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Dendrochronology and links to streamflow

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SUMMARY

Streamflow variability on timescales of decades to centuries becomes increasingly important as water managers grapple with shortages imposed by increasing demand and limited supply, and possibly exacerbated by climate change. Two applications of dendrochronology to the study of flow variability are illustrated for an existing 1244-yr reconstruction of annual flows of the Colorado River at Lees Ferry, Arizona, USA: (1) identification and climatological interpretation of rare flow events, and (2) assessment of vulnerability of water-supply systems to climatic variability. Analysis centers on a sustained drought of the mid-1100s characterized by persistent low flows on both the Colorado and Sacramento Rivers. Analysis of geopotential height anomalies during modern joint-droughts suggests more than one mode of circulation might accompany joint-drought in the two basins. Monte Carlo simulation is used to demonstrate that a drought as severe as that in the 1100s on the Colorado River might be expected about once in every 4–6 centuries by chance alone given the time-series properties of the modern gaged flows. Application of a river-management model suggests a mid-1100s-style drought, were it to occur today, would drop reservoir levels in Lake Mead to dead-pool within a few decades. Uncertainty presents challenges to accurately quantifying severe sustained droughts from streamflow reconstructions, especially early in the tree-ring record. Corroboration by multiple proxy records is essential. Future improvements are likely to require a combination of methodological advancements and expanded basic data.

1. Introduction

Dendrochronology is linked to streamflow through the common responses of tree-growth and streamflow to variations in net precipitation and runoff (Stockton and Jacoby, 1976). The statistical relationship between time series of tree-ring indices and streamflow has been exploited for multi-century reconstructions of flow for river basins in many parts of the world (e.g., Akkemik et al., 2004; Gou et al., 2007; D'Arrigo et al., 2009; Liu et al., 2010). The methodology and applications of streamflow reconstruction from tree rings have been reviewed by Loaiciga et al. (1993) and Meko and Woodhouse (2011).

Nowhere has the attention to streamflow reconstruction been more focused than in the Colorado River basin, a key source of water supply for some 30 million people in the western United States. Climate change and variability are critical issues in this basin. Mean annual flows of the Colorado River are over-allocated by the 1922 Colorado River Compact governing the distribution of water (MacDonnell et al., 1995); demand is expected to continue increasing (National Research Council, 2007); climate-change projections envision imminent drying over the next century (Seager et al., 2007b); and Lake Mead, a major reservoir, is at its lowest level since it began filling in the 1930s (Barringer, 2010). Projected climate change is expected to result in substantial decreases in runoff and further drops in reservoir levels by the end of the 21st century (e.g., Christensen and Lettenmaier, 2006; McCabe and Wolock, 2007; Barnett and Pierce, 2008; Rajagopalan et al., 2009).

The history of Colorado River water woes is closely linked to the development of the science of dendrohydrology in the United States. Schulman (1945) established the physical rationale for reconstruction in assessing water-supply variability of the Colorado for Los Angeles Power and Light. Stockton and Jacoby (1976) first applied modern multivariate statistical methods to reconstruction in extending the Colorado River flows at Lees Ferry, Arizona to A.D. 1520. Subsequent tree-ring studies of reconstructed flow on the Colorado have aimed at improvement of accuracy, temporal extension, climatological interpretation and water-management applications. Approaches to increasing the accuracy have included varying the makeup of the tree-ring network and exploring new methods of statistical reconstruction modeling (e.g., Michaelsen et al., 1990; Hidalgo et al., 2000; Woodhouse et al., 2006; Gangopadhyah et al., 2009). Climatological interpretation has been directed toward examination of ocean-atmosphere drivers of reconstructed flow variations (e.g., Woodhouse et al.,

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2006, 2010). Water managers have long referred to reconstructions as precautionary evidence of extended droughts on the Colorado, but have only recently explored direct use of reconstructions as input to river-management models (Prairie et al., 2008).

In this paper we analyze the longest existing reconstruction for the Colorado River (Meko et al., 2007) to investigate ways the extended flow record can provide additional information on current and future droughts. We frame the analysis around a particular paleo-drought, a multi-decadal period of recurrent low flows in the mid-1100s (Meko et al., 2007). This low-flow period occurred during a medieval period (A.D. 800–1400) characterized by unusually persistent droughts in western North America and large hydroclimatic anomalies in other parts of the globe (Seager et al., 2007a). The ongoing drought, now entering its second decade (Woodhouse et al., 2010) could represent a return to an amplified low-frequency mode of hydroclimatic variability. Here we explore various aspects of the persistent low-flow period in the mid-1100s on the Colorado River: spatial extent and climatology, water-supply implications, and likelihood of recurrence. We also discuss challenges to interpretation cast by uncertainty. Novel aspects of this paper include a simulation-based approach to a probabilistic context of an exceptional persistent paleo-drought, and application of a long-term river planning model to explore potential impacts on management were such a drought to occur in the future.

2. Data

Tree-ring data points and basins are shown on the map in Fig. 1. Reconstructions analyzed include A.D. 762–2005 annual (water-year) flows of the Colorado River at Lees Ferry Arizona (Meko et al., 2007) and A.D. 869–1977 annual flows of the Sacramento River (Meko et al., 2001); both reconstructed time series were downloaded from the International Tree-Ring Data Bank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html). To illustrate aspects of uncertainly in the Colorado River reconstruction, use is also made of calibration-period (post-1905) segments of sub-period, or time-nested, reconstruction models described in Meko et al. (2007). These time series, not available from the ITRDB, were obtained from the files of the main author.

Historical time series of natural flows (flows adjusted for depletions and reservoir storage) for years 1906–2009 were obtained for the Colorado and Sacramento Rivers in the western United States. Flows summed over the water-year for the Colorado River at Lees Ferry, Arizona, were downloaded from the US Bureau of Reclamation (http://www.usbr.gov/lc/region/g4000/NaturalFlow/). Flows for the Sacramento River were downloaded from the California Department of Water Resources (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST).[1] All observed and reconstructed natural-flow series used in this paper are included in the Supplemental Materials. Gridded reconstructed summer (JJA) Palmer Drought Severity Index (PDSI) for North America for the past 2000 yr were obtained from Cook et al. (2010).

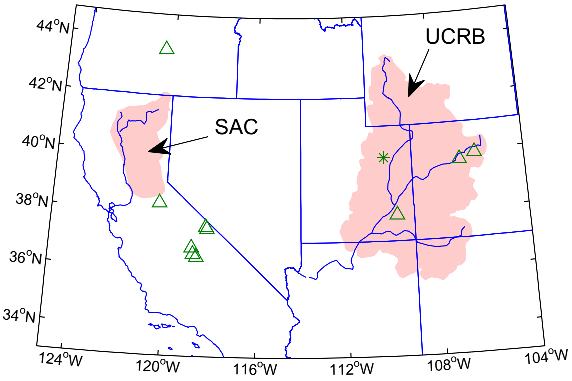

Fig. 1. Map of river basins and tree-ring sites. Sites plotted are Harmon Canyon (∗) and early-1100s tree-ring networks (△) for reconstructions of flow in Upper Colorado River Basin (UCRB) (Meko et al., 2007) and Sacramento River Basin (SAC) (Meko et al., 2001).

Unless otherwise noted, flow units on plots are either km^3 or percentage of "normal", defined here as the 1906–2005 observed mean. Some results are also presented parenthetically in million acre-feet (maf) for the benefit of water managers. Normal flow for the Colorado River at Lees Ferry is 18.6km^3, or 15.1 maf; and for the Sacramento River is 22.4km^3, or 18.0 maf.

3. Methods

Low-frequency time series variations were summarized by a 25-yr running mean and by Gaussian filtering. The Gaussian filter is a symmetric, bell-shaped filter with positive weights that sum to 1. We used guidelines in Mitchell et al. (1966) to design a Gaussian filter with approximately the same wavelength of 50% frequency-response (Panofsky and Brier, 1968) as the 25-yr running mean. This is a 33-weight Gaussian filter, which when used for smoothing weights 33 successive years of a time series with highest weight on the central year of the filtered segment; the filter-weights are listed in the Supplemental Material.

Covariation of pairs of time series was summarized by correlation analysis and spectral analysis. Correlation coefficients were tested for significance (Haan, 2002) after adjusting sample-size for effect of autocorrelation (Dawdy and Matalas, 1964). Covariation as a function of frequency was summarized with cross-spectral analysis using the smoothed periodogram as a spectral estimator (Bloomfield, 2000). Steps in spectral estimation were (1) removal of mean, (2) tapering of 5% of each end of the series, (3) padding with zeros to a length the first power of 2 larger than the original series length, (4) raw-periodogram computation by the fast Fourier transform, and (5) smoothing of periodogram with a set of Daniell filters (Bloomfield, 2000) to get a spectrum of desired smoothness and bandwidth. Cross-periodograms and related quantities — squared coherency and phase — were similarly computed using procedures described in detail by Bloomfield (2000) and implemented previously in a tree-ring study by Meko and Woodhouse (2005).

Synthetic time series of observed flow were generated by exact simulation (Percival and Constantine, 2006), using the circulant embedding method of Dietrich and Newsam (1997), to explore how anomalous the most extreme drought of the tree-ring record is given the time-series properties of flow in the gaged record. Exact simulation preserves the spectral properties of the observed series and has the advantage of not requiring an assumption of a parametric generating mechanism (e.g., autoregressive process). Our non-parametric spectral estimator was the raw periodogram, computed as described in the preceding paragraph, except that for the selected circulant-embedding method zero-padding to the next-highest power of 2 larger than four times the original series length was required to supply simulations of the desired length. As normality is an assumption in the exact simulation method of Percival and Constantine (2006), a Lilliefors test (Conover, 1980) was applied to check that time series used to develop simulations are approximately normal. To check sensitivity of probabilities to simulation method we repeated the simulation analysis with synthetic flows generated by a first-order autoregressive (AR(1)), or Markov, process (Haan, 2002). For AR(1) modeling, the model is

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[1] This series is referred to online as "Sacramento Valley Runoff", Water-Year Sum