

The Relationship between Cool and Warm Season Moisture over the Central United States, 1685–2015

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ABSTRACT

Land surface feedbacks impart a significant degree of persistence between cool and warm season moisture availability in the central United States. However, the degree of correlation between these two variables is subject to major changes that appear to occur on decadal to multidecadal time scales, even in the relatively short 115-yr instrumental record. Tree-ring reconstructions have extended the limited observational record of long-term soil moisture levels, but such reconstructions do not resolve the seasonal differences in moisture conditions. We present two separate 331-yr-long seasonal moisture reconstructions for the central United States, based on sensitive subannual and annual tree-ring chronologies that have strong and separate seasonal moisture signals: an estimate of the long-term May soil moisture balance and a second estimate of the short-term June–August atmospheric moisture balance. The predictors used in each seasonal reconstruction are not significantly correlated with the alternate season target. Both reconstructions capture over 70% of the interannual variance in the instrumental data for the calibration period and also share significant decadal and multidecadal variability with the instrumental record in both the calibration and validation periods. The instrumental and reconstructed moisture levels are both positively correlated between spring and summer strongly enough to have potential value in seasonal prediction. However, the relationship between spring and summer moisture exhibits major decadal changes in strength and even sign that appear to be related to large-scale ocean–atmosphere dynamics associated with the Atlantic multidecadal oscillation.

1. Introduction

Monthly time scale persistence of drought and wetness can play an important role in the forecasting of seasonal moisture levels (Preisler and Westerling 2007; Mason and Baddour 2008; Hao et al. 2014). Spring moisture conditions in the central United States have some skill in predicting the baseline probability of summer drought (Lyon et al. 2012; Otkin et al. 2015). A nationwide perspective on the correlation between spring soil moisture and the atmospheric moisture balance during the following summer is presented in Fig. 1. The self-calibrated Palmer drought severity index (scPDSI; Palmer 1965; Wells et al. 2004) for the month of May is correlated with Palmer's Z index (which is

calculated without prescribed persistence) for June–August (JJA), and the highest correlations are computed in the Mediterranean climate of California and southern Oregon. The weakest spring-to-summer moisture correlations are computed in the monsoon climate of the southwestern United States. A zone of high interseasonal correlation is also present in the central United States, extending from the coast of Texas to central Minnesota (Fig. 1). The seasonal climatology can explain the presence or absence of seasonal persistence in California, the Pacific Northwest, and the Southwest, but in the central United States land surface feedbacks and possibly large-scale ocean–atmospheric forcing may be responsible and could therefore provide a degree of useful forecast potential (Lyon et al. 2012; Otkin et al. 2015).

One consequence of the persistence in moisture levels from spring to summer is that spring drought is unlikely

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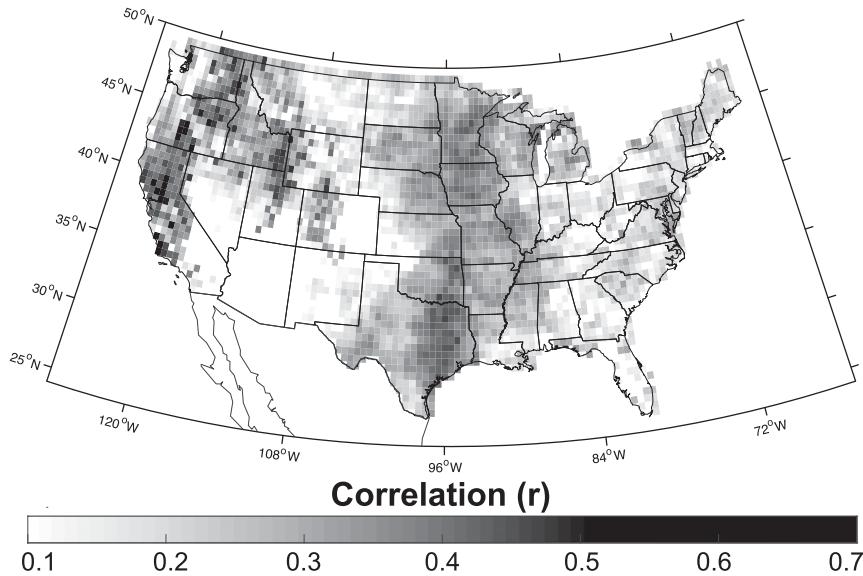


FIG. 1. The correlation between the long-term soil moisture balance ending in May (May scPDSI) and the short-term atmospheric moisture balance for summer (Palmer's Z index for JJA) is plotted for each 0.25° by 0.25° grid point over the United States based on instrumental observations from the period 1895–2015.

to be terminated during the following summer months (Karl et al. 1987). However, the usefulness of seasonal persistence in climate forecasting is dependent on temporal stability. A weakening of the moisture correlation from spring to summer can be observed on decadal time scales in instrumental records, greatly degrading the skill in simple persistence-based forecasts. Large-scale ocean–atmospheric variability may be responsible for some changes in the strength of seasonal moisture persistence. Identifying the factors involved in the change in persistence may lead to improved forecasting. Longer proxy records of persistence, extending beyond the period of observational data, may be helpful in understanding the seasonal evolution of drought and wetness regimes.

Long exactly dated tree-ring chronologies have been used to extend the temporally limited instrumental record of drought and wetness on regional (e.g., Blasing et al. 1988; Watson and Luckman 2002) and continental scales (Cook et al. 1999, 2007, 2015; Palmer et al. 2015). These reconstructions have been valuable for investigations of large-scale ocean–atmospheric forcing and regional climate (Herweijer et al. 2007; Graham et al. 2007; Seager et al. 2009), interactions between climate and ecology (Speer et al. 2001; Woodhouse et al. 2002), and the societal responses to climatic extremes (DeMenocal 2001; Stahle and Dean 2011). These high-quality tree-ring reconstructions have identified decadal regimes of drought and wetness in the past 500–1000 years that were more extreme than those experienced in

the instrumental period (Herweijer et al. 2006; Cook et al. 2011b; Stahle et al. 2011).

Most North American tree-ring chronologies are correlated with the long-term soil moisture balance integrating conditions prior to and during the spring–summer growing season (Fritts 1965). The PDSI is an excellent model of the integrated multiseason moisture signal embedded in many tree-ring chronologies and has been widely used for reconstructions (e.g., Cook et al. 1999, 2007). Reconstructions of strict single-season moisture conditions from tree rings, especially for JJA over the continental United States, are considerably rarer. As a result, there are few annually resolved proxy records of summer moisture that are not also correlated with antecedent conditions during the winter and/or spring. This is an important distinction because the climate dynamics responsible for interannual to decadal variability of drought can change from the cool to warm season (Seager et al. 2009; Coats et al. 2015; Pu et al. 2016). The impact of multiseason droughts will also tend to be more severe than anomalies confined to a single season (e.g., Stahle et al. 2009; Griffin et al. 2013), and with the overestimation of seasonal persistence, the potential predictability of summer conditions from soil moisture during the preceding season cannot be evaluated with tree-ring reconstructions.

The two most extreme decadal droughts of the twentieth century in North America differed across space and seasonality and appear to have involved different climate forcings. In the south-central United

TABLE 1. Tree-ring records used for the reconstructions of seasonal moisture balance over the central United States.

Site code	Site name	Lon (°)	Lat (°)	Start	End	Species	Variable	Study
CANUSA	Canadian River	35.58	98.38	1680	1982	QUST	TRW	Stahle and Cleaveland (1988)
CBKUSA	Cedar Bluff	38.46	99.49	1353	2008	JUVI	TRW	Edmondson (2010)
DNRUSA	Nichols Ranch	32.98	99.18	1681	1995	QUST	TRW	
EPLUSA	Egypt Promised	35.51	90.95	1417	1980	TADI	TRW	Stahle et al. (1985)
HHCUSA	Hemmed in Hollow	36.08	93.31	1359	1992	JUVI	TRW	
KEYUSA	Keystone Lake	36.21	96.22	1611	1995	QUST	TRW	
MAUUSA	Little Maumelle	34.83	92.51	1532	1985	TADI	TRW	Stahle et al. (1985)
BSWUSA	Black Swamp	35.09	91.17	1019	1980	TADI	EWV	Stahle et al. (1985)
DEVUSA	Bayou Devew	34.51	91.17	1133	1985	TADI	EWV	Stahle et al. (1985)
SKYUSA	Sky Lake	33.16	90.29	1238	2010	TADI	EWV	
CCWUSA	Clifty Canyon	36.04	92.15	1672	1980	PIEC	LWW	
LAWUSA	Lake Winona	34.48	92.56	1667	1980	PIEC	LWW	
MCWUSA	McCurtain County	34.18	94.39	1685	1982	PIEC	LWW	
NICUSA	Nickel Preserve	36.03	94.83	1581	2015	PIEC	LWW	

States, the Dust Bowl drought of the 1930s was most intense during summer and developed in part because of a combination of global sea surface temperature (SSTs) anomalies and regional land surface feedbacks (Cook et al. 2011b; Cook and Seager 2013). The 1950s drought was most severe over some sectors of the United States during the winter–spring when La Niña conditions prevailed in the equatorial Pacific (Hoerling et al. 2009; Seager and Hoerling 2014; Pu et al. 2016). If separate seasonal signals, mirroring the relationship in the instrumental data, can be recovered from a subset of the available tree-ring chronologies then it may be possible to use these high-quality climate proxies to gain a greater understanding of the complex seasonal variability and persistence of droughts and pluvials.

In this paper we describe the development of new subannual tree-ring chronologies of latewood width for shortleaf pine [*Pinus echinata* (PIEC)] that have strong signals of JJA moisture conditions (without being excessively correlated with any preceding season). The derived reconstruction of the summer moisture balance is then compared with an equally strong reconstruction of the soil moisture during the preceding winter–spring based on earlywood width and total ring-width chronologies of post oak [*Quercus stellate* (QUST)], eastern red cedar [*Juniperus virginiana* (JUVI)], and bald cypress [*Taxodium distichum* (TADI)] that are only correlated with cool season conditions. These two reconstructions are used to separately describe the history of cool and warm season moisture variability over the south-central United States for the past 330 years, including the co-occurrence of cool and warm season extremes. The persistence of drought from spring to summer is estimated in both the instrumental and reconstructed indices, and periods when the relationship between spring and summer seasonal moisture weakens and even reverses sign are identified. These variations in

interseasonal persistence appear to be related to anomalies in large-scale ocean–atmospheric forcing and Atlantic SSTs, which may provide an empirical basis for improving seasonal forecasts based only on persistence.

2. Methods

Tree-ring data collected by the University of Arkansas Tree-Ring Laboratory from 14 old-growth forest locations in the south-central United States were used in this study (Table 1). Each collection is made up of 40–80 increment core specimens and/or cross sections from living or dead trees, and the annual rings (Fig. 2) on all specimens were exactly dated to their calendar year of formation with dendrochronological methods (Stokes and Smiley 1968). These collections include samples from shortleaf pine, post oak, bald cypress, and eastern cedar. Most of these species exhibit a sharp distinction between earlywood and latewood portions of the annual ring (also known as springwood and summerwood), and interannual variability in these subannual ring components may contain useful proxy information on both cool and warm season climate conditions (e.g., Schulman 1942; Meko and Baisan 2001; Griffin et al. 2013). The dated tree rings from the 14 sites were measured for earlywood width (EWW), latewood width (LWW), and total ring width (TRW) with a precision of 0.001 mm on a stage micrometer. Several different methods of standardization to remove age-related effects on radial growth and to stabilize the variance of each ring with the series were evaluated. The signal-free method of detrending and standardization (Melvin and Briffa 2008; Cook et al. 2014), using age-dependent splines, was chosen because of its ability to retain low- and medium-frequency variability. The EWW, LWW, and TRW measurements were first power transformed and then an age-dependent spline (Cook and Peters 1981; Melvin

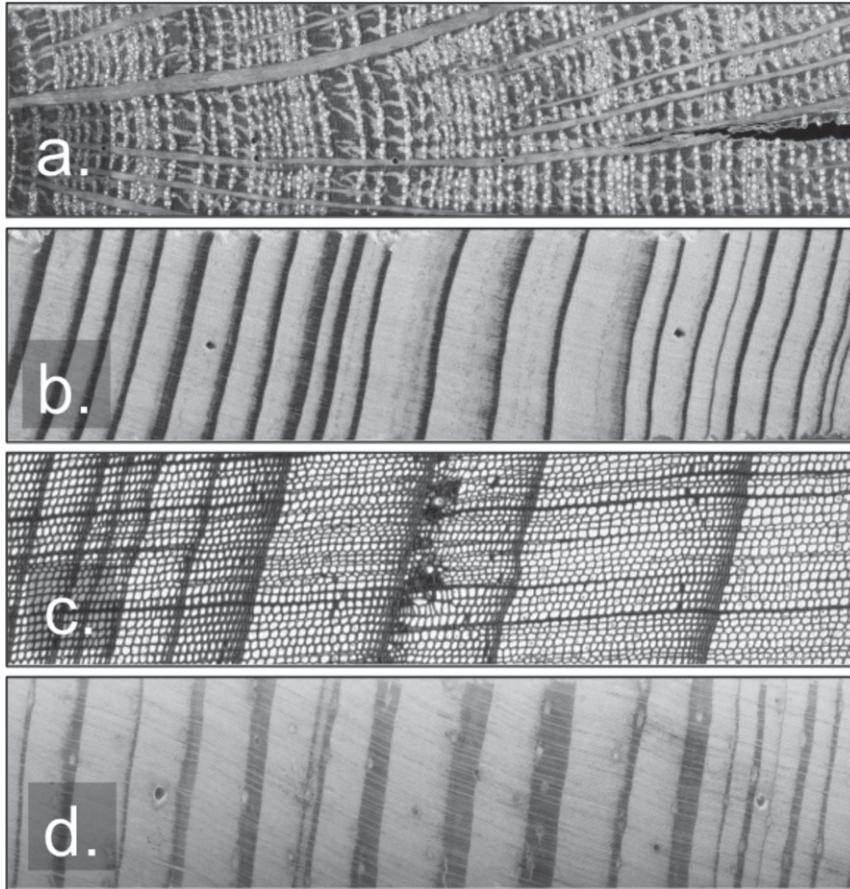


FIG. 2. Photomicrographs of the annual growth rings for the tree species used for seasonal moisture reconstructions are illustrated: (a) QUST, (b) TADI, and (c) JUVI, all used for the cool season; and (d) PIEC, used for the warm season estimates.

et al. 2007) that allowed for a positive asymptote was fitted to each measurement series. The width indices were calculated as residuals from the fitted curve values and then averaged to produce master chronologies of EWW, LWW, and TRW for each collection, which represent the mean radial growth conditions at each collection site.

The various types of ring-width chronologies were correlated with the closest grid point of monthly moisture balance indices (scPDSI and Z index; Williams et al. 2015) based on PRISM data (Daly et al. 2004) for the common period 1921–80 to identify the season of highest association between hydroclimate and tree growth. The 14 chronologies include 10 that were mainly correlated with cool season moisture and four that were mainly correlated with the warm season. Principal component analysis (PCA; Jolliffe 2002) was performed on the 10 EWW and TRW chronologies displaying correlations above $r = 0.30$ with local May scPDSI. This group of EWW and TRW chronologies is referred to as the cool

season network. PCA was also performed on a separate group of four shortleaf pine LWW chronologies that are all highly correlated with the moisture balance in JJA, referred to as the warm season network. Because none of the chronologies used in either seasonal network is correlated higher with the alternate climate season (Table 2) or higher than the range of intercorrelation between the instrumental data (see below), it was possible to develop two separate cool and warm season moisture reconstructions for our study region.

a. Cool season reconstruction

The first principal component time series (PC1) of the cool season chronology network is correlated the highest with observed May scPDSI data (Fig. 3a). The scPDSI uses instrumental precipitation and temperature to estimate available soil moisture (Palmer 1965) and is calibrated with local climate data to allow for comparisons of drought and wetness intensity across space (Wells et al. 2004). The index prescribes a strong

TABLE 2. Correlations between tree-ring chronology predictors of May scPDSI and JJA Z index and local (closest grid point) climate data for the period 1921–80. Correlations in bold indicate $r > 0.50$ ($p < 0.001$).

May scPDSI predictors			r May scPDSI	r JJA Z
CANUSA	QUST	TRW	0.622	0.317
CBKUSA	JUVI	TRW	0.419	0.368
DNRUSA	QUST	TRW	0.334	0.268
EPLUSA	TADI	TRW	0.500	0.325
HHCUSA	JUVI	TRW	0.302	0.216
KEYUSA	QUST	TRW	0.583	0.308
MAUUSA	TADI	TRW	0.444	0.246
BSWUSA	TADI	EWV	0.501	0.289
DEVUSA	TADI	EWV	0.676	0.193
SKYUSA	TADI	EWV	0.557	0.279
JJA Z index predictors				
CCWUSA	PIEC	LWW	0.351	0.648
LAWUSA	PIEC	LWW	0.402	0.564
MCWUSA	PIEC	LWW	0.128	0.746
NICUSA	PIEC	LWW	0.456	0.724

month-to-month persistence term of 0.897 and has been a standard for calculating long-term meteorological drought in climatology (Heim 2002) and paleoclimatology (Cook et al. 2007). Based on the spatial pattern of correlations between the first principal component of the cool season chronology network and the scPDSI, a regional time series was computed by averaging the scPDSI from grid points within a bounding box covering 32.75°–38.25°N and 90.25°–98.25°W.

Forward stepwise regression between the tree-ring predictors (i.e., PC1 in year t , $t-1$, and $t+1$) and May scPDSI was computed. The coefficients of the regression model were used to estimate May drought severity back to 1685. The predictor PC1 time series computed from the cool season network was calibrated with the predictand May scPDSI for the period 1941–80, and the reconstruction was verified on independent instrumental data for the period 1895–1940. Standard regression and statistical metrics were used to quantify the agreement between reconstructed and instrumental May PDSI at interannual time scales, including the calibration period explained variance, the square of the Pearson correlation coefficient, the reduction of error (RE), and coefficient of efficiency (CE) during the validation period (Fritts 1976; Cook et al. 1999). The instrumental May scPDSI variance lost in regression was restored to the reconstruction so that the instrumental data could be used to extend the full estimate from 1685 to 2015 (331 years) using both reconstructed and instrumental data. Spectral coherence analysis (Percival and Constantine 2006) was employed to estimate how well the reconstruction and instrumental data of May scPDSI agree on time scales greater than the

interannual. The similarity of the time series' periodogram (Bloomfield 2000) was compared to standard Gaussian noise using bootstrap simulations ($n = 10\,000$). Singular spectrum analysis (SSA; Ghil et al. 2002; St. George and Ault 2011) was performed to decompose the reconstructions into temporal eigenvectors in order to estimate the relative importance of variability at different periodicities.

b. Warm season reconstruction

PC1 of the warm season chronology network displays the highest correlation with the JJA Z index (Fig. 3b). Unlike the scPDSI, no month-to-month persistence is included in the calculation of the Z index (Palmer 1965; Heim 2002). Therefore, any correlation between May scPDSI and the subsequent summer moisture balance represented by the JJA Z index would be due to persistence in the physical climate system and would not arise from the statistical design of the indices. Furthermore, we only use shortleaf pine LWW chronologies to estimate the JJA Z index. These LWW chronologies are not significantly correlated with the winter–spring scPDSI, and there can be no physiological persistence between the cool and warm season proxies, which are based on separate chronologies from different species. Precipitation dictates a large portion of the variability in the summer Z index in our study region, with more than 70% of the variance in the JJA Z index explained by JJA precipitation. The first PC time series of the warm season network was used to reconstruct the regional average JJA Z index for the central United States from the period 1685–1980, and updated to 2015 with the instrumental Z indices for summer, using the same regional domain, calibration, and validation procedures that were used estimate May scPDSI (above).

c. Analysis of the possible persistence between cool and warm season moisture

Running correlations between instrumental May scPDSI and the JJA Z index for a 25-yr moving window, advancing in 1-yr increments, were computed to examine the stability of the relationship between cool and warm season moisture availability over time. The same analyses were performed on the reconstructed data. Spectral coherence analysis (Ghil et al. 2002; St. George and Ault 2011) was used to identify any frequency-band-limited coherence between reconstructed cool and warm season moisture from 1685 to 2015. Each year in the reconstructions was also ranked according to the severity of spring and summer drought, respectively. To estimate the persistence in interseasonal moisture conditions, the absolute difference in rank between spring and summer was computed. The reconstructions and

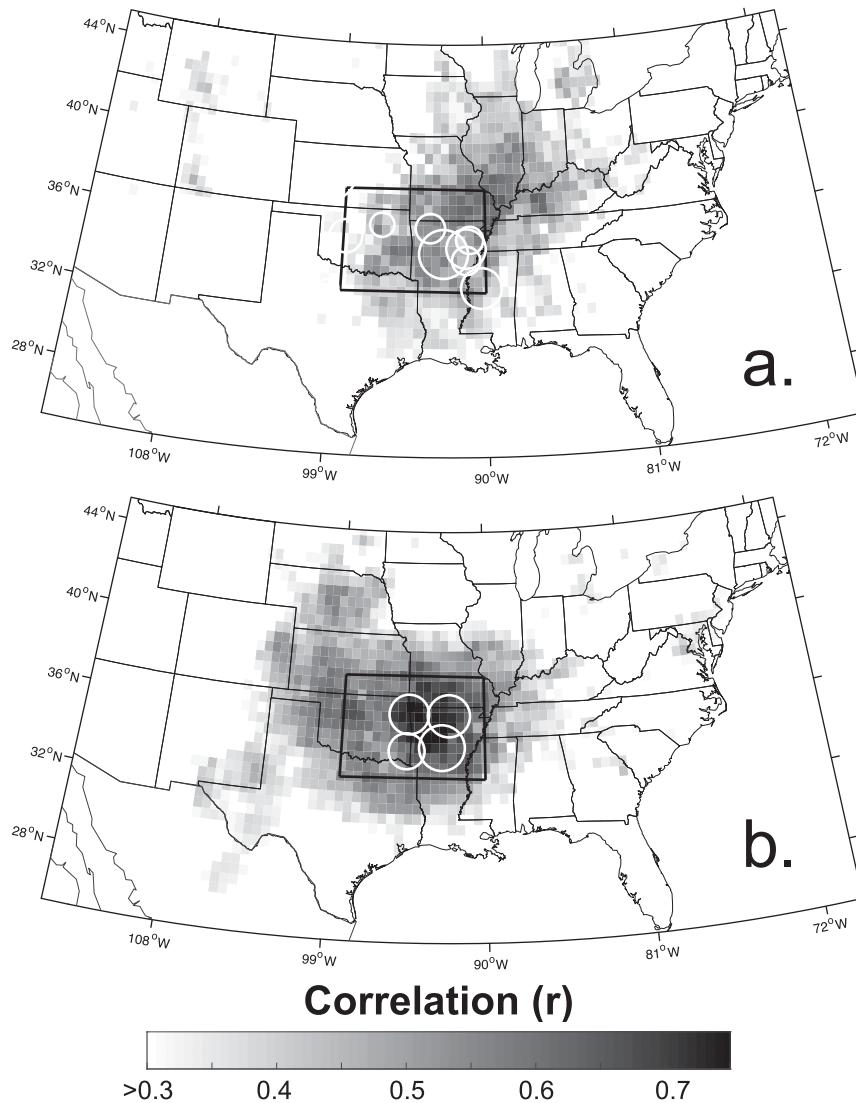


FIG. 3. The spatial correlation between (a) the first PC time series of the cool season tree-ring network and instrumental May scPDSI for the period 1895–1980, and (b) as in (a), but for the warm season tree-ring network and the instrumental JJA Z index. Circles indicate the location of each tree-ring chronology, and the circle diameter is scaled to the relative loading of each chronology on PC1. The black boxes show the area of the central United States within which the regional average May scPDSI and JJA Z indices were calculated.

rank difference time series were compared to the Atlantic multidecadal oscillation (AMO) index (Enfield et al. 2001) for the period 1871–2015.

3. Results

The results for each reconstruction will first be described, followed by a discussion of annual and decadal extremes, confirmation of selected extremes with historical information, analysis of the frequency and characteristics of moisture reversals, and analyses of the time

dependency in the potential predictability of summer moisture based on conditions during spring.

a. Reconstruction of May scPDSI

The PC1 time series based on the 10 cool season chronologies in year t makes up the predictor of May scPDSI in the forward regression for the 1941–80 calibration period. The transfer function used for the reconstruction of regional May scPDSI is simply

$$\hat{Y}_t = 0.01 + 0.634X_t, \quad (1)$$

TABLE 3. Calibration and verification statistics for the reconstructions of May soil moisture and summer atmospheric moisture balance over the central United States.

Variable	Calibration			Verification		
	Period	R^2 adj.	Durbin–Watson	Period	r	RE/CE
May scPDSI	1941–80	0.704	1.801, $p = 0.485$	1895–1940	0.728	0.486/0.449
JJA Z index	1941–80	0.735	2.632, $p = 0.826$	1895–1940	0.797	0.683/0.682
May scPDSI	1895–1980	0.628	1.472, $p = 0.020$	—	—	—
JJA Z index	1895–1980	0.679	1.794, $p = 0.325$	—	—	—

where \hat{Y}_t is the estimated May scPDSI value for year t , and X_t is the value for the cool season PC1 time series also in year t . The transfer function explains 70.4% of the interannual variability in May scPDSI during the calibration period (1941–80; Table 3; Fig. 4a). This

strong empirical relationship between cool season PC1 and May scPDSI weakens somewhat in the validation period (1895–1940), but even during the statistically independent early twentieth century the reconstruction is still representing over 50% of the variance in the

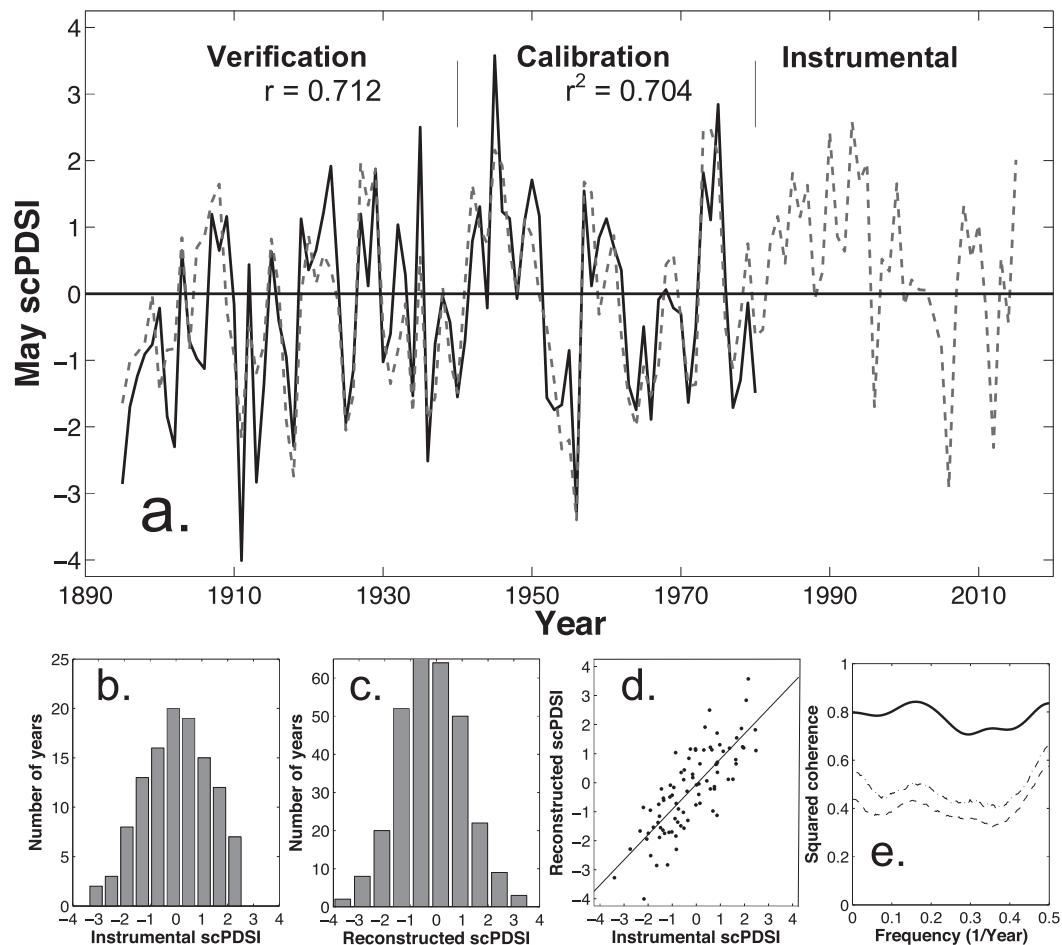


FIG. 4. (a) The time series comparison between instrumental (dashed line) and reconstructed (solid line) regionally averaged May scPDSI for the central United States. The reconstruction was based on the cool season network of tree-ring chronologies and was calibrated for the period 1941–80 and verified by comparison with the instrumental data from the period 1895–1940. The frequency distributions of the scPDSI values are plotted for the (b) instrumental observations (1895–1980) and (c) reconstructed estimates (1685–1980). (d) The scatterplot between instrumental and reconstructed May scPDSI is presented for the full overlap period (1895–1980). (e) The squared coherence between the instrumental and reconstructed scPDSI for the period 1895–1980 is plotted (solid line; dashed lines represent the 95% and 99% confidence thresholds for significant coherence).

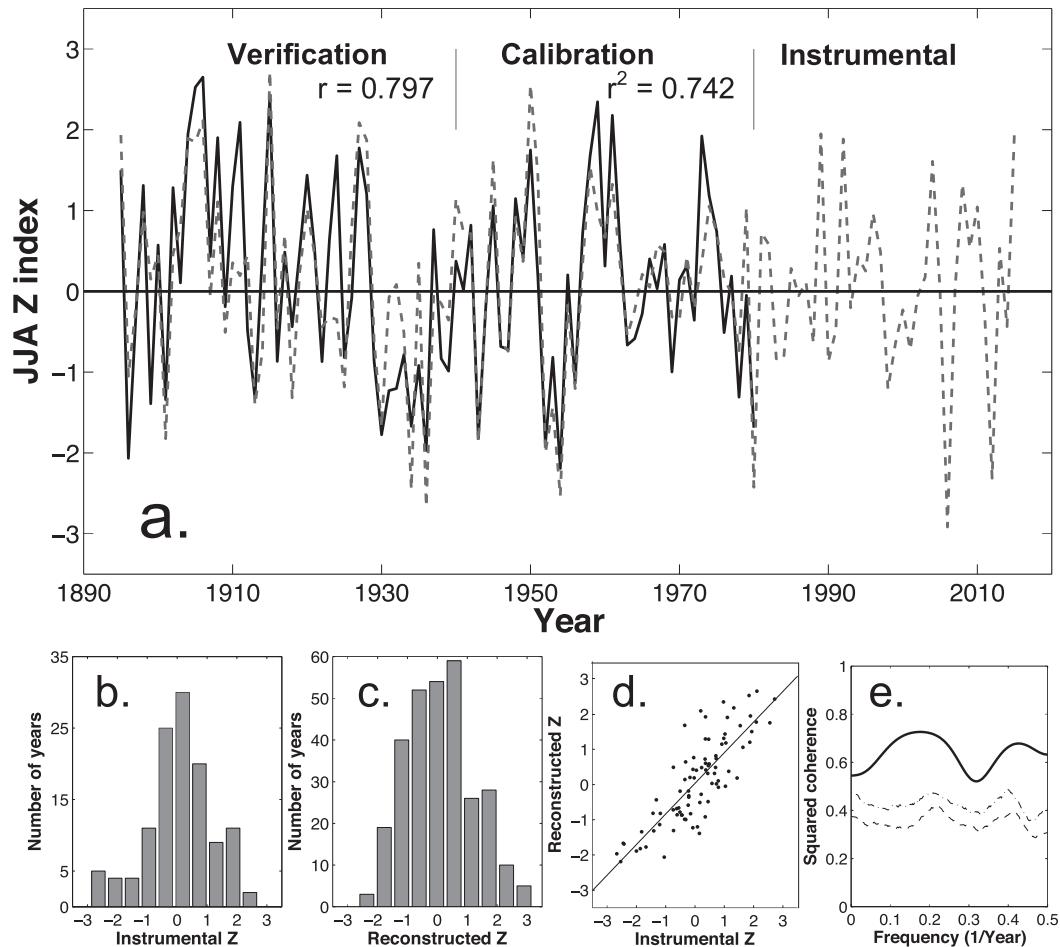


FIG. 5. As in Fig. 4, but for the warm season network estimation of the JJA Z index.

instrumental May scPDSI ($r = 0.728$; Table 3). An alternative calibration period, using the full instrumental data, reaffirms the strong hydroclimate signal that exists in the 10 cool season chronologies. The reconstruction passes the reduction of error ($RE = 0.486$) and the coefficient of efficiency ($CE = 0.449$) tests, indicating that the reconstruction provides a skillful estimation of the independent moisture balance data (Cook and Kairiukstis 1990). The scPDSI values in the instrumental data (Fig. 4b) and the reconstructed time series (Fig. 4c) are both normally distributed [Lilliefors test ($p > 0.05$); Conover 1980] but the more numerous reconstructed values are more symmetrical around the mean. The reconstruction and instrumental data are highly correlated ($r = 0.79$) over the full overlapping period (1895–1980), and the scatterplot indicates only a slight deviation from linearity in the point cloud (Fig. 4d). The results of the spectral coherence analysis indicate that the instrumental and reconstructed May scPDSI time series share significant common variability at all frequencies, including decadal and multidecadal time scales (Fig. 4e).

b. Reconstruction of JJA Z index

The PC1 time series based on the four shortleaf pine LWW chronologies in year t was entered as a potential predictor in a regression with the summer Z index for the central United States for 1941–80. The transfer function for reconstructing the regional JJA Z index is

$$\hat{Y}_t = 0.076 + 0.593X_t, \quad (2)$$

where \hat{Y}_t is the estimated JJA Z index for year t , and X_t is the value of PC1 of the four LWW chronologies in year t . The instrumental data for 1895–1940 were withheld for independent statistical verification of the reconstruction. The transfer function explains 74.2% of the interannual variability in JJA Z index during the calibration period (1941–80; Fig. 5a). Similar to the reconstruction of May scPDSI, the strong relationship during the calibration period weakens only a little when the reconstruction is compared with independent Z indices during the validation period 1895–1940 ($r = 0.797$). The distribution of instrumental Z-index values

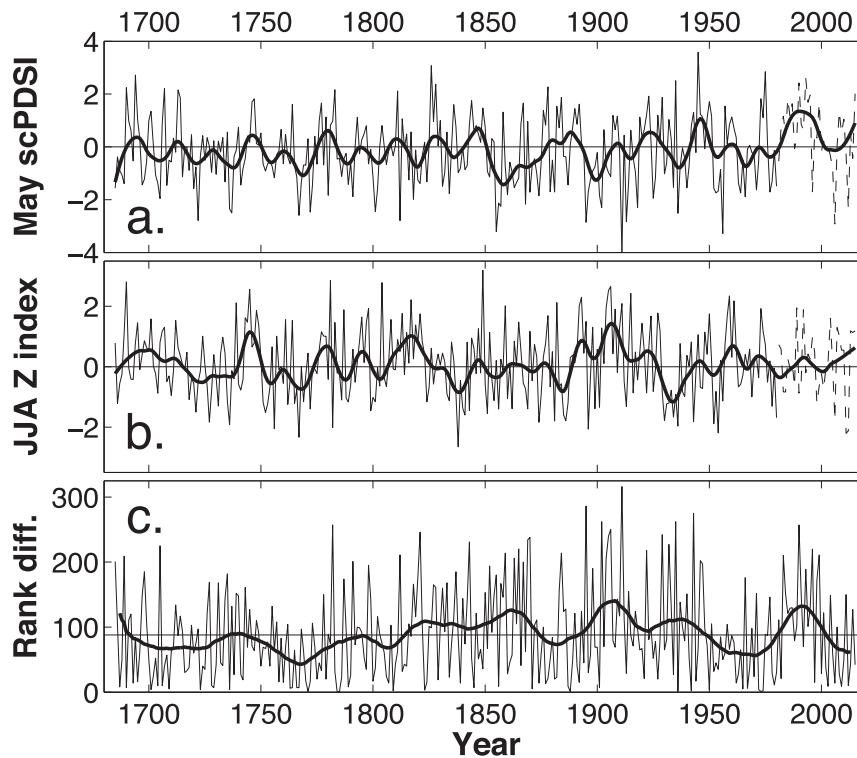


FIG. 6. Moisture reconstructions for the central United States extending from 1685 to 2015 based on the tree-ring chronologies in Table 1 and Figs. 3a and 3b, (a) May scPDSI and (b) JJA Z index. Instrumental observations extend each seasonal reconstruction to 2015 (dashed lines). The reconstructions are fitted with a cubic spline designed to highlight the decadal variability of the time series (black curve; Cook and Peters 1981). (c) Each year of the reconstructions was ranked and the absolute difference calculated to estimate the interannual change in persistence from spring to summer. A cubic spline (25 years) is fitted to the time series (black curve).

(Fig. 5b) is largely in agreement with the reconstructed time series (Fig. 5c), and both instrumental and reconstructed data are normally distributed.

c. Persistence between May scPDSI and JJA Z index

The correlation between the regionally averaged spring scPDSI and the summer Z index in the instrumental data is statistically significant for the study area ($r = 0.38$ for 1895–2015, $p < 0.01$; $r = 0.43$ for 1895–1980, $p < 0.01$). The central United States is one of few regions in North America where simple persistence of these seasonal moisture balances could have some modest value in climate forecasts (Fig. 1). However, the correlation between the two variables shows great variability over the instrumental era. The period 1978–2002 displays the weakest relationship between spring and summer hydroclimate, with the correlation falling below 0.0, while other 25-yr periods reach correlations above 0.60.

The relationship between the reconstructed indices mimics the varying correlation between the instrumental data [$r = 0.24$, 1895–1980, no statistical

difference from the correlation of the instrumental data for the same period ($p > 0.05$; Fisher 1921)]. The correlation for the full period of reconstruction (1685–2015; $r = 0.33$; Figs. 6a,b) is not statistically different from the correlation of instrumental data for 1895–2015 ($r = 0.38$), and as with the instrumental data, the relationship between spring and summer moisture varies significantly over time. For some periods the running correlation exceeds 0.7, and for shorter intervals it falls below zero. The overall correlation between the reconstructions is slightly lower than for the instrumental data for the overlapping period (1895–1980) but is not statistically different, and the running correlations fluctuate in a similar way (Fig. 7a). Notable breakdowns in the correlation are found in the 1980s and 1990s, around 1900, in the 1860s and 1820s, and periods of high correlations are noted for the 1950s, 1880s, and the second half of the eighteenth century. During the last 145 years of available instrumental data (1871–2015), the AMO was in the negative phase for 81 years and in the positive phase for 64 years. Testing the rank differences of the two

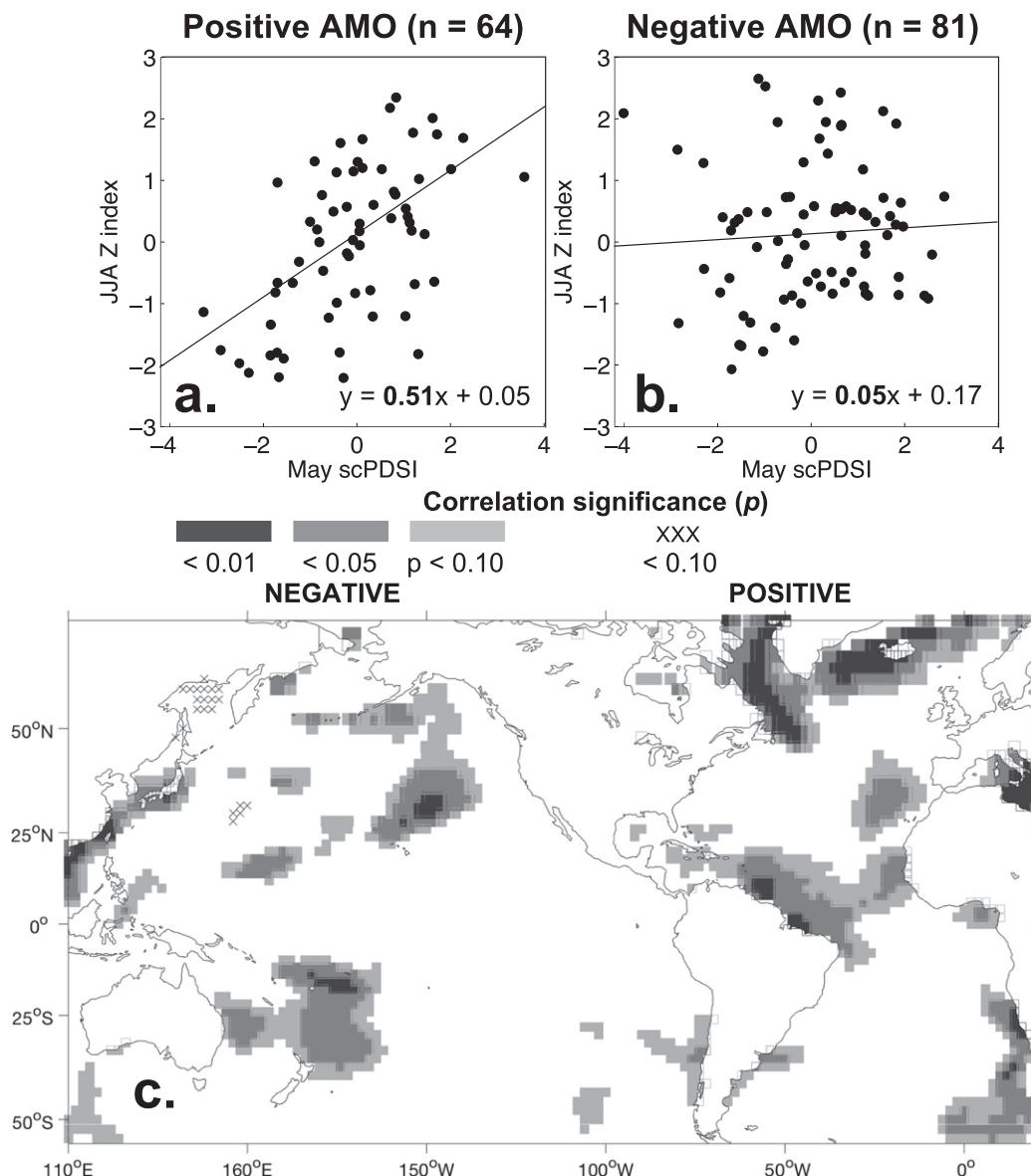


FIG. 7. Scatterplots between the reconstructed May scPDSI and JJA Z index during years of (a) positive AMO and (b) negative AMO. (c) Correlation significance between detrended prior October to current March SSTs and the ranked differences time series, 1871–2015 (Fig. 6c).

AMO phases with Welch's t test (Welch 1947) reveals a significant ($p = 0.0078$) difference in the sample populations, with greater similarity (or persistence) between spring and summer ranks during years of positive AMO (Figs. 8a,b), likely to explain the time-dependent relationship seen in the running correlation (Fig. 7a).

4. Discussion

The strong reconstructions of spring and summer moisture presented in this paper offer new insights into the hydroclimatic history of the central United States for

the past 331 years. Cool season precipitation, and its effect on spring soil moisture, has a defining impact on radial growth of post oak, bald cypress, and eastern red cedar (e.g., Blasing et al. 1988; Stahle and Cleaveland 1988) and tree-ring chronologies from these species therefore represent excellent proxies of May scPDSI. Extended periods of drought and pluvials are prominent in the reconstruction (Fig. 6a), with the 1980s and 1990s standing out as the wettest sustained spring conditions of the past 330 years. The decade of lowest reconstructed values is recorded for 1855–64 (mean scPDSI: -1.33), which has previously been dubbed the

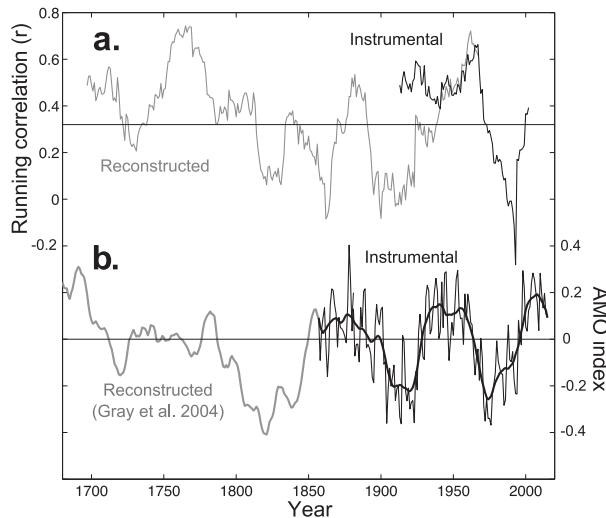


FIG. 8. (a) The running correlation (25-yr window) between the May scPDSI and the JJA Z index is plotted for the instrumental data from 1907 to 2004 (black), and for the reconstructed data from 1697 to 1968 (gray). A black line is plotted for the mean correlation between the reconstructions. (b) Observational AMO index from prior October to current March in black (with 10-yr spline fitted in thick) and reconstructed AMO (Gray et al. 2004) fitted with a 10-yr spline in gray prior to 1871.

“Civil War Drought” (Stahle and Cleaveland 1988; Woodhouse and Overpeck 1998; Fye et al. 2003; Herweijer et al. 2006). These low-frequency swings are apparent in the spectral properties of the record, and the first reconstructed components of the SSA fall around 16 years, explaining more than 20% of the variance in May scPDSI.

The strong statistics for the JJA Z-index reconstruction is based on the LWW chronologies of shortleaf pine. Schulman (1942) first discovered the remarkable summer moisture signal embedded in the latewood of this species but little work has been done since to further utilize the proxy climate information in this subannual ring-width variable. Because tree-ring chronologies from North America tend to be correlated mainly with long-term integrated cool and warm season hydroclimate variables, records of only summer conditions are rare (St. George 2014). Shortleaf pine also displays some of the lowest correlation between earlywood and latewood width of any conifer species on the continent (Torbenso et al. 2016), suggesting that on average there is little climate information shared between earlywood and latewood. Similar to the decadal-to-bidecadal variability recorded in the spring scPDSI reconstruction, the first reconstructed components of the summer Z-index reconstruction fall around 16 years. The 1930s Dust Bowl drought stands out as the lowest estimates of summer drought period in the record but

individual years of greater severity are recorded in the preinstrumental era (Fig. 6b).

We note that there is a modest positive trend in the May scPDSI since the midnineteenth century (Fig. 6a) that might be consistent with the increase in both streamflow and precipitation in the instrumental record for the north-central United States (Lettenmaier et al. 1994; Lins and Slack 1999; Hirsch and Ryberg 2012). No significant trend is present in the summer Z-index reconstruction over this interval. However, the early twentieth-century pluvial (Woodhouse et al. 2005; Cook et al. 2011a) is strongly expressed in the summer atmospheric moisture balance reconstruction (Fig. 6b), in fact more so than in the May scPDSI estimate.

a. Historical validation of the reconstructions

The reliability and strength of both reconstructions is further supported by historical sources, which validate many of the years and periods of extreme values recorded by the proxy records. The lowest preinstrumental value in the May scPDSI reconstruction occurs in 1855, a year that in previous studies has been described as the “driest summer of the past 500 years,” or the Kiowa “sitting summer” of drought so severe that their horses were too weak to ride (Mooney 1979; Stahle et al. 2007). Although the reconstructed May soil moisture balance indicates very dry conditions in our study region in 1855, the JJA Z reconstruction shows just-above-average conditions ($Z = 0.21$). In fact, using the Karl et al. (1987) thresholds for drought termination and amelioration, the reconstructed Z-index value for 1855 suggests that the summer conditions would have ameliorated the antecedent spring drought. The presence of average summer rainfall in 1855 is also supported by historical records (Hickmon 1920).

The lowest single-year value in the summer reconstruction is recorded for 1838, when the estimated JJA Z index was -2.65 . Period accounts from Arkansas suggest that it was the most disastrous drought ever experienced, despite average spring conditions, and that the corn harvest averaged less than half of what was generally expected (Hickmon 1920). During 1838, the U.S. government initiated the forceful removal of the Cherokee nation from the land in present-day Georgia, what is known as the Trail of Tears (Perdue and Green 2007). The estimated number of deaths on the journey to Oklahoma totaled at least 4000 (Knight 1954) but the true number may have been considerably higher (Thornton 1984). Drought is said to have been so bad in the southeastern United States that the migration had to be halted during the early summer of 1838. By that time, however, three detachments of Cherokee had already been sent by 17 June (Perdue and Green 2007).

These parties traveled through some of the worst summer conditions the south-central United States has experienced in the past 330 years, and the lack of moisture in 1838 undoubtedly added to the traumatic conditions the Cherokee had to endure.

b. The relationship between spring soil moisture and the subsequent atmospheric moisture balance in summer

Running correlation analyses suggest that the relationship between spring and summer hydroclimate over the central United States is subject to strong decadal modulation, due in part to large-scale ocean-atmospheric variability. The running correlation between instrumental May scPDSI and JJA Z index is plotted from 1895 to 2015 (Fig. 7a) and documents major changes in the magnitude of seasonal persistence. The running correlation for the instrumental spring and summer data exceeded $r = 0.7$ during the 1970s, but then became negative below $r = -0.3$ during the 1990s. The running correlation between reconstructed May scPDSI and reconstructed summer Z index is also plotted in Fig. 7a and largely reproduces the changes in magnitude seen in the instrumental data. In fact, the reconstructions indicate that strong multidecadal changes in the correlation between spring and summer moisture have been a significant reoccurring feature of the seasonal hydroclimate variability over the central United States since 1685. The running correlation was above 0.7 for several decades after 1750 and showed negative values around 1825, the 1850s and 1860s, and around 1900. During these phases, the chance of summer rainfall to mitigate spring drought is significantly lessened.

The coupling between soil moisture in spring and the atmospheric moisture balance in the following months is likely due in part to land surface feedbacks and the recycling of moisture through evapotranspiration and precipitation (Betts et al. 1996). These processes are the strongest over midcontinent regions for the summer months (Brubaker et al. 1993; Koster et al. 2000), and correlations between May and August soil moistures in our study region have been found to range from 0.2 to 0.5 in models and instrumental data (Huang et al. 1996; Maurer et al. 2002). Our results, using both the instrumental and reconstructed scPDSI and Z index, fall within these reported correlations.

Land surface feedbacks have been shown to play a significant role in the amount of memory imparted from spring to summer moisture conditions but the impact is thought to be greater during years of drought (Hu and Feng 2004). However, there does not appear to be any preference toward dry years in the relationship between spring and summer conditions in the instrumental nor

the reconstructed data in our study. The decadal to multidecadal modulation of the correlation between spring and summer moisture further indicates that land surface feedbacks may not be the sole driver of seasonal persistence. The reconstructions suggest a few episodes of strong association when 25% of the variance in the summer moisture balance may be explained by antecedent spring soil moisture conditions. During the 1750s and 1950s the relationship may have exceeded 40% of the variance (Fig. 7a).

This regime-like relationship between spring and summer moisture raises important questions about potential teleconnections that may be involved. Certainly, land surface feedbacks must be considered, but ocean-atmosphere processes appear to have some impact on the relationship. Other research has suggested that SSTs may influence the amount of persistence imparted on seasonal precipitation in parts of North America (Mo and Paegle 2000; Feng et al. 2011). If the breakdowns in correlation have a dynamical component that can be identified, then the potential usefulness for forecasting could be strengthened. Below, we hypothesize on one such possible component: the Atlantic multidecadal oscillation.

c. The possible influence of SSTs on seasonal moisture balance persistence

North Atlantic SSTs have been highlighted as a possible predictor in forecasting North American climate (Sutton and Allen 1997), and drought variability in the central United States has previously been linked to the AMO (Enfield et al. 2001; Rogers and Coleman 2003; McCabe et al. 2004). The reconstructed time series of ranked differences between spring and summer (Fig. 6c) displays significant negative correlation with cool season (from October through March) SSTs in the waters south and southeast of Greenland, as well as weaker but significant negative correlations with the North Pacific (Fig. 8a). This pattern is similar to the spatial pattern of the AMO (Xie and Tanimoto 1998; Enfield et al. 2001; Ting et al. 2009; Deser et al. 2010). The positive (warm) phase of the AMO is strongly associated with fall season precipitation deficits in the central United States (Knight et al. 2006), and significant deficits are also recorded for spring and summer (Nigam et al. 2011), resulting in interseasonal drought persistence during years of positive AMO. Warmer North Atlantic SSTs are thought to drive moisture transport south across the continent and reduce the amount of precipitation coming from the Gulf of Mexico (Nigam and Ruiz-Barradas 2006; Nigam et al. 2011). This multiseason impact could, at least in part, explain the stronger correlation between May scPDSI and JJA Z index in our study region during periods of positive AMO. However, the relationship

between warmer North Atlantic SSTs and seasonal moisture persistence in our study area is not confined solely to years of drought.

In the instrumental era, the highest-rank differences occur in the first decade of the twentieth century (Fig. 6c). Not surprisingly, this period displays the lowest extended correlation between May scPDSI and JJA Z index and it coincides with a strong negative excursion in the AMO index (Fig. 8). The 1950s and early 1960s are characterized by low-rank differences and also occur during one of the warmest periods of observational SSTs south of Greenland (Dijkstra et al. 2006). A sharp decrease in the running correlation is recorded during the decades of cold North Atlantic SST following 1970. The AMO has been in a positive phase during the most recent 15–20 years, and although the window length of the running correlation only allows for an upward trend, the rank differences have been below the mean for most years since 2000 (Fig. 6c).

Models suggest that the AMO has been a stable feature of North Atlantic climate variability in periods prior to the instrumental record (Grosfeld et al. 2007; Feng et al. 2008; Ting et al. 2011) and the reconstructions indicate that the time-dependent coupling between spring and summer moisture during the twentieth and early twenty-first century may be part of the long-term climate dynamics of the region in the preinstrumental era as well. Gray et al. (2004) produced a 12-month-averaged AMO index based on tree-ring chronologies from eastern United States, western Europe, and north Africa that extends from 1567 to 1990. The running correlation between reconstructed May scPDSI and JJA Z index exhibits similar multidecadal variability with the Gray et al. (2004) AMO reconstruction (Fig. 7). The relationship is not perfect, perhaps partly because of the different seasonal window for the AMO, but the lowest extended period of correlation between spring soil moisture and the subsequent summer atmospheric-moisture balance is recorded for the decades after 1900, the longest negative spell of the AMO in the instrumental data. Similarly, a breakdown in correlation between May scPDSI and JJA Z index occurred during the most negative period of the AMO reconstruction (the 1810s and 1820s), and negative AMO values and low correlations can also be found in the 1720s. Periods of exceptionally strong correlation between spring and summer moisture over the past 300 years appear to occur during times when the reconstruction of the AMO index is in a positive phase.

5. Conclusions

The new reconstructions of spring and summer moisture each represent over 70% of the instrumental

moisture variability during the calibration period and provide high-quality records of seasonal moisture variability over the central United States from 1685 to 2015. The reconstructions indicate major differences between cool and warm season moisture regimes since 1685, including the 1850–60s when the cool season suffered severe sustained dryness but the warm season was near normal. During the 1880s the warm season was dry but the cool season was relatively wet.

Similar to the instrumental data, the cool and warm season reconstructions are weakly but significantly correlated and can be used to examine decadal variations in seasonal persistence over the past 330 years. In fact, the running correlation between May scPDSI and the JJA Z index in both the instrumental and reconstructed series varies substantially over time. Significant positive correlation prevails, but decadal episodes of both high and low correlation are evident. Even brief episodes of zero correlation between the cool and warm season are observed in the instrumental and reconstructed data for the central United States, when all predictive skill would have been lost. These decadal variations in seasonal persistence suggest that land surface feedbacks may not be the only drivers of the correlation between May soil moisture and the subsequent summer atmospheric moisture balance.

The variability shared by the reconstructions probably does not arise from biological growth persistence and likely reflects forcing from the physical climate system. The two reconstructions are produced using not only different tree-ring chronologies but they also represent separate tree species. The predictors for each reconstruction represent the strongest seasonal signal in the trees without any correlation with the alternate season falling outside the range of climatological persistence in the region. The relationship between the two reconstructions largely mirrors that of the instrumental data, and because of this separation of seasons, information that may have been muddled in an integrated drought variable such as summer PDSI can be extracted from these selected high-quality seasonal proxies. Fluctuations in the correlation between the reconstructions in the preinstrumental era appear to largely represent the time-varying relationship between spring and summer moisture availability.

The AMO has been implicated in the development of drought and pluvial conditions over the central United States, and our results suggest that the AMO may also influence the level of moisture persistence from the cool to warm season. Persistent atmospheric pressure fields over the interior United States appear to be more common during years of warmer North Atlantic SSTs associated with the AMO. The new cool and warm

season reconstructions also suggest that multidecadal variability in moisture persistence has been an important feature of climate over the study area during the past 330 years. Warm North Atlantic SSTs might therefore change the probability of cool to warm season moisture persistence and have some modest value for seasonal climate prediction over the central United States.

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