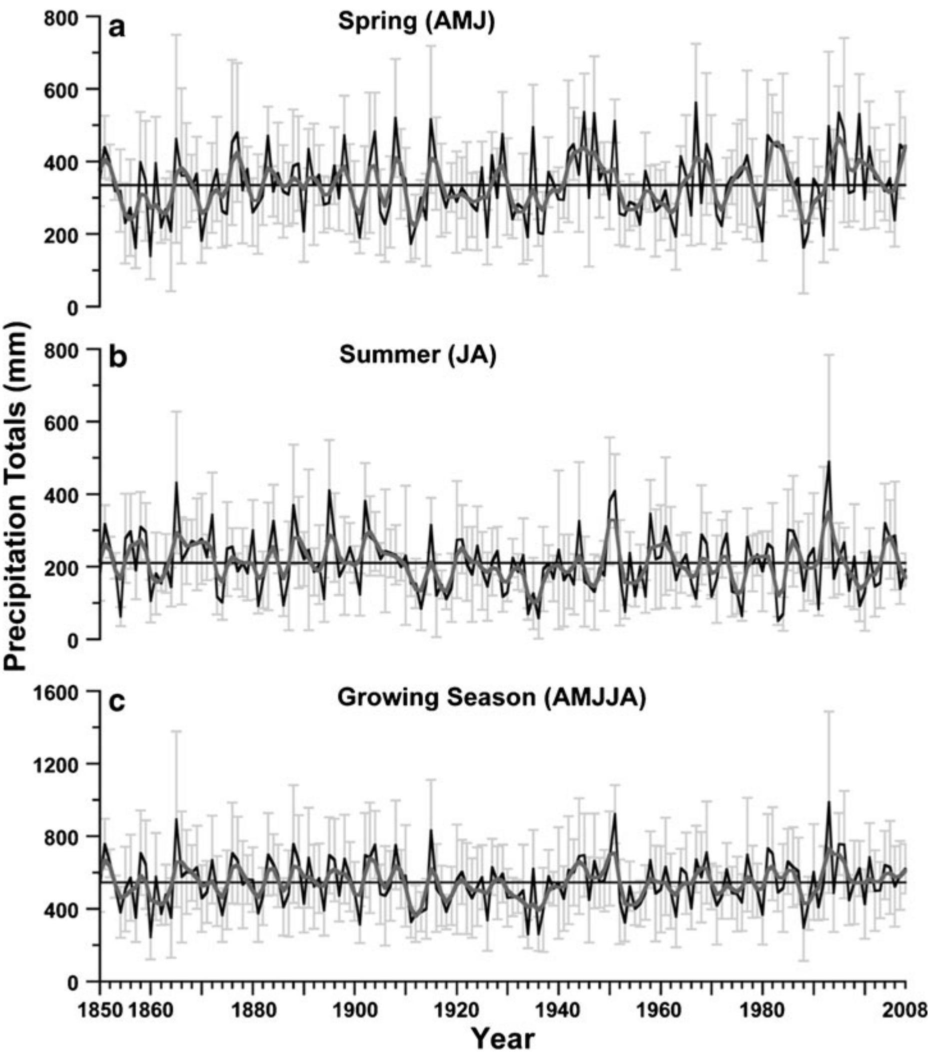

Fig. 4 The adjusted reconstructions of spring (**a**), summer (**b**), and growing season (**c**) precipitation totals are plotted with the interquartile range from 1850 to 2008, along with the mean and 5-year cubic smoothing spline (Cook and Peters 1981)

inter-annual and decadal variability (Fig. 4a). Prolonged wet episodes occurred in the 1940s and 1990s–2000s. The most severe and sustained dry periods in the spring precipitation estimates occurred in the 1850s–60s, 1910s, 1930s, and 1950s–60s (Fig. 4a). The estimated mid-19th century dry spring event may yet be impacted by undercount, and the true spring deficit during this period needs confirmation with additional instrumental and documentary data.

Precipitation totals for the July–August summer season averaged 210 mm since 1850 (Fig. 4b). Strong year-to-year variability is also noted for summer, but decadal precipitation variability appears to have been lower than estimated for the spring season (Fig. 4a vs. 4b). Summer precipitation was well above average in 1865, 1888, 1895, 1902, 1950, 1951, and 1993 (Fig. 4b). One of the worst flood events in Kansas history occurred in July 1951, when high water caused extensive damage in Kansas City, Lawrence, Manhattan, and Topeka (Juracek et al. 2001). The heavy rainfall in 1951 was exceeded in 1993, when many stations in the Upper Mississippi River Basin reported rainfall totals that were the largest of the 20th century (Kunkel et al. 1994). The highest JA precipitation totals in the past 159 years for the Kansas and Missouri study area also occurred in 1993 (Fig. 4b). Fortunately, 1993 flood flows in this area were limited by flood-control structures (Juracek et al. 2001).

The most severe and sustained summer dry periods, with at least four consecutive years of below mean precipitation occurred in the 1910s, 1930s, and 1940s (Fig. 4b). The driest summer episode appears to have occurred in the 1930s, but this Dust Bowl era summer precipitation deficit in the Kansas-Missouri study area was not dramatically lower than the precipitation deficits of the 1910s (Fig. 4b). Note also that no sustained multi-year summer wet periods were evident in the estimate from 1911 to 1949 (Fig. 4b).

Total precipitation during the growing season over the study area averaged 546 mm from 1850 to 2008, and indicates that the decade-long drought of the mid-19th century may have approached the severity of the growing season precipitation deficit during the 1930s Dust Bowl drought. Growing season precipitation was generally below average from 1853 to 1864, and the driest years of the Dust Bowl occurred from 1930 to 1941 (Fig. 4c). The most severe and uninterrupted growing season precipitation deficit is estimated to have occurred from 1911 to 1914 (Fig. 4c). While no statistically significant trends were detected in any of the seasonal precipitation reconstructions, Garbrecht and Rossel (2002) observed an increase in annual precipitation over the central and southern Great Plains during the late 20th century, including the our study area. Most of this increase during the growing season appears to have occurred during spring, when wet regimes were observed in the 1980s and the 1990s (Fig. 4a).

The effective moisture reconstruction indicates that the 1930s Dust Bowl was the most severe and sustained summer and growing season drought since 1855 (Fig. 5). The warmest temperatures of the past 180-years were recorded in the summer drought of the 1930s in northeastern Kansas (Burnette et al. 2010), and this intense heat is reflected in the summer moisture deficits. Effective moisture anomalies for spring indicate several drought episodes of approximately 5-year duration (1860s, 1910s, 1930s, 1950s, and 1980s), but the 1930s spring anomalies were not clearly more severe than the other episodes (Fig. 5).

b. The most severe drought periods

The four most intense growing-season droughts of the past 159 years over northeastern Kansas and northwestern Missouri occurred in the 1850–60s, 1910s, 1930s, and 1950s and are compared in Table 1. Total precipitation and effective moisture anomalies were summarized for these events during their worst consecutive 5- and 10-year periods (i.e., 1860–64, 1910–14, 1933–37, 1952–56, 1855–64, 1910–19, 1930–39, and 1952–61, Table 1). The lowest 5-year precipitation amounts and effective moisture anomalies during the spring season were observed during the mid-19th century drought (Table 1). However, the Dust Bowl drought had by far the lowest 5-year precipitation and moisture indices during the summer season (Table 1). When this comparison was extended to 10 years, the mid-19th century drought was again the worst in terms of precipitation totals and effective moisture anomalies during the spring season, but the Dust Bowl drought was worse during the summer (Table 1). The growing season moisture deficit during the Dust Bowl was also much more significant relative to the other droughts when the worst 10-year periods were compared (Table 1).

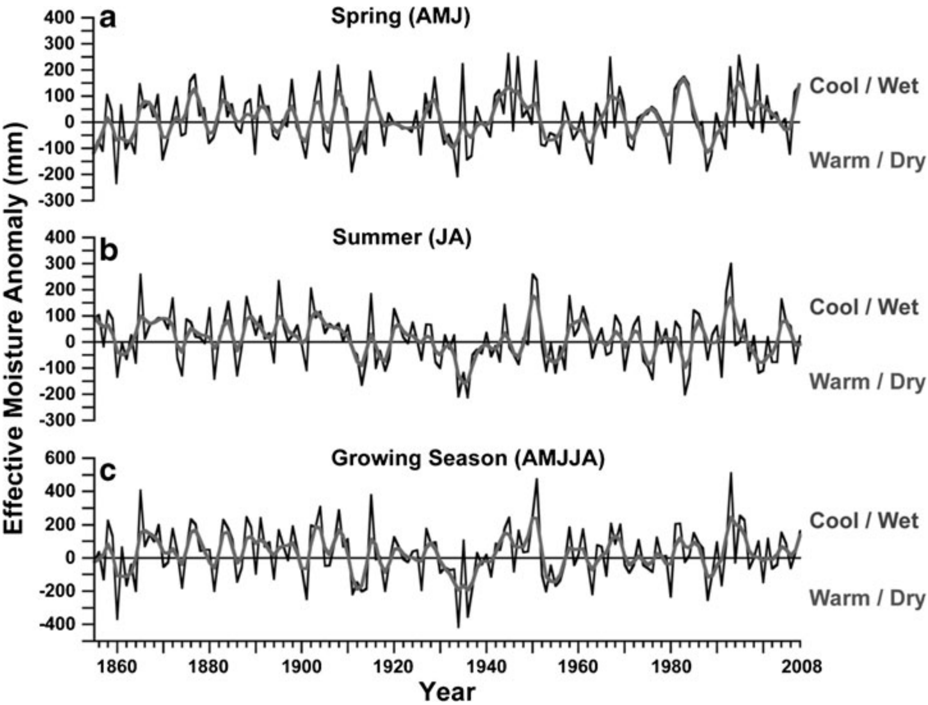

Fig. 5 Effective moisture anomalies were derived from the adjusted monthly precipitation reconstruction (this study) and the daily mean temperature data from Burnette et al. (2010). The monthly anomalies were then summed for the spring (**a**), summer (**b**), and growing season (**c**). Zero lines and 5-year smoothing splines are also plotted

Tree-ring reconstructions of the June–August PDSI suggest that the mid-19th century drought was much more intense across the central and southern Great Plains than the Dust Bowl (Burnette 2009; Cook et al. 2010). The Kansas-Missouri study area is located near the eastern edge of these two intense drought episodes, but tree-ring reconstructed drought intensity is of approximately equal magnitude during both events (see Burnette 2009). Evidence for intense dust storms and dune activation during the 1860s drought has been reported in the historical and geomorphological literature (Malin 1946a, b; Muhs and Holliday 1995; Dodds et al. 2009), which might indicate that dust emissions and vegetative cover played a role in the occurrence of this intense drought. However, additional instrumental and documentary data will be necessary from the Great Plains for a more comprehensive comparison.

c. Wavelet analysis

The morlet wavelet was used to assess the concentration of time series variance by frequency for spring, summer, and growing season precipitation totals and the growing season effective moisture (Torrence and Compo 1998). Wavelet spectra for spring and summer precipitation revealed differences in the frequency concentration of time series variance, where spring precipitation is dominated by power in the bidecadal to multi-decadal range and the summer precipitation reconstruction is dominated by power at the sub-decadal timescale (not shown). The reconstructions of precipitation and effective moisture anomalies for the growing season as a whole have similar wavelet spectra, but the most persistent wavelet power was computed for effective moisture in the bidecadal

Table 1 The precipitation and drought reconstructions during the worst 5- and 10-year periods of the mid-19th century, 1910s, Dust Bowl, and 1950s droughts are summarized (all in mm)

	Worst 5 years			
	1860–1864	1910–1914	1933–1937	1952–1956
Spring				
Precipitation	246	257	272	261
Moisture index	−91	−78	−69	−77
Summer				
Precipitation	159	157	136	163
Moisture index	−51	−49	−112	−53
Growing season				
Precipitation	405	414	408	424
Moisture index	−142	−127	−182	−130
	Worst 10 years			
	1855–1864	1910–1919	1930–1939	1952–1961
Spring				
Precipitation	264	312	293	287
Moisture index	−60	−12	−40	−36
Summer				
Precipitation	217	162	160	204
Moisture index	13	−36	−73	2
Growing season				
Precipitation	481	474	452	491
Moisture index	−47	−48	−114	−34

band (Fig. 6). Significant power in the bidecadal band has also been identified in tree-ring reconstructions of drought and drought area over the central and western United States (e.g., Cook and Krusic 2004; Cook et al. 2004; Herweijer et al. 2007). However, the concentration of wavelet variance in the bidecadal band for precipitation and the effective moisture over the study area was restricted to the first half of the 20th century. This suggests that any physical forcing of the moisture balance over Kansas-Missouri at bidecadal timescales has been episodic, but might include influences from the Pacific and Atlantic Oceans (McCabe et al. 2004).

4 Conclusions

New 159-year reconstructions of spring, summer, and growing season precipitation amounts have been developed for northeastern Kansas and northwestern Missouri by screening and correcting the longest available daily precipitation records of the U.S. Army Surgeon General, the Smithsonian Institution, and the U.S. Signal Service. These historical instrumental observations were appended to the modern GHCN precipitation observations for the same or nearby stations to complete precipitation estimates for the past 159 years. Threshold analyses of the 19th and early 20th century data suggested that precipitation totals were biased by undercount despite attempts to eliminate poor quality observations. This undercount bias seemed to be lessened for daily precipitation totals of 0.50 in. and greater.

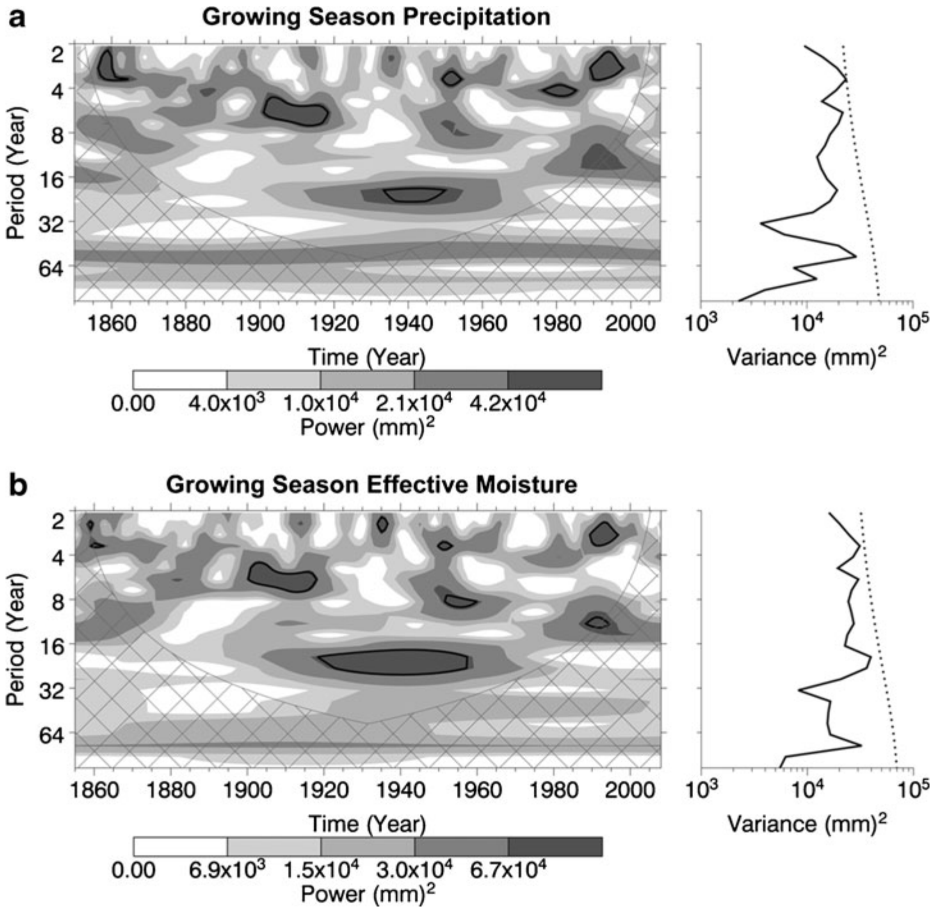

Fig. 6 Wavelet power spectra (*left*) and global wavelets (*right*) were computed for the growing season precipitation (**a**) and effective moisture (**b**) reconstructions. The contour levels were chosen so that 75 %, 50 %, 25 %, and 5 % of the wavelet power was above each level, respectively. The cone of influence is denoted by the cross-hatched region, where zero padding has reduced the variance. The 5 % significance level is denoted by the *thick black* contour on the wavelet spectra, using a white-noise background spectrum. The 5 % significance level is denoted by the *dotted line* in the global wavelet (Torrence and Compo 1998)

Therefore, half-inch thresholds were used to minimize the undercount bias within each station cluster. Adjusted reconstructions of total precipitation from 1850 to 2008 for the spring, summer, and growing seasons were developed by adding the average modern precipitation observed at each station cluster below 0.50 in. to the amounts above the half-inch threshold. These adjustments treat the undercount in the historical observations as a constant, but in reality the undercount was due to human error that occurred irregularly in the record. This makes it difficult to objectively assess and fully correct these early records, and it remains possible that the adjusted precipitation data prior to 1880 contain hidden undercount biases, especially in the spring. More observations from diarists who recorded precipitation variability would likely yield important clues about the overall quality of each precipitation record used in this study, and help evaluate the robustness of the adjusted reconstruction.

Our results suggest that:

- The drought that developed in the mid-1850s and extended through the Civil War to 1864 may have been the most severe and sustained *spring* (AMJ) moisture deficit over the Kansas-Missouri study area for the past 159 years.
- The drought of the Dust Bowl era was by far the most severe and sustained *summer* (JA) precipitation deficit over the area for the past 159 years, but when the precipitation data are summarized by growing season (AMJJA), the Dust Bowl drought was not remarkably more severe than the droughts of the 1860s, 1910s, and 1950s.
- When the temperature and precipitation data are used to compute an effective moisture index, the growing season moisture deficit during the Dust Bowl exceeded all other drought events from 1855 to 2008.

The Kansas-Missouri study area is located on the eastern edge of the Civil War and Dust Bowl droughts, and additional instrumental and documentary climate data from the Great Plains during the 19th century will be necessary for a more detailed comparison of these droughts. Daily instrumental observations of precipitation, temperature, wind direction, and wind speed are available for several military and civilian stations in and near the Great Plains during the 1850s and 1860s (Darter 1942). These observations could be supplemented with diary and newspaper accounts of weather conditions, blowing dust, and socioeconomic impacts to better document the true intensity and geographic coverage of the Civil War era drought, which appears to have been one of the worst droughts in the last 700 years (Cook et al. 2004).

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