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Analysis of drought determinants for the Colorado River Basin

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Abstract Ongoing drought in the Colorado River Basin, unprecedented urban growth in the watershed, and numerical model simulations showing higher temperatures and lower precipitation totals in the future have all combined to heighten interest in drought in this region. In this investigation, we use principal components analysis (PCA) to independently assess the influence of various teleconnections on Basin-wide and sub-regional winter season Palmer Hydrological Drought Index (PHDI) and precipitation variations in the Basin. We find that the Pacific Decadal Oscillation (PDO) explains more variance in PHDI than El Niño-Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), and the planetary temperature combined for the Basin as a whole. When rotated PCA is used to separate the Basin into two regions, the lower portion of the Basin is similar to the Basin as a whole while the upper portion, which contains the high-elevation locations important to hydrologic yield for the watershed, demonstrates poorly defined relationships with the teleconnections. The PHDI for the two portions of the Basin are shown to have been out of synch for much of the twentieth century. In general, teleconnection indices account for 19% of the variance in PHDI leaving large uncertainties in drought forecasting.

1 Introduction

Over the past decade, hydroclimatic variability in the western United States has emerged as a dominant environmental issue of concern among climate scientists. Since 1996, a

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substantial portion of the western United States has experienced drought conditions of similar severity and spatial scale to historical droughts of the 1930s and 1950s. Various paleoclimatic studies using tree-ring and coral have uncovered evidence of multidecadal drought signals over the past 500 to 2,000 years (Woodhouse and Overpeck 1998; Stahle et al. 2000, 2003). While some recent studies have examined hydroclimatic variability of the entire country (McCabe et al. 2004) or just the western United States (Hidalgo 2004), a number of scientists are focusing on climate variability at regional and sub-regional scales. Climate controls over regional areas such as individual river basins in the West are complex and often have mixed relationships to atmospheric and oceanic teleconnections (Cayan et al. 1999; Brown and Comrie 2004).

This hydroclimatic complexity is substantially compounded in the Colorado River Basin (CRB) given that several of North America's fastest growing metropolitan areas, most notably Phoenix and Las Vegas, are located in this Basin. Faced with alternatives between extreme aridity and episodic flooding, waves of desert dwellers took steps over the years to implement one of the most extensive water storage and delivery systems on the planet. Recent drought conditions in the region awakened residents and policymakers to a reality that their climate is highly variable and capable of sustaining severe drought over long periods of time. Barnett et al. (2004, p. 7) recently found "the fully allocated Colorado system to be at the brink of failure, wherein virtually any reduction in precipitation over the Basin, either natural or anthropogenic, will lead to the failure to meet mandated allocations."

The most recent scientific assessment of the Intergovernmental Panel on Climate Change (IPCC) reports that temperatures in the CRB, particularly the winter season values, are expected to rise more quickly than the globally averaged temperatures due to elevated greenhouse gas concentrations (Houghton et al. 2001). Furthermore, IPCC suggests that winter season precipitation will experience a 'slight' decline over the next 50 years of 5% to 20% and that snowpacks in the headwaters of the Colorado River will decline substantially. The IPCC scientists note that the region has warmed by approximately 0.2 °C decade^{-1} from 1901 to 2000, the warming rate doubled over the most recent 25 years, and precipitation levels have increased and decreased in different parts of the Basin from 1900 to 1999. Detailed regional numerical simulations using the USDOE/NCAR Parallel Climate Model (PCM) and the Variable Infiltration Capacity (VIC) macroscale hydrology model predict that by 2050, temperatures in the CRB will increase by 1.7 °C relative to 1950–1999, precipitation will decline by 6%, snowpack will be reduced by 30% in terms of snow water equivalent, runoff will decrease by 18%, and water storage will decline by 32% (Christensen et al. 2004; Leung et al. 2004).

The reality of high natural climate variability, anticipated continued urban growth in the region, and the threat of deleterious regional climate change have increased interest in understanding forcing mechanisms responsible for variations in climate in the CRB. For years, scientists linked moisture conditions in the region with El Niño-Southern Oscillation (Ropelewski and Halpert 1986; Redmond and Koch 1991; Hidalgo and Dracup 2003), but a significant literature is growing linking moisture variations in the southwestern United States to a variety of teleconnections including the Pacific Decadal Oscillation, the Atlantic Multidecadal Oscillation, and hemispheric and global temperatures. Hidalgo (2004) used a tree-ring constructed summer (JJA) drought index (from Cook et al. 1999) while McCabe et al. (2004) used annual drought frequency to establish that vast areas of the western United States are associated with multidecadal oscillations in the Pacific and Atlantic Oceans.

This study will build off the research of Hidalgo (2004) and McCabe et al. (2004) by providing a more regionalized look at the independent influences of the various teleconnections on Basin-wide and sub-regional moisture patterns in the CRB during the winter season. Since water storage on the Colorado River is largely controlled by cold season precipitation, this study will be confined to the winter months of November–April. A series of multivariate statistical procedures will be used in an attempt to isolate the important climatic controls on precipitation, temperature, and a hydrologic drought index. The relative importance of each will be established and estimates will be made of accuracy of resultant statistical predictive equations. The research may be useful in reducing uncertainty in the climate controls of drought in the CRB.

2 Databases

The climate variability in the Basin is represented by three readily available datasets updated monthly by scientists at the National Climatic Data Center. We elected to use climate divisional data largely because of the availability of relatively long-term time series for popular drought indices. The three primary climate variables used in this study include divisional mean monthly temperature, total precipitation, and the Palmer Hydrological Drought Index (PHDI).

Palmer (1965) developed the PHDI, along with other drought measures, and these indices have been used in countless research studies as well as in operational drought monitoring during the past 40 years. The PHDI accounts not only for precipitation totals, but also for temperature, evapotranspiration, soil runoff, and soil recharge. The index varies roughly between −6.0 and +6.0 although there are a few values in the magnitude of +7 or −7. Values near zero indicate normal conditions for a region, values less than −2 indicate moderate drought, values less than −3 indicate severe drought, and values less than −4 indicate extreme drought. Oppositely, values greater than +2 indicate moderately wet conditions, those above +3 represent very wet conditions, and PHDI values above +4 are for extremely wet conditions. Alley (1984) identified three positive characteristics of the index that contribute to its popularity: (a) it provides decision makers with a measurement of the abnormality of recent weather for a region; (b) it provides an opportunity to place current conditions in an historical perspective; and (c) it provides spatial and temporal representations of historical droughts. There are certainly limitations when using the PHDI (or any other index), and these are described in detail by Alley (1984), Karl and Knight (1985), and Guttman (1991).

There are 23 climate divisions in seven states that contain some part of the CRB (Fig. 1) and the monthly temperature, precipitation, and PHDI data are available for all divisions for a study period from January, 1895 to April, 2004. A monthly Basin-wide value of each hydroclimatic variable was constructed by areally weighting the average of the 23 values based on the area of each division contained within the CRB.

In order to explain temporal variance in these various climatic variables, we selected teleconnections that others have identified as important in controlling climate in the Southwest, one of the most popular being El Niño-Southern Oscillation (ENSO). During the warm phase of ENSO, El Niño, the westerly flow shifts southward resulting in increased winter precipitation with lower temperatures in the southwestern United States (Cayan and Peterson 1989; Kiladis and Diaz 1989; Redmond and Koch 1991; Sheppard et al. 2002; Zhu et al. 2004). During the cool phase of ENSO, La Niña, the Southwest is drier and maximum temperatures increase (Woodhouse 1997). We assembled two different variables to characterize ENSO over the 1895 to 2004 time period. One variable, labeled SOI, is based on the difference between standardized sea level pressures at Tahiti and Darwin, with the resultant time series of differences then being standardized. Large

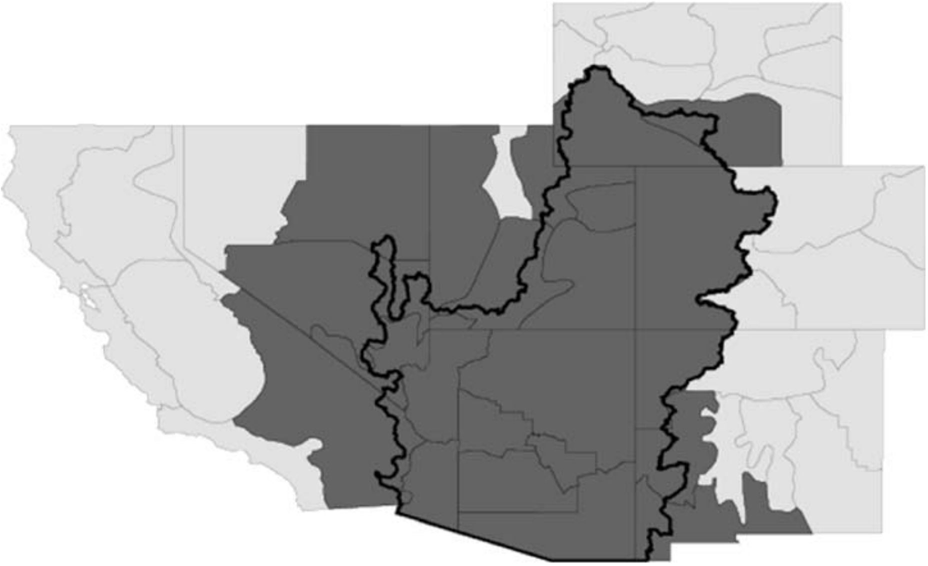

Fig. 1 Map of the seven states and 23 climate divisions containing some portion of the Colorado River Basin; the *thick black line* shows the drainage divide for the Basin

negative values indicate periods of El Niño while large positive values indicate periods of La Niña.

While the SOI is determined by atmospheric circulation, we used a second indicator of ENSO based on sea surface temperatures (SSTs). Trenberth (1997) determined that the Niño 3.4 SSTs (5°N–5°S, 120–170°W) are particularly good indicators of ENSO, and accordingly, we selected the monthly SST anomalies (based on a 1950–1979 normal period) for that region.

The Pacific Decadal Oscillation (PDO) characterizes low frequency changes in the North Pacific Ocean with a period of approximately 50 years. The PDO index is the leading principal component or eigenvector of the mean monthly SSTs in the Pacific Ocean north of 20°N (Mantua et al. 1997). Positive values of the index refer to above normal SSTs along the west coast of North America and along the equator and below normal SSTs in the central and western North Pacific around 45°N. During positive PDO, pressures are low in the northern Pacific, and winter precipitation increases in the western United States (Mantua et al. 1997). Zhu et al. (2004) found that the CRB warms by over 1 °C in winter during the warm phase of the PDO based on data from 1900 to 1994. Gershunov and Barnett (1998), McCabe and Dettinger (1999, 2002), Gutzler et al. (2002), and Goodrich (2004) have shown that adding PDO to ENSO can increase skill in predicting winter precipitation in the Southwest, and therefore, monthly values of PDO index were added to our matrix of predictor variables.

During the past century, there have been only two complete cycles of the PDO (Mantua and Hare 2002). Cool phases of the PDO have persisted from 1890 to 1924 and from 1947 to 1976 while warm phases persisted from 1925 to 1946 and from 1977 through at least the late 1990s. While several researchers (Hare and Mantua 2000; Schwing and Moore 2000) have shown there may have been a phase change at the completion of the 1997–1998 El Niño, the current phase of the PDO is uncertain as the index has displayed greater interannual variability than usual in recent years. Whether or not 1999 represents the beginning of a multidecadal cool phase will not be known for some time.

The Atlantic Multidecadal Oscillation (AMO) is a recent label for a climate oscillation in the North Atlantic with a period of 65–80 years (Kerr 2000; Hurrell et al. 2003); the AMO is essentially the 10-year running mean of detrended Atlantic SST anomalies north of the Equator. AMO warm phases occurred from 1860 to 1880 and 1930 to 1960 while cool phases occurred during 1905–1925 and 1970–1990. Years between warm and cool phases represent a neutral or transitional phase. Many scientists believe that AMO has returned to the warm phase in recent years. Positive (warm) AMO is associated with drought throughout the United States (McCabe et al. 2004), and Enfield et al. (2001) showed a significant negative correlation between rainfall in the CRB and AMO.

The North Pacific Index (NPI) is the area-averaged sea level pressure anomaly in the region 160°E–140°W, 30–65°N and represents the strength of the Aleutian Low (Trenberth and Hurrell, 1994). A deeper Aleutian Low typically drives cyclonic storms southward bringing increased winter precipitation to the southwestern United States. The NPI dataset was obtained from the online dataset maintained by the National Center for Atmospheric Research (NCAR).

Finally, we added monthly northern hemispheric and global temperature anomalies (based on a 1961–1990 normal period) from the widely used Jones et al. (1999) dataset. This resulted in monthly data from 1895 to 2004 for Basin mean temperature, total precipitation, PHDI, and teleconnection indices including SOI, Niño 3.4, PDO, AMO, NPI, and the hemispheric and global temperatures. There were several missing values in the record, and we used multiple regression and/or Box–Jenkins modeling to provide estimates for the missing values (in the end, we found these procedures to not significantly influence any of our results).

3 Analyses and results

3.1 Basin wide

As noted by Sheppard et al. (2002), Hidalgo and Dracup (2003), and many others, the Colorado River system's water supply is almost entirely dependent upon winter precipitation. Cyclonic storms passing over the region in winter deposit water in the form of rain and snow during a time when potential evapotranspiration rates are low. Summer events are spatially variable, short lived, and occur during a period of high potential evapotranspiration rates. Therefore, the analyses conducted in this investigation are limited to November through April when precipitation events have a major role in controlling moisture conditions in the CRB.

Accordingly, the monthly data for all variables were averaged, or totaled in the case of precipitation, for the November through April time frame. In addition, we averaged the teleconnection variables for September and October to capture their state in a period antecedent to the November through April low-sun season. This resulted in a final matrix of 109 rows, one for each winter season from 1895 to 1896 through 2003–2004, and 15 columns, one each for the variables described in Table 1.

With our focus on PHDI, we conducted analyses to determine the spatial variation in the resultant PHDI time series. The Pearson product-moment correlation coefficients between individual climate divisions and the Basin-wide values ranged from 0.89 to 0.38 and averaged 0.72. A principal components analysis of the 109 by 23 matrix of divisional PHDI

Table 1 Correlation coefficients (r_{PHDI}) of raw teleconnection variables with Palmer Hydrological Drought Index (PHDI), standardized coefficients of skewness (z_1) and kurtosis (z_2), and principal component loadings (α_1, α_2, α_3) of teleconnection variables

Variable	r_{PHDI}	z_1	z_2	α_1	α_2	α_3
Basin PHDI	1.00	0.58	0.12			
Basin precipitation	0.58	3.56	1.06			
Basin temperature	−0.37	−0.49	−0.05			
Global temperature	0.02	1.36	−0.45	0.23	0.88	0.17
N. H. temperature	−0.07	1.80	−0.08	0.16	0.90	0.13
Niño 3.4	0.18	1.32	−0.91	0.95	0.04	0.10
SOI	−0.29	−1.86	1.29	−0.88	−0.12	−0.16
PDO	0.31	−0.47	0.19	0.09	−0.02	0.85
NPI	−0.10	−1.83	−0.31	−0.36	−0.40	−0.38
AMO	−0.20	0.36	−1.20	0.01	0.92	−0.53
Antecedent Niño 3.4	0.19	2.07	−0.19	0.92	0.04	0.09
Antecedent SOI	−0.20	0.19	−1.10	−0.83	−0.11	−0.13
Antecedent PDO	0.34	−0.47	−0.02	0.45	−0.06	0.68
Antecedent NPI	0.08	−0.86	−0.74	−0.14	−0.26	−0.19
Antecedent AMO	−0.24	0.34	0.41	−0.17	0.87	0.01
Eigenvalue				4.80	2.99	1.55
Variance explained				0.37	0.23	0.12
Cumulative variance				0.37	0.60	0.72

N. H. Temperature Northern Hemisphere Temperature, *SOI* Southern Oscillation Index, *PDO* Pacific Decadal Oscillation, *NPI* North Pacific Index, *AMO* Atlantic Multidecadal Oscillation.

values produced a first unrotated component explaining 54% of the variance in the matrix with component score correlation with our Basin-averaged PHDI values of 0.98. The second component explained an additional 15% of the variance and was related to conditions in the upper portion of the CRB.

Because several of the statistical techniques used in our study assumed that the data are normally distributed (a Gaussian distribution), we tested both the hydroclimatic variables as well as the teleconnection indices for this property using the standardized coefficients of skewness, z_1, and kurtosis, z_2, calculated as:

$$z_1 = \frac{\left[\sum_{i=1}^{N} (x_i - \overline{X})^3 \big/ N\right] \left[\sum_{i=1}^{N} (x_i - \overline{X})^2 \big/ N\right]^{-3/2}}{(6/N)^{1/2}}$$

and

$$z_2 = \frac{\left\{\left[\sum_{i=1}^{N} (x_i - \overline{X})^4 \big/ N\right] \left[\sum_{i=1}^{N} (x_i - \overline{X})^2 \big/ N\right]^{2}\right\} - 3}{(24/N)^{1/2}}$$

where the resulting z values are compared against a t-value deemed appropriate for a selected level of confidence (e.g., for $N = 109$, $t = 1.98$ for the 0.05 confidence level and $t = 2.63$ for the 0.01 level). If the absolute value of z_1 or z_2 exceeds the selected value of t, a significant deviation from the normal curve is confirmed. Otherwise, no statistically significant deviation from a normal distribution is determined (the null hypothesis that the samples came from a normal distribution cannot be rejected). We also used the Kolmogorov–Smirnov one-sample test to further evaluate each variable. As seen in Table 1, only total seasonal precipitation is confirmed as non-normal, which is confirmed by the Kolmogorov–Smirnov one-sample test. A square-root transformation ‘normalized’ the precipitation data.

Figure 2 presents a time series plot of the three primary hydroclimate variables for the Basin. Over the entire time period, PHDI and precipitation show no significant trend while temperature has increased linearly at a rate of 0.07 °C decade^{-1} (ρ = 0.03). From 1975 to 2004, PHDI has decreased 0.90 decade^{-1} (ρ = 0.05), precipitation has no significant trend, and temperature has increased by 0.40 °C decade^{-1} (ρ = 0.03). The correlation coefficient between PHDI and precipitation is 0.58 (ρ = 0.00), the coefficient between PHDI and temperature is −0.37 (ρ = 0.00), and the correlation between temperature and precipitation is −0.19 (ρ = 0.05). These results show that drought in the Basin is far more related to local precipitation than to local temperature.

The primary focus of this investigation is on how the various teleconnections control PHDI in our study area. The correlation coefficients between PHDI and all teleconnection indices are also shown in Table 1. The pattern of coefficients reveals relatively low absolute values for any potential predictor of PHDI levels, with the highest absolute values related to concurrent and antecedent PDO. Obviously, these predictor variables are interrelated to some extent, and we used principal components analyses, with varimax rotation, to transform the twelve teleconnection indices onto independent, orthogonal axes.

The loading pattern (Table 1) reveals that the first component is highly related to ENSO variables, and therefore is labeled the El Niño factor. The second component is dominated by global and hemisphere temperature and the AMO while the third vector is completely dominated by PDO. A fourth component had a high loading on antecedent NPI, but the

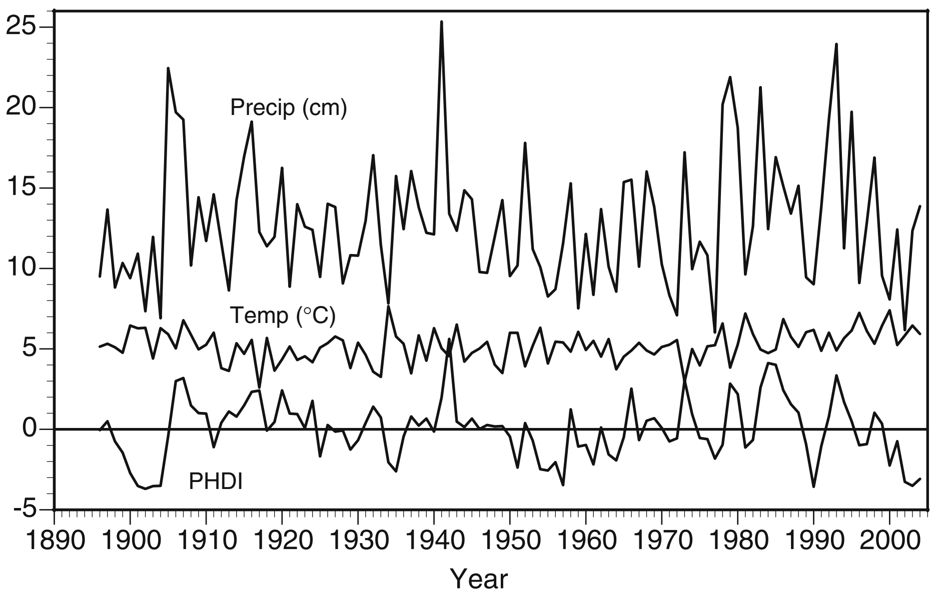

Fig. 2 Time series plot of areally-averaged Colorado River Basin November–April total precipitation (cm), temperature (°C), and Palmer Hydrological Drought Index (*PHDI*) over the period November, 1895 to April, 2004

eigenvalue was below 1.00 and the component appeared to have no significant statistical link to PHDI, temperature, or precipitation in the Basin.

The normality tests were applied to the component scores, and no significant deviation from normality could be confirmed. The time series plot of the three independent time series (Fig. 3) shows remarkably different patterns for time series that by definition have a mean of zero and a standard deviation of one. The El Niño vector shows high year-to-year variance with no trend, the PDO factor reveals its characteristic 50-year periodicity, and the planetary temperature/AMO vector shows a periodicity of near 70 years and an upward trend in recent decades.

Component scores for these three independent eigenvectors were used as predictors in a multiple regression analysis with Basin-wide PHDI as the dependent variable. The resultant equation shows that all three components explain a significant ($\rho < 0.03$) amount of variance in PHDI values with a multiple R value of 0.44, R^2 is 0.19, and adjusted R^2 is 0.17. The residuals had no significant trend, periodicities, changes in variance, and/or autocorrelation. The standardized regression coefficients are 0.34 for the PDO vector, 0.21 for the El Niño vector, and −0.19 for the AMO-planetary temperature vector. The PDO vector explains 11% of the variance in PHDI for the Basin as a whole, while the El Niño and AMO-planetary temperature vectors explained 4% each; 81% of the variance in winter season PHDI remains unexplained. The PDO explains more than twice the variance of El Niño and the AMO because it is the only one of the three teleconnections to have a coherent climate signal across the Basin as a whole. The deepening (weakening) of the Aleutian low during the warm (cold) phase of the PDO produces a more southerly (northerly) Pacific jet stream that brings increased (decreased) moisture into the entire CRB

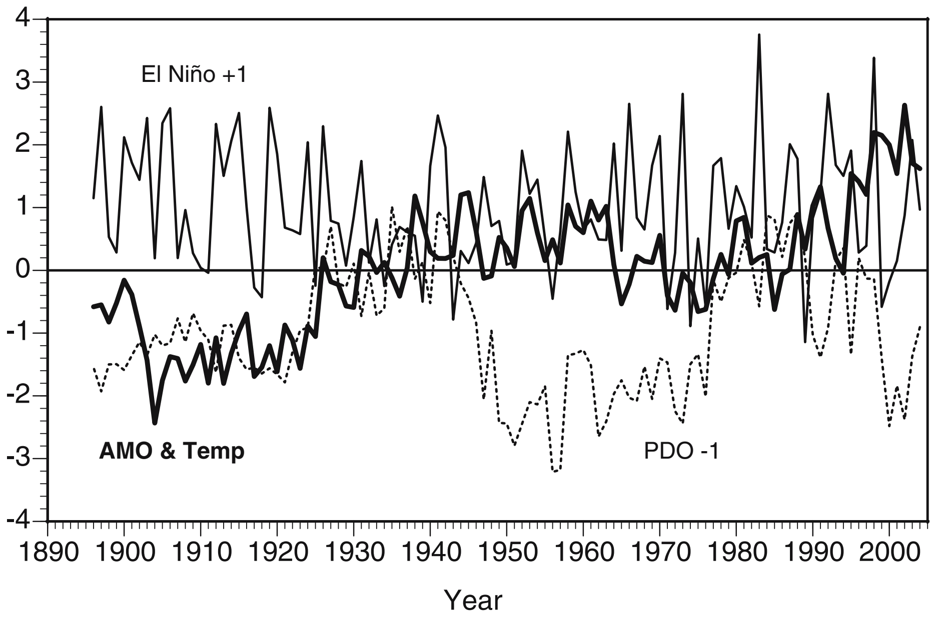

Fig. 3 Time series of principal component standardized scores; for graphical purposes, 1 has been added to the 'El Niño' factor and 1 has been subtracted from the 'Pacific Decadal Oscillation (*PDO*)' component scores

(Mantua et al. 1997). We will further discuss the physical mechanisms behind sub-regional differences in teleconnective response in “Section 3.2.”

For each of the three eigenvectors, we used a *t*-test to determine the difference in the mean PHDI when components scores were > +1 or < −1. In the case of the El Niño component, PHDI averaged 0.52 when component scores are high and −0.47 when they are low; the value of *t* is 1.63 indicating no significant difference between the two means. However, the *t*-value for the PDO and AMO-temperature components were significant (both *t*-values were near 2.5) with drier conditions with cool PDO and the warm-phase of the AMO-planetary temperature. We also computed the *t* statistic for each component given PHDI < −2 and PHDI > +2. During the wet phase of PHDI, the PDO component averaged 0.40 while during the dry periods, the PDO scored averaged −0.61, and the *t*-value of 2.66 was significant ($\rho = 0.02$). The *t* statistics for the El Niño and AMO-temperature components indicated no significant difference in means given relatively high or low PHDI values. A stepwise multiple discriminant analysis produced basically the same results. In discriminating years with PHDI > +2 and PHDI < −2 with the three eigenvectors, the PDO component was most significant while the inclusion of the other two components produced significant ($\rho < 0.05$) increases in the discriminating power of the equation.

With respect to Basin-averaged precipitation totals, the El Niño vector has a standardized regression coefficient of 0.41 while the PDO vector has a value of 0.28, and both are significant at $\rho < 0.01$. The multiple R value is 0.50, R^2 is 0.25, and adjusted R^2 is 0.23. The only significant predictor of Basin temperature is the planetary temperature/AMO vector with an R value of 0.30, R^2 of 0.09, and adjusted R^2 of 0.06. These results show that PHDI in the Basin as a whole is controlled largely by PDO, precipitation is related mostly to ENSO, and temperature is most explained by AMO and planetary temperature levels. The tendency for the Basin to have long-lasting drought and pluvial periods (Diaz 1983) is likely related to the PDO being the primary predictor of PHDI.

We repeated our analyses for the period 1950 to 2004 recognizing that the quality of some data values may deteriorate in earlier years of the study and to account for the known non-stationary character of ENSO teleconnections relating to both the PDO and AMO. We found that the multiple R value for the regression equation between PHDI and the three components increased from 0.44 for the entire time series to 0.63 for the 54-year subset, a finding which is consistent with previous studies that found that ENSO teleconnections with winter precipitation in the West are more robust since 1950 (McCabe and Dettinger 1999, 2002; Enfield et al. 2001). We used a test statistic suggested by Kleinbaum and Kupper (1978) computed as:

$$Z = \frac{0.5\ln\left(\frac{1+R_1}{1-R_1}\right) - 0.5\ln\left(\frac{1+R_2}{1-R_2}\right)}{\sqrt{\frac{1}{N_1-3} + \frac{1}{N_2-3}}}$$

where R_1 and R_2 are the multiple correlation coefficients from the two different equations, and N_1 and N_2 are the number of cases in the development of each equation. The value of Z is compared to critical values of t with a total N size of $N_1 + N_2 - 6$. We found that Z was equal to 1.58 and therefore did not establish a significant difference between the two multiple R values. The basic relationships remained stable in the two analyses, and the standard error of the estimate for PHDI was 1.70 for the entire time series and 1.56 for the 1950 to 2004 series. Inspection of Fig. 4 indicates that PDO and PHDI have been in phase since 1940 but out of phase from 1905 to 1940 thereby accounting for the increased accuracy of the discriminant model in the recent subperiod. We suggest that this out of phase

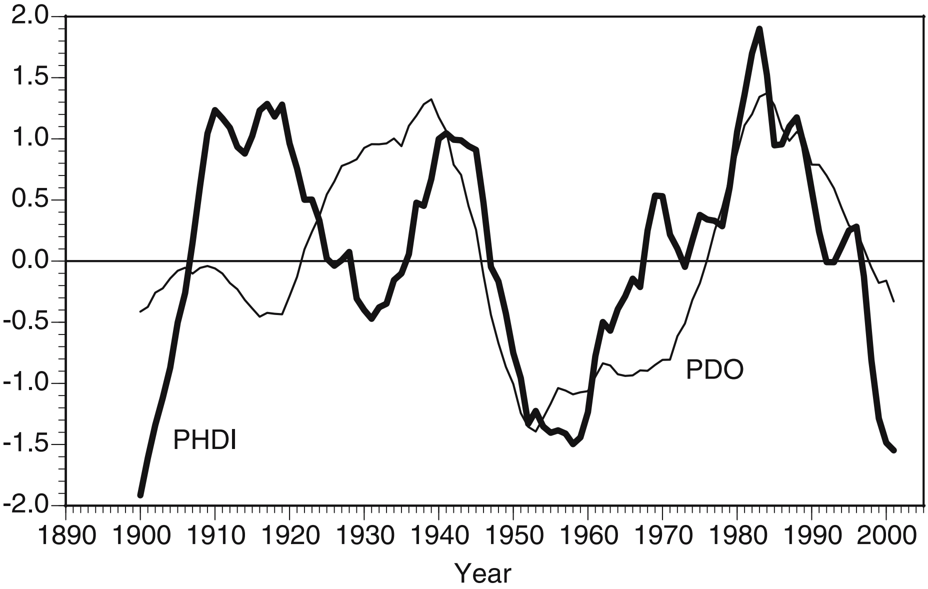

Fig. 4 Ten-year smoothed winter Palmer Hydrological Drought Index (*PHDI*) values and Pacific Decadal Oscillation (*PDO*) factor scores over the 1895–2004 time period

relationship between PDO and PHDI from 1905 to 1940 could be related to a breakdown in the relationship between ENSO and PDO as discussed by McCabe and Dettinger (1999). However, McCabe et al. (2004) discuss that certain combinations of AMO and PDO lead to increased drought frequency in the CRB. Years of cold PDO-warm AMO, which last occurred from 1944 to 1963, are associated with drought in the CRB, which may explain why the PDO and PHDI became phase locked after 1940. It is worth speculating whether the PDO and PHDI will remain phase locked in the future in a time when the PDO has become more inter-annual (since the 1998 La Niña event) than at any time during the twentieth century.

Finally, we computed ΔPHDI from one winter season to the next to determine what variable most controls interannual change in this variable. Not surprisingly given its relatively high interannual variability, the El Niño vector was the only significant ($\rho < 0.01$) predictor with an R value of 0.51, R^2 of 0.26, and adjusted R^2 of 0.24.

3.2 Sub-regional variability

Recognizing that others (Cayan et al. 1999; Brown and Comrie 2004) have demonstrated that the CRB can at times produce a dipole effect with opposite moisture regimes from the upper Basin to the lower Basin, we conducted a principal components analysis of the seasonal PHDI data for the 23 climate divisions (Fig. 5). The first rotated component explained more than half the total variance in PHDI across all climate divisions, but had highest loadings (> 0.70) for the divisions within the lower portion of the Basin (centered over the deserts of central Arizona). The second rotated component explained approximately 15% of the total variance and produce high loadings with the divisions in the upper portion of the Basin (centered over the mountains of western Colorado and eastern Utah). Remaining components explained small amounts of variance and were related to divisions at the margins of the CRB.

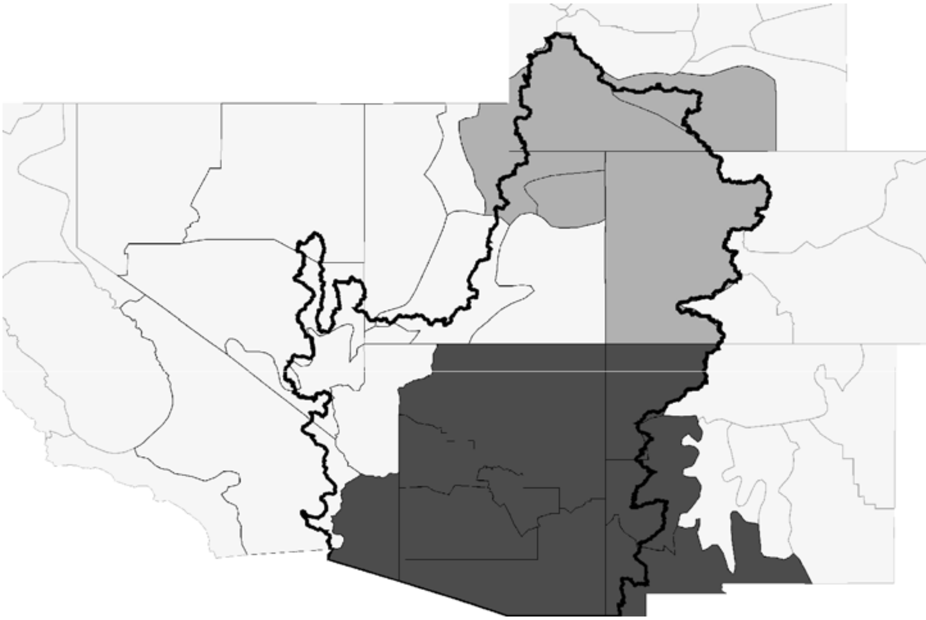

Fig. 5 Map showing results of principal components analysis with varimax rotation of the Palmer Hydrological Drought Index for all 23 climate divisions in the Colorado River Basin. The first (second) principal component, shown in *dark* (*light*) *gray*, had the highest loadings (>0.70) over the *lower* (*upper*) Basin. Remaining components, shown in *white*, are related to climate divisions on the margins of the Basin

A plot of the component scores for the first two components shows considerable differences through the period of record (Fig. 6). One noticeable feature of the plot is that drought from 1898 to 1905 gripped all parts of the CRB; at other times, the moisture patterns could be opposite of one another. This feature may also be explained by the tendency for different parts of the CRB to be experience droughts based on combinations of the PDO and AMO (McCabe et al. 2004). By definition in the principal components analysis, the time series of the two components have a correlation of 0.00.

We repeated many of the analyses described for the entire Basin to the component scores from the lower and upper Basin areas. Multiple regression analyses were conducted with the PHDI component scores as dependent variables and the El Niño, temperature/AMO, and PDO vectors as independent variables. For the first component representing variance from the lower portion of the Basin, the results were quite similar to what was found for the entire Basin. Over the entire 1896–2004 period, the regression equation shows that all three components explain a significant ($\rho < 0.00$) amount of variance in PHDI values with a multiple R value of 0.41, R^2 of 0.17, and adjusted R^2 of 0.15. The standardized regression coefficients are 0.29 for both the PDO and El Niño eigenvectors, but only 0.04 (not significant) for the temperature/AMO vector. El Niño is an important predictor for the lower CRB because the traditional positive side of the ENSO dipole between the Southwest and Pacific Northwest is centered over this region. The fact that the AMO is not an important predictor for the lower CRB is not surprising since significant correlations between AMO and precipitation occur only along the Mexican border (Enfield et al. 2001), an area which is not included in our lower CRB map (Fig. 5). The results for the 1950–2004 subperiod

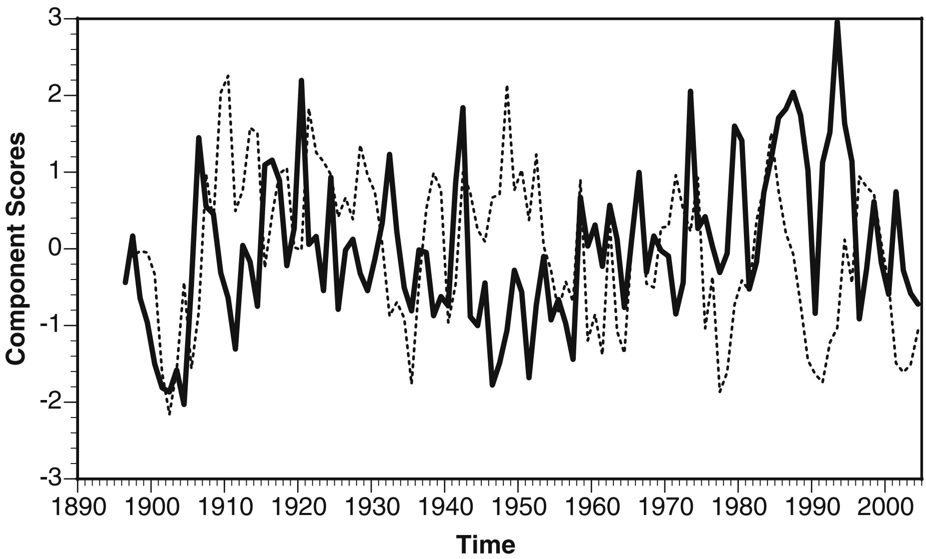

Fig. 6 Winter-season Palmer Hydrological Drought Index (*PHDI*) component scores for the lower Basin (*solid line*) and upper Basin (*dotted line*)

showed multiple *R* value of 0.62, R^2 of 0.39, and adjusted R^2 of 0.35 with PDO and El Niño explaining most of that variance.

When these same analyses were conducted for the PHDI component scores from the upper Basin for the 1896–2004 period, the multiple *R* value is 0.31, R^2 is 0.10, and adjusted R^2 is 0.08. The only significant standardized regression coefficient was −0.27 for the temperature/AMO factor; PDO and El Niño did not appear to significantly influence the winter-season PHDI of the upper reaches of the Basin. This finding is consistent with the results of Enfield et al. (2001), who found negative correlations between precipitation and the AMO in the upper CRB. When repeated for the 1950–2004, the multiple regression equation was not significant ($\rho = 0.44$) overall and none of the standardized regression coefficients were significant (the temperature/AMO factor was highest with $\rho = 0.11$).

Rotated PCA conducted on the winter precipitation totals from the 23 climate divisions that make up the CRB also created two components that together explained 78% of the variance of the dataset. As with PHDI, the lower portion of the Basin was dominant (60% variance) compared to the upper portion (18% variance) and the overall spatial patterns of the components were similar to that of PHDI. When the three predictor eigenvectors were regressed against the lower Basin component scores, the regression equation was highly significant ($\rho < 0.00$) with a multiple *R* value of 0.59, R^2 of 0.34, and adjusted R^2 of 0.33. Both El Niño ($r = 0.52$) and PDO ($r = 0.27$) were statistically significant. The regression equation from the upper Basin component had a multiple *R* value of only 0.22 (R^2 of 0.05) with $\rho = 0.13$. The dipole relationship in the CRB is evident as the standardized regression coefficient for the upper portion of the Basin with El Niño was −0.18 at $\rho = 0.06$.

3.3 Inter-annual vs. decadal teleconnections

While the analysis to this point has utilized climate indices on an annual time scale, recent research (Hidalgo 2004; McCabe et al. 2004) has demonstrated that multidecadal

Table 2 *R* values of three regression equations between Basin-wide moisture variables (Palmer Hydrological Drought Index (PHDI) and precipitation (PREC)) and teleconnections indices (Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO))

	AMO	PDO	AMO10	PDO10	AMO20	PDO20
PHDI	−0.05	**0.22**	–	–	–	–
PHDI10	–	–	**−0.43**	**0.53**	–	–
PHDI20	–	–	–	–	**−0.44**	**0.65**
PREC	0.09	**0.36**	–	–	–	–
PREC10	–	–	−0.15	**0.77**	–	–
PREC20	–	–	–	–	−0.11	**0.80**

Regressions used unsmoothed (annual) and smoothed (10- and 20-year moving averages) times series of each variable. Significant values ($P<0.05$) in bold.

teleconnections such as PDO and AMO are useful indicators of climate regimes, and that smoothed versions of these time series can be a more useful indicator of drought than unsmoothed time series. We created 10- and 20-year moving averages of the AMO and PDO as well as Basin-wide PHDI and precipitation. When the smoothed moisture variables were used as dependent variables in a regression against the smoothed teleconnections indices, the correlations between variables increased substantially (Table 2). The AMO, which was not a significant predictor of PHDI or precipitation on annual time scales, did become a significant predictor of PHDI when smoothed ($r = -0.44$, $\rho < 0.05$), though not as important as the smoothed time series of PDO ($r = 0.65$, $\rho < 0.05$). If we account for the autocorrelation in the smoothed time series and reduce the degrees of freedom to $1 + (2/N)[(N-1)r_1 + (N-2)r_2...]$, where r_j is the autorcorrelation coefficient at lag j, the results remain statistically significant (Quenouille 1952). However, smoothed time series of AMO were not significant predictors of Basin-wide precipitation at any time scale. In contrast, the 10- and 20-year moving averages of PDO were important and significant predictors of precipitation with r-values near 0.80 at both time scales. We suggest that the link between NH temps and the AMO we found in the rotated principal components analysis may be the reason that smoothed AMO is a significant predictor of drought but not precipitation. The warm (cold) phase of the AMO is associated with increased (decreased) temperatures in the interior US, which when combined with certain phases of the PDO then influences the drought signal in the CRB.

Further analysis using the 20-year smoothed time series of each variable shows that using only PDO to predict Basin-wide PHDI ($R^2 = 0.67$) or precipitation ($R^2 = 0.56$) is a useful tool. However, the inclusion of AMO to the equation will only significantly increase the variance explained for PHDI (0.56 to 0.75) while variance explained for precipitation does not change significantly (0.67 to 0.68). The results in this section demonstrate that regardless of time scale, the PDO is a better predictor of moisture variables in the Colorado River Basin than the AMO.

4 Conclusions

One goal in this investigation was to reduce uncertainty in predicting winter season drought in the Colorado River Basin given knowledge of teleconnections that have been linked by many others to the climate of the region. The area has coped with drought in the recent decade, human population growth is expected to continue, and forecasts of increased drought remain given the ongoing buildup of greenhouse gases. In this investigation, we found that for the Basin as a whole, the PDO explains more variance in PHDI than ENSO, AMO, and the planetary temperature combined. However, these predictors account for 19% of the variance in PHDI leaving large uncertainties in drought forecasting. For Basin-wide precipitation, slightly more variance is explained by the teleconnections (25%), with ENSO being the leading predictor. These results did not change even when smoothed versions of the multidecadal teleconnections were used. Since others have shown a dipole relationship between predictors and hydroclimatic variables in the Colorado River Basin, we used Rotated Principal Components Analysis on PHDI and precipitation to separate the Basin into an upper and lower portion. The lower portion showed similar results to that of the entire Basin while the upper portion, which represents the mountains of Utah and Colorado that supply much of the hydrologic input into the watershed, showed little correlation with the teleconnection indices. This may be related to the mixed correlations between ENSO and winter precipitation found in the Upper Colorado River Basin between high- and low-elevation stations by Hidalgo and Dracup (2003). However, the non-stationarity of ENSO teleconnections during different phases of the PDO and AMO may also weaken the signal in different parts of the Basin. Additionally, a plot representing the winter-season PHDI show that the upper and lower portions of the Colorado River Basin have been out of synch for much of the past 100 years, suggesting that teleconnections from multidecadal signals in the Atlantic and Pacific Oceans may not be as regionally coherent on their influence on drought as suggested by Hidalgo (2004) and McCabe et al. (2004).

Both Hidalgo (2004) and McCabe et al. (2004) speculate that the persistent positive phase of the AMO since the late 1990s suggests an increase of drought probability in the western United States. They also speculate that the phase of the PDO may modulate the spatial pattern of drought with cold (warm) PDO creating a tendency towards drought in the lower (upper) portion of the Colorado River Basin. Our results suggest that the weak PDO/ENSO signal for PHDI and precipitation in the upper portion of the Basin and the high level of remaining variance unexplained by teleconnections make drought outlooks based on these teleconnection indices difficult for the Colorado River Basin. In addition, not only does the recent (since 1998) increase in the inter-annual variability of the PDO make determination of the current PDO phase difficult, it may also weaken the strong in-phase relationship between smoothed PDO and PHDI that has occurred since 1940.

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