Climatic Influences on Midwest Drought during the Twentieth Century

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ABSTRACT

The Dustbowl Era drought in the 1930s was the principal Midwest drought of the twentieth century, occurring primarily in late spring–summer [April–August (AMJJA)] when >70% of annual rainfall normally occurred. Another major Midwest drought occurred in the 1950s but primarily in fall–early winter [September–December (SOND)] when normal rainfall was ~1/2 as much. Optimized canonical correlation analysis (CCA) is applied to forecast AMJJA and SOND Midwest rainfall variability in cross-validated fashion from antecedent DJF and JJA sea surface temperature (SST) variability in the surrounding oceans. These CCA models simulate (i.e., hindcast, not forecast) the Dustbowl Era drought of the 1930s and four of seven secondary AMJJA droughts (≥3-yr duration) during the twentieth century, and the principal Midwest drought of the 1950s and one of three secondary SOND droughts. Diagnosing the model canonical correlations finds the superposition of tropical Pacific cool phases of the quasi-decadal oscillation (QDO) and interdecadal oscillation (IDO) responsible for secondary droughts in AMJJA when ENSO was weak and finds the eastern equatorial Pacific cool phase of the ENSO responsible for secondary droughts during SOND when ENSO was strong. These explain why secondary droughts in AMJJA occurred more often (nearly every decade) and were of longer duration than secondary droughts in SOND when decadal drought tendencies were usually interrupted by ENSO. These diagnostics also find the AMJJA Dustbowl Era drought in the 1930s and the principal SOND drought in the 1950s driven primarily by different phases (i.e., in quadrature) of the pentadecadal signal in the Pacific decadal oscillation (PDO).

1. Introduction

This work is motivated by the predictability study of Schubert et al. (2005), who simulated annual rainfall variability over the U.S. Midwest during the twentieth century by driving an atmosphere general circulation model (AGCM) with contemporaneous annual sea surface temperature (SST) variability across the Pacific and Atlantic Oceans. They successfully predicted the Dustbowl Era drought in the 1930s, but predicted (incorrectly) an even larger Midwest drought in the 1970s that did not exist. Here we seek to understand how these successful and unsuccessful simulations of Midwest drought could have derived from the spatiotemporal evolution of SST variability over the Pacific and Atlantic Oceans during the twentieth century.

To accomplish this task, we utilize the statistical prediction scheme of Gershunov and Cayan (2003), who forecast winter rainfall variability across the contiguous United States from antecedent SST variability across the Pacific Ocean. Here we adapt this methodology to the problem of forecasting seasonal rainfall across the Midwest from antecedent seasonal SST variability across the Pacific and Atlantic Oceans during the twentieth century. We could have used this statistical prediction scheme in real time to forecast a developing Midwest drought (i.e., defined here at below-normal seasonal rainfall of ≥3-yr duration) by establishing whether below-normal rainfall of 2-yr duration (known a priori) would have been fully realized (or not) with the forecast of seasonal Midwest rainfall in the impending third year. Instead, we decided to utilize this statistical prediction scheme in non–real time to simulate (i.e., hindcast, not forecast) the seasonal Midwest
droughts during the twentieth century and then diagnose the canonical correlations for known climatic signals.

The relative success of this simulation (i.e., simulating the Dustbowl Era drought in the 1930s, with no false positives in the 1970s) allows us to place Midwest drought in general (i.e., its phase, magnitude, and duration throughout the twentieth century) within the context of known climatic signals observed in global patterns of SST and sea level pressure (SLP) variability during the twentieth century (Allan 2000; White and Tourre 2003). These signals include the quasi-biennial oscillation (QBO) of ~2.3-yr period; the four El Niño–Southern Oscillation (ENSO) signals of ~2.9-, 3.5-, 4.4-, and 5.5-yr period; the quasi-decadal oscillation (QDO) of ~11-yr period; the interdecadal oscillation (IDO) of 15–25-yr period; and global warming (Allan 2000; Tourre et al. 2001; White and Tourre 2003). These climatic signals are accompanied by the 40–60-yr period pentadecadal signal observed in North Pacific SST and SLP variability (Minobe 1997) and in the Pacific decadal oscillation (PDO) (Mantua et al. 1997; Minobe 2000). Each of these global and basin-scale climatic signals are associated with patterns of SST variability in the tropical Pacific Ocean that could, in principle, influence rainfall variability over the Midwest via meridional atmospheric teleconnections (e.g., Sardeshmukh and Hoskins 1988).

Initially we planned to follow the experimental design of Schubert et al. (2005) by simulating annual Midwest drought from contemporaneous annual SST variability over the Pacific and Atlantic Oceans. However, we decided to simulate seasonal Midwest drought once we realized that the Dustbowl Era drought of the 1930s occurred principally in the late spring and summer seasons from April to August (AMJJA) when >70% of annual rainfall variability normally falls across the Midwest. The Dustbowl Era drought lasted 12 yr from 1929 to 1940 during AMJJA, while extending into fall and early winter from September to December (SOND) only over the last 4 yr from 1937 to 1940. Subsequently, we also decided to simulate Midwest drought during SOND, when the long-term mean rainfall was ~1/2 that during AMJJA but the rainfall variance was about the same. In SOND, we found another principal Midwest drought in the 1950s lasting 9 yr from 1950 to 1958, it extending into AMJJA over the middle 5 yr from 1952 to 1956. While the principal SOND Midwest drought of the 1950s was comparable in longevity to the AMJJA Dustbowl Era drought of the 1930s, its intensity was ~1/2 that of the latter.

Given this seasonal breakdown of Midwest drought incidence, our statistical scheme consists of adapting the optimized cross-validated canonical correlation analysis (CCA) to the forecast of AMJJA and SOND Midwest rainfall variability (i.e., the predictands) each year of the twentieth century from the antecedent winter (DJF) and summer (JJA) SST variability, respectively, over the Pacific and Atlantic Oceans (i.e., the predictors). We find that these CCA models successfully simulate the AMJJA Midwest Dustbowl Era drought of the 1930s and the principal SOND Midwest drought of the 1950s, and most of the secondary AMJJA droughts (of ≥3-yr duration) during the twentieth century. Diagnosing the canonical correlates (CCs) of these CCA models allows us to address two major questions: 1) why the two principal Midwest droughts in the 1930s and the 1950s occurred in different seasons of the year (AMJJA and SOND) two decades apart (in the 1930s and the 1950s) and 2) why Schubert et al. (2005) simulated a principal drought in the 1970s (i.e., a false positive), which we were able to avoid, even though both studies (theirs and ours) used the same SST dataset over the Pacific and Atlantic Oceans as predictors.

2. Data and methods
   a. Predictand and predictor datasets

The predictand is seasonal rainfall variability over the Midwest and eastern United States east of the Rocky Mountains during the late spring and summer (AMJJA) and fall and early winter (SOND) for 99 yr from 1900 to 1998. Inclusion of the eastern United States in this domain allows more complex patterns of variability to exist in the corresponding principal components (PCs), contrasting variability across the Midwest with that of the Southeast and the Northwest; the latter’s exclusion (i.e., focusing on the Midwest alone) did not improve the forecast skill across the Midwest. These seasonal-average rainfall estimates were computed from monthly rainfall estimates provided by Hulme and Jones (1993), the latter interpolated from individual station locations onto a 2.5° latitude by 3.75° longitude grid. (The updated version of this gridded rainfall dataset is available from Hulme’s Web site at the University of East Anglia at http://www.mikehulme.org/.) This grid allows us to examine predictability on the regional and national scale, but not on the state or county scale.

The predictor for AMJJA rainfall variability over the United States is seasonal SST variability over the Pacific and Atlantic Oceans (20°S–60°N) during the previous winter (DJF), while the predictor for SOND rainfall variability over the United States is seasonal SST variability over the Pacific and Atlantic Oceans during the previous summer (JJA). We utilize SST from the
First Hadley Centre Sea Ice and SST (HadISST1) dataset, which consists of complete global fields of monthly SST on a 1° latitude–longitude grid from 1870 to 2004 (Rayner et al. 2003). This SST dataset is based on in situ observations from the Met Office’s Marine Data Bank, including SST data received through the Global Telecommunication System from 1982 onward, supplemented with data from the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987; Worley et al. 2005). Reduced space optimal interpolation was used to obtain the globally complete SST fields (Kaplan et al. 1997), yielding results that compare well with other published SST datasets (Rayner et al. 2003).

b. Optimized CCA forecast methodology

Barnett and Preisendorfer (1987) first used canonical correlation analysis in diagnostic and predictability studies of climate variability. Applied to geophysical data, CCA is efficient at matching patterns in two fields of space–time data, making it ideal for statistical climate prediction when the evolution of the predictor dataset allows it to lead the predictand dataset by some reasonable time increment. Because there are more observations in space (i.e., numbers of variables) than there are time steps (i.e., the number of observations), both the predictor and predictand fields should be pre-filtered using principle component analysis (PCA), a data reduction technique. Barnston and Smith (1996) applied CCA to diagnose and forecast global terrestrial rainfall patterns from global SST variability. Our methodology differs from theirs by including a fully cross-validated optimization module that gives the approximately optimal model complexity [i.e., number of patterns (principle components) and the number of relationships (canonical correlates)] required to efficiently describe the coupled structure of the predictor–predictand fields (Gershunov and Cayan 2003).

To produce realistic forecasts of each season’s variability, leave-one-year-out cross validation is used throughout the optimization module, as well as in skill estimation with the optimal model (Box et al. 1994). This means that for every year in the 99-yr record the entire predictive model was reestimated starting with PCA prefiltering done on the remaining 98 yr. The antecedent seasonal SST variability for year \( n \) was used to estimate seasonal rainfall variability via a model constructed from the remaining years \( n - 1 \). After cross-validated forecasts are computed for each season from 1900 to 1998, forecast skill is estimated by the correlation coefficient between cross-validated forecasts and observed seasonal rainfall over the 99-yr record at each grid point. This yields maps of cross-validated forecast skill over the Midwest and the eastern United States (i.e., east of the Rocky Mountains). Temporal-lag autocorrelation of seasonal Midwest rainfall variability at each grid point (not shown) finds the decorrelation time scale to be \( \leq 1 \) yr, consistent with that observed for monthly tropical SST variability (White 1995), indicating that each year’s estimate is statistically independent of the previous year. So, while Midwest drought is by definition a decadal-scale phenomenon, year-to-year Midwest rainfall variability is dominated by uncorrelated noise and by interannual variability of 3–5-yr periodicity, as is true of SST variability across the tropical Pacific Ocean (White 1995).

To estimate the effect of temporal autocorrelation upon prediction skill, we also computed the skill maps based on leave-\( n \)-years-out cross validation with \( n \) ranging from 1 to 5. While reducing the skill somewhat, as expected, increasing \( n \) did not result in appreciable changes to either skill pattern or the forecasts of the principal and secondary Midwest drought episodes during the twentieth century. Regardless, our emphasis is on the ability of these CCA models to simulate (hindcast, not forecast) the principal and secondary AMJJA and SOND Midwest droughts, the success of which allows us to gain a better understanding of their incidence through diagnosis of model CCs. The latter allows the incidences of Midwest drought to be placed within the context of known climate signals in global patterns of SST and SLP variability observed during the twentieth century (Allan 2000; White and Tourre 2003).

c. Spatial and temporal averaging

We average individual monthly anomalies to form individual DJF and JJA SST anomalies (i.e., the predictors) and individual AMJJA and SOND rainfall anomalies (i.e., the predictands). These latter monthly grouping were chosen so that the AMJJA rainfall predictand encompassed the principal peak in the standard deviation of rainfall variability (Fig. 1b), while the SOND rainfall predictand encompassed the secondary peak in the standard deviation of rainfall variability (Fig. 1b). Furthermore, during late spring and summer (AMJJA) the mean rainfall derives principally from afternoon thunderstorm activity, while during fall and early winter (SOND) it derives principally from extratropical cyclone activity (Carbone et al. 2002, 2003). We did not try to predict Midwest rainfall variability during late winter and early spring (JFM) because this time of the year coincided with the minimum in both mean rainfall and its variance (Figs. 1a,b).

We follow the lead of Schubert et al. (2005) by forming a Midwest rainfall index from the gridded observa-
tions, averaging AMJJA and SOND rainfall anomalies spatially from 34° to 46°N, 102° to 93°W (Fig. 1, top). Also following Schubert et al. (2005), we perform a 5-yr running mean of the Midwest rainfall index, observed and predicted, but we utilize Hanning weights of 1, 3, 4, 3, 1, respectively. This Hanning low-pass filter suppresses the 2–4-yr period biennial-to-interannual variability in seasonal time sequences from 1900 to 1998. We define a drought episode to be below-average rainfall for ≥3 yr running in the AMJJA and SOND seasonal (unfiltered) Midwest rainfall indices.

3. Mean seasonal cycle of Midwest rainfall and its variability

We begin by computing the seasonal cycle of the long-term monthly mean rainfall (Fig. 1a) averaged across a domain that defines the Midwest rainfall index (Fig. 1, top). The long-term monthly mean rainfall index was 3–4 times larger in AMJJA (i.e., maximum of ~100 mm month$^{-1}$ in May and June) than in DJF (i.e., minimum of ~22 mm month$^{-1}$ in January), with >70% of the mean annual rainfall occurring in AMJJA (Fig. 1a).
The standard deviation of individual monthly rainfall anomalies about the long-term monthly mean rainfall displayed two seasonal maxima—one near the middle of AMJJA (i.e., ~27 mm month\(^{-1}\) in May, June, and July) and one near the beginning of SOND (i.e., ~25 mm month\(^{-1}\) in September and October)—with minimum standard deviation in DJF (i.e., ~14 mm month\(^{-1}\) in January and February; Fig. 1b). Thus, the standard deviation of Midwest rainfall variability averaged across AMJJA at ~22 mm month\(^{-1}\) is about the same as that averaged across SOND, while that averaged across DJF at ~12 mm month\(^{-1}\) is ~1/2 as large.

4. AMJJA and SOND Midwest rainfall indices

The AMJJA Midwest rainfall index (Fig. 2a) finds the major Midwest drought of the twentieth century occurring during the Dustbowl Era from 1929 to 1940 when seasonal rainfall variability was 10–40 mm month\(^{-1}\) below average in most years. During these 12 yr, AMJJA rainfall variability was not uniformly below normal, punctuated by QBO variability (e.g., ~36 mm month\(^{-1}\) in 1934, +8 mm month\(^{-1}\) in 1935, and ~39 mm month\(^{-1}\) in 1936; Fig. 2a). Toward the end of the Dustbowl Era drought, a secondary drought of 4-yr duration can be found in the SOND Midwest rainfall in-

Fig. 2. (a) The AMJJA Midwest rainfall index for 1900–98, displaying AMJJA rainfall variability averaged over AMJJA of each year (black curve). Also displayed is the AMJJA Niño-3.4 SST index averaged from 5°S to 5°N, 170° to 120°W in the central and eastern equatorial Pacific Ocean (gray curve). (b) Same as in (a), but for the 5-yr Hanning low-pass filtered version. (c) The SOND Midwest rainfall index for 1900–98, displaying SOND rainfall variability averaged over SOND of each year. Also displayed is the SOND Niño-3.4 SST index averaged from 5°S to 5°N, 170° to 120°W (gray curve). (d) As in (c) but for the 5-yr Hanning low-pass filtered version. Seasonal rainfall indices range over ~40 mm month\(^{-1}\), while low-pass filtered rainfall indices range over ±20 mm month\(^{-1}\). Temporal-lag cross correlations between Midwest rainfall and Niño-3.4 SST indices are displayed to the right of (a)–(d).
index (Fig. 2c), indicating that the Dustbowl Era drought spanned AMJJA-SOND from 1937 to 1940. Seven secondary AMJJA Midwest droughts (i.e., epochs of ≥3 yr of below-average rainfall in the unfiltered seasonal index) were centered near 1911, 1917, 1925, 1955, 1973, 1984, and 1988 (Fig. 2a).

In the low-pass filtered AMJJA Midwest rainfall index (Fig. 2b), the Dustbowl Era drought can be identified by rainfall variability 5–20 mm month⁻¹ below average extending over 11 yr from 1929 to 1939, while revealing the quasi-decadal frequency of the seven secondary AMJJA Midwest droughts centered near 1911, 1917, 1925, 1954, 1972, and 1987 (i.e., nearly one in each decade including the Dustbowl Era drought).

The SOND Midwest rainfall index (Fig. 2c) finds the principal SOND Midwest drought of the twentieth century occurring over the 9 yr from 1950 to 1958 when seasonal rainfall variability was 5–20 mm month⁻¹ below average in most of these years. Near the middle of the principal SOND Midwest drought, a secondary drought of 5-yr duration can be found in the AMJJA Midwest rainfall index (Fig. 2a), indicating that the SOND drought spanned AMJJA-SOND from 1952 to 1956 during the middle 5 yr of the 9-yr drought. Three secondary SOND Midwest drought episodes were centered near 1938, 1963, and 1979 (Fig. 2c).

In the low-pass filtered SOND Midwest rainfall index (Fig. 2d), the principal SOND Midwest drought of the 1950s can be identified by rainfall variability 4–12 mm month⁻¹ below average extending over 9 yr from 1949 to 1958, while the intermittency of the three secondary SOND Midwest droughts in the unfiltered index (Fig. 2c) can be seen supplemented by below-average filtered SOND Midwest rainfall variability for ≥3-yr duration also for 1903–05, 1915–17, 1921–23, and 1932–39. However, these latter 3-yr runs of below-normal filtered SOND rainfall variability do not count as “droughts” because they were interrupted by above-normal QBO and ENSO variability in the unfiltered SOND Midwest rainfall index (Fig. 2c).

Comparing the AMJJA Midwest rainfall and Niño-3.4 SST indices (Fig. 2a) indicates ENSO variability dominating both indices, with the temporal-lag cross-correlation (Fig. 2a, right) maximum (~0.32) at 0-yr lag, significant at the 99% confidence level (Snedecor and Cochran 1980) and decorrelating at ~3-yr lag. The association between these two indices was better during the second half of the twentieth century than during the first half, yielding cross correlations of ~0.46 and ~0.13, respectively. Comparing the low-pass filtered SOND rainfall and Niño-3.4 SST indices (Fig. 2d) reveals the longer period ENSO signal of 5–7-yr period (White and Tourre 2003) dominating both indices during the first half of the twentieth century (i.e., with the average peak separation of ~6 yr), with quasi-decadal variability dominating the SOND rainfall index during the second half of the twentieth century (and different from the ENSO activity in the Niño-3.4 SST index), with the temporal-lag cross correlation over the entire record (Fig. 2d, right) maximum (~0.36) at 0-yr lag, significant at the 95% confidence level (Snedecor and Cochran 1980), and decorrelating at ~2-yr lag. The principal SOND Midwest drought of the 1950s can be seen associated with the trough of a pentadecadal signal (from 1947 to 1957), with two broad peaks on either side centered near 1925 and 1985.

5. Optimized CCA forecast of AMJJA rainfall variability over the Midwest

We now construct the CCA model that optimizes the cross-validated forecast skill of AMJJA rainfall variability over the Midwest and eastern United States from antecedent DJF SST patterns over the Pacific and Atlantic Oceans (20°S–60°N, 120°–10°E). The optimum model chooses nine PCs and five CCs to represent this association, the first three CCs of which are displayed (Fig. 3). Each CC pair optimizes the correlation between the time evolution of the corresponding antecedent DJF SST pattern (the predictor in black) and that of the AMJJA rainfall (the predictand in red).

In the first CC pair (CC1), the amplitude time sequence of the antecedent DJF SST pattern (Fig. 3a, black curve) that correlated best (i.e., 0.52) with the amplitude time sequence of the first AMJJA rainfall
FIG. 3. The cross-validated forecast of AMJJA rainfall variability over the Midwest and eastern United States from antecedent DJF SST variability over the Pacific and Atlantic Oceans from 20°S to 60°N, from the optimized CCA forecast model. (a), (b), (c) Amplitude time sequences for the first three CCs of the DJF SST predictor (black curve) and the AMJJA rainfall predictand (red curve), with magnitudes ranging over ±4 standard deviations. (d), (e), (f), (g), (h), (i) Normalized spatial patterns of the first three CCs of the predictor and predictand corresponding to amplitude time sequences in (a)–(c), with the color bar at bottom showing standard deviation units in increments of 0.2. (j) Histograms of cross-validated forecast skill of AMJJA rainfall (noise) variability over the Midwest and eastern United States given by the red (black) curve. (k) Distribution of cross-validated forecast skill of observed AMJJA rainfall variability over the Midwest and eastern United States, with the color bar below showing forecast skill in increments of 0.2.
pattern (red curve) during the twentieth century is displayed, with spatial patterns (Figs. 3d,g) displaying above-normal AMJJA Midwest rainfall variability maximum across Oklahoma, Kansas, eastern Nebraska, and Iowa associated with the tropical warm phases of the QDO and IDO in SST and SLP variability across the Pacific and Atlantic Oceans (White and Tourre 2003). The amplitude time sequences of the DJF SST and AMJJA rainfall patterns (Fig. 3a) shared principle troughs centered near 1910, 1925, 1935, 1955, 1964, 1972, and 1988. Six of these seven troughs nominally coincided with the constructive interference of the tropical cool phases of the QDO and IDO centered near 1909, 1924, 1935, 1954, 1973, and 1988 (White and Tourre 2003). It turns out that these latter troughs nominally coincided with six of the eight AMJJA Midwest droughts centered near 1911, 1925, 1935, 1954, 1973, and 1988 (White and Tourre 2003). Multiplying the amplitude time sequence of the DJF SST and AMJJA rainfall patterns (Fig. 3a) also contained a pentadecadal signal (Minobe 1997) with peaks centered near 1900, 1925, 1935, 1955, 1973, and 1988, including the Dustbowl Era drought (Fig. 2a). The amplitude time sequences of the DJF SST and AMJJA rainfall patterns (Fig. 3a) also contained a pentadecadal signal (Minobe 1997) with peaks centered near 1900, 1925, 1935, 1955, and 1995 accompanied by a trough from ~1920 to 1945 that contained with the Dustbowl Era drought (Fig. 3a). Significant ENSO variability can also be seen in these time sequences, fluctuating with quasiperiodicity of 3–5 yr (White and Tourre 2003). Multiplying the amplitude time sequence and spatial weights of this AMJJA Midwest rainfall pattern (Figs. 3a,g) finds the product below normal during the 1930s, contributing significantly to the AMJJA Dustbowl Era drought (Fig. 2a).

In the second CC (CC2), the amplitude time sequence of the antecedent DJF SST pattern (Fig. 3b, black curve) that correlated best (i.e., 0.33) with the amplitude time sequence of the second AMJJA rainfall pattern (red curve) was dominated by the characteristic signature of global warming (Allan 2000). Global warming trended upward over the course of the twentieth century but was interrupted by a broad trough from ~1950 to 1980 (Allan 2000), which was more evident in the DJF SST variability than in the AMJJA Midwest rainfall variability (Fig. 3s). The corresponding spatial patterns (Figs. 3e,h) displayed below-normal (above normal) AMJJA rainfall variability in the U.S. Midwest (Northeast), associated with above-normal DJF SST variability over most of the Pacific and Atlantic Oceans with the Pacific–Atlantic SST pattern nearly identical to that associated with global warming (Allan 2000). Multiplying the amplitude time sequence and spatial weights of this AMJJA Midwest rainfall pattern (Figs. 3b,h) results in the product being above normal during the 1930s in the Southwest (centered in the Texas Panhandle), mitigating against the Dustbowl Era drought while promoting less rainfall over the latter 2/3 of the twentieth century (Fig. 2a).

In the third CC (CC3), the amplitude time sequence of the antecedent DJF SST pattern (Fig. 3c, black curve) that correlated best (i.e., 0.31) with the amplitude time sequence of the third AMJJA rainfall pattern (red curve) was dominated by ENSO variability (White and Tourre 2003), with troughs occurring every 3–7 yr, superimposed on a pentadecadal signal similar to that observed in the PDO (Minobe 2000) characterized by two broad peaks centered near 1930 and 1985, and a trough from ~1944 to 1970. The corresponding spatial patterns (Figs. 3f,i) display below-normal AMJJA rainfall variability over the upper Missouri River basin associated with above-normal DJF SST variability in the eastern/central equatorial Pacific and tropical South Atlantic Oceans, the latter similar to the tropical warm phases of the ENSO (Allan 2000; White and Tourre 2003) and the PDO (Mantua et al. 1997; Minobe 2000). Multiplying the amplitude time sequence and spatial weights of this Midwest rainfall pattern (Figs. 3c,i) finds their product below normal during the 1930s in the Missouri River basin, where it contributed to the Dustbowl Era drought (Fig. 2a).

When this optimized CCA forecast model is cross-validated, the resulting forecast skill is >0.20 over most of the Midwest rainfall grid (Fig. 3k), significant at the 95% confidence level (see section 2). The histogram of forecast skill across the Midwest and eastern United States (red curve) is significantly different from that (black curve) obtained when the optimized CCA model forecasts white noise rainfall variability over the same domain (Fig. 3j). The latter model yields an average forecast skill of <0.01, confirming the absence of artificial forecast skill in the optimized CCA methodology.

Averaging the AMJJA forecasts over the Midwest rainfall index region (Fig. 3k) and comparing the resulting index (Fig. 4a, red curve) with that of observed rainfall estimates (Fig. 4a, black curve, repeated from Fig. 2a), yields a forecast skill for the index of 0.42 that is significant at the >99% confidence level (Snedecor and Cochran 1980), as determined from the decorrelation of ~1-yr lag in the corresponding temporal-lag autocorrelation (not shown). The increase in forecast skill of the AMJJA Midwest rainfall index (Fig. 4a) over the skill at individual grid points (Fig. 3k) arise from suppression of random noise by spatial averaging across the index region (Fig. 1, top). This comparison finds the Dustbowl Era drought of the 1930s (i.e., 1929–40) simulated from 1928 to 1939, and four of the seven secondary AMJJA Midwest droughts during the twentieth century simulated successfully near 1911, 1925,
1973, and 1984 (Fig. 4a), with two false positives centered near 1944 and 1961.

Applying the 5-yr Hanning low-pass filter to these observed and forecast AMJJA Midwest rainfall indices (Fig. 4b, black and red curves) yields a hindcast skill (i.e., it is no longer a forecast after the filtering operation) of 0.69 that is significant at the 99% confidence level (Snedecor and Cochran 1980). These low-pass filtered indices suppresses the penchant for the 3–4-yr period ENSO activity to disrupt the quasi-decadal AMJJA Midwest drought tendencies associated with constructive interference of the tropical cool phases of the QDO and IDO discerned in both indices near 1909, 1924, 1935, 1954, 1973, and 1988 (White and Tourre 2003). These low-pass filtered indices also emphasize the importance of a pentadecadal signal (Minobe 1997), with broad peaks discerned near 1905, 1955, and 1995 and a trough from ~1929 to 1939 that coincided with the AMJJA Dustbowl Era drought of the 1930s.

6. Optimized CCA forecast of SOND rainfall variability over the Midwest

The CCA model, which optimizes the cross-validated forecast skill of SOND rainfall variability over the Midwest and the eastern United States from antecedent JJA SST patterns in the Pacific and Atlantic Oceans (20°S–60°N, 120°–10°E), chooses nine PCs and three CCs to represent the association. The three CCs are displayed (Fig. 5). Each CC pair optimizes the correlation between the time evolution of the corresponding antecedent JJA SST pattern (the predictor in black) and that of the SOND rainfall (the predictand in red).

In the first CC (CC1), the amplitude time sequence of the antecedent JJA SST pattern (Fig. 5a, black curve) that correlated best (i.e., 0.42) with the amplitude time sequence of the first SOND rainfall pattern (red curve) was dominated by ENSO and a pentadecadal signal. The ENSO variability displayed troughs in 1903, 1909, 1917, 1921, 1927, 1934, 1938, 1944, 1950, 1956, 1962, 1967, 1971, 1975, 1985, 1989, and 1995 (Fig. 5a) that coincided with the eastern tropical Pacific cool phase of ENSO (i.e., La Niña) in the Niño-3 SST index (White and Tourre 2003). The pentadecadal signal displayed broad peaks centered near 1925 and 1985, and a trough from ~1947 to 1957 that coincided with peaks and troughs of the pentadecadal signal in the PDO index (Mantua et al. 1997; Minobe 2000), the trough coinciding with the principal SOND Midwest drought of the 1950s (Fig. 2c). The corresponding spatial patterns (Figs. 5d,g) have above-normal rainfall variability over the Midwest (maximum over Texas, Louisiana, Oklahoma, and Kansas) associated with a pattern of SST variability similar to that of the eastern tropical Pacific.
FIG. 5. The cross-validated forecast of SOND rainfall variability over the Midwest and eastern United States from antecedent JJA SST variability over the Pacific and Atlantic Oceans from 20°S to 60°N, from the optimized CCA forecast model. (a), (b), (c) Amplitude time sequences for the first three CCs of the JJA SST predictor (black curve) and the SOND rainfall predictand (red curve), with magnitudes ranging over ±4 standard deviations. (d), (e), (f), (g), (h), (i) Normalized spatial patterns of the CCs of the predictor and predictand corresponding to amplitude time sequences in (a)–(c), with the color bar at bottom showing standard deviation units in increments of 0.2. (j) Histograms of cross-validated forecast skill of observed SOND rainfall (noise) variability over the Midwest and eastern United States given by the red (black) curve. (k) Distribution of cross-validated forecast skill of observed SOND rainfall variability over the Midwest and eastern United States, with the color bar below showing forecast skill in increments of 0.2.
warm phase of the ENSO (Allan 2000; White and Tourre 2003) and the PDO (Mantua et al. 1997). Multiplying the amplitude time sequence and spatial weights of the Midwest rainfall pattern (Figs. 5a,g) results in the product being below normal from ~1947 to 1957, contributing significantly to the principal SOND Midwest drought of the 1950s (Fig. 2c).

In the second CC (CC2), the amplitude time sequence of the antecedent JJA SST pattern (Fig. 5b, black curve) that correlated best (i.e., 0.33) with the amplitude time sequence of the second SOND rainfall pattern (red curve) was dominated by a combination of the QBO and the ~70-yr period Sahelian drought mode (Allan 2000), the latter displaying two broad peaks centered near 1910 and 1980 and a trough from ~1947 to 1962. The corresponding spatial patterns (Figs. 5c,h) display below-normal (above normal) SOND rainfall variability in the Southwest (upper Mississippi River basin and the Great Lakes region) associated with a pattern of SST variability in the tropical Pacific Ocean similar to cool phases of the QBO (Allan 2000; Tourre et al. 2001) and of the global SST pattern associated with the Sahelian drought mode (Allan 2000). Multiplying the amplitude time sequence and spatial weights of the Midwest rainfall pattern (Figs. 5b,h) results in the product being below normal in the upper Mississippi River basin and the Great Lakes region from ~1947 to 1965, contributing significantly to the principal SOND Midwest drought of the 1950s (Fig. 2c).

In the third CC (CC3), the amplitude time sequence of the antecedent JJA SST pattern (Fig. 5c, black curve) that correlated best (i.e., 0.21) with the amplitude time sequence of the third SOND rainfall pattern (red curve) was dominated by the characteristic signature of global warming (Allan 2000), more evident in SST variability (black curve) than in rainfall variability (red curve). The corresponding spatial patterns (Figs. 5f,i) have below-normal SOND rainfall variability over the upper Missouri River basin associated with above-normal JJA SST variability across the Pacific and Atlantic Oceans with patterns similar to that associated with global warming (Allan 2000). Multiplying the amplitude time sequence and spatial weights for the Midwest rainfall pattern (Figs. 5c,i) results in their product being below normal from 1950 to 1958, contributing significantly to the principal SOND Midwest drought during the 1950s (Fig. 2c).

When this optimized CCA forecast model is cross-validated, the forecast skill is >0.20 over most of the Midwest rainfall grid (Fig. 5k), larger there than over the eastern United States and significant at the 95% confidence level (see section 2). The histogram of forecast skill across the Midwest and eastern United States (red curve) is significantly different from that (black curve) obtained when the CCA model forecasts white noise rainfall variability over the same domain (Fig. 5j). The latter model yields an average forecast skill of <0.01 over the United States, confirming the absence of artificial forecast skill in the optimized CCA methodology.

Averaging the SOND forecasts over the Midwest rainfall index region (Fig. 5k) and comparing the resulting index (Fig. 6a, red curve) with that of observed rainfall estimates (Fig. 6a, black curve, repeated from Fig. 2c), yields a forecast skill for the index of 0.35, significant at >95% confidence level (Snedecor and Cochran 1980), as determined from the decorrelation of ~1-yr lag in the corresponding temporal-lag autocorrelation (not shown). This comparison finds the principal SOND Midwest drought of the 1950s (i.e., 1950–58) simulated from 1948 to 1957, but only one of the three secondary SOND Midwest droughts (i.e., in 1963) was simulated successfully (Fig. 6a), with three false positives centered near 1910, 1923, and 1975.

Applying the 5-yr Hanning low-pass filter to the time sequences of observed and forecast SOND Midwest rainfall indices (Fig. 6b, black and red curves) yields a hindcast skill (i.e., it is no longer a forecast after the filtering operation) of 0.45 that is significant at the 95% confidence level (Snedecor and Cochran 1980). These low-pass filtered indices suppress the penchant for the QBO and higher-frequency ENSO signals of 3–4-yr period to disrupt the lower-frequency ENSO signal of 5–7-yr period that dominate both low-passed filtered indices from 1900 to 1960, that is, those associated with eastern tropical Pacific cool phases (La Niña) near 1910, 1916, 1922, 1928, 1933, 1938, 1944, 1950, 1956, and 1962 (White and Tourre 2003; see Fig. 6b). Thereafter, from 1960 to 1998 the CCA model fails to simulate the lower-frequency QDO variability that dominated the low-pass filtered SOND Midwest rainfall index (i.e., with peaks near 1960, 1972, 1985, and 1997) and was quite different from the low-frequency ENSO activity dominating the low-pass filtered rainfall index prior to 1960. These filtered indices also emphasize the importance of a pentadecadal signal similar to that observed in the PDO (Mantua et al. 1997; Minobe 2000), with broad peaks discerned near 1925 and 1985 and a trough from ~1947 to 1957 that coincided with the SOND principal drought of the 1950s.

7. Discussion and conclusions

We found the Dustbowl Era drought in the Midwest extending over the 12 yr from 1929 to 1940 during AMJJA when >70% of annual rainfall normally falls
during the twentieth century. Even so, it extended right across AMJJA to SOND during the last 4 yr from 1937 to 1940. During most of this Dustbowl Era, AMJJA rainfall variability was 10–40 mm month$^{-1}$ below normal, most severe across Oklahoma, Kansas, eastern Nebraska, and Iowa, though weakly above normal in 1934 and 1936. We found another principal Midwest drought of the twentieth century extending over the 9 yr from 1950 to 1958 during SOND, when the long-term mean was much less but the standard deviation of rainfall variability during the twentieth century was comparable with that during AMJJA. It extended right across AMJJA to SOND over the middle 5 yr from 1952 to 1956. During most of this drought period, SOND rainfall variability was 5–20 mm month$^{-1}$ below normal, most severe across Texas, Louisiana, Oklahoma, and Kansas, though weakly above normal in 1951 and 1957.

There were seven secondary AMJJA Midwest droughts of 3–7-yr duration during the twentieth century centered near 1911, 1917, 1925, 1955, 1973, 1984, and 1988, and three secondary SOND droughts of 3–4-yr duration centered near 1938, 1963, and 1979. The secondary SOND drought near 1938 was an extension of the AMJJA Dustbowl Era drought of the 1930s, while the secondary AMJJA drought near 1955 was an extension of the principal SOND drought of the 1950s. However, most secondary Midwest droughts in AMJJA were independent of those in SOND, occurring more often and of longer duration.

Comparing the AMJJA and SOND Midwest rainfall indices against corresponding Niño-3.4 SST indices in the central equatorial Pacific Ocean from 170° to 120°W found them significantly correlated during both times of the year. These associations are consistent with the hypothesis that tropical Pacific SST variability drove anomalous Hadley cell circulation in both seasons that altered planetary wave balances in upper-level westerly winds over the North Pacific Ocean and North America (Sardeshmukh and Hoskins 1988). Subsequently, diagnosis of the CC1 in the CCA models for Midwest rainfall variability in both seasons found maximum cool SST variability in the western (eastern/central) tropical Pacific Ocean associated with AMJJA (SOND) Midwest rainfall variability. We conclude from this that Midwest rainfall variability during AMJJA responded to atmospheric teleconnections from maximum cool SST variability in the western (eastern/central) tropical Pacific Ocean associated with AMJJA (SOND) Midwest rainfall variability. We found the AMJJA Midwest rainfall index better correlated with the AMJJA Niño-3.4 SST index during the second half of the twentieth century than during the first half, while the SOND Midwest rainfall index was better correlated with the SOND Niño-3.4 SST index.
during the first half of the twentieth century than during the second half. Because we expect these correlations to increase with increasing background SST in the Niño-3.4 SST index region (Sardeshmukh and Hoskins 1988), we are not surprised to find the summer (JJA) SST global warming pattern (in the CC2 of the CCA model for AMJJA Midwest rainfall) displaying warmer SST across the central tropical Pacific Ocean during the second half of the twentieth century, and the winter (DJF) SST global warming pattern (in the CC3 of the CCA model for SOND Midwest rainfall) displaying cooler SST across this domain during the second half of the twentieth century. Thus, we conclude that relatively small changes in the background SST in the eastern/central tropical Pacific Ocean due to global warming (different in different seasons) modulated the anomalous SST-induced meridional atmospheric teleconnections that influenced seasonal Midwest rainfall. This global warming modulation is similar in principle to interdecadal modulation of ENSO teleconnections influencing North American rainfall variability (Gershunov and Barnett 1998; Gershunov et al. 1999).

The optimum CCA model for forecasting AMJJA Midwest rainfall chose nine PCs and five CCs to attain the highest forecast skill over the Midwest and the eastern United States. It simulated (hindcasted, not forecasted) the Midwest Dustbowl Era drought of the 1930s (i.e., 1929–40) from 1927 to 1940 and four of the seven secondary AMJJA droughts centered near 1911, 1925, 1973, and 1984, with two false positives. The optimum CCA model for forecasting SOND Midwest rainfall chose nine PCs and three CCs to attain the highest forecast skill over the Midwest and the eastern United States. It simulated the principal SOND Midwest drought of the 1950s (i.e., 1950–58) from 1948 to 1957, but only one of three secondary SOND droughts centered near 1963, with three false positives.

Diagnosis of the CC1 in the optimized CCA model for AMJJA Midwest rainfall variability found the Midwest Dustbowl Era drought of the 1930s and five of the seven secondary AMJJA Midwest droughts represented. These AMJJA droughts were associated with a pattern of cool SST variability across the western equatorial and central/eastern tropical North Pacific Ocean similar to the tropical cool phases of the QDO and IDO found in global SST and SLP patterns of variability during the twentieth century (Tourre et al. 2001; White and Tourre 2003). Comparing these amplitude time sequences with those modulating the global SST and SLP patterns of the QDO and IDO (White and Tourre 2003) finds the constructive interference of the latter producing troughs in 1909, 1924, 1935, 1954, 1973, and 1988 that nominally coincide with those in the model amplitude time sequences and with six of the eight AMJJA Midwest droughts (i.e., 1911, 1925, 1935, 1955, 1973, and 1988), including the AMJJA Dustbowl Era drought of the 1930s.

These amplitude time sequences of the QDO and IDO (White and Tourre 2003) have also been observed fluctuating in phase with the nominal 11- and 22-yr period signals in the sun’s irradiance, respectively, throughout the twentieth century (White et al. 1997, 1998). The thermodynamics of the corresponding tropical global-average atmosphere and upper-ocean temperature variability associated with the QDO has recently been explained in terms of the radiative forcing by the 11-yr period signal in irradiance (White et al. 2003a; White 2006). Furthermore, the delayed action oscillator responsible for the spatial pattern and evolution the QDO in the Pacific basin (White et al. 2003b) has been shown to be resonantly forced by the 11-yr period signal in the sun’s irradiance in a fully coupled general circulation model of the ocean–atmosphere–terrestrial climate system (White and Liu 2007). These results are consistent with the hypothesis that the tropical Pacific pattern of SST variability associated with the solar-forced QDO drives a significant portion of Midwest drought activity (Perry 2006).

Yet, the constructive interference of the QDO and IDO only partially explains the AMJJA Dustbowl Era drought from ~1929 to 1940; it is primarily associated with a pentadecadal signal in the amplitude time sequences of the CC1 in the CCA model. The latter displays broad peaks centered near 1900 and 1955 and a broad trough from ~1920 to 1945, the latter indicating anomalous dry conditions over the central Midwest during the Dustbowl Era occurring in association with cool SST variability across the eastern/central tropical Pacific Ocean, achieving maximum magnitude in the western equatorial Pacific Ocean near 170°E. This pentadecadal signal in the CC1 amplitude time sequence leads that in the PDO index (Mantua et al. 1997) by 15–20 yr, both signals in nominal temporal quadrature. Furthermore, the corresponding SST spatial pattern in the CC1 resembles that expected of the transition phase in the PDO, that is, in nominal spatial quadrature with the eastern tropical Pacific warm phase of the PDO (Mantua et al. 1997). Thus, it appears that the Dustbowl Era drought in the 1930s coincided with cool SST variability in the western equatorial Pacific Ocean as the pentadecadal signal in the PDO transitioned from its eastern tropical Pacific warm phase centered near 1930 to its eastern tropical Pacific cool phase centered near 1955 (Minobe 2000).

Schubert et al. (2005) found the Dustbowl Era drought of the 1930s linked to cool SST variability in
the western equatorial Pacific Ocean and eastern tropical North Pacific Ocean accompanied by strong above-normal annual SST variability in the tropical and mid-latitude North Atlantic Ocean. Here we find the global pattern of DJF SST variability in the CC1 of the AMJJA CCA model to be similar to that of Schubert et al. (2005) in the Pacific Ocean, but lacking the strong above-normal SST variability in the North Atlantic Ocean. Moreover, we found earlier that this DJF SST pattern is similar to tropical Pacific cool phases of both the QDO and IDO, which constructively interfered from ∼1931 to 1937 (Allan 2000; White and Tourre 2003), and of the transition phase of the pentadecadal signal in the PDO centered near 1930. Moreover, when we restricted the domain of the SST predictor to the Northern Hemisphere (20°–60°N), we lose the ability to simulate the Dustbowl Era drought. From this we conclude that the tropical Pacific SST variability associated with the QDO, IDO, and the pentadecadal signal was necessary for driving the Dustbowl Era drought via anomalous SST-induced meridional atmosphere teleconnections in the western equatorial Pacific Ocean (Sardeshmukh and Hoskins 1988).

Diagnosis of the CC1 in the optimized CCA model for the SOND Midwest rainfall variability found cool JJA SST variability in the eastern/central equatorial Pacific Ocean during each of the three secondary SOND Midwest droughts and during the principal SOND Midwest drought of the 1950s. This pattern of cool SST variability was similar to that observed during tropical cool phases of the QBO and of the four ENSO signals ranging in period from 3 to 7 yr during the twentieth century (Allan 2000; Tourre et al. 2001; White and Tourre 2003). In addition, a pentadecadal signal in the amplitude time sequence of the CC1 was also indicated, with broad peaks near 1925 and 1985 and a principal trough from ∼1947 to 1957, the latter associated with the eastern tropical Pacific cool phase of the corresponding SST pattern. The peaks and troughs of this pentadecadal signal displayed the same combination as observed in the PDO index, while the corresponding spatial pattern of SST variability was the same as that associated with the PDO (Mantua et al. 1997).

These diagnostics revealed a number of simplifying principles at work in AMJJA and SOND Midwest drought development: 1) strong ENSO activity can break Midwest droughts associated with QDO, IDO, and pentadecadal activity; 2) AMJJA Midwest droughts occur during the constructive interference of the QDO and IDO, both aligned with nominal 11- and 22-yr quasi-periodic signals in the sun’s total irradiance (White et al. 1997, 1998), and thus relatively predictable; 3) SOND Midwest rainfall variability is associated with the ENSO SST variability in the eastern/central equatorial Pacific Ocean because it attains a maximum there in SOND (Philander 1990); 4) AMJJA Midwest rainfall variability is associated with the QDO, IDO, and pentadecadal SST variability in the western equatorial Pacific Ocean because the ENSO SST variability attains its seasonal minimum in AMJJA; 5) secondary Midwest drought was primarily an AMJJA phenomenon (yielding 7 of the 10 secondary droughts in the twentieth century in both seasons) because ENSO was generally too weak during AMJJA to interrupt QDO and IDO drought tendencies; and 6) the principal decade-long droughts of the twentieth century in the 1930s and 1950s responded principally to the evolution of the pentadecadal signal in SST variability across the tropical Pacific basin.

Unlike Schubert et al. (2005), the optimized CCA models did not (incorrectly) simulate a principal Midwest drought in the 1970s that was twice the intensity of the Midwest Dustbowl Era drought. Rather, it correctly simulated a secondary AMJJA Midwest drought of 8-yr duration centered near 1974 with 1/2 the intensity of the Dustbowl Era drought. Yet, because the AMJJA Midwest Dustbowl Era drought formed during the trough of the pentadecadal signal in SST variability from ∼1930 to ∼1945, it is fair to ask why it did not recur in the subsequent pentadecadal trough in the 1970s (as it did in Schubert et al. 2005). The answer is twofold. First, global warming across the tropical Pacific Ocean during the second half of the twentieth century in the CC1 overwhelmed AMJJA Midwest drought tendencies by the pentadecadal signal in SST variability. Second, relatively strong ENSO activity in the tropical Pacific Ocean in the 1970s in the CC1 interrupted AMJJA Midwest drought tendencies by the pentadecadal signal in SST variability. One or the other of these phenomena was not properly simulated in the Schubert et al. (2005) AGCM experiments. Furthermore, the Dustbowl Era drought occurred primarily in late spring/summer when rainfall derives from afternoon thunderstorm activity (Carbone et al. 2002, 2003), which is generally poorly resolved in weather forecast models and would have been even more poorly resolved in the relatively coarse-grid AGCM utilized by Schubert et al. (2005).

It is sobering to realize that the largest Midwest droughts of the twentieth century occurred over 70 yr ago in AMJJA during the Dustbowl Era of the 1930s, and over 50 yr ago in SOND during the 1950s. Both of these principal drought episodes were of ∼10-yr duration, twice that of any Midwest drought occurring since. Because the Dustbowl Era drought occurred during the constructive interference of the cool phases of the natu-
rally occurring QDO, IDO, and pentadecadal signal, we can expect another principal drought of this duration and magnitude to occur at some point during the twenty-first century when these condition recur. Unless a mechanism is put in place to recognize the onset of such a decade-long drought, with plans ready to mitigate its effects, its occurrence could devastate the economic and social wellbeing of the U.S. Midwest.

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