GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L10705, doi:10.1029/2007GL029988, 2007

Medieval drought in the upper Colorado River Basin

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Received 14 March 2007; revised 11 April 2007; accepted 17 April 2007; published 24 May 2007.

[1] New tree-ring records of ring-width from remnant preserved wood are analyzed to extend the record of reconstructed annual flows of the Colorado River at Lee Ferry into the Medieval Climate Anomaly, when epic droughts are hypothesized from other paleoclimatic evidence to have affected various parts of western North America. The most extreme low-frequency feature of the new reconstruction, covering A.D. 762-2005, is a hydrologic drought in the mid-1100s. The drought is characterized by a decrease of more than 15% in mean annual flow averaged over 25 years, and by the absence of high annual flows over a longer period of about six decades. The drought is consistent in timing with dry conditions inferred from tree-ring data in the Great Basin and Colorado Plateau, but regional differences in intensity emphasize the importance of basin-specific paleoclimatic data in quantifying likely effects of drought on water supply.
Citation: Meko, D., C. A. Woodhouse, C. A. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer (2007), Medieval drought in the upper Colorado River Basin, *Geophys. Res. Lett.*, *34*, L10705, doi:10.1029/2007GL029988.

1. Introduction

[2] Improved understanding of the variability of runoff and streamflow in the upper Colorado River Basin (UCRB) on decadal and longer timescales is essential to regional water resources planning and management in the western United States. Well-replicated networks of tree-ring sites in the UCRB have yielded annual streamflow reconstructions back to the 1400s [e.g., *Woodhouse et al.*, 2006]. Paleoclimatic data from elsewhere in the western United States suggest that these reconstructions fall short of sampling some of the most important hydroclimatic fluctuations of the past thousand years. Hydrologic droughts were unusually widespread and persistent in the Medieval Climate Anomaly (MCA), roughly A.D. 900–1300 [e.g., *Stine*, 1994; *Hughes and Funkhouser*, 1998; *Benson et al.*, 2002; *Cook et al.*, 2004]. For example, Mono Lake low stands reported by *Stine* [1994] are estimated to have been accompanied by multi-decadal precipitation decreases of greater than 20% in the Sierra Nevada of California (N. Graham and M. Hughes, Reconstructing the medieval Mono Lake low stands, submitted to *Holocene*, 2006, hereinafter referred to as Graham and Hughes, submitted manuscript, 2006). In this paper we attempt to quantify MCA drought magnitude in the UCRB by analysis of a newly developed network of tree-ring sites located within the basin. Annual flow of the Colorado River at Lee Ferry, Arizona, is reconstructed to A.D. 762 with ring-width using tree-ring samples from living trees, augmented by samples from logs and dead standing trees (remnant wood). We identify multi-decadal UCRB droughts of the MCA, quantify the year-by-year sequence of flow anomalies in the most severe drought, and check the consistency of the new reconstruction with other tree-ring evidence of regional-scale moisture and temperature departures.

2. Data and Methods

[3] Cores from living trees and cross-sections from remnant wood were collected between 2002 and 2005 at 11 sites in the UCRB (Figure 1 and auxiliary material).[1] Ring widths were dated and measured by conventional methods [*Stokes and Smiley*, 1968], and dimensionless core indices were computed as the ratio of ring width to an empirically fit growth curve [*Cook et al.*, 1990]. For uniformity of treatment and to reduce loss of low-frequency variance, a cubic smoothing spline [*Cook and Peters*, 1981] with frequency response 0.95 at a wavelength twice the series length was used as the growth curve. Core indices were converted to autoregressive residuals to remove the low-order persistence, which varies widely among trees and is likely due at least in part to biological factors [*Cook et al.*, 1990]. Indices at each site were then averaged over cores to compute "site chronologies". Segment-lengths shorter than 250 were excluded from chronology development to reduce possible damping of the low-frequency climatic signal [e.g., *Cook et al.*, 1995; *Ni et al.*, 2002], and site chronologies were truncated to begin when the subsample signal strength first reached a threshold of SSS $\geq$ 0.85 [*Wigley et al.*, 1984]. As the number of cores averaged varies over time, variance-stabilization, following *Osborn et al.* [1997], was applied to the retained portion of the site chronology to reduce the likelihood of spurious residual trends in variance.

[4] Streamflow data consisted of water-year-total natural flow of the Colorado River at Lee Ferry, Arizona, 1906–2004. These data, obtained from the U.S. Bureau of Reclamation (J. Prairie, personal communication, 2006), represent the best available estimate of what the flow at Lee Ferry would have been without reservoir regulation and other anthropogenic influences. For brevity, the time series

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0094-8276/07/2007GL029988$05.00

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl029988. Other auxiliary material files are in the HTML.

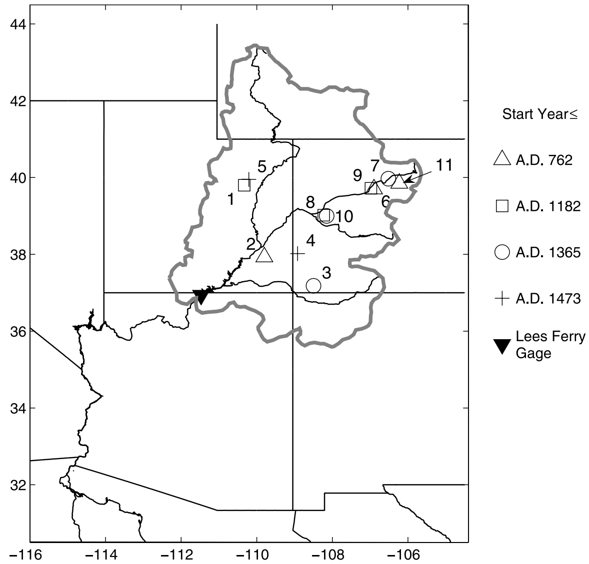

Figure 1. Tree-ring network for Colorado River reconstruction. Symbols indicate start year of earliest sub-period reconstruction model using the chronology (see Table 1). Sites (see auxiliary material) are 1) Harmon Canyon, 2) Beef Basin, 3) Navajo Canyon, 4) Slick Rock, 5) Wells Draw, 6) Eagle, 7) Pump House, 8) Wild Rose, 9) Trail Gulch, 10) Lands End, 11) Green Mtn. Resevoir. The earliest reconstruction segment (A.D. 762-1181) is based on model using sites 2, 6, and 11.

of water-year-total natural flows is referred to hereafter as ''flow''.

[5] The reconstruction was generated in a two-stage linear regression procedure previously described in greater detail elsewhere in the context of a precipitation reconstruction [*Meko*, 1997]. The first stage is regression of flow in year t separately on each residual site chronology in years $t-2$ to $t+2$ (five predictors). This steps yields a single-site reconstruction of flow (SSR) for each chronology. A principal components analysis (PCA) on the covariance matrix of the SSRs yields an orthogonal set of new variables that are linear combinations of the SSRs. The second stage of the regression procedure is stepwise regression of flow on the scores of the most important PCs, defined arbitrarily as those contributing at least 5% of the variance of the SSRs. This regression equation essentially ''weights'' the individual SSRs into a single reconstructed time series of flow. The PCA and second stage of regression is repeated several times using different sets of tree-ring chronologies to extend the reconstruction, albeit with diminished accuracy, to the earlier and more poorly replicated part of the tree-ring record. For any given year of the tree-ring record, the most accurate available model – lowest root-mean-square error of validation ($RMSE_v$) – was used to generate the final reconstructed flow value. Error bars for the final reconstruction were estimated by Monte Carlo simulation following *Meko et al.* [2001]: 1000 different time series of random noise were drawn from a normal distribution with zero mean and standard deviation equal to $RMSE_v$ and were superimposed on the reconstruction to produce 1000 noise-added reconstructions. Each of these is a plausible realization of true natural flow given the reconstruction model and its uncertainty.

3. Results and Discussion

[6] Single-site regression modeling indicated that each of the 11 tree-ring chronologies has a statistically significant signal for flow, with chronologies individually capable of explaining 25% to 57% of the flow variance (see auxiliary material). Split-sample validation [*Snee*, 1977] of these models using the reduction-of-error statistic [*Fritts et al.*, 1990] to measure accuracy indicated that all 11 models have positive skill when fit to one half of the data and validated on the other (see auxiliary material). From an assessment of signal strength and time coverage of the SSRs, four groupings of chronologies were selected for PCA and subset reconstruction modeling. The chronology subsets have starting years (A.D.) 762, 1182, 1365, and 1473. Model subsets of chronologies are cumulative for the earliest three models: three sites were available by A.D. 762, three more by A.D. 1182, and three more by A.D. 1365. The model for the subset starting in A.D. 1473 is based on four sites whose tree-ring data extend to 2005, and was used only to generate reconstructed flows for years 2004 and 2005.

[7] Results for the second stage of regression are summarized in Table 1. As indicated by column ''q'', each of the final reconstruction models includes just the first principal component of the SSRs as a predictor of flow. The variance of flow explained by the reconstruction increases with number of chronologies. In the earliest centuries, the reconstruction relies on three chronologies and explains 60% of the calibration variance. This percentage jumps to 74% by A.D. 1182, and to 77% by A.D. 1365. Cross-correlation analysis, cross-spectral analysis, and time series plots of observed and reconstructed flows indicated that each of the four sub-period reconstructions successfully tracks the observed flows for the instrumental period, and that coherence of observed and reconstructed flows remains significant at wavelengths longer than about 10 years (auxiliary material). The reconstructions by the four sub-period models are consistent with *Woodhouse et al.*'s [2006] Lees-A flow reconstruction over the common period A.D. 1490–1997: r = 0.76 for the A.D. 762 model and r = 0.91 for the A.D. 1182 model.

Table 1. Summary Statistics of Sub-Period Reconstruction Models

		Calibration[c]			Validation[d]		
Sequence[a]	Start[b]	Years	n-p-q	R^2_{adj}	m	RE	RMSE
1	762	1906–2003	3-3-1	0.60	9	0.58	3.46
2	1182	1906–2002	6-5-1	0.74	9	0.73	2.78
3	1365	1906–2002	9-4-1	0.77	9	0.76	2.64
4	1473	1906–2004	4-4-1	0.57	9	0.54	2.63

[a]Sequence number of sub-period model (1 is earliest).

[b]Start year of reconstruction sub-period.

[c]Calibration statistics: years, calibration period; n, the number of chronologies available; p, the number of potential predictors in the predictor pool; q, the number of predictors in the final model; R^2_{adj}, the adjusted coefficient of determination.

[d]Validation statistics (cross-validation): m, the number of observations left out in ''leave-m-out'' validation; RE, the reduction of error statistic; RMSE, the root-mean-square error of cross-validation, in billion cubic meters (BCM).

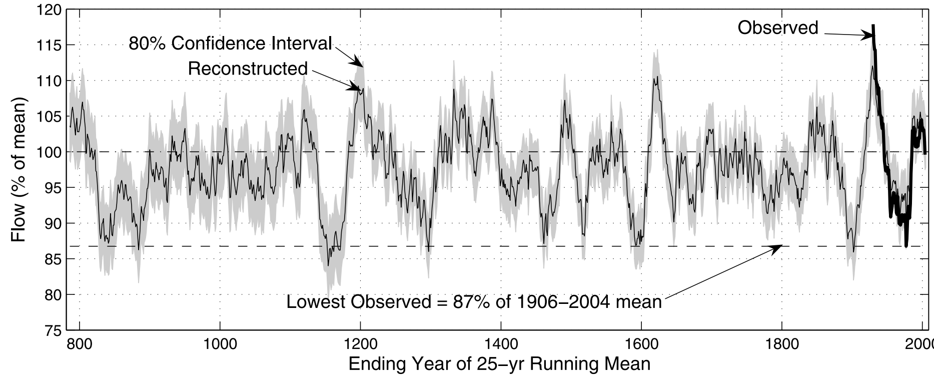

Figure 2. Time series plot of 25-year running mean of reconstructed flows. Flows are plotted as percentage of the 1906–2004 mean of observed natural flows (18.53 billion cubic meters, or 15.03 million acre-ft). Confidence interval derived from 0.10 and 0.90 probability points of ensemble of 1000 noise-added reconstructions. Horizontal dashed line is lowest 25-year running mean of observed flows (1953–1977).

[8] A 25-year running mean of the reconstructed flows illustrates the overall importance of variations at multi-decadal time scales, and identifies intervals of amplified low-frequency variance (Figure 2). The most recent such interval began in the mid-1800s and has continued to present. The beginning of the tree-ring record is also characterized by amplified low-frequency variance, as evidenced by the swing from wet conditions to dry conditions beginning in the early A.D. 800s. Running means are persistently below normal for most of the 9th century. The most prominent feature of the smoothed long-term reconstruction is the major period of low flow in the mid-1100s. The lowest reconstructed 25-year running mean occurred in A.D 1130–1154. These results suggest that – at least for this level of smoothing – conditions in the mid-1100s in the UCRB were even drier than during the extremely widespread late-1500s North American mega-drought [e.g., *Stahle et al.*, 2000]. If "normal" is defined as the observed mean annual flow for 1906–2004, the anomalous flow for A.D. 1130–1154 was less than 84% of normal. By comparison, the lowest 25-year mean of observed flows (1953–1977) was 87% of normal. Because regression biases the reconstructed flows toward the calibration-period mean, flows in the mid-1100s were quite possibly lower than indicated by the reconstruction. For example, the 80% confidence band plotted in Figure 2 suggests a greater than 10% probability that the true mean for A.D. 1130–1154 was as low as 79% of normal.

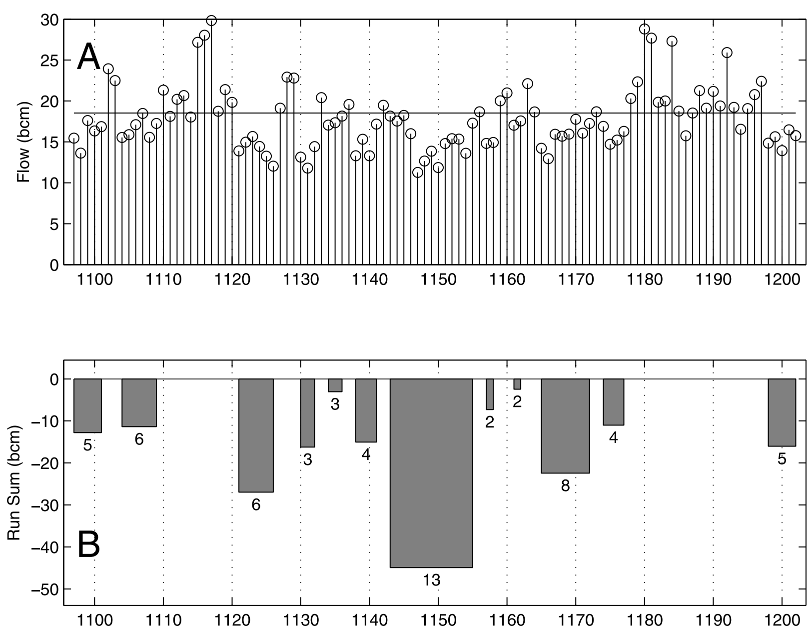

Figure 3. Runs properties of 1100s drought. (a) Time series of reconstructed flow in units of billion cubic meters (BCM) for segment A.D. 1098–1202. Horizontal line at 18.53 BCM is observed mean for 1906–2004. (b) Time series of runs below the observed mean flow. Bars mark runs of two-or-more years. Run-length annotated below bar. Run-sum (cumulative departure from mean) given by length of bar.

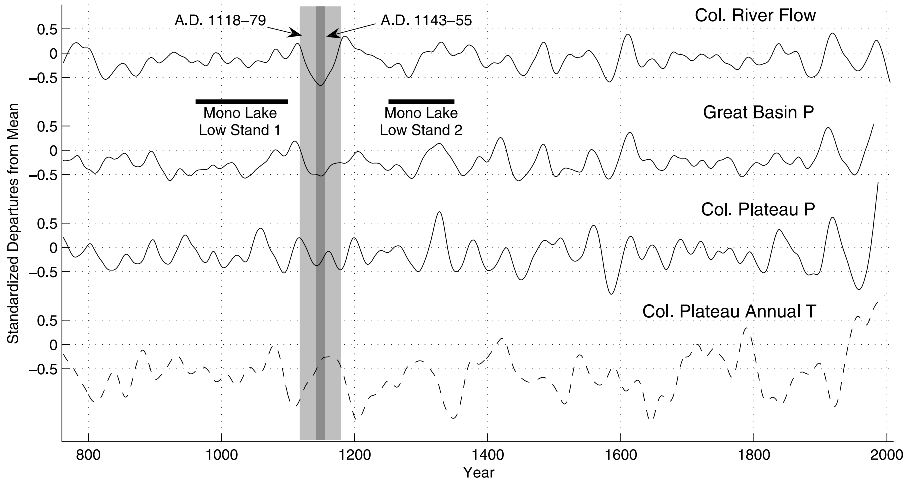

Figure 4. Medieval drought on Colorado River in regional context of other paleoclimatic reconstructions. Core and broad window for Colorado River drought shaded. Other plotted series are: Great Basin annual precipitation [*Hughes and Funkhouser*, 1998] (six-chronology reconstruction), Colorado Plateau October-July precipitation, and Colorado Plateau annual average maximum temperature [*Salzer and Kipfmueller*, 2005]. All plotted series generated by converting annual reconstructions to standardized departures (using means and standard deviations for period beginning with 1906), followed by smoothing with 41-year spline to emphasize multidecadal departures. Horizontal bars at inferred Mono Lake low stands follow *Stine* [1994].

[9] A distinct attribute of tree-ring data is the ability to resolve year-to-year fluctuations in climate. A detailed view of the time series of annual reconstructed flow reveals that the mid-1100s is characterized by a series of multi-year low-flow pulses imbedded in a generally dry 62-year period (1118–1179) (Figure 3a). A signature for this period is the absence of years with flow much above normal. The key drought signature is a stretch of 13 consecutive years of below normal flow (1143–1155), with cumulative negative departure from normal of 45 billion cubic meters (Figure 3b). In no other period of the reconstruction was flow below normal for more than 10 consecutive years, and the longest stretch of consecutive dry years in the reconstruction for the modern instrumental period (post 1905) was just 5 years.

[10] Other tree-ring reconstructions for the western United States allow the mid-1100s drought in the UCRB to be placed in a larger regional context. In a much broader region of the western United States, a 1200-year index of the total area in drought, smoothed to emphasize multi-decadal-to-century variation, reaches its major peak at A.D. 1150 [*Cook et al.*, 2004]. Tree-ring data indicate that the correlation of moisture anomalies in the Sierra Nevada and Colorado Rockies is generally weak, but is occasionally enhanced during severe drought [*Meko and Woodhouse*, 2005]. The mid-1100s may be an extreme example of such enhancement. A reconstruction of annual flow of the Sacramento River covering more than 1100 years identifies A.D. 1139–1158 as the second-lowest 20-year mean flow [*Meko et al.*, 2001]. A 1000-year reconstruction of temperature and precipitation for the southern Sierra Nevada of California identifies A.D. 1150–1169 as the warmest 20-year period, and 1140–1159 as the fourth driest [*Graumlich*, 1993]. As the early part of the Sacramento River reconstruction depends greatly on tree-ring chronologies somewhat north of the basin – in south-central Oregon –these two reconstructions are jointly consistent with a northward retreat of the winter storm track over the far western United States during the mid-1100s drought on the Colorado.

[11] Closer to the UCRB, paleoclimatic records are consistent in identifying the mid-1100s as a regional major or minor low in moisture (dry period) and high in temperature (Figure 4). Aligned with the major low in Colorado River flow centered on A.D. 1148 are lows in reconstructed precipitation for the Great Basin [*Hughes and Funkhouser*, 1998] and the Colorado Plateau [*Salzer and Kipfmueller*, 2005]. Suggestions from the Sierra Nevada that the mid-1100s was a relatively warm epoch [*Graumlich*, 1993] are reinforced by the local peak in reconstructed Colorado Plateau annual temperature (bottom plot in Figure 4). If the spline-smoothed flow and precipitation series in Figure 4 are re-expressed as a percentage of the recent (period starting in 1906) mean, the mid-1100s lows range from 83.4% for Colorado River Flow to 89.9% for Colorado Plateau precipitation.

[12] The mid-1100s UCRB drought does not coincide with either of two century-long Sierra Nevada droughts inferred by *Stine* [1994] from radiocarbon-dated tree stumps and other material from Mono Lake and nearby lakes and rivers (Figure 4). Two possible reasons for the asynchrony are radiocarbon-dating uncertainty (Graham and Hughes, submitted manuscript, 2006) and the spatial heterogeneity of drought patterns at large regional spatial scales. It should be noted, however, that the smoothing by a 25-year running mean emphasizes droughts of somewhat shorter duration than those associated with the Mono Lake low stands reported by *Stine* [1994], and that the Mono Lake low stands do overlap with other extended dry periods in the UCRB (Figure 4).

[13] The results presented here for the UCRB rely on a relatively sparse network of tree-ring chronologies, and assessments of magnitude of flow anomalies will likely change as future remnant-wood collections yield better spatial coverage and sample depth in the MCA. It is also important to consider the possibility that gradual trend in flow is undetected or perhaps underestimated in the reconstructions – especially trends represented by wavelengths longer than 250 years. Additionally, it is also possible that some other climate variables not included in the in the calibration may have had some systematic long-term influence on tree growth. These variables might include direct response of growth to changes in temperature through length of growing season and snowpack storage of available moisture.

[14] **Acknowledgments.** This work was supported by the California Department of Water Resources (DWR agreement 4600003882), U.S. Geological Survey, Earth Surface Processes program, and the U.S. Bureau of Reclamation (award 04-FG-32-0260).

References

Benson, L., M. Kashgarian, R. Rye, S. Lund, F. Paillet, J. Smoot, C. Kester, S. Mensing, D. Meko, and S. Lindstrom (2002), Holocene multidecadal and multicentennial droughts affecting northern California and Nevada, *Quat. Sci. Rev.*, *21*, 659–682.

Cook, E. R., and K. Peters (1981), The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies, *Tree-Ring Bull.*, *41*, 45–53.

Cook, E. R., K. Briffa, S. Shiyatov, and V. Mazepa (1990), Tree-ring standardization and growth-trend estimation, in *Methods of Dendrochronology, Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 104–123, Springer, New York.

Cook, E. R., K. R. Briffa, D. M. Meko, D. A. Graybill, and G. Funkhouser (1995), The "segment length curse" in long tree-ring chronology development for palaeolclimatic studies, *Holocene*, *5*(2), 229–237.

Cook, E. R., C. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle (2004), Long-term aridity changes in the western United States, *Science*, *306*, 1015–1018.

Fritts, H. C., J. Guiot, and G. A. Gordon (1990), Verification, in *Methods of Dendrochronology, Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 178–185, Springer, New York.

Graumlich, L. (1993), A 1000-year record of temperature and precipitation in the Sierra Nevada, *Quat. Res.*, *39*, 249–255.

Hughes, M. K., and G. Funkhouser (1998), Extremes of moisture availability reconstructed from tree rings for recent millennia in the Great Basin of western North America, in *The Impacts of Climate Variability on Forests*, edited by M. Beniston and J. L. Innes, pp. 99–107, Springer, New York.

Meko, D. M. (1997), Dendroclimatic reconstruction with time varying subsets of tree indices, *J. Clim.*, *10*, 687–696.

Meko, D. M., and C. A. Woodhouse (2005), Tree-ring footprint of joint hydrologic drought in Sacramento and upper Colorado River basins, western USA, *J. Hydrol.*, *308*, 196–213.

Meko, D. M., M. D. Therrell, C. H. Baisan, and M. K. Hughes (2001), Sacramento River flow reconstructed to A. D. 869 from tree rings, *J. Am. Water Resour. Assoc.*, *37*(4), 1029–1040.

Ni, F., T. Cavazos, M. K. Hughes, A. C. Comrie, and G. Funkhouser (2002), Cool-season precipitation in the southwestern USA since A. D. 1000: Comparison of linear and nonlinear techniques for reconstruction, *J. Int. Climatol.*, *22*, 1645–1662.

Osborn, T. J., K. R. Briffa, and P. D. Jones (1997), Adjusting variance for sample-size in tree-ring chronologies and other regional mean timeseries, *Dendrochronologia*, *15*, 89–99.

Salzer, M. W., and K. F. Kipfmueller (2005), Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, *Clim. Change*, *70*, 465–487.

Snee, R. D. (1977), Validation of regression models: Methods and examples, *Technometrics*, *19*, 415–428.

Stahle, D. W., E. R. Cook, M. K. Cleaveland, M. D. Therrell, D. M. Meko, H. D. Grissino-Mayer, E. Watson, and B. H. Luckman (2000), Tree-ring data document 16th century megadrought over North America, *Eos Trans. AGU*, *81*(12), 121–125.

Stine, S. (1994), Extreme and persistent drought in California and Patagonia during mediaeval time, *Nature*, *369*, 546–549.

Stokes, M. A., and T. L. Smiley (1968), *An Introduction to Tree-Ring Dating*, 73 pp., Univ. of Ariz. Press, Tucson.

Wigley, T. M. L., K. R. Briffa, and P. D. Jones (1984), On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *J. Clim. Appl. Meteorol.*, *23*, 201–213.

Woodhouse, C. A., S. T. Gray, and D. M. Meko (2006), Updated streamflow reconstructions for the Upper Colorado River Basin, *Water Resour. Res.*, *42*, W05415, doi:10.1029/2005WR004455.

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