A thousand years of drought and climatic variability in Kansas: Implications for water resources management

Anthony L. Layzell

Kansas Geological Survey

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1. Introduction

Periods of severe drought are one of the greatest recurring natural disasters in North America. In any given year, droughts occur all across North America resulting in significant impacts on local economies, societies, and the natural environment. Drought conditions in the United States cost on average $6-8 billion every year, but have ranged as high as $39 billion during the three-year drought of 1987-89 (Riebsame et al., 1991). In Kansas alone, the recent 2011 drought resulted in losses in excess of $1.7 billion (Kansas Department of Agriculture, 2011).

Droughts impact both surface- and ground-water resources and often result in reductions in water supply and crop failure particularly in agriculturally sensitive areas such as the High Plains of western Kansas. This region is becoming increasingly vulnerable to drought due to a variety of factors including the increased cultivation of marginal lands and the increased use of ground-water resources from the High Plains aquifer (Woodhouse and Overpeck, 1998), where water withdrawal has exceeded recharge for many years (e.g. McGuire, 2009).

The droughts of the 1930s and the 1950s remain the benchmarks in terms of duration, severity, and spatial extent for Kansas in the 20th century. Therefore, determining how representative these historic droughts have been in terms of drought occurrence is vitally important. The key question is how unusual are severe droughts, such as the Dust Bowl? Was this drought a rare event or should we expect droughts of similar or even greater magnitude in the future?

Direct observations of temperature and precipitation from instrumental records are largely restricted to the past 100 years and are therefore too short to adequately answer these questions. Therefore, in order to assess the full range of drought variability, it is important to place historic droughts in a longer-term context by utilizing paleoclimate proxy records.

This report investigates past drought occurrences from paleoclimate records over the last 1000 years. In particular, we focus on Palmer Drought Severity Index (PDSI) reconstructions calculated from annual tree-ring chronologies. Additional paleoclimate proxies and historical records are also examined to lend further support to reported past drought variability.

2. Types and Measures of Data

2.1 Drought Indices

The Palmer Drought Severity Index (PDSI) is one of the most widely used indices to measure drought in North America. The PDSI was developed by Palmer (1965) to measure the intensity and duration of long-term drought. It uses precipitation and temperature data to determine how much soil moisture is available compared to average conditions. PDSI values therefore provide data on both relative wetness and dryness over a given period. The index typically ranges between -4 (extremely dry) and 4 (extremely wet) but the range limit is not explicitly bound. As the index is standardized to local climate, it may be applied to any part of the country to demonstrate relative wetness and dryness.

2.2 Paleoclimate Data

PDSI values calculated from instrumental data provide a valuable means to assess drought variability over the instrumental record (i.e. the past 100 years). Recently, the Kansas Geological Survey has published historic climate and PDSI data (1895 to 2011) online in the form of the Kansas High Plains Aquifer Atlas (http://www.kgs.ku.edu/HighPlains/HPA_Atlas/Climate%20and%20Climate%20Trends/index.html#). Based on these data alone, the droughts of the 1930s and 1950s appear to be anomalous in terms of their severity and duration (Fig. 1).

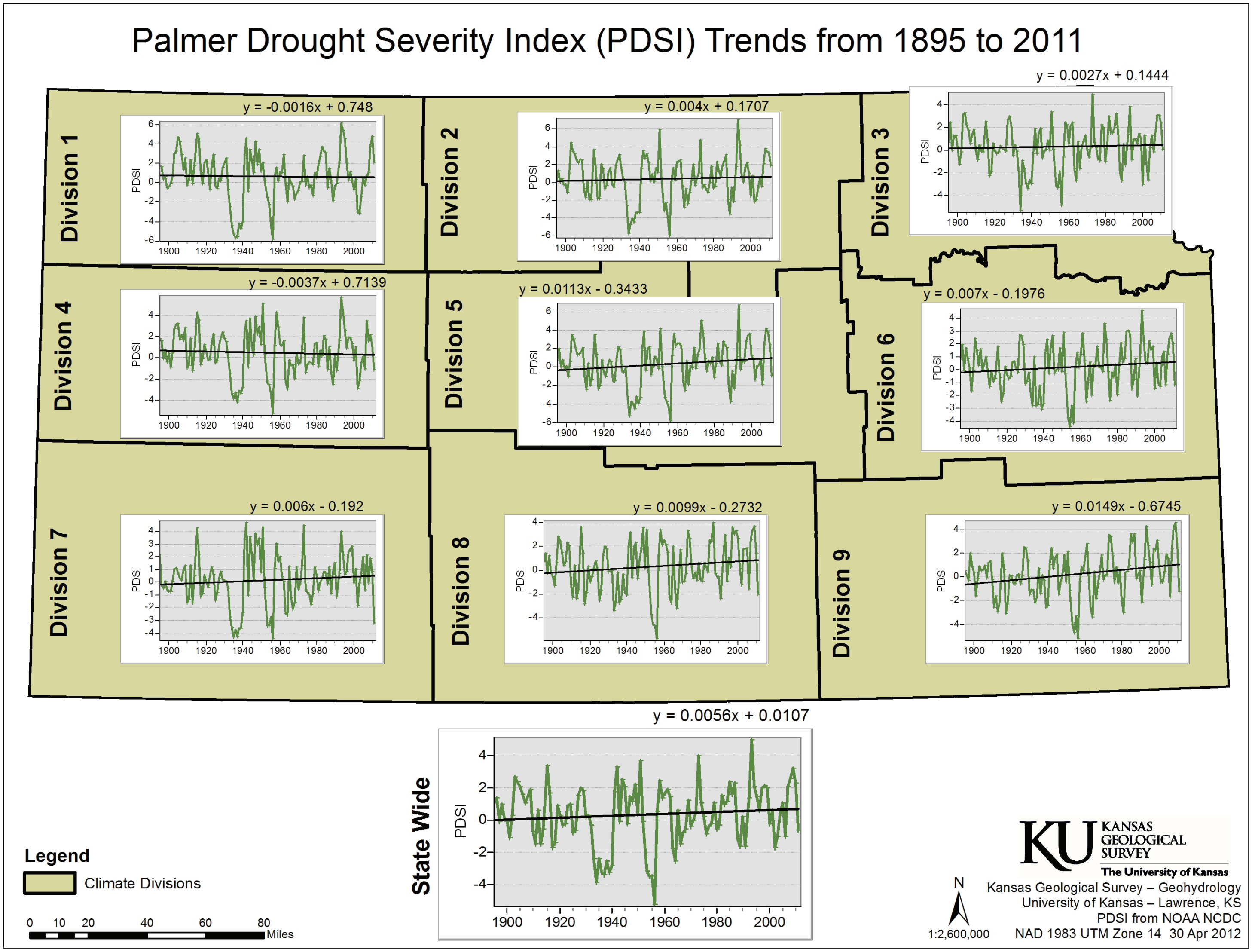


Figure 1. Instrumental PDSI trends for Kansas from 1895 to 2011. Image from the High Plains Aquifer Atlas (www.kgs.ku.edu/HighPlalins/HPA_Atlas/index.html).

However, paleoclimatic records allow one to assess the full range of drought variability by utilizing data that span longer periods of time. Long-term records have been developed from a variety of different proxies that span a range of time periods from hundreds to thousands of years. Proxies include tree-rings, sediments from lakes, sand dunes, and rivers, as well as historical and archeological records. These proxies record natural variability in drought occurrence and allow us to compare historic droughts of the 20th century with those of the past.

This report will focus on the paleoclimatic record developed from tree-ring studies. However, it is important to note that when used together, multiple proxy records provide a more complete picture of past change than that offered by any one proxy or instrumental data alone. Therefore, this report will supplement tree-ring reconstructions with data from historical, archeological, and geomorphic records in order to more fully investigate past drought variability.

2.2.1 Long-term PDSI Reconstructions

Tree-rings chronologies are based on the actual growth rate of highly drought-sensitive trees and therefore function as an important indicator of past droughts. Adequate moisture and a long growing season result in wide tree rings while drought years create very narrow rings. Importantly, individual tree-rings can be dated to the exact calendar year using cross-matching techniques.

Recently, an extensive network of annual tree-ring chronologies has been developed and made publically available through the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html). Utilizing these data, annual PDSI reconstructions have been developed for 286 grid points across most of North America (Cook and Krusic, 2004). Reconstructions utilized the nearest available tree-ring chronologies to each grid point and were produced with a well-tested point-by-point principal-components regression procedure. See Cook et al. (1999) for detailed methodology used to develop PDSI reconstructions. PDSI reconstructions are evaluated using four statistics, which indicate high overall calibration and verification (see appendix for more details).

Regression based tree-ring PDSI reconstructions tend to underestimate extreme values, although dry extremes are better represented than wet extremes, but are reasonably accurate in terms of extent and duration (Woodhouse and Overpeck, 1998). Therefore, such reconstructions facilitate accurate assessment of the relative severity of 20th-century droughts compared to droughts in the more distant past.

A previous paleoclimate report for the Ogallala region by Young and Buddemeier (2002) utilized PDSI reconstructions by Cook et al. (1999), which were developed from 425 tree-ring chronologies and extended from ~1170 to 1978 AD for western Kansas. Since the publication of this report, new PDSI reconstructions have been produced that represent a substantial spatial and temporal improvement and enable us to better assess the nature of past drought variability. New reconstructions are now based on almost twice as many tree-ring chronologies (835 in total) and extend over longer time periods (from 837 to 2003 AD for western Kansas). PDSI estimates are based on instrumental data after 1978. PDSI data are available publically in the form of the North American Drought Atlas (http://iridl.ldeo.columbia.edu/SOURCES/.LDEO/.TRL/.NADA2004/.pdsi-atlas.html). Data were obtained for six grid points in Kansas, thereby dividing the state into six regions (Northwest, Southwest, North-central, South-central, Northeast, Southeast) for analysis in this report.

3. Analyses

3.1 Drought Severity

Figure 2 contains plots of annually resolved PDSI tree-ring reconstructions for six regions in Kansas. *These plots highlight numerous years in the past where drought conditions exceeded the severity of the 1930s and 1950s droughts in each region*. The peak individual drought years during the 1930s and 1950s droughts were determined to be 1934 and 1956 respectively. PDSI values for these years are highlighted with dashed lines on figure 2 and provide a benchmark by which to assess drought occurrence within each region. This type of analysis, however, does not favor regional comparisons as different PDSI thresholds are used in each region.

In order to facilitate regional comparison, we averaged the six regional PDSI values for 1934 and 1956 respectively, generating two thresholds by which to compare the different regions. These thresholds enable us to determine the number of years where droughts of a similar or greater magnitude occurred (i.e. years where PDSI is less than the threshold values). The averaged PDSI values for 1934 and 1956 are -4.9 and -5.9 respectively. Figure 3 highlights the total number of drought years in each region where PDSI values were less than or equal to the threshold values. Note that data were unavailable for some regions between 837-1000 AD and therefore, in order to facilitate fair comparison between regions, this analysis was restricted to data post 1000 AD.

The PDSI data indicate that western Kansas has experienced more severe droughts than eastern Kansas over the past 1000 years. Furthermore, the data also indicate that northern Kansas has typically experienced more severe droughts than southern Kansas. The west to east trend is not surprising given the strong latitudinal

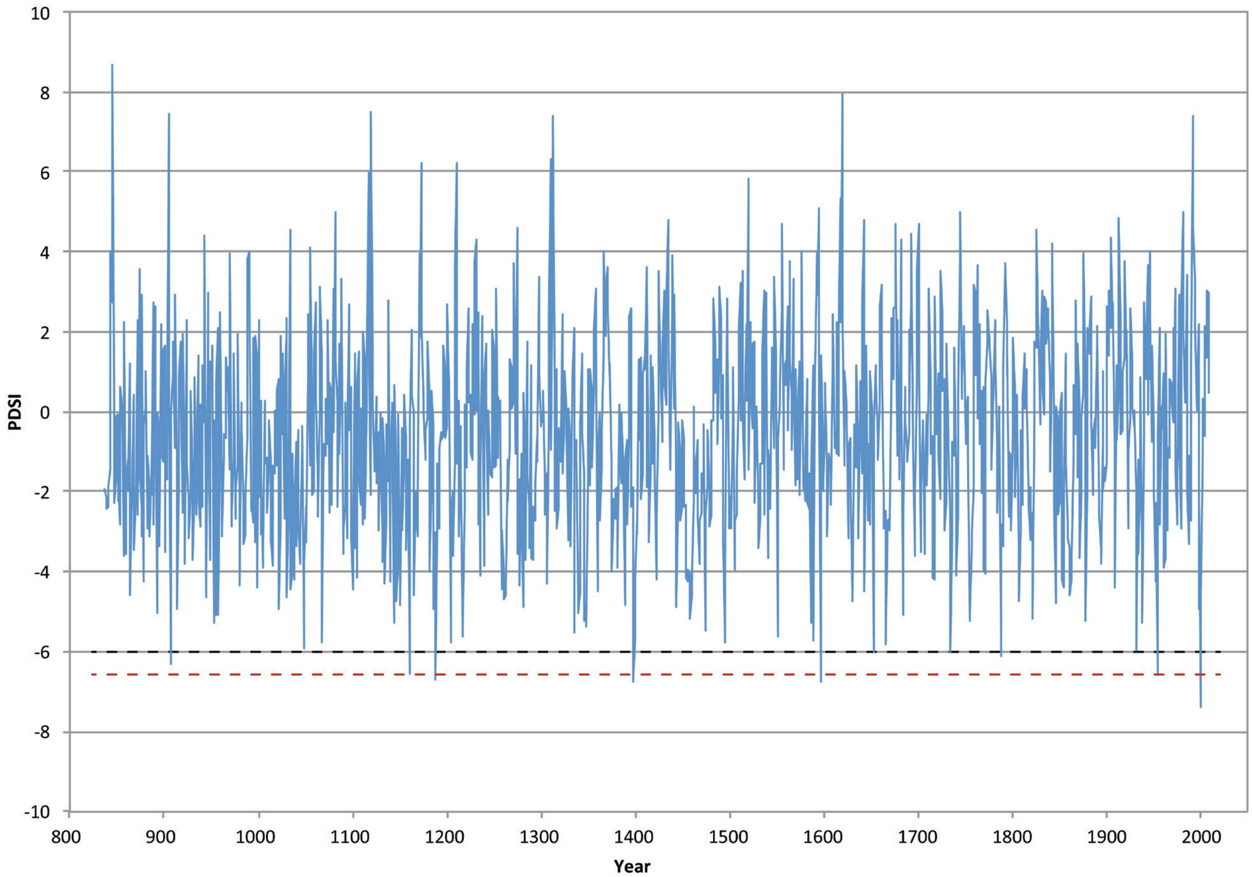


Figure 2a. Annual PDSI reconstructions from tree rings for northwestern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

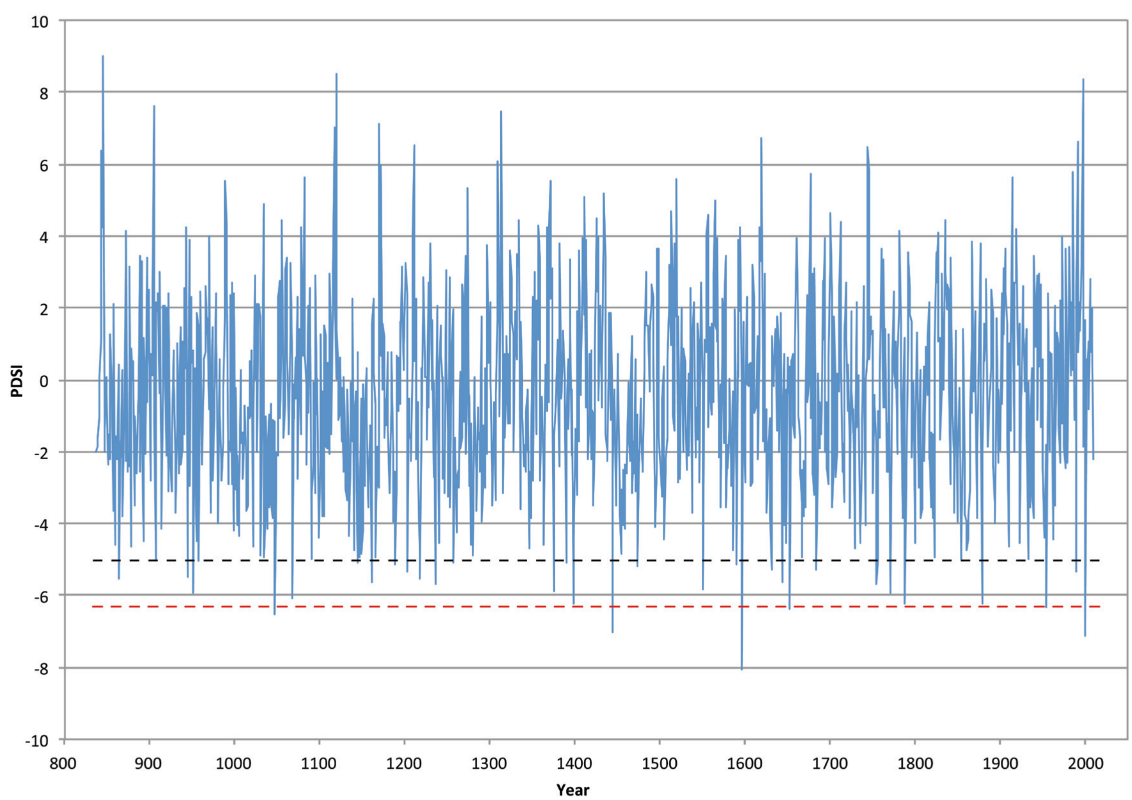


Figure 2b. Annual PDSI reconstructions from tree rings for southwestern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

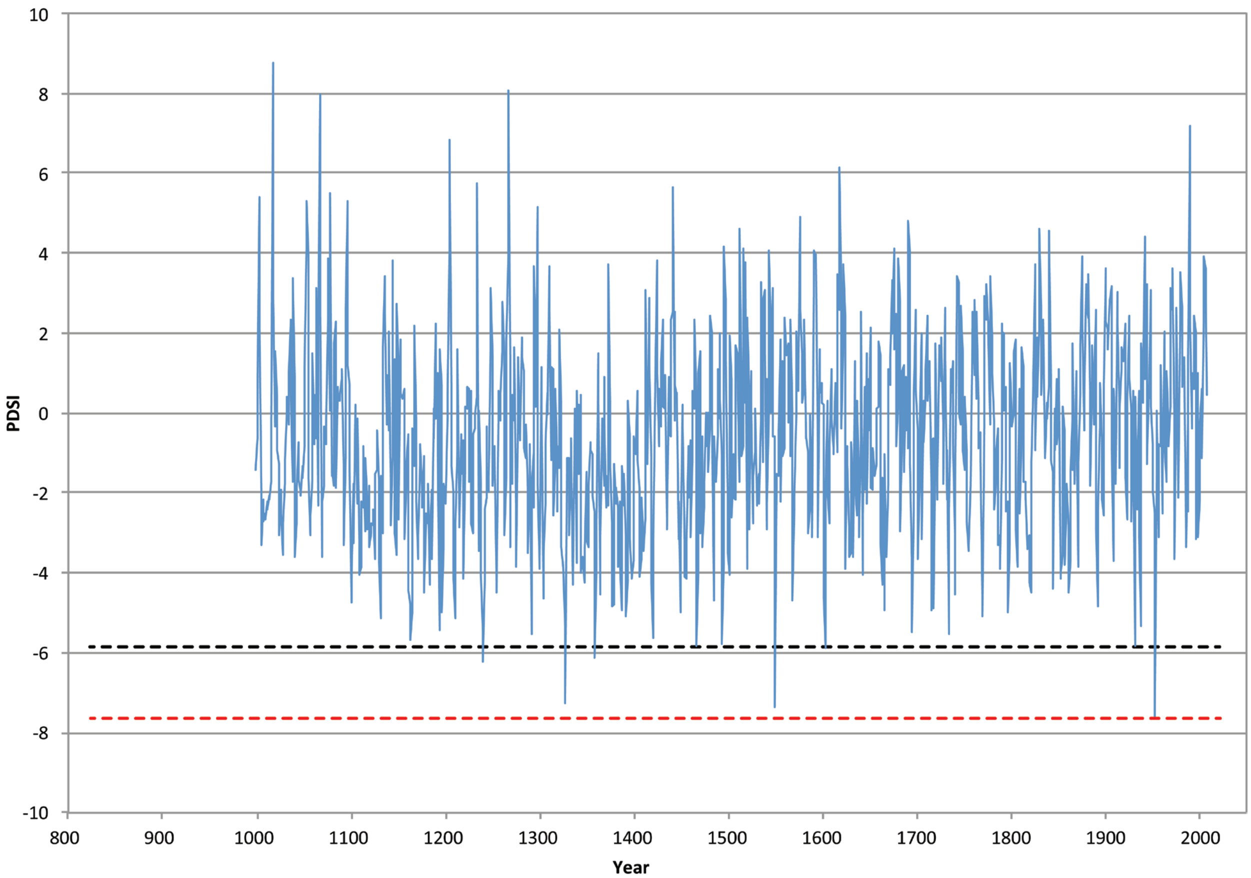


Figure 2c. Annual PDSI reconstructions from tree rings for north-central Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

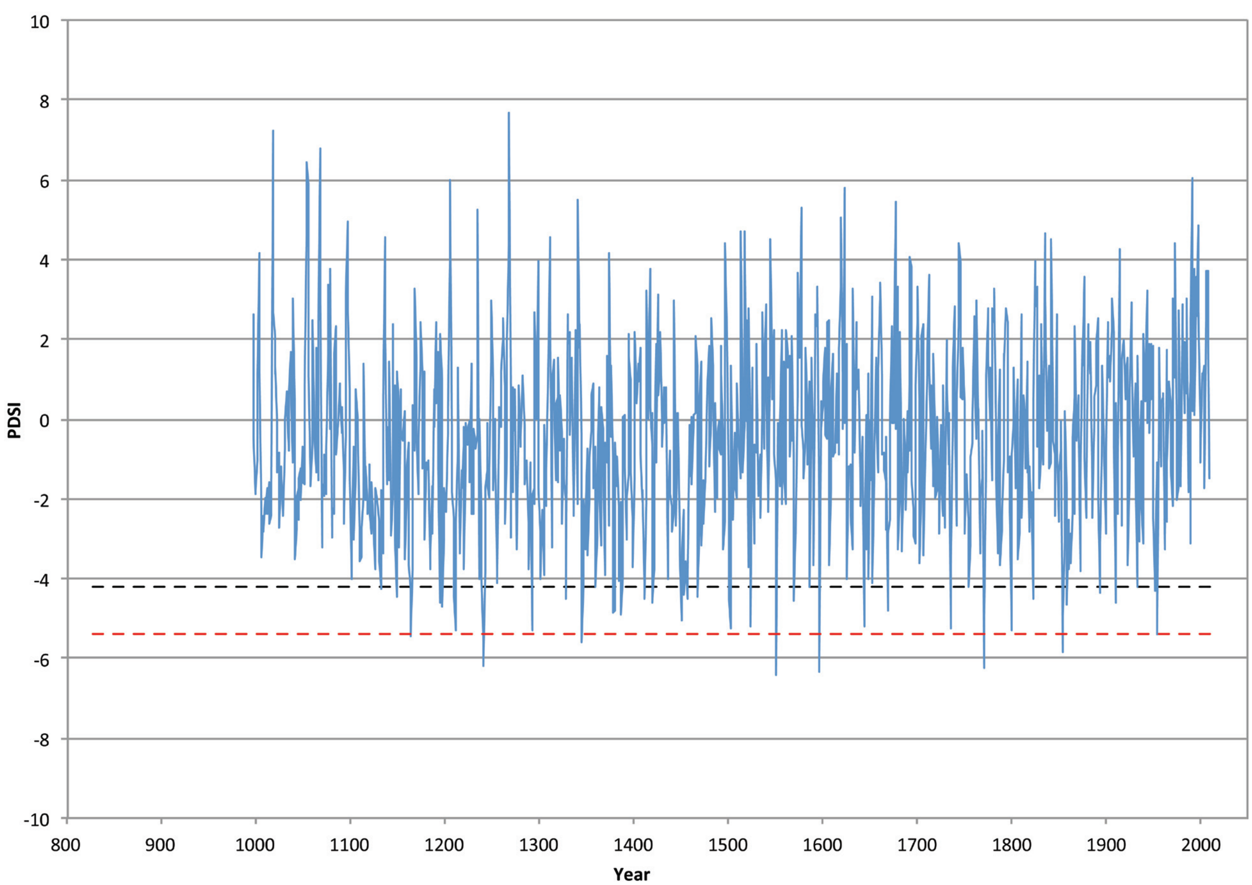


Figure 2d. Annual PDSI reconstructions from tree rings for south-central Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

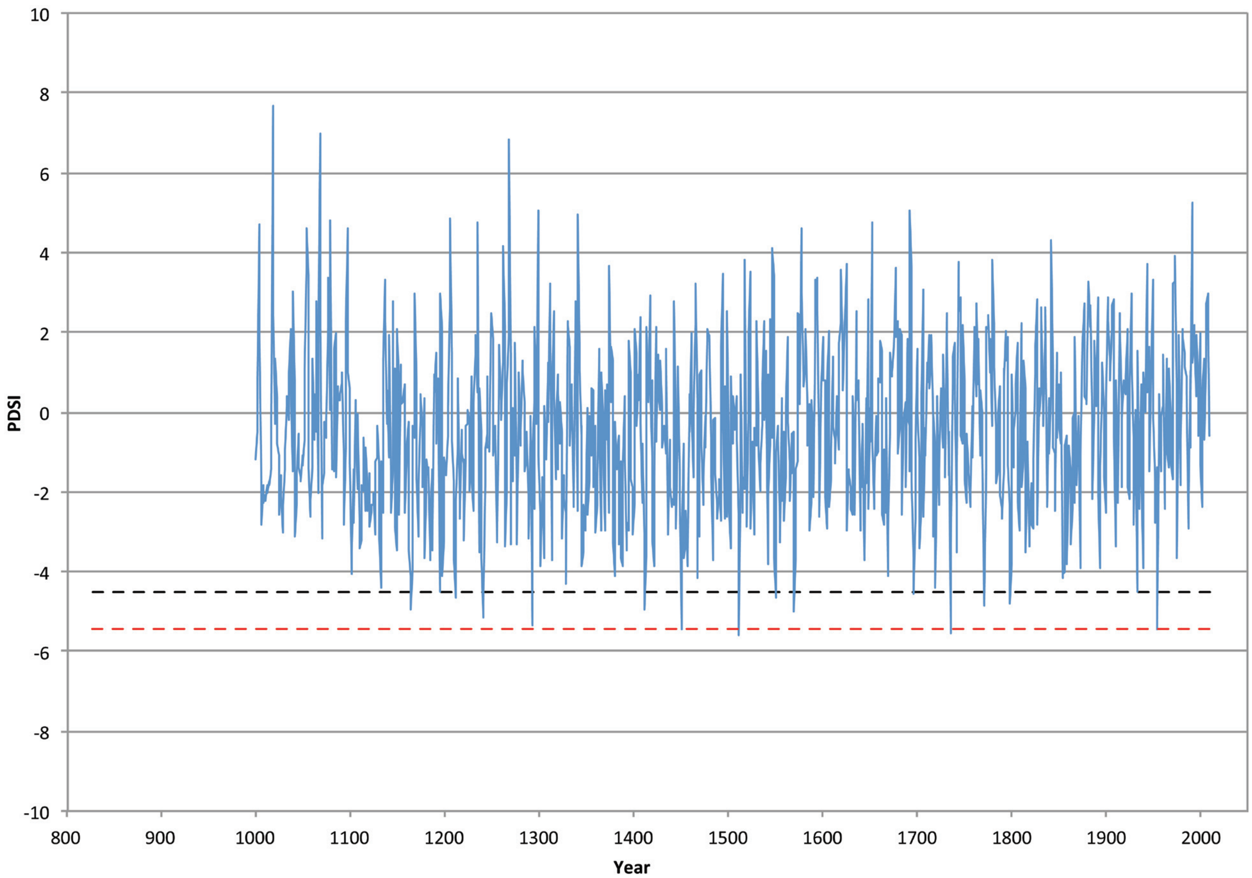


Figure 2e. Annual PDSI reconstructions from tree rings for northeastern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

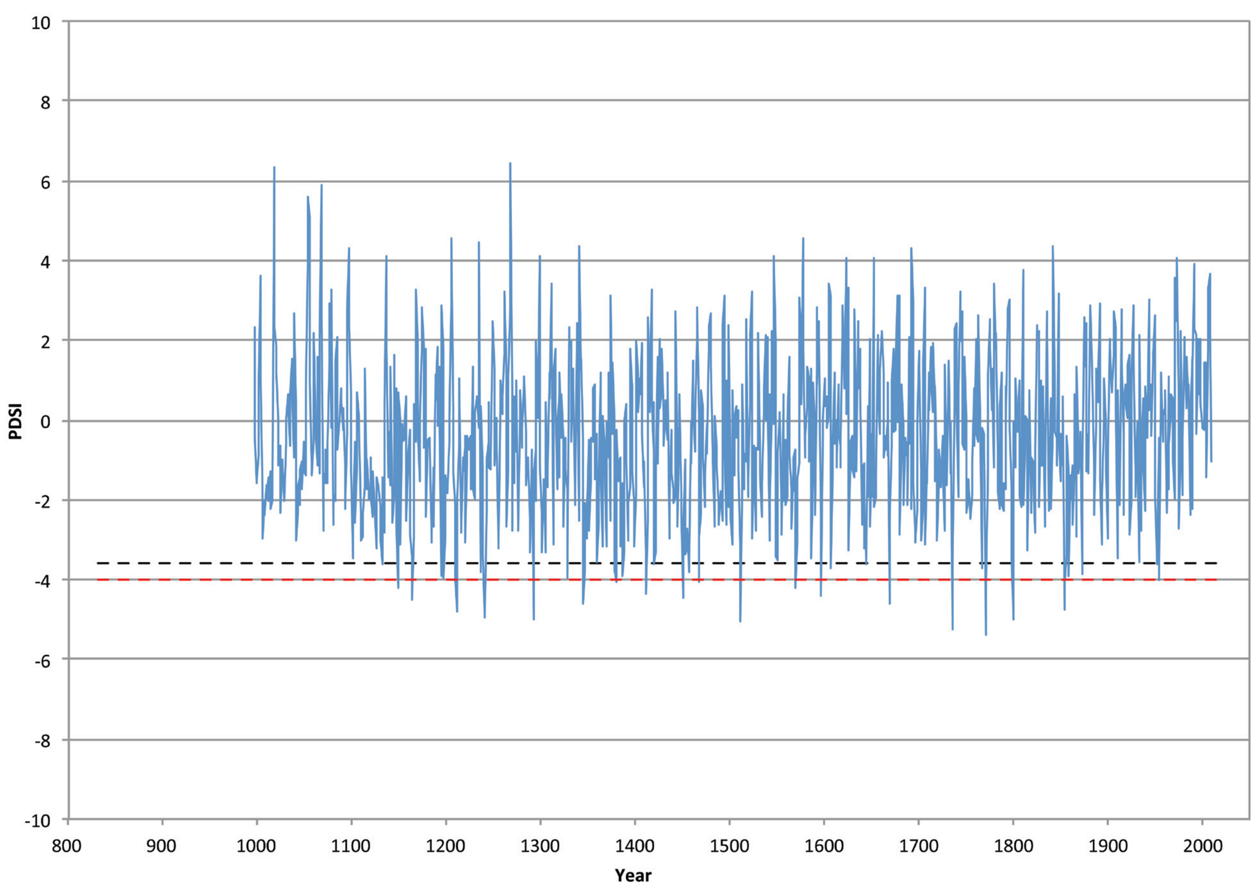


Figure 2f. Annual PDSI reconstructions from tree rings for southeastern Kansas. Dashed lines indicate the 1934 (black) and 1956 (red) PDSI values.

climate gradient in Kansas. The north to south trend can be explained by investigating the spatial patterns of historic 20th-century droughts. For example, the Dust Bowl drought was spatially centered over the Pacific Northwest and later over the northern Plains while the 1950s drought, in contrast, was centered over the southern Great Plains and later shifted into the southwest US (e.g. Stahle et al., 2007; Fig. 4). Hoerling et al. (2009) suggest that the 1950s drought was driven by changes in sea-surface temperatures, more specifically the El Niño-Southern Oscillation. They found that during La Niña years, characterized by cold sea-surface temperatures in the equatorial Pacific, droughts are common in the southern Plains. In contrast, they suggest that the Dust Bowl drought was caused by random atmospheric variation rather than changes in ocean temperatures. Therefore, the PDSI data appear to suggest that the random forcing mechanisms of the Dust Bowl drought have been more common over the past 1000 years than those that resulted in the 1950s drought.

Another way to analyze the PDSI data is to determine how many years exceed the threshold in a given century. By this method *we should expect individual drought years at least as severe as 1934 on average 3-4 times a century in western Kansas, 2-3 times in central Kansas, and about once a century in eastern Kansas*.

However, this analytical method (i.e. using averaged PDSI thresholds) can be misleading. For example, figure 3 indicates that there are no droughts in the paleorecord that exceed the 1956 threshold in eastern Kansas. This is misleading because of the strong regional expression of drought in the state. For example, in southeastern Kansas the 1956 PDSI was -4.0, which indicates extreme drought. However, because drought conditions were more severe elsewhere in the state, the regionally averaged threshold for 1956 is skewed to -5.9. While there are no past drought years with PDSI values less than -5.9 in southeastern Kansas, there are at least 22 past drought years with PDSI values less than -4.0 (see Fig. 2f). We therefore suggest that both methods of analysis (i.e. assessing drought severity *within* and *between* regions) should be used in conjunction when assessing the variability of drought severity across Kansas.

3.2 Drought Duration

One of the key characteristics of the 1930s and 1950s droughts was not only their severity in a given year but their *duration*. Individual drought years are therefore not necessarily good indicators of cumulative socioeconomic or environmental impacts as one dry year may be accommodated if it is sufficiently offset by wetter conditions the following year (Cook et al., 2007). For example, the 2002 drought year in southwestern Kansas was more severe than the peak year of the Dust Bowl (PDSI values of -7.1 and -5.0 respectively). However, 2002 was bounded by years of positive PDSI values whereas the Dust Bowl drought consisted of several consecutive years of drought conditions. It is therefore important to assess the duration of past periods of drought.

The duration of droughts is more difficult to estimate because climatic variability tends to punctuate dry multi-year intervals with occasional wet years (Cook et al., 2009). Furthermore, there is no unique solution for calculating drought duration. For example, the 1930s and 1950s droughts have been estimated to have lasted 12 and 14 years (Stahle et al., 2007) or 7 and 8 years (Andreadis et al., 2005) respectively. One method to determine drought duration is to utilize a low-pass filter, such as a moving-average, which allows for analysis of decadal to multi-decadal changes in aridity.

Figure 5 contains plots of PDSI values smoothed over 10- and 50-year periods. For this analysis we determine the beginning and end of a drought period from the smoothed data by identifying when it is preceded or followed by more than two consecutive years of positive PDSI values. Using this technique we identify the duration of the 1930s and 1950s droughts in Kansas as lasting 13 and 18 years respectively.

Using these durations we are able to identify several periods of past drought with durations similar (i.e. 10-20 years) to the severe historic droughts of the 20th century. These droughts are highlighted in figure 5 by light gray bars. Figure 6 shows the number of droughts of similar duration to the historic 20th century droughts over the past 500 years. We limit this analysis to the past 500 years because the majority of droughts prior to this appear to be of much greater duration. Drought duration over the past 500 years illustrates a similar pattern to

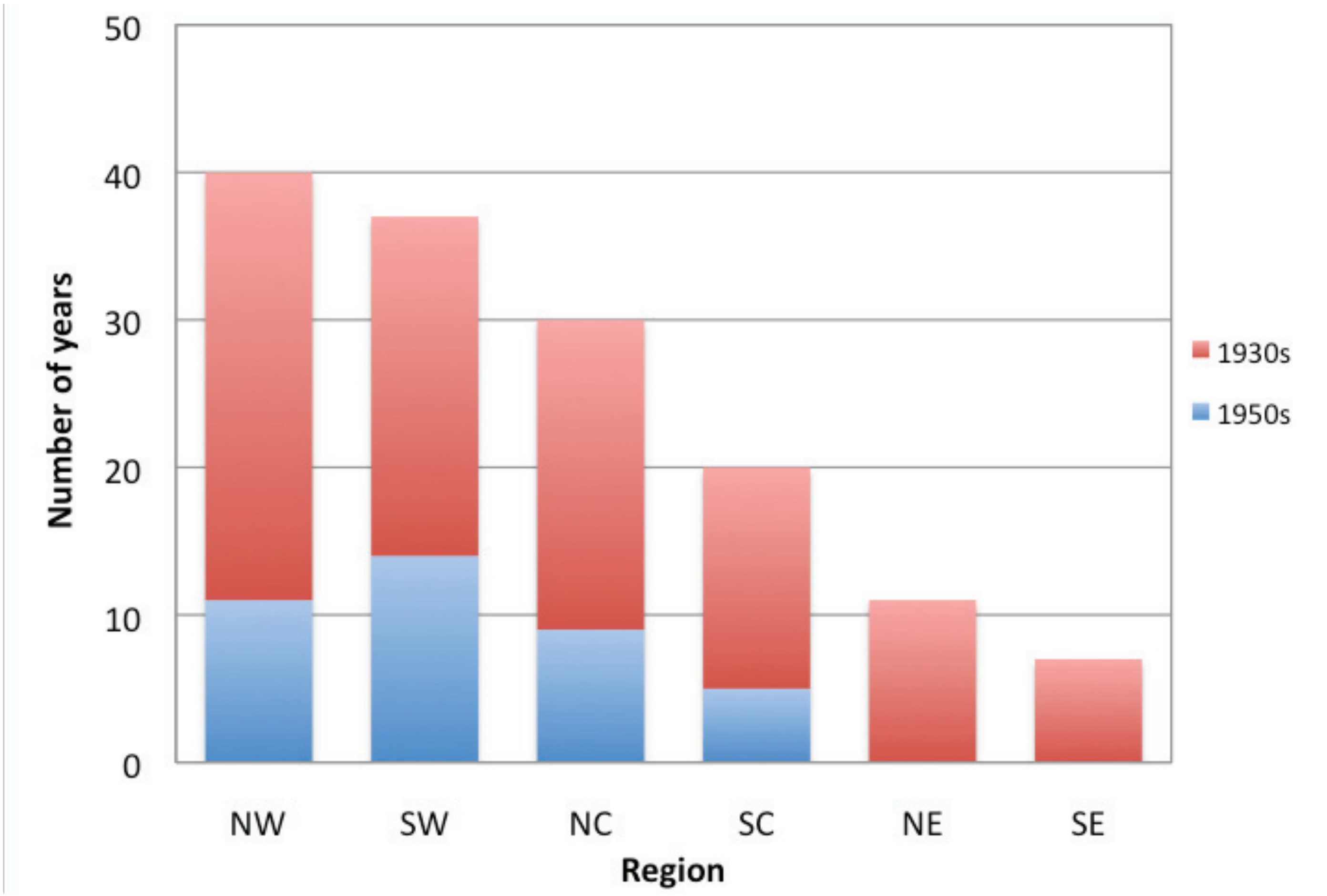


Figure 3. Number of drought years more severe than the peak years of the 1930s and 1950s droughts. Note that this analysis uses threshold PDSI values averaged across all six regions.

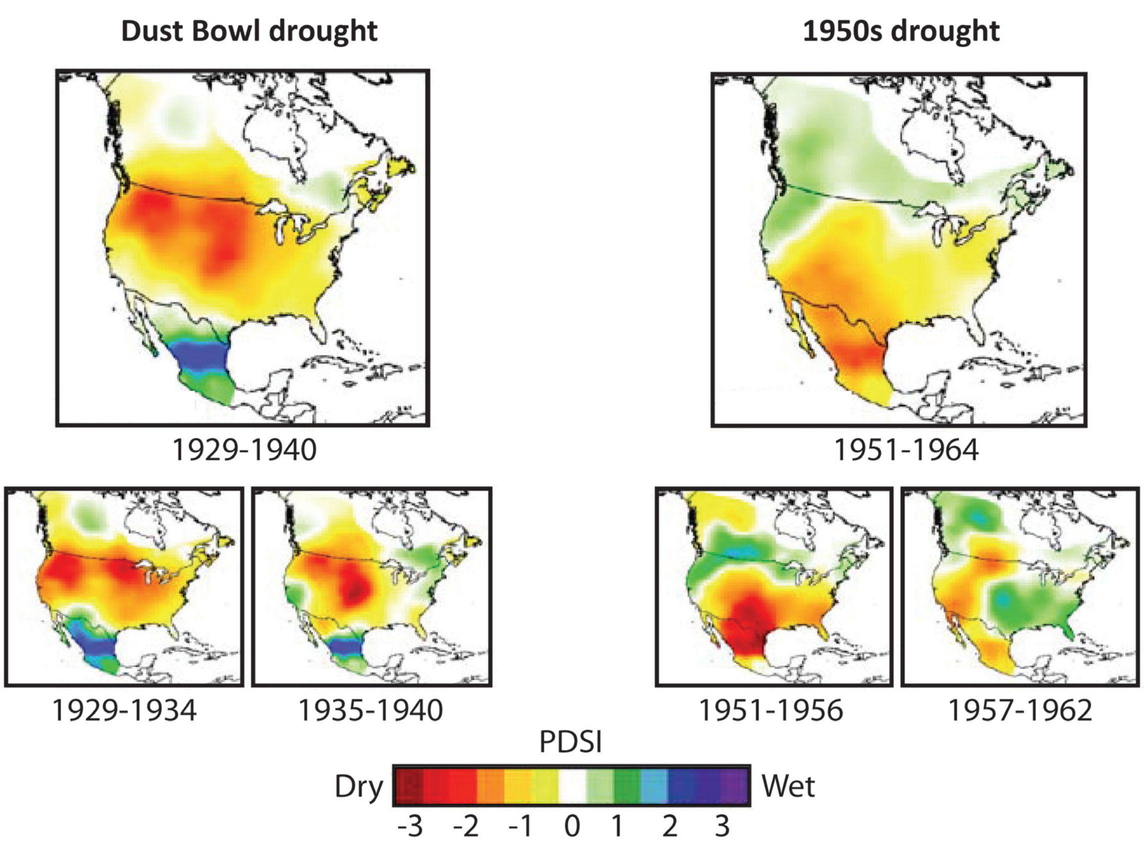


Figure 4. Mapped spatial patterns of the 1930s and 1950s droughts using instrumental PDSI data. Figure modified from Stahle et al. (2007).

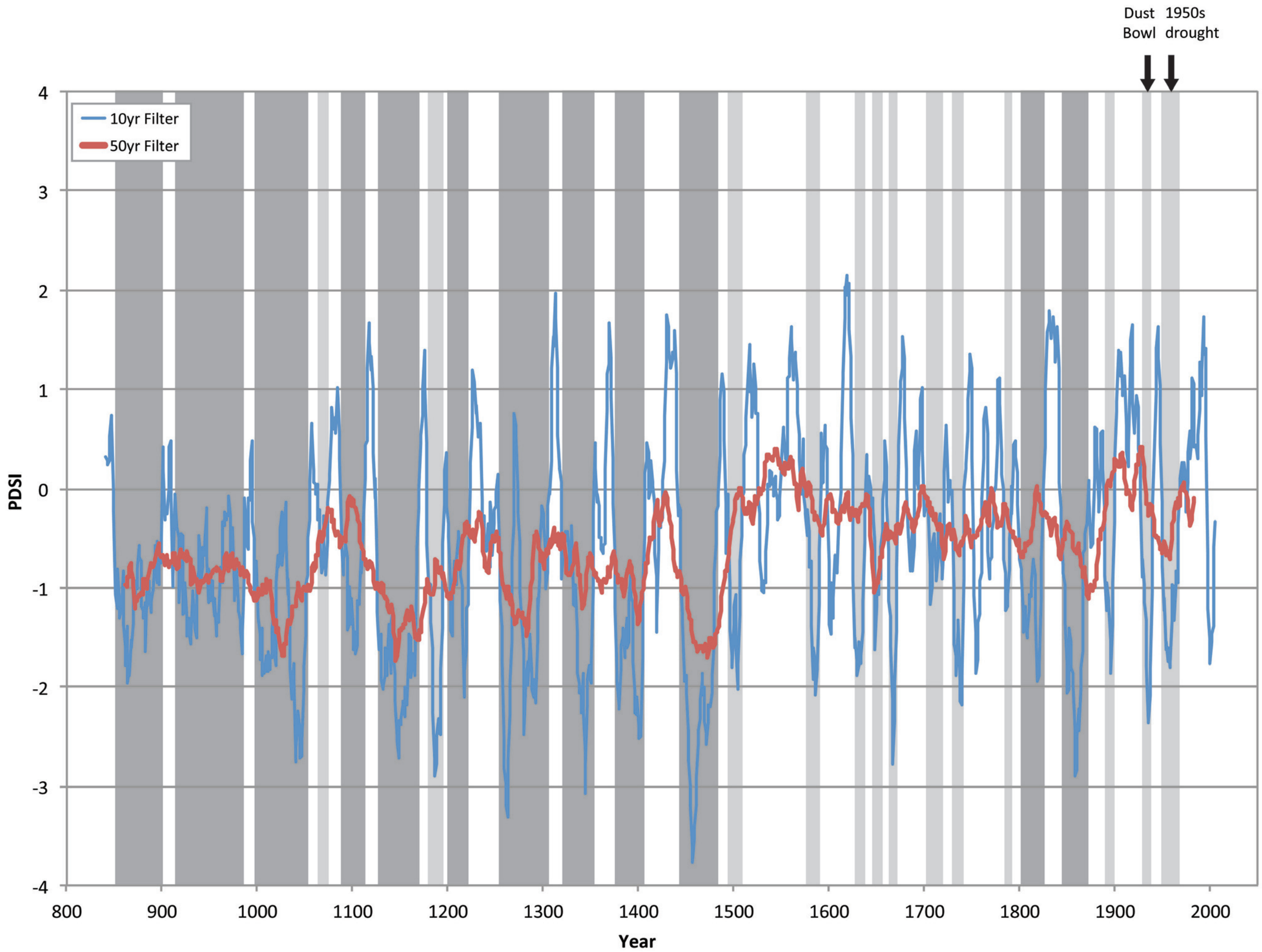


Figure 5a. Smoothed PDSI reconstructions for northwestern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

drought severity with western and northern Kansas experiencing more decadal drought periods than eastern Kansas. From these data *we should expect decadal droughts on average two times a century in western Kansas and about once a century in eastern Kansas*.

3.2.1 Megadroughts

Droughts of unusually long duration compared to those observed in the instrumental record are often called 'megadroughts.' In order to constitute a megadrought, a past multi-year drought must exceed the duration of the most extreme droughts in the 20th century. Therefore, for this study, a megadrought is defined as a drought lasting more than 20 years in duration.

PDSI reconstructions highlight several periods of extreme drought in the past with much longer durations compared to those of the 20th century, particular prior to 1500 AD. These multi-decadal droughts are highlighted in figure 5 by dark gray bars. Additionally, documented megadroughts are typically at least as severe as the 1930s and 1950s droughts.

It is important to validate the occurrence of past megadroughts by utilizing other proxy records. Figure 7 synthesizes the records of drought variability shown in figure 5 and in addition highlights different lines of environmental and societal evidence that support drought conditions during documented megadroughts.

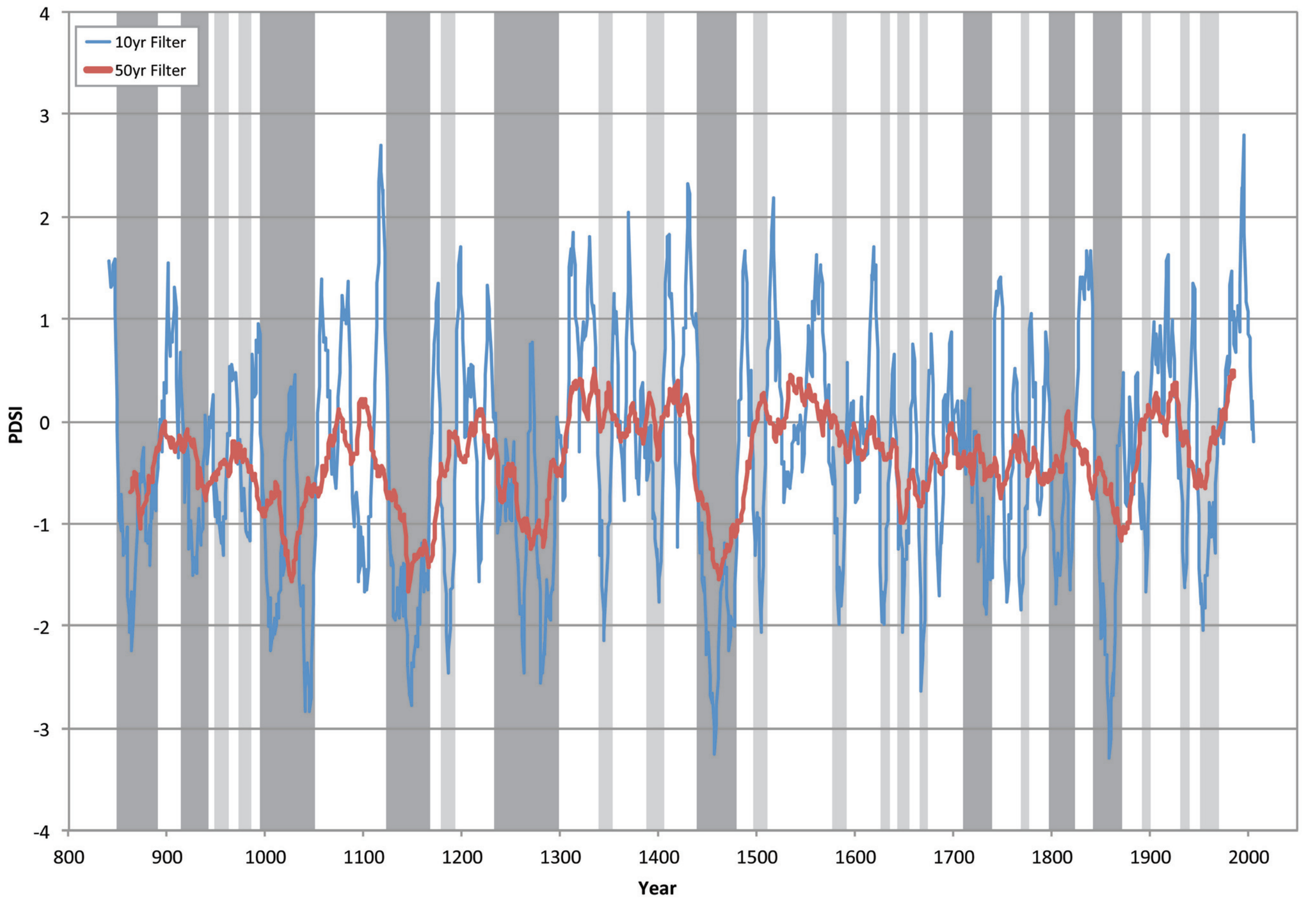


Figure 5b. Smoothed PDSI reconstructions for southwestern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

3.2.2. Megadroughts from 1500 to 2011 AD

PDSI reconstructions indicate the likely occurrence of megadroughts in the beginning and middle part of the 19th century, which persisted on average for 30 years (Figs. 5 and 7). Drought conditions around 1850 are noted in a variety of historical data, including early meteorological records (Ludlum, 1971). Stahle et al. (2007) cite evidence from the Kiowa of the southern Great Plains that cites 1855, known among the Kiowa as the "sitting summer," as a year of severe drought. Woodhouse and Overpeck (1998) note that drought conditions were also documented in Kansas newspapers in 1860. Woodhouse et al. (2002) used streamflow reconstructions from eastern Colorado to document a period of remarkable sustained drought from approximately 1845 to 1856. This period of drought, together with human impacts, may have also resulted in a severe decline in the populations of the Great Plains bison (Woodhouse et al., 2002). Historical accounts from early explorers in the region during the 19th century report periods of blowing sand indicative of eolian activity and sand-dune activation for an area extending from northern Nebraska to southern Texas (Muhs and Holiday, 1995). Eolian activity is primarily driven by droughts severe enough to remove the stabilizing effects of vegetation. Forman et al. (2008) observed discrete episodes of sand deposition in the Arkansas River valley of southwestern Kansas between 1620-1680 and 1800-1820 AD (Fig. 6).

3.2.3 Megadroughts from 850 to 1500 AD

PDSI data highlight several likely past megadroughts from 850 to 1500 AD (Figs 5 and 7). Although these mega-droughts were punctuated with wet intervals, overall they suggest protracted aridity lasting on average 40-50 years in duration. The longest megadrought on record occurred in north-central Kansas and lasted 110 years

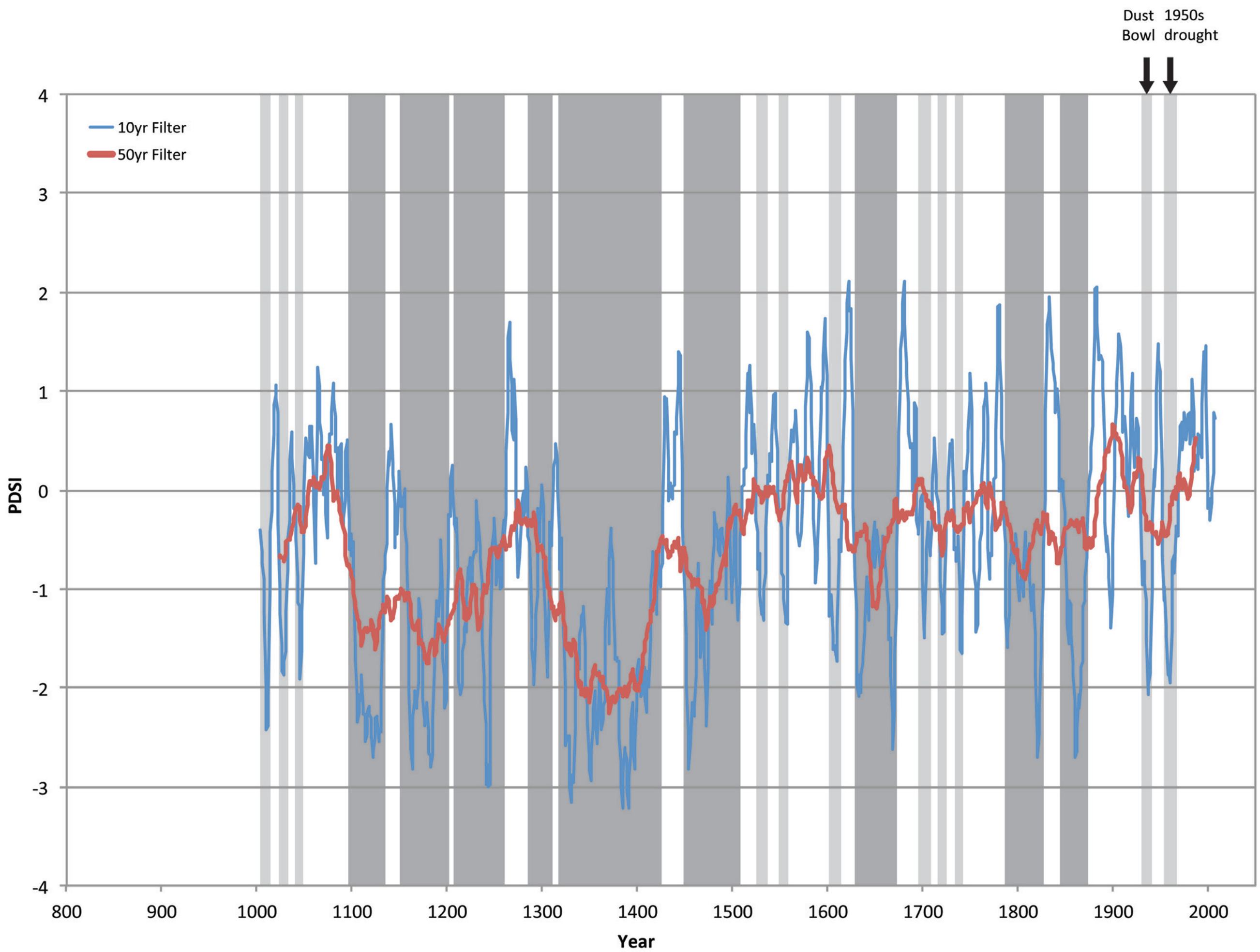


Figure 5c. Smoothed PDSI reconstructions for north-central Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

from 1317 to 1427 AD. This megadrought was also much more severe than historic 20th-century droughts. Figure 7 highlights the spatial variability of megadroughts across the state. For example, the protracted 110-year megadrought in north-central Kansas was separated into two separate decadal droughts in western Kansas.

Most dune records from the central Great Plains show significant sand-dune activation due to increasing aridity and reductions in vegetation cover between 950-1350 AD. Evidence of sand-dune mobilization from the Great Bend Sand Prairie in south-central Kansas – the largest dune field in Kansas – has been documented between 1050-1250 and 1450-1650 AD (Arbogast, 1996). Halfen et al. (2011) also identified active dune migration in south-central Kansas between 1000-1100 AD. Dunes in the Cimarron River valley of southwestern Kansas were active between 1050 and 1250 AD (Lepper and Scott, 2005) while dunes in the Abilene dune field of north-central Kansas were active more broadly between 890-1490 AD (Hanson et al., 2010). The time intervals for dune activation overlap periods of megadroughts identified from PDSI reconstructions.

Support for the occurrence of megadroughts between 850 and 1500 AD can also be gleaned from the archeological record, which highlights the destabilizing effects of past severe droughts. Benson et al. (2007) suggest that multi-decadal droughts between 990-1060, 1135-1170, and 1276-1297 AD had significant impacts on a variety of prehistoric populations in the Southwest, including Anasazi and Fremont cultures, and the Midwest, such as the Mississippian society.

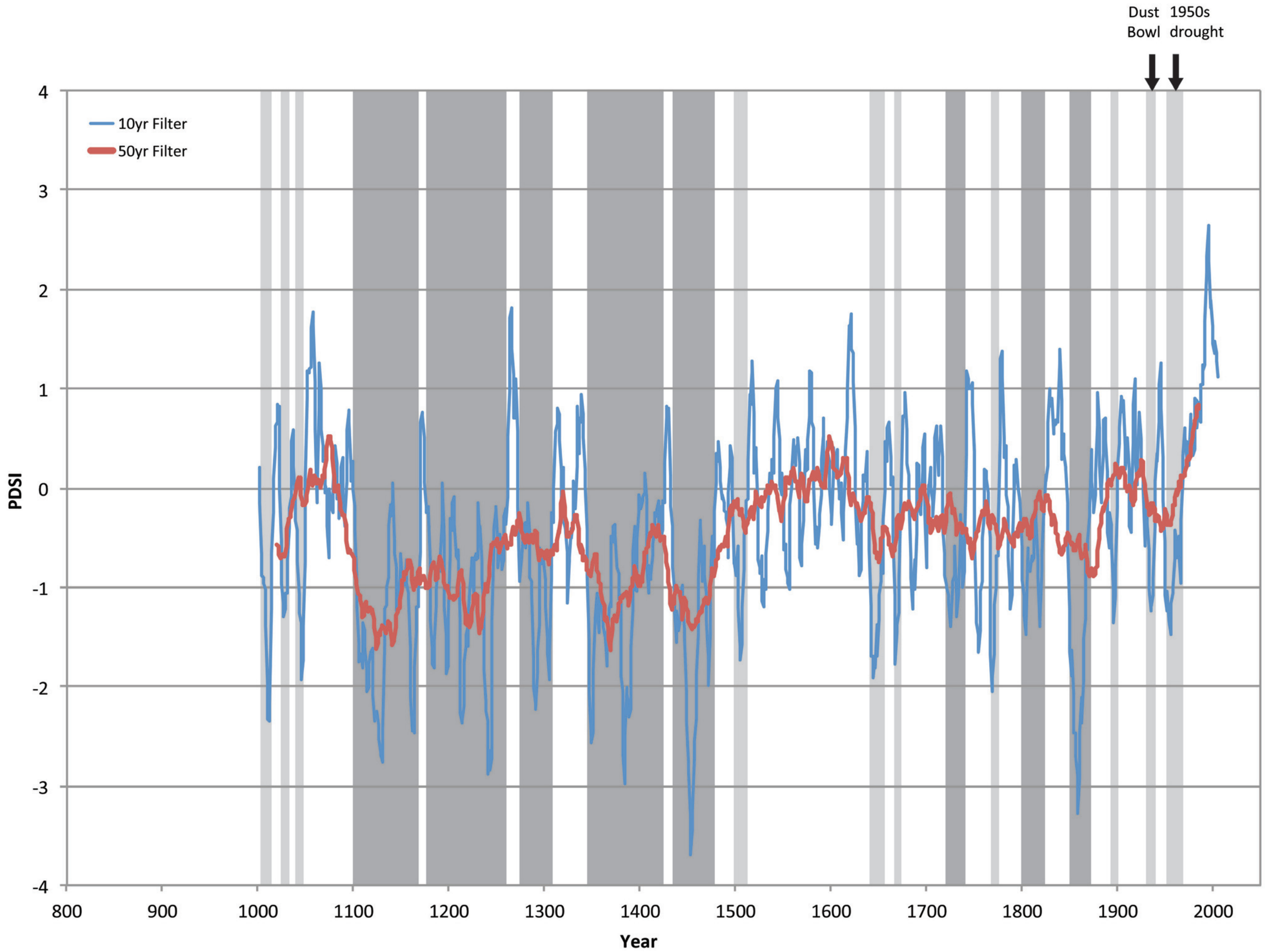


Figure 5d. Smoothed PDSI reconstructions for south-central Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

The 13th century drought is commonly referred to as the "Great Drought" in the southwest and contributed to significant social change in the Four Corners region through severe population loss and the abandonment of Anasazi settlements. This megadrought would have strongly impacted maize agriculture, which had become the dietary staple of the Anasazi (Benson et al., 2007). Rapid population declines have been documented from archeological sites starting at 1130 and 1280 AD. Studies have also reported population declines in the Fremont cultures located in the Four Corners region around 1000 AD, which may be attributable to the 990-1060 drought.

Severe multi-decadal droughts during the 14th and 15th centuries likely contributed to the decline of Mississippian agricultural societies (e.g. Cobb and Butler, 2002; Cook et al., 2007). Cook et al. (2007) suggest that widespread droughts at this time would likely have caused a sequence of poor harvests that would have proved disastrous. Several Mississippian settlements were abandoned by 1450 including Cahokia, located near the confluence of the Mississippi and Missouri rivers, and Spiro, situated in eastern Oklahoma. Evidence also suggests that the late 13th century megadrought also impacted the Cahokia region (e.g. Benson et al., 2007).

Overall the paleoclimate record suggests that Kansas has experienced droughts of far greater duration in the past than any experienced in the 20th century. This conclusion is supported by several historic, geomorphic, and archeological studies.

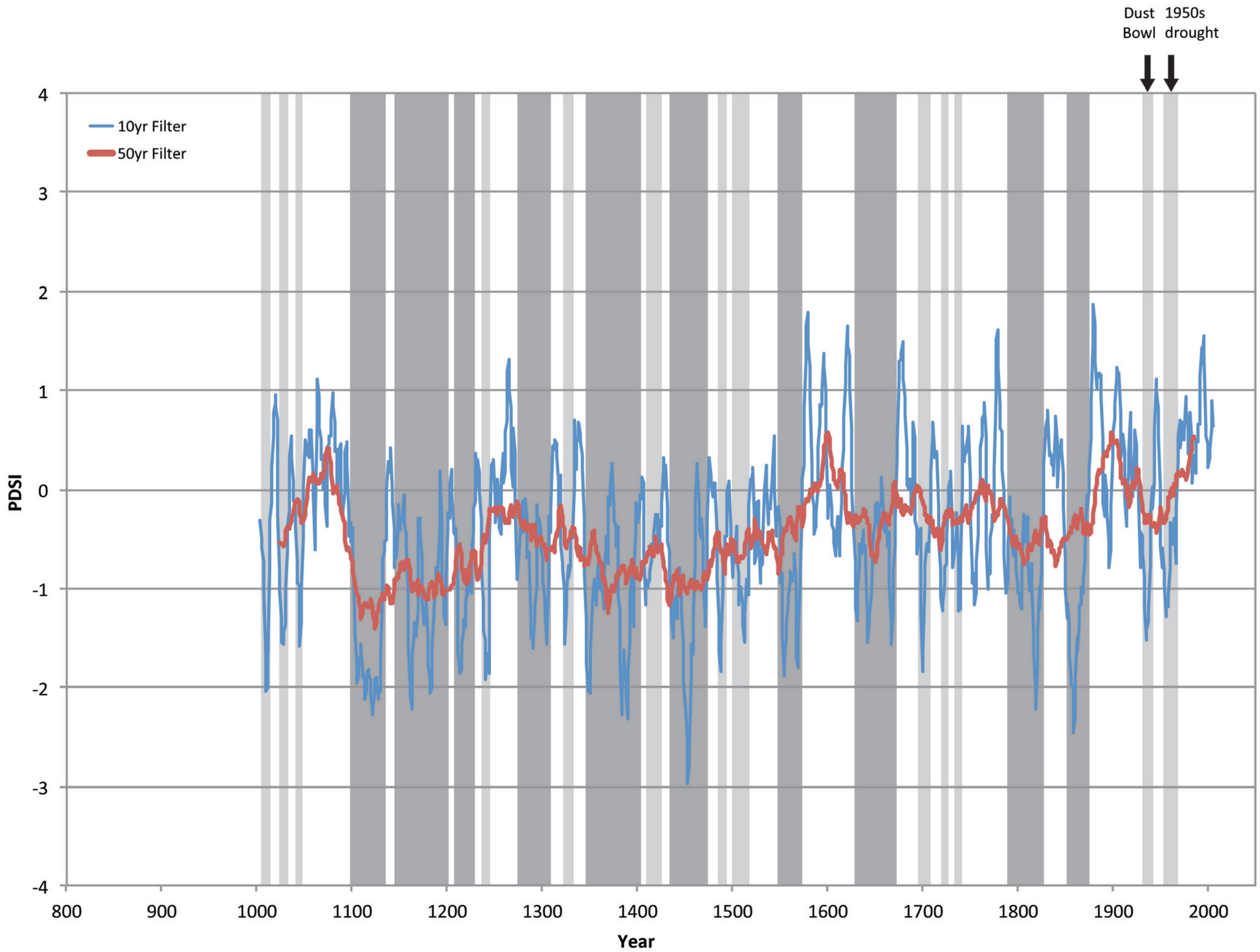


Figure 5e. Smoothed PDSI reconstructions for northeastern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

3.3 The Medieval Warm Period

Many of the past megadroughts documented in the paleoclimate record occurred during an era known as the Medieval Warm Period (MWP). The occurrence of several megadroughts during the MWP is troubling as it suggests that the climate system has the capacity to get 'stuck' in drought-inducing modes over the Great Plains that can last several decades to a century or more (Cook et al., 2009).

The MWP has been suggested as an approximate analog for likely future warming and drought conditions (e.g. Woodhouse et al., 2010) and thus serves as an important period to investigate. The MWP lasted from approximately 900 to 1300 AD and was characterized by significant climatic variability compared to the modern period. This period was identified by Lamb (1965) as a period of unusual warm temperatures in northern Europe but has since been documented in proxy records from across the globe (e.g. Graham et al., 2011). Other paleoclimate studies record a series of severe droughts across western North America (Cook et al., 2004) during this period, extending eastward into the central Great Plains (e.g. Daniels and Knox, 2005). In addition, the paleoclimatic data suggest a drought-regime change about 500 years ago (Fig. 7). The shift around 1500 AD to droughts of shorter duration may coincide with the onset of cooler climatic conditions during the Little Ice Age.

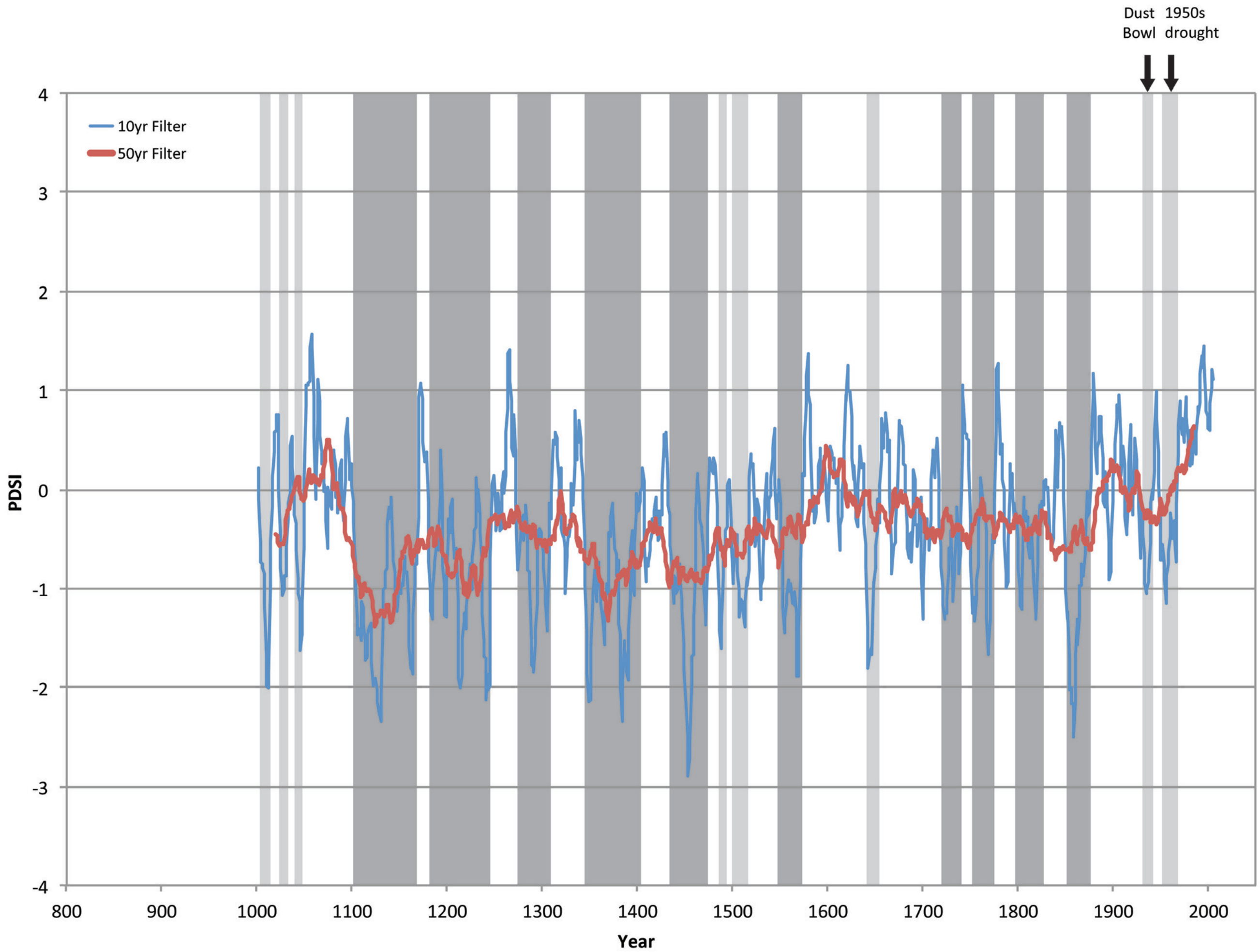


Figure 5f. Smoothed PDSI reconstructions for southeastern Kansas. Light-gray bars indicate droughts of similar duration to the 1930s and 1950s droughts while dark-gray bars indicate droughts of greater duration.

3.4 Risk analysis

Utilizing a similar approach to a previous paleoclimate report published by the Kansas Geological Survey (Young and Buddemeier, 2002), we can provide a quantitative analysis for assessing the risk of drought in Kansas. The paleoclimate data indicate that for western Kansas a drought as severe as the Dust Bowl has occurred on average 3 to 4 times a century. If “3 to 4 times a century” means that there has been on average 3.5 droughts more severe than the Dust Bowl per 100 years, then there is a 3.5% chance that any given year within a 100-year period will have such a severe drought. We can further estimate probabilities for shorter periods using simple arithmetic. For example, there is a 35% chance of a severe drought year in any decade, a 70% chance over a 20-year planning horizon and, in terms of probability, a 100% chance over the estimated 40-year working lifetime of an individual farmer in western Kansas. In eastern Kansas the probabilities are lower as droughts as severe as the Dust Bowl have only occurred about once every century.

We can do a similar analysis for drought duration. For western Kansas, decadal-length droughts have occurred on average twice a century. Therefore, there is a 20% chance of a Dust Bowl length drought in a given decade, a 40% chance over a 20-year period, and an 80% chance over a 40-year period in western Kansas.

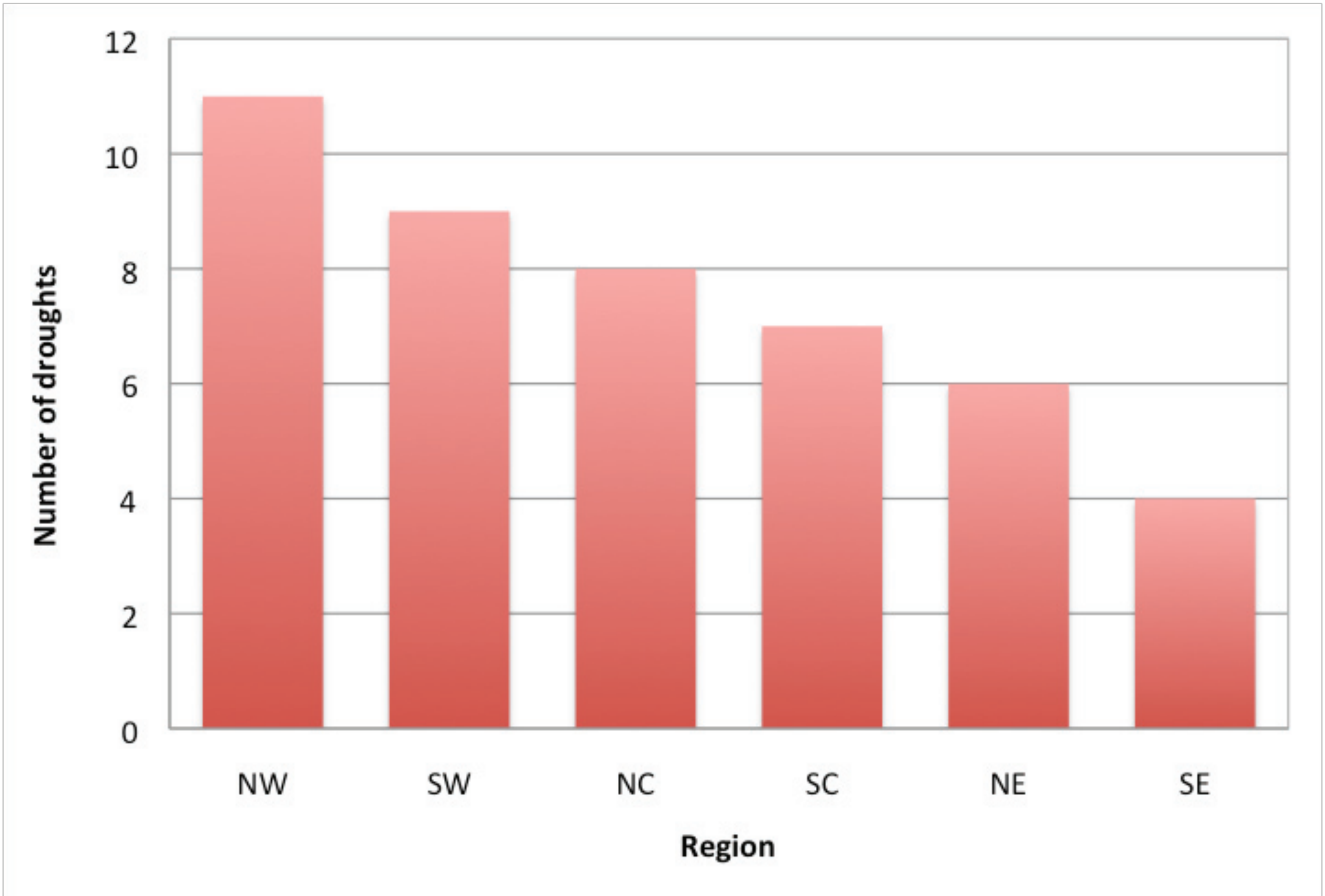


Figure 6. Number of drought periods from 1500 to 2011 AD of similar duration to the 1930s and 1950s droughts (i.e. lasting 10-20 years) by region.

4. Policy and Management Implications

Drought conditions have a significant impact on surface- and ground-water resources through heightened demand and reductions in water supply. Water systems are commonly designed to handle the "drought of record," identified as the most severe hydrological event from the instrumental record. For the state of Kansas, the 1950s drought (1952-57) remains the planning benchmark and is used to calculate reservoir yield through droughts with a 2% chance of occurrence in any one year (K.A.R. 98-5-8). However, this report provides multiple lines of evidence to support the conclusion that drought variability in the 20th century is just a subset of the full range of variability that one should expect under naturally occurring climatic conditions. In other words, in terms of the long-term record of drought variability, the 1930s and 1950s droughts are not unusual. In fact, the paleoclimatic record indicates that droughts of greater severity and longer duration have occurred in the past. Furthermore, it is possible that the conditions that led to past megadroughts, such as those that occurred during the MWP, could occur in the future. Such severe drought conditions are of great concern because modern-day agricultural and water systems may not have the resilience to survive droughts beyond the "worst case scenario" droughts of the past 100 years (Cook et al., 2007).

Figure 7. Synthesis of regional reconstructed PDSI data with additional paleoenvironmental proxy data from geomorphic and archeological sources.

In terms of water-resource management, paleoclimatic data have important implications. For example, reservoirs are typically designed with conservation pools to specific meet water demand during drought conditions. However, would these designs be adequate under megadrought conditions? Additionally, management of aquifer resources must be designed to accommodate high demand during protracted droughts while sustaining or extending the usable lifetime of the resource.

Woodhouse and Overpeck (1998) highlight two factors that may compound the susceptibility of the Great Plains to future drought: 1) increased vulnerability due to land-use practices, specifically the use of irrigation to bring marginal lands into agricultural production, and 2) the enhanced likelihood of drought due to global warming. Furthermore, certain factors present challenges to effective water-resource management including 1) current levels of uncertainty in predicting future drought occurrence, 2) the assumption of climatic stationarity by water-resource planners, and 3) competing management interests (e.g. Lins and Stakhiv, 1998; Hartmann, 2005).

Given these challenges, it would be wise to adopt a probabilistic approach to drought forecasting and planning that incorporates the full range of drought variability indicated in the paleoclimatic record.

5. References

Andreadis, K. M., Clark, E. A., Wood, A. W., Hamlet, A. F., and Lettenmaier, D. P., 2005, Twentieth-century drought in the conterminous United States: Journal of Hydrometeorology, v. 6, p. 985-1001.

Arbogast, A. F., 1996, Stratigraphic evidence for late-Holocene aeolian sand mobilization and soil formation in south-central Kansas, USA: Journal of Arid Environments, v. 34, p. 403–414.

Benson, L. V., Berry, M. S., Jolie, E. A., Spangler, J. D., Stahle, D. W., and Hattori, E. M., 2007, Possible impacts of early-11th-, middle-12th-, and late-13th-century droughts on western native Americans and the Mississippian Cahokians: Quaternary Science Reviews, v. 26, p. 336–350.

Cobb, C. R., and Butler, B. M., 2002, The vacant quarter revisited: late Mississippian abandonment of the Lower Ohio Valley: American Antiquity, v. 67, p. 625–641.

Cook, E. R., Meko, D. M., Stahle, D. W., and Cleaveland, M. K., 1999, Drought reconstructions for the continental United States: Journal of Climate, v. 12, p. 1145–1162.

Cook, E., and Krusic, P., 2004, North American summer PDSI reconstructions. IGBP PAGES/World Data Center for Paleoclimatology 2004–045: Paleoclimatology Program, National Geophysical Data Center Boulder, CO.

Cook, E. R., Woodhouse, C., Eakin, C. M., Meko, D. M., and Stahle, D. W., 2004, Long-term aridity changes in the western United States: Science, v. 306, p. 1015–1018.

Cook, E. R., Seager, R., Cane, M. A., and Stahle, D. W., 2007, North American drought: reconstructions, causes and consequences: Earth Science Reviews, v. 81, p. 93–134.

Cook, E. R., Seager, R., Heim, R. R., Vose, R. S., Herweijer, C., and Woodhouse, C., 2009, Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context: Journal of Quaternary Science, v. 25, p. 48–61.

Daniels, J. M., and Knox, J. C., 2005, Alluvial stratigraphic evidence for channel incision during the Mediaeval Warm Period on the central Great Plains, USA: The Holocene, v. 15, p. 736–747.

Forman, S. L., Marin, L., Gomez, J., and Pierson, J., 2008, Late Quaternary sand depositional record for southwestern Kansas: landscape sensitivity to droughts: Paleogeography, Paleoclimatology, Paleoecology, v. 265, p. 107–120.

Graham, N. E., Ammann, C. M., Fleitmann, D., Cobb, K. M., and Lutervacher, J., 2011, Support for global climate reorganization during the "Medieval Climate Anomaly": Climate Dynamics, v. 37, p. 1217–1245.

Halfen, A. F., Johnson, W. C., Hanson, P. R., Woodburn, T. L., Young, A. R., and Ludvigson, G. A., 2012, Activation history of the Hutchinson dunes in east-central Kansas, USA, during the past 2200 years: Aeolian Research, v. 5, p. 9-20.

Hartmann, H. C., 2005, Use of climate information in water resources management; *in*, Encyclopedia of Hydrological Sciences, M. G. Anderson, ed.: John Wiley and Sons, Ltd: Malden, MA, 202 p.

Hanson, P. R., Arbogast, A. F., Johnson, W. C., Joeckel, R. M., and Young, A. R., 2010, Megadroughts and late Holocene dune activation at the eastern margin of the Great Plains, north-central Kansas, USA. Aeolian Research, v. 1, p. 101–110.

Hoerling, M., Quan, X., and Eischeid, J., 2009, Distinct causes for two principal U.S. droughts of the 20th century: Geophysical Research Letters, v. 36, p. L19708 doi:10.1029/2009GL039860

Kansas Department of Agriculture, 2011: http://www.ksda.gov/news/id/405

Lamb, H. H., 1965, The early medieval warm epoch and its sequel: Paleogeography, Paleoclimatology, Paleoecology, v. 1, p. 13-37.

Lepper, K., and Scott, G. F., 2005, Late Holocene eolian activity in the Cimarron River valley of west-central Oklahoma: Geomorphology, v. 70, p. 42–52.

Lins, H. F, and Stakhiv, E. Z., 1998, Managing the nation's water in a changing climate: Journal of the American Water Resources Association, v. 34, p. 125–126.

Ludlum, D. M., 1971, Weather record book: Weatherwise, 98 p.

McGuire, V. L., 2009, Water-level changes in the High Plains aquifer, predevelopment to 2007, 2005-06, and 2006-07: U.S. Geological Survey, Circular 2009-5019, 9 p.

Muhs, D. R., and Holliday, V. T., 1995, Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers: Quaternary Research, v. 43, p. 198–208.

Palmer, W. C., 1965, Meteorological drought:. U.S. Weather Bureau, Research Paper, vol. 45.

Riebsame, W. E., Changnon, S. A., and Karl, T. R., 1991, Drought and natural resources management in the United States: impacts and implications of the 1987-89 drought: Westview Press, Boulder, 174 p.

Stahle, D. W., Fye, F. K., Cook, E. R., and Griffin, R. D., 2007, Tree-ring reconstructed megadroughts over North American since A.D. 1300: Climate Change, v. 83, p. 133–149.

Woodhouse, C. A., and Overpeck, J. A., 1998, 2000 years of drought variability in the central United States: Bulletin of the American Meteorological Society, v. 79, p. 2643–2714.

Woodhouse, C. A., Lukas, J. J., and Brown, P. M., 2002, Drought in the western Great Plains, 1845-56: Bulletin of the American Meteorological Society, v. 83, p. 1485-1493.

Woodhouse, C. A., Meko, D. N., MacDonald, G. M., Stahle, D. W., and Cook, E. R., 2010, A 1,200-year perspective of 21st century drought in southwestern North America: Proceedings of the National Academy of Science, v. 107, no. 50, p. 21283-21288.

Young, D. P., and Buddemeier, R. W., 2002, Climate variation: Implications of long-term records and recent observations: Kansas Geological Survey, Open-file Report 2002-25E.

Appendix: Calibration and Verification Statistics

The data used in this report were obtained from the North American Drought Atlas (Cook and Krusic, 2004). Cook and Krusic used four statistics as measures of association between the actual and estimated PDSI in order to test the fidelity of PDSI reconstructions.

1) Calibration R-SQuare (CRSQ). This statistic measures the percent PDSI variance explained by the tree-ring chronologies at each grid point over the 1928-1978 calibration period, based on a regression modeling procedure described in Cook et al. (1999). As defined here, CRSQ is equivalent to the "coefficient of multiple determination" found in standard statistic texts. It ranges from 0 (no calibrated variance) to 1.0 (perfect agreement between instrumental PDSI and the tree-ring estimates). The former represents complete failure to estimate PDSI from tree rings and the latter is not plausible if the model is not seriously over-fit.

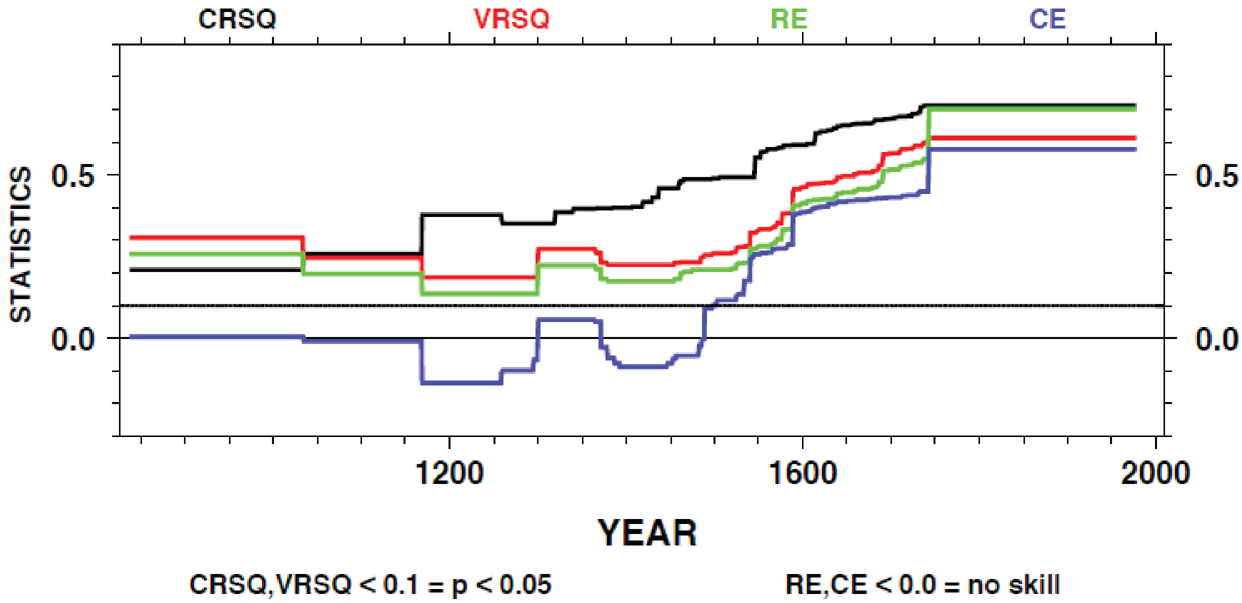
2) Verification R-SQuare (VRSQ). This statistic measures the percent PDSI variance in common between actual and estimated PDSI in the 1900-1927 verification period. It is calculated as the square of the Pearson correlation coefficient, which is a well known measure of association between two variables. VRSQ also ranges from 0 to 1.0 (VRSQ is assigned a 0 value if the correlation is negative). Roughly speaking, VRSQ>0.11 is statistically significant at the 1-tailed 95% level using our 28-year verification period data.

3) Verification reduction of error (RE). This statistic was originally derived by Edward Lorenz as a test of meteorological forecast skill. Unlike CRSQ and VRSQ, RE has a theoretical range of -infinity to 1.0. Over the range 0-1.0, RE expresses the degree to which the estimates over the verification period are better than "climatology," i.e. the calibration period mean of the actual data. So, a positive RE means that the PDSI estimates are better than just using the calibration period mean as a reconstruction of past PDSI behavior. A negative RE is generally interpreted as meaning that the estimates are worse than the calibration period mean and, therefore, have no skill. The use of the calibration period mean as the "yardstick" for assessing reconstruction skill makes this statistic more difficult to pass than VRSQ. However, it is also less robust, meaning that it is very sensitive to even a few bad estimates in the verification period. Therefore, RE>0 is interpreted as evidence for a reconstruction that contains some skill over that of climatology.

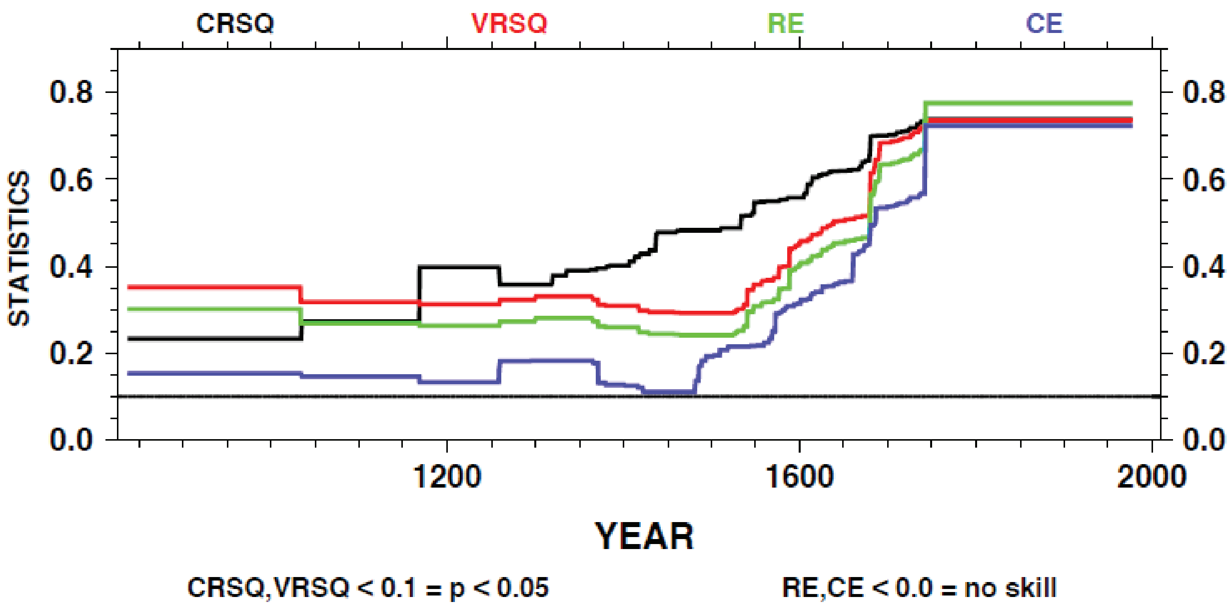
4) Verification coefficient of efficiency (CE). This statistic comes from the hydrology literature and is very similar to the RE. It too has a theoretical range of -infinity to 1.0. The crucial difference is that the CE uses the verification period mean of the withheld actual data as the "yardstick" for assessing the skill of the estimates. This seemingly minor difference is important because it results in the CE being even more difficult than the RE to pass (i.e., a CE>0).

Here we include the calibration and verification statistics for the six gridpoints utilized in this report. Note that all data are statistically significant for the period of record with the exception of northwestern Kansas, which fails the notoriously hard-to-pass CE test before 1500 AD. Overall the PDSI data are well calibrated and verified.

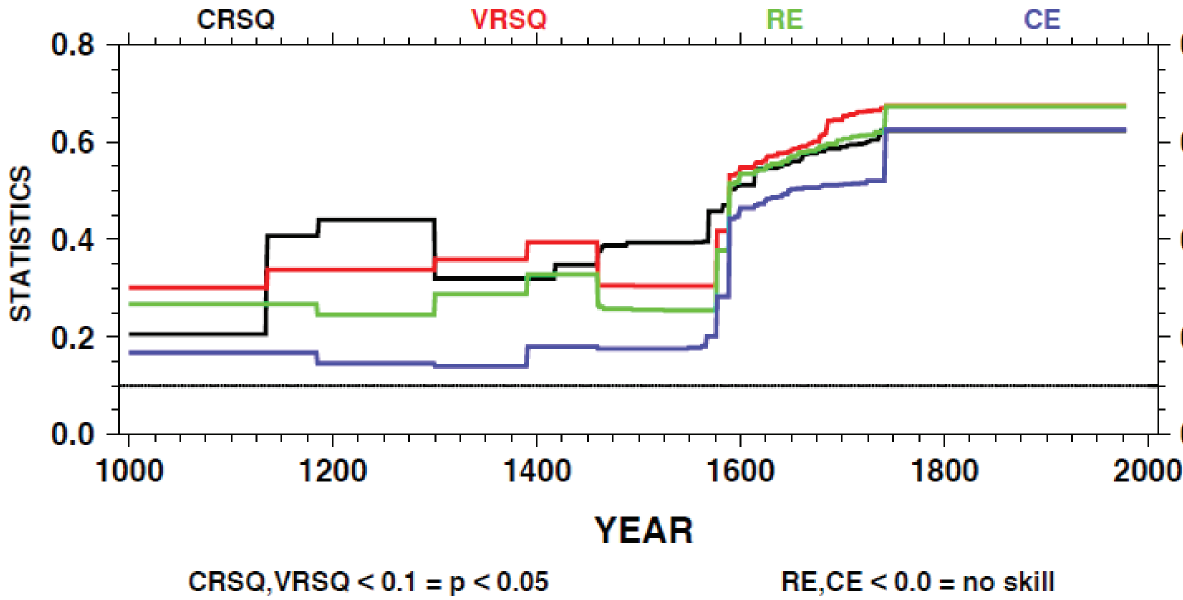
Northwestern Kansas



Southwestern Kansas



North-central Kansas



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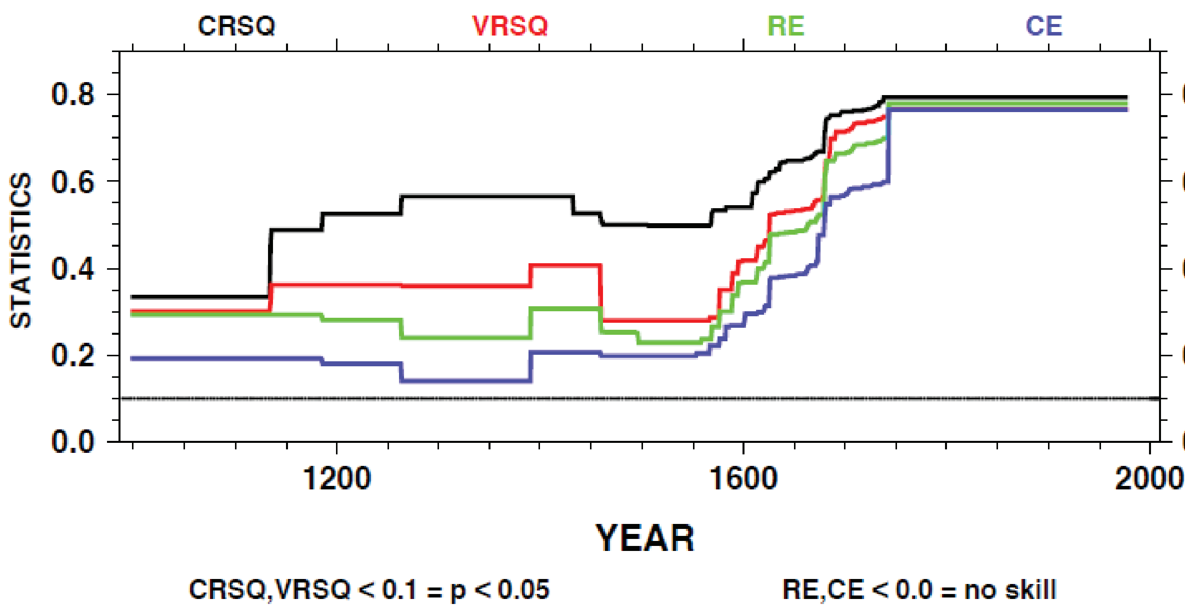
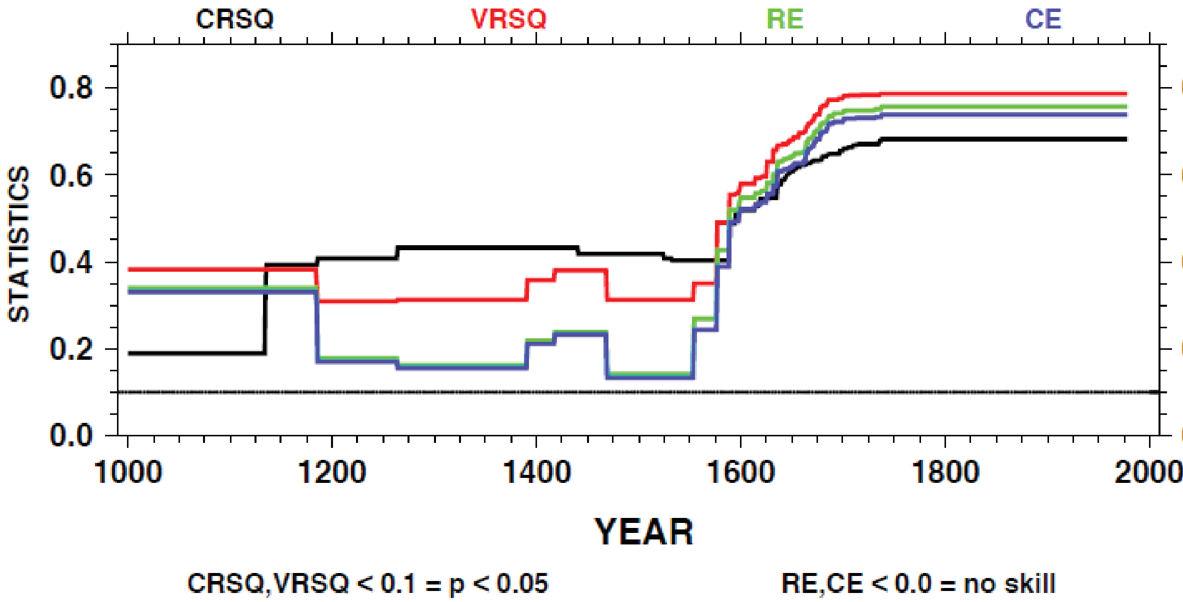


Northeastern Kansas



Southeastern Kansas