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ASSOCIATIONS OF DECADAL TO MULTIDECADAL SEA-SURFACE TEMPERATURE VARIABILITY WITH UPPER COLORADO RIVER FLOW[1]

Gregory J. McCabe, Julio L. Betancourt, and Hugo G. Hidalgo[2]

Abstract: The relations of decadal to multidecadal (D2M) variability in global sea-surface temperatures (SSTs) with D2M variability in the flow of the Upper Colorado River Basin (UCRB) are examined for the years 1906-2003. Results indicate that D2M variability of SSTs in the North Atlantic, North Pacific, tropical Pacific, and Indian Oceans is associated with D2M variability of the UCRB. A principal components analysis (with varimax rotation) of detrended and 11-year smoothed global SSTs indicates that the two leading rotated principal components (RPCs) explain 56% of the variability in the transformed SST data. The first RPC (RPC1) strongly reflects variability associated with the Atlantic Multidecadal Oscillation and the second RPC (RPC2) represents variability of the Pacific Decadal Oscillation, the tropical Pacific Ocean, and Indian Ocean SSTs. Results indicate that SSTs in the North Atlantic Ocean (RPC1) explain as much of the D2M variability in global SSTs as does the combination of Indian and Pacific Ocean variability (RPC2). These results suggest that SSTs in all of the oceans have some relation with flow of the UCRB, but the North Atlantic may have the strongest and most consistent association on D2M time scales. Hydroclimatic persistence on these time scales introduces significant nonstationarity in mean annual streamflow, with critical implications for UCRB water resource management.

(KEY TERMS: Colorado River; Atlantic Multidecadal Oscillation; decadal variability.)

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INTRODUCTION

The Upper Colorado River Basin (UCRB), defined as that part of the basin that is upstream from the gage at Lees Ferry, Arizona (Figure 1), generates approximately 90% of total Colorado River Basin streamflow, and through the Colorado River Compact, supplies water and hydropower for much of the southwestern United States. In particular, the two main reservoirs in the Colorado River Basin, Lake Powell and Lake Mead, represent approximately 85% of the storage capacity of the entire Colorado River Basin. UCRB streamflow is allocated and regulated on the assumption that the mean and higher moments of the statistical distribution of annual and decadal inflow to Lake Powell and Lake Mead do not change significantly over time (the stationarity assumption).

The stationarity assumption is not inconsequential. Most of the policies that govern current UCRB

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[2]Respectively, Physical Scientist, U.S. Geological Survey, Denver Federal Center, MS 412, Denver, Colorado 80225; Research Hydrologist, U.S. Geological Survey, Tucson, Arizona; and Assistant Project Scientist, Scripps Institution of Oceanography, La Jolla, California (E-mail/McCabe: gmccabe@usgs.gov).

water allocations were written based on hydrologic information from an initial period of abnormally high flows (1905-21) that was too brief to characterize low-frequency streamflow variability. In effect, the Colorado River Compact assumes that the annual streamflow series exhibits stationarity through time. Specifically, Article III of the Compact apportions 7.5 million acre feet (MAF) per year each to the Upper and Lower Basins, stipulates that UCRB States cannot deplete the flow at Lees Ferry to less than 75 MAF over a period of 10 consecutive years, and mandates a moving 10-year average release of 8.23 MAF/year from Lake Powell into the Lower Basin (Christensen *et al.*, 2004).

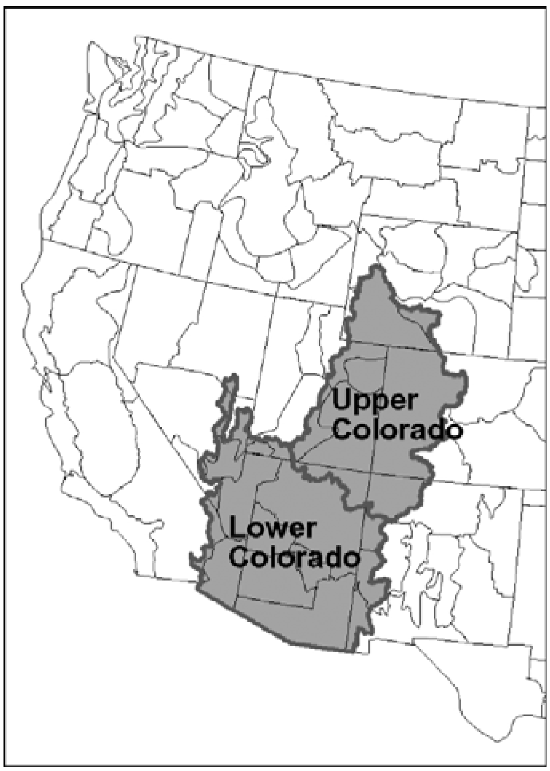

FIGURE 1. Climate Divisions in the Western United States and Outlines of the Upper and Lower Colorado River Basins.

For the UCRB, assumptions of stationarity can be challenged on at least two premises: (1) hydroclimatic analysis indicates considerable nonstationarity in measured and reconstructed precipitation and streamflow estimates for the basin that may be linked to decadal, multidecadal and even secular variations in ocean temperatures (Redmond and Koch, 1991; Cook *et al.*, 2004; Gray *et al.*, 2004a; Hidalgo, 2004; McCabe *et al.*, 2004) and (2) tree-ring reconstructions indicate that the period of measured or estimated streamflow (1906-2003) was unusually wet for the last century (Stockton and Jacoby, 1976; Meko *et al.*, 1995; Hidalgo *et al.*, 2000; Gray *et al.*, 2004a; Woodhouse *et al.*, 2006) and may underestimate the risk of sustained low flows. This risk was highlighted recently by five consecutive years of drought and low inflow that had left Lake Powell at 36% of usable capacity by January 1, 2005, the lowest it has been since 1969 when the reservoir was initially infilling (Fulp, 2005). The degree of nonstationarity in the streamflow time series affects probabilities that future levels in Lake Powell could drop below the reservoir's power pool or to the dead pool in the event that the drought continues for two or three more years. Nonstationarity of streamflows will likewise modulate the probability that a return to wetter conditions alone can restore Lake Powell to full storage capacity.

Climate change also may play a role in the likelihood of future drought in the UCRB. Recent climate model simulations routed through a water management model suggest 30-40% reductions in future (after 2010) total Colorado River Basin storage, mostly due to increasing temperatures associated with increasing greenhouse gases in the atmosphere due to human activities (Christensen *et al.*, 2004). In part, this reflects the sensitivity of cycles of snow accumulation and melt to warming, but the impacts of climate change and drought in general also are aggravated in a system in which water demands match or exceed the total available water supply (Harding *et al.*, 1995; Christensen *et al.*, 2004; Piechota *et al.*, 2004). Prospects could be even dimmer if the effects of increasing temperatures are combined with severe and sustained droughts such as those identified in the tree-ring record of the UCRB (Stockton and Jacoby, 1976; Meko *et al.*, 1995; Gray *et al.*, 2004a). Clearly, there is a need to understand sources of decadal to multidecadal (D2M) hydroclimatic variability in the UCRB to improve water resource planning over the long term.

Hydroclimatic variations in the western United States (particularly at D2M time scales) are related to variability in oceanic and atmospheric conditions, normally indexed using sea-surface temperature (SST) or related atmospheric pressure anomalies (Redmond and Koch, 1991; Enfield *et al.*, 2001; Hoerling and Kumar, 2003; Hidalgo, 2004). Many previous studies have shown the influence of the tropical Pacific Ocean on hydroclimatic variability of the United States, including the occurrence of persistent dry and wet periods (Redmond and Koch, 1991; Hoerling and Kumar, 2003; Schubert *et al.*, 2004; Seager *et al.*, 2005). In addition, other studies have shown that SST variability of the North Atlantic Ocean also has significant effects on the hydroclimate of the United States (Enfield *et al.*, 2001; Gray *et al.*, 2003; Rogers and Coleman, 2003; Sutton and Hodson, 2003, 2005; Hidalgo, 2004; McCabe *et al.*, 2004; Schubert *et al.*, 2004; Shabbar and Skinner, 2004). For example, Enfield *et al.* (2001) reported a significant negative correlation between D2M variability of SSTs in the North Atlantic Ocean and precipitation in the United States, as well as flow of the Mississippi River. When North Atlantic SSTs are warmer than average, precipitation over much of the conterminous United States is below average and temperature is generally above average, resulting in an increase in the probability of drought for much of the conterminous United States (Enfield *et al.*, 2001; Hidalgo, 2004; McCabe *et al.*, 2004; Sutton and Hodson, 2005).

An understanding of the links between SST variations and variability of the hydroclimate of the United States may be useful in modifying the probabilities of drought risk by conditioning them on D2M SST variability (Enfield and Cid-Serrano, 2006). Depending on the regularity of these SST processes, opportunities may exist to anticipate the prevalence of multidecadal epochs of higher or lower drought risk. The objective of this study was to identify the relations between D2M variability in SSTs and D2M variability in flow of the UCRB, and to identify SST indices that may be useful to describe these relations.

DATA AND METHODS

Water-year (October through September) flow values of the UCRB for the period 1906-2003 were obtained from the U.S. Bureau of Reclamation (Tom Ryan, personal communication, 2004). Values prior to 1923, when the stream gage was installed at Lees Ferry, are extrapolated from records at downstream gages. Values since 1923 reflect the record of streamflow observations at Lees Ferry and have been adjusted for consumptive water use in the basin and represent, as near as possible, natural flow of the UCRB. A brief discussion of the accuracy of this streamflow record can be found in Hidalgo and Dracup (2003).

Annualized water-year streamflow in the UCRB is derived primarily from snowmelt in the central Rocky Mountains of Wyoming, Colorado, Utah, and accordingly runoff is generally highest during the months of April through July. Flows were high during the early part of the 20th century and were below the long-term average during the 1930s, 1950s, late 1970s, and early 21st century (Figure 2a). A linear regression of UCRB flow with time indicates a long-term decreasing trend (correlation with time is −0.22). Both the correlation coefficient with time and the regression coefficient are statistically significant at a 95% confidence level. Although the trend is statistically significant, it only accounts for approximately 4% of the variance in UCRB flow and probably has little physical significance. By detrending and smoothing the data with an 11-year moving average, much of the interannual variability can be removed from the time series (Figure 2b), thus providing a time series that illustrates the D2M variability in the flow data. The D2M variability of the UCRB is important because it reflects periods with tendencies for above-average and below-average flow conditions. This temporal scale of variability has significant control on the likelihood of dry and wet conditions in the UCRB (McCabe *et al.*, 2004).

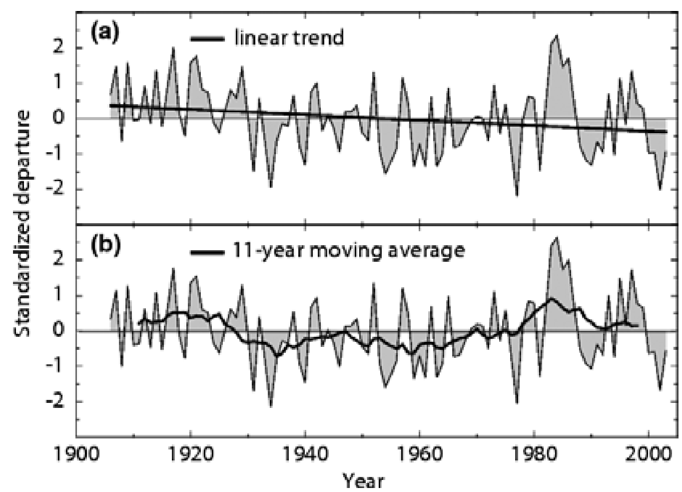

FIGURE 2. (a) Standardized Departures of Upper Colorado River Basin Water-Year Streamflow, With the Long-Term Linear Trend Indicated and (b) Detrended Standardized Departures of Upper Colorado River Basin Water-Year Streamflow, With an 11-Year Moving Average.

Sea-surface temperature data for the analyses were obtained from the Kaplan *et al.* (1998) extended SST data. Monthly SST data were used to compute mean water-year SSTs for the 1906-2003 period. Indices of standard SST variability also were used [i.e., the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), and Indian Ocean SSTs]. The PDO is an index of decadal-scale SST variability in the North Pacific Ocean (Mantua *et al.*, 1997) and has important effects on the hydroclimate of the western United States (Mantua *et al.*, 1997; Gershunov and Barnett, 1998; McCabe and Dettinger, 1999, 2002; Hidalgo and Dracup, 2003). A time series of the monthly PDO was obtained from the University of Washington (2005). The AMO (Enfield *et al.*, 2001) is an index of SST anomalies averaged over the North Atlantic Ocean and has been identified as an important mode of D2M climate variability that, like the PDO, has significant effects on the climate of the United States (Enfield *et al.*, 2001; Gray *et al.*, 2003; Rogers and Coleman, 2003; McCabe *et al.*, 2004; Sutton and Hodson, 2005). A time series of the monthly AMO from 1856 through 1999 was obtained from David Enfield (NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida). The AMO time series was extended through 2003 by using averaged monthly SSTs for the North Atlantic Ocean (for the region 0°N to 60°N latitude and from 60°W to 10°W longitude). These SSTs were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCAR/NCEP, Kalnay *et al.*, 1996) reanalysis dataset (NOAA-CIRES Climate Diagnostics Center, 2005a,b).

In addition to the PDO and AMO time series, a time series of Indian Ocean SSTs was computed by averaging SSTs from the Kaplan dataset (Kaplan *et al.*, 1998) for the region 30°S to 10°N latitude and from 50°E to 100°E longitude. The monthly time series of the PDO, AMO, and Indian Ocean SSTs were used to compute water-year time series of each of these SST indices.

A number of analyses were performed to identify relations between UCRB flow and SSTs. First, the gridded SST time series and the SST index time series (i.e., PDO, AMO, and Indian Ocean SSTs) were detrended and smoothed with an 11-year moving average to match the river flow records. Mean SST anomaly maps comparing conditions during high- and low-flow periods in the UCRB were then created. Another analysis involved subjecting the gridded SST data to a principal components analysis (PCA) to extract the primary modes of D2M SST variability (Johnston, 1980). The resulting components were then analyzed and compared with the UCRB flow time series.

Because the data were smoothed, there are large lag-1 correlations inherent in the time series and too few degrees of freedom for traditional statistical significance tests. Instead, Monte Carlo analyses were used to estimate the statistical significance of all correlations presented in this study (Noreen, 1989; McCabe *et al.*, 2004). The Monte Carlo analyses were used to generate 1,000 time series of each variable. The generated time series preserved the mean, variance, skew, and lag-1 correlations of the D2M time series. Correlations between sets of the 1,000 simulations were computed, and subsequently percentiles of the distribution of the correlations were computed and used to estimate the statistical significance of the correlations between the D2M data time series.

In addition to the SST and climate index data, monthly temperature and precipitation data for the 344 climate divisions in the United States also were examined (Figure 1). The climate division temperature and precipitation data were obtained from the National Climatic Data Center (2005). The climate division temperature and precipitation data also were annualized to water-year values and subsequently detrended and smoothed.

RESULTS AND DISCUSSION

From the 11-year smoothed time series of UCRB flow (Figure 2b), two extended wet (1914-24 and 1978-88) and two extended dry (1930-40 and 1954-64) periods were identified. Composite water-year SST anomalies for the two wet periods and two dry periods reveal strong relations between SSTs and UCRB flow. For the two wet periods (Figure 3a), the SST

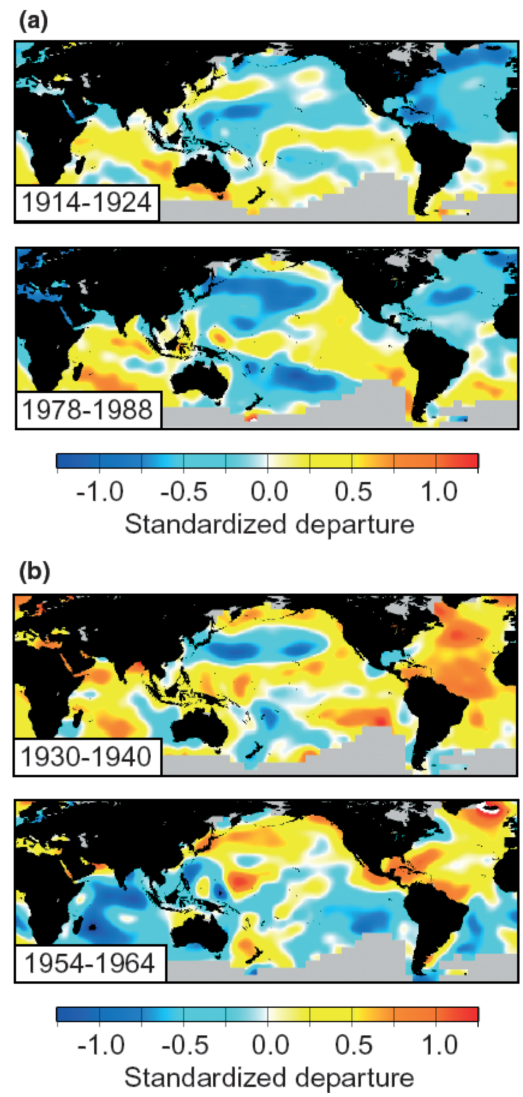

FIGURE 3. Mean Standardized Sea-Surface Temperature Anomalies for (a) Periods of High Water-Year Streamflow in the Upper Colorado River Basin and (b) Periods of Low Water-Year Streamflow.

anomalies are positive in the Indian Ocean and negative in the North Atlantic Oceans. In addition, SSTs in the eastern tropical Pacific Ocean are mostly positive for both wet periods, and in the central North Pacific Ocean the SST anomalies are mostly negative. The SSTs in the Pacific Ocean for 1978-88 reflect the increased frequency of EI Nino/Southern Oscillation (ENSO) and the disproportionate influence of the strong 1982-83 event during this period. However, the patterns of SST anomalies in the Pacific Ocean are not as consistent for the two wet periods as are the SSTs in the Indian and North Atlantic Oceans.

For the two dry periods, there are large differences in the pattern of D2M SST anomalies in the Pacific and Indian Oceans (Figure 3b). In the North Atlantic Ocean, however, the SST anomalies are positive for both dry periods. In addition, the North Atlantic SSTs for the dry periods are of an opposite sign than of those for the wet periods. Overall, these results suggest that SSTs in all of the oceans have some relation with flow of the UCRB, but the North Atlantic indicates the most consistent associations on D2M time scales.

Note that the period from 1930 to 1940 (Figure 3b) includes one of the most severe U.S. droughts as recorded by instrumental records (known as the Dust Bowl). The Dust Bowl has been associated with sustained cooler than normal conditions in the eastern tropical Pacific Ocean (Schubert *et al.*, 2004). In contrast, Figure 3b indicates positive SST anomalies in the eastern tropical Pacific Ocean for the 1930-40 period. The period from 1932 to 1938, which corresponds to the central years of the Dust Bowl, was characterized by weak negative SST anomalies. However, 1930, 1931, and particularly 1940 were associated with warm eastern tropical Pacific events that produce the positive anomalies shown in Figure 3b.

The relations between SSTs and river flows observed here raise the question of whether regional variations in SSTs are independently associated with the UCRB, or if there is a large amount of covariability among these SST regions. To answer this question, a PCA was performed on the SST data to determine the primary modes of SST variability. The PCA (with varimax rotation) of the D2M water-year SST data resulted in two components that explain 56% of the variability in the D2M SST data (Figure 4). Before rotation, the first component explains 30.3% of the variance in the D2M SST data, and the second rotated principal component (RPC2) explains 25.9% of the variance. After varimax rotation, the two RPCs explain 28.6% and 27.6% of the variance, respectively. In addition, after rotation, the mutual correlation between the score time series of the two RPCs is small (−0.14), and statistically nonsignificant.

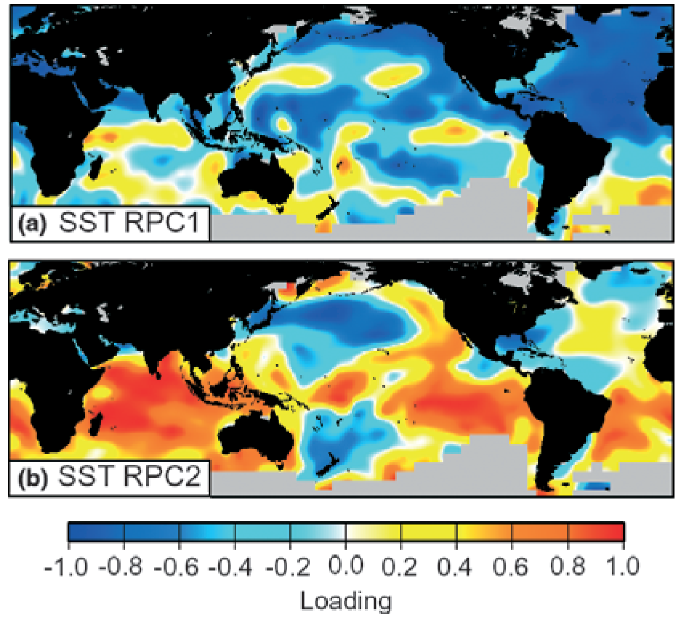

FIGURE 4. Loadings of the First Two Components From a Principal Components Analysis (With Varimax Rotation) of Detrended 11-Year Smoothed Water-Year Global Sea-Surface Temperatures, 1906-2003.

The loadings of D2M SST time series on each of the components (Figure 4a,b) indicate that RPC1 primarily reflects SST variability in the North Atlantic Ocean and scattered parts of the North Pacific Ocean, and the loadings for RPC2 reflect D2M SST variability in the central North and South Pacific Oceans, the eastern tropical Pacific Ocean, and the Indian Ocean. Correlations between the score time series of RPC1 and RPC2 and climate indices representing regional SSTs (i.e., the PDO, the AMO, and Indian Ocean SSTs) indicate that RPC1 is significantly correlated with the AMO, whereas RPC2 is strongly correlated with PDO and Indian Ocean SSTs (Table 1).

TABLE 1. Correlations Between Detrended and 11-Year Smoothed Sea-Surface Temperature (SST) Indices (i.e., the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), and Indian Ocean SSTs) and the First Two Components (PC1 and PC2) Resulting From a Principal Components Analysis (With Varimax Rotation) of Detrended and 11-Year Smoothed Water-Year SSTs, 1906-2003.

	PC1	PC2
PDO	−0.15	0.98*
AMO	−0.95*	−0.10
Indian Ocean SSTs	−0.04	0.96*

*Correlations that are significant at a 95% confidence level.

Because of the strong correlations between the RPCs and the regional SST indices (Table 1), the regional SST indices were used to further examine relations between SSTs and flow of the UCRB. The AMO was used to represent RPC1, and the PDO was used to represent RPC2. These indices were chosen because they are highly correlated with the SST RPCs and have been identified as important D2M SST indices in previous studies (Enfield *et al.*, 2001; Gray *et al.*, 2003; Hidalgo, 2004; McCabe *et al.*, 2004). Just as RPC1 and RPC2 are uncorrelated, the correlation between detrended and 11-year smoothed AMO and PDO is only −0.07 and is statistically nonsignificant.

The results indicate that low UCRB flow generally occurs when the AMO is positive and high flows generally occur when the AMO is negative, whereas the relation between UCRB flow and the PDO does not appear to be as strong as is the correlation between UCRB flow and the AMO (Figure 5). The correlation between UCRB flow and the AMO is −0.74 (significant at a 95% confidence level), whereas the correlation between UCRB flow and the PDO is only 0.40 (nonsignificant correlation, see also Hidalgo and Dracup, 2003). There appears to be a tendency for UCRB flow to be high when AMO is negative and PDO is positive, whereas UCRB flow is generally low when AMO is positive, regardless of PDO conditions.

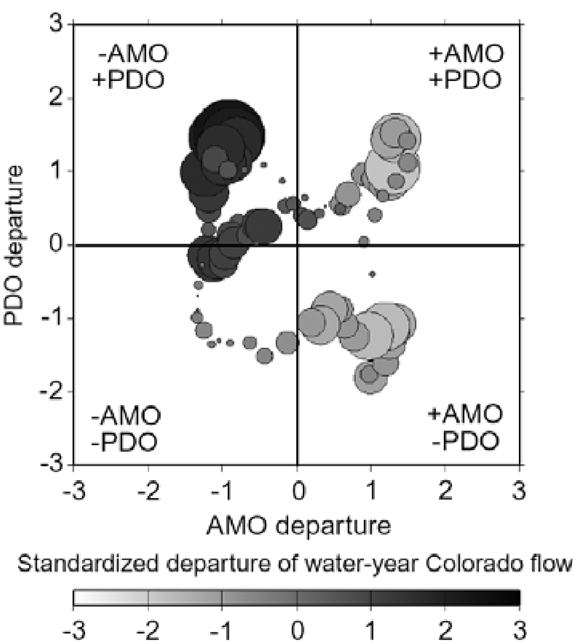

FIGURE 5. Standardized Departures of Detrended 11-Year Smoothed Water-Year Flow of the Upper Colorado River Basin Plotted for Standardized Departures of Detrended 11-Year Smoothed Water-Year Values of the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation, 1906-2003.

The UCRB is located in a region in which the modulation of winter precipitation by the PDO is not as consistent as in regions such as the Pacific Northwest (Hidalgo and Dracup, 2003). As seen in Figure 5, a positive PDO alone does not consistently produce greater UCRB streamflows but must be accompanied by negative AMO. This suggests the possibility that there are consequences to D2M variability in the AMO, or to some closely associated phenomena that modulates upper-air circulation on similar time scales (e.g., the first annual mode of the Arctic Oscillation). Therefore, the possibility that low-frequency processes from the Pacific and the Atlantic Oceans could be related to each other through modulations in other hemispheric climate mechanisms is not discarded (Delworth and Mann, 2000; Sutton and Hodson, 2003).

A comparison of cumulative standardized departures of the D2M AMO, PDO, and UCRB flow more clearly illustrates the relation between SSTs and UCRB flow at low frequencies (Figure 6). Correlation between the cumulative departures of UCRB flow and AMO was −0.89 (significant at a 95% confidence level). Although not significant at the 95% confidence level, UCRB flow and PDO showed a correlation of 0.65.

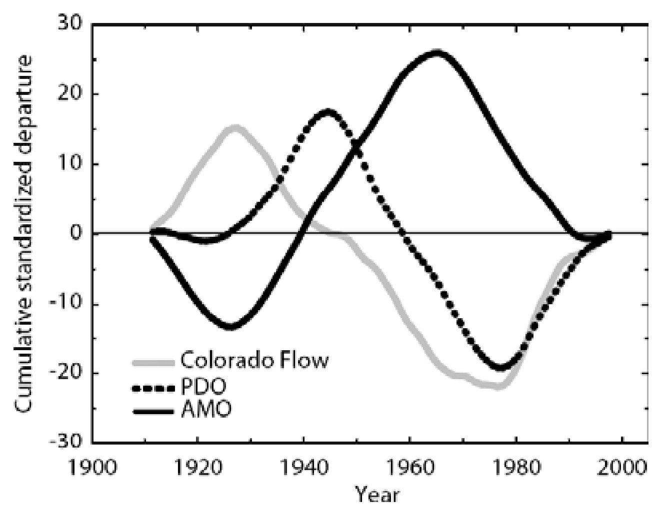

FIGURE 6. Time Series of Cumulative Standardized Departures of 11-Year Smoothed Water-Year Flow of the Upper Colorado River Basin, the Atlantic Multidecadal Oscillation, and the Pacific Decadal Oscillation, 1906-2003.

Correlations between detrended and 11-year smoothed AMO and detrended and 11-year smoothed precipitation and temperature are consistent with the correlations between AMO and UCRB flow (Figure 7). These correlations indicate that, when AMO is positive, precipitation is generally below average for a large part of the United States, and temperatures are generally above average (Figure 7). The combined effect of decreased precipitation and increased temperature over the western United States during positive AMO conditions results in decreased flow of the UCRB.

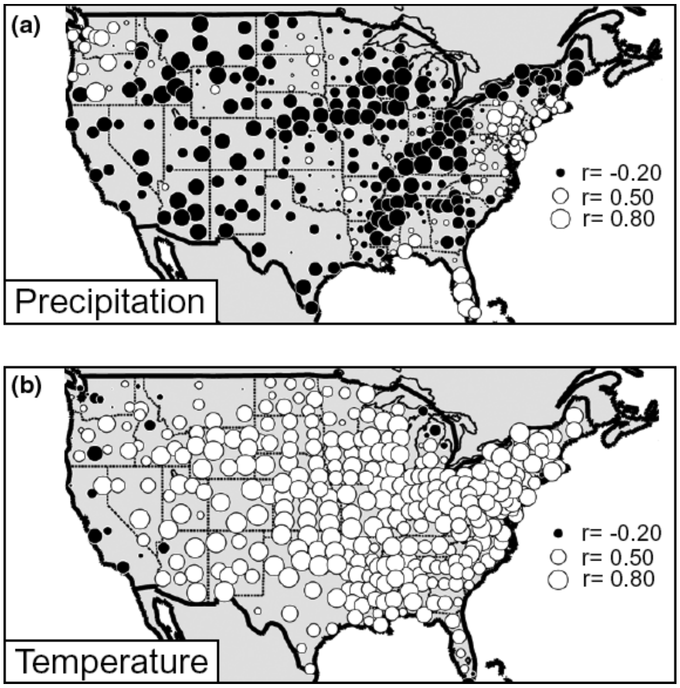

FIGURE 7. Correlations Between Detrended 11-Year Smoothed Water-Year Atlantic Multidecadal Oscillation and Detrended 11-Year Smoothed Water-Year (a) Precipitation and (b) Temperature for the 344 Climate Divisions in the Conterminous United States, 1906-2003. White circles indicate positive correlations and black circles indicate negative correlations. The size of the circle indicates the relative magnitude of the correlation.

CONCLUSIONS

Detrended and smoothed time series of water-year flow measured on the UCRB were examined to identify effects of D2M variability in SSTs on flow in this basin. Results indicate that D2M variability of SSTs in the North Atlantic, North Pacific, tropical Pacific, and Indian Oceans has an effect on the D2M variability of the UCRB. SST anomalies from the Pacific, Indian, and North Atlantic Oceans are teleconnected with flow anomalies from the UCRB, but the North Atlantic indicates the most consistent association on D2M time scales. Positive SST anomalies in the North Atlantic generally result in long periods of decreased mean flow in the UCRB and vice versa.

A rotated PCA of detrended and smoothed global water-year SSTs indicates that two leading RPCs explain 56% of the D2M variability in the SST data. The first RPC is strongly correlated with the AMO and the second RPC is strongly correlated with both the PDO and Indian Ocean SSTs. Although SST information from the Pacific Ocean is often used for hydroclimatic studies and forecasts for the United States (Redmond and Koch, 1991; McCabe and Dettinger, 1999; Hoerling and Kumar, 2003), the results of this study suggest that there is also important information in the Atlantic Ocean that can be used to improve our understanding of the sources of D2M variability in UCRB flow. North Atlantic SSTs provide information to (1) better characterize the probabilities of above-average and below-average flow and (2) revisit risky assumptions about stationarity of hydrologic variability in water resource management and planning in the UCRB.

The relations presented in this study are statistical in nature and the physical mechanisms that drive these relations are not fully understood at this time. Because instrumental records are too short to perform comprehensive analyses of multidecadal variability of ocean temperatures and regional precipitation, modeling studies are likely the most readily available approach to understand the physics underlying the statistical relations. A promising approach entails atmospheric general circulation model simulations that use historical SST data for the global ocean as a lower boundary condition. These models can simulate low-frequency variations in precipitation over land and, working in iterative fashion, can be used to isolate the influence of specific ocean sectors and explore mechanisms underlying important teleconnections. Model experiments in which tropical SSTs are specified are more suitable than those with specified extratropical SSTs because the latter can interfere with the atmosphere-ocean interactions in the models (Bretherton and Battisti, 2000).

Examples of such modeling studies relevant to the UCRB include successful attempts to model low-frequency precipitation variability in the Great Plains by Schubert *et al.* (2004) using the NASA Seasonal to Interannual Prediction Project (NSIPP) model, in the Great Plains by Seager *et al.* (2005) using National Center for Atmospheric Research (NCAR) Community Climate Model 3 (CCM3), and for European and North American summers by Sutton and Hodson (2005) using the Hadley Centre Atmospheric Model Version 3 (HadAM3). In modeling the Dust Bowl and other droughts, Schubert *et al.* (2004) found the forcing to come primarily from tropical SSTs, with Atlantic tropical SSTs that were slightly (a few tenths of a degree Celsius) warmer than usual, and tropical Pacific SSTs that were slightly cooler than average. Seager *et al.* (2005) found that persistent droughts and pluvials in both the Great Plains and the Southwest were ultimately forced by persistent variations in the tropical Pacific, but these moisture anomalies become amplified with incorporation of SST anomalies in other oceans. In both the Schubert *et al.* (2004) and Seager *et al.* (2005) studies, summer moisture deficits in the Great Plains and western United States were forced partly by the land memory effects of drought in the previous winter. By contrast, Sutton and Hodson (2005) were able to simulate low-frequency, summer precipitation variability in the Great Plains by driving HadAM3 with just the time history of North Atlantic SSTs (i.e., the AMO).

These model results leave open to question what physical role, if any, the AMO plays in D2M variability of UCRB streamflow, which is derived predominantly from snow accumulation in winter when the UCRB is downwind from the Pacific and upwind of the Atlantic. There are several possible explanations: (1) The relation of UCRB streamflow to the AMO is the product of low-frequency atmospheric bridging between the North Atlantic and North Pacific by way of the Arctic Oscillation, which can affect the location and persistence of winter storm tracks (focused over the UCRB during the cold AMO phase) (Enfield *et al.*, 2001). (2) The AMO can impact upper-air circulation over the UCRB in the late spring/early summer (April-June) with blocking of Pacific storms during the warm AMO phase. These late spring frontal storms are an important component of UCRB streamflow. During the AMO warm phase, the normal (long-term average) winter ridge-trough pattern across the northern United States is flattened (weaker ridge in the west, shallower trough in the east) with the opposite (weaker ridge in the east, shallower trough in the west) occurring across the southern United States (Enfield *et al.*, 2001). (3) The statistical association between the AMO and UCRB streamflow is happenstance and limited to the last 100 years.

A full evaluation of these hypotheses is beyond the scope of this article, but perhaps a few observations are in order. First, as demonstrated in a 1,400-year simulation using HadCM3, the AMO does appear to be a genuine quasi-periodic cycle of internal climate variability related to the oceanic thermohaline circulation (Knight *et al.*, 2005). As such, the AMO may be suitable for both long-term reconstruction (Mann *et al.* 1995; Delworth and Mann, 2000; Gray *et al.*, 2004b) and possibly prediction (e.g., Griffies and Bryan, 1997; Collins and Sinha, 2003). We note that, in light of this finding, coherent changes appear to occur between the northern high latitudes and the tropical Pacific and Atlantic on a variety of time scales, from decadal to glacial-interglacial (e.g., Peterson *et al.*, 2000). Such teleconnections, involving extratropical forcing of north-south displacements in the Atlantic Inter-tropical Convergence Zone in the boreal spring and possible feedback responses in ENSO, are currently being explored in model simulations (Chiang and Vimont, 2004).

In a reconstruction of AMO variability over the past 500 years using select tree-ring chronologies from Europe, the Middle East, and the eastern United States, Gray *et al.* (2004b) show that positive and negative phases of the AMO last an average of 23 years, with durations ranging from 9 to 53 years. The Gray *et al.* (2004b) reconstruction also identifies a rare interlude of subdued AMO variability in the 18th century. If the statistical association we identify between AMO and UCRB streamflow is stable, subdued AMO variability should both dampen and shorten the time scale of streamflow variability.

Second, in a PCA of gridded tree-ring reconstructions of the Palmer Drought Severity Index (PDSI) for the western United States since 1536, Hidalgo (2004) identified spatial patterns of persistent droughts and pluvials in the western United States that were very similar to the loadings attributed to the PDO and AMO in a PCA of 20-year drought frequencies using the instrumental precipitation record (McCabe *et al.*, 2004). In loadings related to the PDO (31% of the variance explained), the anomalies were strongly antiphased between the Pacific Northwest and the Southwest/Great Basin/Intermountain Region. In loadings related to the AMO (24%), the strongest anomalies are focused over the Rockies and Great Plains. A third PC related to low-frequency ENSO variability (19%) juxtaposes opposite anomalies in the Southwest and the Great Basin/Intermountain Region/Pacific Northwest.

Third, Hidalgo (2004) also found that western U.S. PDSI variability is strongly multidecadal (32-64 yrs) except from 1700 to 1825, when it is strongly bidecadal (8-23 years). We note that the 18th century is a period when the AMO is subdued, climate variability is strongly bidecadal across the western United States, wet and dry anomalies are juxtaposed in the northwest/southwest, and precipitation anomalies may have canceled one another in the upper (more northwest-like) and lower (more southwest-like) parts of the UCRB. Accordingly, variability in all UCRB streamflow reconstructions (Stockton and Jacoby, 1976; Hidalgo *et al.*, 2000; Woodhouse *et al.*, 2006) is noticeably dampened in the 18th century.

Finally, we think that there are too many coincidences in both measured and reconstructed streamflow time series, and too much at stake in Colorado River water management, to discount a possible role for the AMO. We note that the most recent shift to a positive AMO phase occurred about November 1994, and that in the Gray *et al.* (2004b) reconstruction, AMO warm phases generally last more than a decade. Despite the moderate El Niño and wet conditions in the winter of 2004-05, anomalously warm surface waters throughout the North Atlantic, should they persist, could heighten the probability for continued low flows in the UCRB. Those interested in the management of water resources in the western United States should stay posted.

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