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LONG-TERM RELATIONSHIPS BETWEEN OCEAN VARIABILITY AND WATER RESOURCES IN NORTHEASTERN UTAH[1]

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ABSTRACT: The Uinta Mountains in the northwestern Colorado River Basin are an important source of water for Utah and the western United States. This article examines 20th Century hydrology in the Uinta Mountains region in the context of the previous four to eight centuries as well as possible relationships with Pacific and Atlantic Ocean variability using new tree-ring based reconstructions for streamflow and snowpack. The 20th Century appears to have been unusually wet compared with previous centuries. Relationships between hydrology in the region and the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) are largely insignificant in instrumental datasets but may have been stronger, although inconsistent, over the longer time spans represented by the paleoclimate records. Impacts of individual modes of sea surface temperature variability may sometimes be enhanced by periods when climate forcing by ENSO, PDO, and/or AMO coincide. Such episodes are associated with deviations from mean hydrology as high as +14% and as low as −18%. The 20th Century could be a misleading benchmark to base water resource estimates upon and flexible water management strategies are necessary to take into account the large range of natural variability observed in the longer-term hydroclimatology as well as the challenges to predictability due to the apparently complex and inconsistent influence of ocean-driven variability.

(KEY TERMS: water resources; drought; climate variability/change; El Niño-Southern Oscillation; Pacific Decadal Oscillation; Atlantic Multidecadal Oscillation; dendrochronology; paleohydrology.)

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INTRODUCTION

The Uinta Mountains region in northeastern Utah generates important local and regional water supplies. Water is delivered to 17 counties including Salt Lake for municipal, industrial, and agricultural uses (Utah Division of Water Resources, http://www.water.utah.gov, *accessed* June 2009) and as much as 25% of Utah's developable water supply is in this area (Utah State Water Plan, http://www.water.utah.gov/waterplan/SWP_pff.pdf, *accessed* April 2008). The high elevation areas in northeastern Utah also contribute substantial amounts of water to the Upper Colorado River Basin (UCRB). Calculations based on Bureau of Reclamation naturalized flow data (http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html, *accessed* June 2009) indicate that approximately 10-15% of Colorado River flow at Lees Ferry originates in northeastern Utah.

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Hydrological extremes in the western United States (U.S.) during the 20th Century have been associated with Pacific and Atlantic sea surface temperature (SST) variability related to the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (e.g., Redmond and Koch, 1991; Cayan *et al.*, 1999; Dettinger and Diaz, 2000; Enfield *et al.*, 2001; Hunter *et al.*, 2006; McCabe *et al.*, 2007). Briefly, ENSO is a recurring phenomenon with a period of approximately two to eight years that is characterized by shifts in equatorial Pacific SST and atmospheric pressure patterns that generate precipitation anomalies in western North America (Cane and Zebiak, 1985; Philander, 1990). Two common indices that describe ENSO are the Southern Oscillation Index (SOI), the anomaly in the standardized slp (sea level pressure) difference between Papeete (Tahiti) and Darwin (Australia) and the NINO-3 index, the SST anomaly in the geographical rectangle bounded by 90W, 150W, 5S, and 5N. PDO has similar impacts on precipitation in western North America to ENSO, with key differences being that SST anomalies associated with PDO are more strongly manifested in the Northern Pacific region and can persist over several decades (it has periods of approximately 15-25 and 50-70 years) (Mantua *et al.*, 1997; Mantua and Hare, 2002). The PDO index, which is computed as the leading principal component of monthly Pacific SST variability in the region north of 20 degrees from 1900 to 1993, can be used to track this phenomenon. AMO, which has a period of 65-80 years, is a recurring pattern of SST anomalies in the North Atlantic. The AMO index is the 10-year running mean of the detrended North Atlantic SST anomaly north of 0 degrees (Enfield *et al.*, 2001; Knight *et al.*, 2006). Positive AMO index values have been associated with drought in the continental U.S. during the 20th Century (Enfield *et al.*, 2001).

Instrumental data used in water resource planning typically reflect 20th Century hydrology, which has been shown to represent generally wet conditions in western North America over the last 1,000 years or so (e.g., Meko *et al.*, 1995; Case and MacDonald, 2003; Cleaveland *et al.*, 2003; Woodhouse, 2003; Gray *et al.*, 2004a; Meko and Woodhouse, 2005; Woodhouse and Lukas, 2006; Woodhouse *et al.*, 2006; MacDonald *et al.*, 2008; Watson *et al.*, 2009). Tree-rings collected from moisture-sensitive areas can provide centuries-long annual records of variables critical to effective water resource management such as precipitation, streamflow, and snowpack (e.g., Stockton and Jacoby, 1976; D'Arrigo and Jacoby, 1991; Meko *et al.*, 1995, 2007; Woodhouse, 2003). Extending relatively short instrumental climate records using tree-rings helps identify more realistic hydrological base lines as well as best/worst case scenarios to ascertain the robustness of long-term management plans. In addition, tree-ring reconstructions allow investigation of the range and consistency of hydrological impacts related to ENSO, PDO, and AMO, which is important for establishing whether SST conditions might be used to forecast northeastern Utah hydroclimatology.

Here, we present tree-ring based reconstructions for water-year (October to September) discharge in the Duchesne River, the major river originating in the Uinta Mountains and a tributary to the Colorado River, and April 1 Snow Water Equivalent (SWE) at two northeastern Utah sites. Although reconstructions of prehistoric aridity as represented in precipitation (Gray *et al.*, 2004a) and Palmer Drought Severity Index (PDSI) (MacDonald and Tingstad, 2007) exist for northeastern Utah, streamflow and snowpack are two of the most important measures used in operational water management (e.g., Snover *et al.*, 2003; Christensen *et al.*, 2004; Barnett *et al.*, 2005), and reconstructions of Duchesne River flow and northeastern Utah snowpack are not currently available. The records presented here, which span five to nine centuries, are used together with previously published tree-ring reconstructions of ENSO, PDO, and AMO to answer the following three questions:

1. How does 20th Century hydrology compare with preinstrumental variations in streamflow and snowpack in northeastern Utah?
2. Does Pacific and Atlantic Ocean SST variability impact streamflow and snowpack in northeastern Utah and are these relationships stable?
3. What is the mean magnitude of ENSO, PDO, and AMO influence on northeastern Utah hydrology?

Answering these questions is important for robust, long-term decision making within the state of Utah as well as in the context of Colorado River resource management.

STUDY AREA

The Uinta Mountains are located in the northeastern corner of Utah, approximately 70 km from Salt Lake City (Figure 1). Immediately south of the range is the Uintah Basin, which is bounded on its southern end by the Book Cliffs and Tavaputs Plateau. The Uinta Mountains region refers collectively to the Uinta Mountains and adjacent Uintah Basin. As defined, the Uinta Mountains region covers an area of approximately 43,500 km^2.

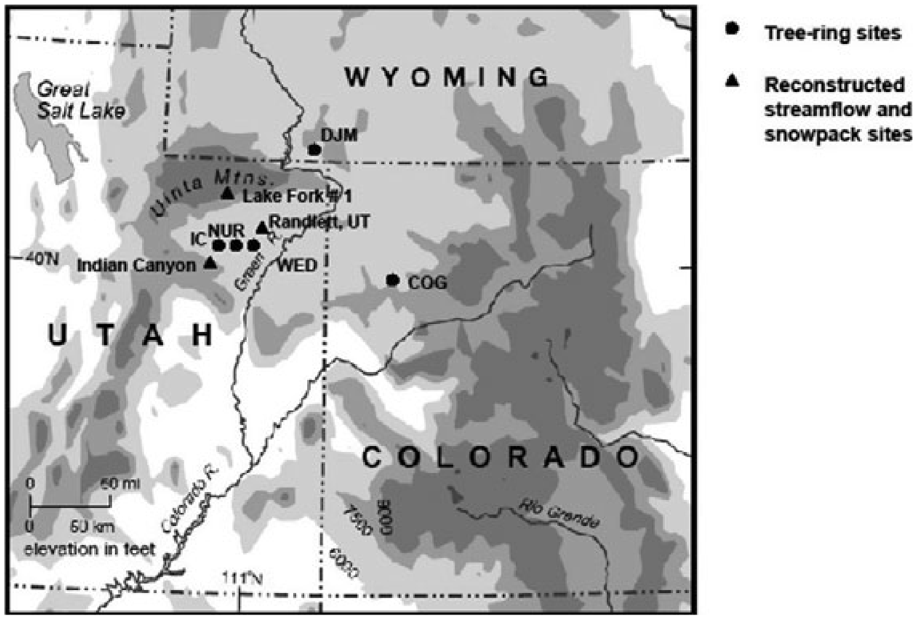

FIGURE 1. Uinta Mountains and Study Site Locations.

Northeastern Utah experiences hot, dry summers and cold, relatively wetter winters (MacDonald and Tingstad, 2007) (Figure 2). Most precipitation in this region falls during winter and spring, although late summer storms contribute substantially to the annual total, particularly at the eastern end of the range. Average annual precipitation from 1971 to 2000 for water-producing areas in the Uinta Mountains region was 38-127 cm, whereas the average maximum temperature ranged from 3 to 17°C, and average minimum temperature ranged from −13 to 3°C over the same period (PRISM Climate Group, http://www.prism.oregonstate.edu, *accessed* July, 2009). Average April 1 SWE from 1971 to 2000 for the Uinta Mountains region was 34 cm (National Water and Climate Center, http://www3.wcc.nrcs.usda.gov, *accessed* July 2009).

Northeastern Utah may be sensitive to changes in ocean-atmosphere dynamics because of its interior continental location. Although ENSO and PDO do not appear to be strongly linked to hydrological variability in the Uinta Mountains during the 20th Century, these phenomena may have had greater impacts prior to the start of the instrumental record (MacDonald and Tingstad, 2007). ENSO and PDO have been associated with Colorado River Basin hydrological variability (e.g., Cayan and Peterson, 1989; Gray *et al.*, 2003; Hidalgo and Dracup, 2003; Woodhouse, 2003; Meko and Woodhouse, 2005; McCabe *et al.*, 2007; Timilsena *et al.*, 2009). Although there may be links between AMO and water balance in the UCRB (Enfield *et al.*, 2001; McCabe *et al.*, 2007), these

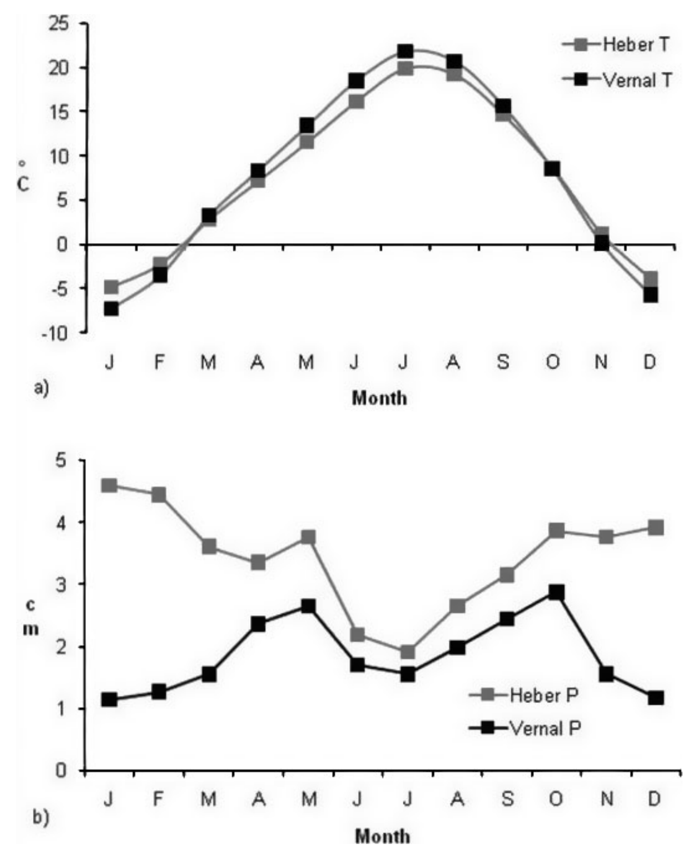

FIGURE 2. (a) Average Monthly Temperature and (b) Precipitation for Heber, Utah and Vernal, Utah, Near the Western and Eastern Ends of the Uinta Mountains, Respectively, From 1971 to 2000. Data are from the Western Regional Climate Center (WRCC) (http://wrcc.dri.edu, *accessed* January 2010).

connections have recently been shown to be insignificant for several basin streams (Timilsena *et al.*, 2009). Connections between Uinta Mountains region hydroclimate and other major modes of climatic variability, such as the Pacific North American pattern (e.g., Leathers *et al.*, 1991), may also be possible but are not investigated in this study.

METHODS

Tree-Ring Data

Annual ring-width chronologies from five- to two-needle Piñon Pine (*Pinus edulis* Engelm.) sites were acquired, the locations of which are shown in Figure 1. Two-needle Piñon Pine has been recognized as sensitive to moisture (Hidalgo *et al.*, 2001), and was the only species used in this study to minimize differences in the relationship between hydrology and ring-width. Of these chronologies, three (Dutch John Mountain, DJM; Wells Draw, WED; and Nutters Ridge, NUR) were originally published in Gray *et al.* (2004a,b) and one (Collins Gulch, COG) was obtained from the World Data Center for Paleoclimatology (WDCP) (http://www.ncdc.noaa.gov/paleo/paleo.html, *accessed* May 2009) and originally published in Woodhouse *et al.* (2006).

The Indian Canyon chronology (IND) is an original dataset developed from samples collected during the summers of 2006 and 2007. Live and dead samples were collected in the field using an increment borer. Samples were then taken back to the UCLA dendrochronology laboratory and prepared for analysis using standard techniques outlined in Stokes and Smiley (1968). Samples were mounted onto wooden holders and then sanded using progressively finer sand paper. Rings on each sample were then counted and measured with the aid of a light microscope.

Cross-dating of the IND samples was done using standard practices (Stokes and Smiley, 1968) and ring measurements and cross-dating were checked using the software package COFECHA (Holmes, 1983). Samples displaying low correlations with the master chronology were examined for potential sources of counting errors (generally missing rings) and were then either corrected or removed from the analysis. Data from all five tree-ring sites were detrended using a single negative exponential curve or linear regression to remove the biological growth pattern but maintain longer term climate signals (Cook, 1987). Tree-ring data for each site were then standardized so that all samples had means of 1 and equal variances (Douglass, 1919; Fritts, 1976). These were then averaged at each location to develop site chronologies. Both detrending and standardization were done using the software package ARSTAN (Cook and Holmes, 1996).

Streamflow and Snowpack Reconstructions

Water-year naturalized Duchesne River flow near Randlett, Utah (USGS Gauge 09302000) was reconstructed (Figure 1). This location was chosen because it is the largest Colorado River tributary with headwaters in the Uinta Mountains. According to Bureau of Reclamation naturalized flow data (http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html, *accessed* June 2009), average water-year discharge from 1906 to 2005 was 985 Mm^3 (799,100 acre-feet). Flow in the Duchesne River correlates significantly ($p < 0.001$) with other rivers and streams in the Uinta Mountains region (r ranges from 0.832 to 0.887) and with Colorado River flow at Lees Ferry ($r = 0.867$).

Annual stream discharge in the Uinta Mountains is largely snowmelt driven (Carson and Munroe, 2005). Thus, April 1 SWE at two locations in the northern and southern Uinta Mountains region, respectively, was reconstructed (Figure 1). Lake Fork 1 is located on the southern slope of the Uinta Mountains at an elevation of 3,174 m. Indian Canyon is located on the Tavaputs Plateau at an elevation of 2,797 m. Continuous April 1 SWE records for these sites are available from the National Water and Climate Center (http://www.wcc.nrcs.usda.gov/snow/, *accessed* May 2009) since 1930 and 1931, respectively. Snowpack at these locations correlates significantly ($p < 0.001$) together ($r = 0.783$), with other April 1 SWE records in the Uinta Mountains region (r ranges from 0.632 to 0.832), with Duchesne River streamflow (Lake Fork 1: $r = 0.738$; Indian Canyon: $r = 0.687$), and with Colorado River flow at Lees Ferry (Lake Fork 1: $r = 0.611$; Indian Canyon: $r = 0.633$).

Multiple linear regression using backwards stepwise selection of predictor variables was used to construct models for streamflow and April 1 SWE, which were evaluated by the magnitude of the adjusted coefficient of determination (r^2_{adj}), which represents the percentage of variance explained by the model, as well as by the magnitude and significance of the F-ratio. Models were verified by dividing each instrumental calibration dataset into roughly equal early and late periods, and then constructing early and late models using multiple linear regression. Early models were then used to reconstruct late period data and vice versa. The reduction of error and coefficient of efficiency statistics were evaluated for early and late models (Cook *et al.*, 1999). Once verified, the full models were applied to the entire tree-ring chronologies to produce reconstructions of the hydrological variables.

Pacific and Atlantic Ocean Index Reconstructions

Previously published tree-ring based reconstructions of the SOI (ENSO), PDO, and AMO indices were obtained from the WDCP website (http://www.ncdc.noaa.gov/paleo/treering.html, *accessed* May 2009). The reconstructions chosen for SOI, PDO, and AMO were originally published in Stahle *et al.* (1998a,b), Biondi *et al.* (2001), and Gray *et al.* (2004b), respectively, and were developed using tree-ring chronologies from the following locations: northern Mexico, the western U.S., and Java (Indonesia) (SOI); southern and Baja California (PDO); and, eastern North America, western Europe, Scandinavia, and the Middle East (AMO). The reconstructions extend from 1706 to 1977, 1661 to 1991, and 1572 to 1985 for the SOI, PDO, and AMO, respectively. These were specifically selected to allow direct comparisons with work by Timilsena *et al.* (2009), who used the same ocean index records to examine relationships between SST variability and reconstructed streamflow in 19 other Colorado River Basin streams. Reconstructions in this previous study were based on tree-ring data obtained from the WDCP and unimpaired water-year streamflow data.

Determining Relationships Between Hydrology and Ocean Variability

Two methods were used to examine the impacts of SST variability on Uinta Mountains region hydrology. Wavelet analysis using the Morlet Wavelet (Torrance and Compo, 1998) was performed on the streamflow and snowpack reconstructions. The resulting wavelet power spectra were then examined for signal period, strength, significance, and continuity.

Secondly, Pearson correlation coefficients were calculated for each reconstructed hydrological variable and type of SST variability over the respective periods of overlap. In addition, 50-year moving correlations (i.e., 1706-1755, 1707-1756, etc.) between each reconstructed hydrological variable and ocean index were tracked over the respective periods of overlap. Fifty-year moving correlations were chosen because this time frame is long enough for statistically meaningful correlations, but short enough to capture persistent low frequency changes in ocean index values. Although correlation does not inherently imply causation, this is an effective means to investigate possible relationships between Uinta Mountains region hydrology and SST variability and how these may change over time.

It should be noted that such tree-ring record comparisons may not solely reflect connections between reconstructed variables for a number of reasons. First, statistical relationships can potentially demonstrate regional climatic coherence unrelated to atmospheric linkages of interest. Here, this is more likely an issue for comparisons made with reconstructed SOI and PDO than for AMO because the tree-ring chronologies used to generate the first two records are from the same general region as those used to reconstruct Uinta Mountains hydrology. Secondly, it is not possible to positively verify the stability of SOI, PDO, and AMO teleconnections with the locations where the tree-ring chronologies used to reconstruct these indices were collected. Finally, some nonclimatic variability could be introduced into the analyses due to differential climatic response between tree species, especially because all the Uinta Mountains region chronologies were constructed using one species, *P. edulis*.

To partially address these issues, wavelet coherency was used to confirm that correlations between each respective tree-ring based time series pair captured associations at temporal frequencies characteristic of ENSO, PDO, and AMO variability. Furthermore, instrumental streamflow and snowpack were also correlated with instrumental SOI (http://www.cgd.ucar.edu/cas/catalog/climind/soi.html, *accessed* 2009) (Trenberth, 1984; Trenberth and Hoar, 1996), PDO (http://jisao.washington.edu/pdo/PDO.latest, *accessed* 2009) (Mantua *et al.*, 1997; Zhang *et al.*, 1997), and AMO (http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data, *accessed* 2009) (Enfield *et al.*, 2001) records over the periods 1906-2000, 1931-2000, and 1930-2000, respectively, to determine the significance and direction of recent relationships between Uinta Mountains hydrology and ocean SST variability using nonproxy data.

Determining Impacts of Ocean Variability on Hydrology

Significant differences in streamflow and April 1 SWE associated with the SOI, PDO, and AMO individually and together were determined using nonparametric Wilcoxon rank sum tests. These were performed by comparing reconstructed streamflow and April 1 SWE for different ocean conditions (e.g., SOI+ *vs.* SOI−, PDO+ *vs.* PDO−, SOI+/PDO+ *vs.* SOI−/PDO−, etc.) over the common period 1706-1977. The Wilcoxon rank sum tests determined when differences were significant, and resulting shifts in streamflow or snow pack were then calculated as a percent of 1706-1977 mean hydrological conditions in these cases.

To make these comparisons, El Niño (warm SST) events were defined as years with SOI < −1, whereas La Niña (cold SST) events were designated as years with SOI > +1 after Timilsena *et al.* (2009). Warm PDO and AMO (positive SST anomalies in the northeastern Pacific and tropical Atlantic, respectively) were identified as years when indices were above zero, whereas cold PDO and AMO (negative SST anomalies in the northeastern Pacific and tropical Atlantic, respectively) were identified as years when these indices were below zero (also after Timilsena *et al.*, 2009).

RESULTS AND DISCUSSION

Model Statistics and Reconstructions

For this study, standard chronologies generated by the ARSTAN program were used for all models and reconstructions. Tree-ring chronologies displayed significant inter-series correlations, ranging from 0.451 ($p < 0.001$) (DJM and IC) to 0.800 ($p < 0.001$) (NUR and WED).

Predictor variables used in the Duchesne River water-year streamflow model were sites DJM ($r_{\text{ring-width,streamflow}} = 0.644$, $p < 0.001$) and NUR ($r_{\text{ring-width,streamflow}} = 0.485$, $p < 0.001$), whereas IC ($r_{\text{ring-width,snowpack}} = 0.624$, $p < 0.001$) and CG ($r_{\text{ring-width,snowpack}} = 0.517$, $p < 0.001$) were used to build the Lake Fork 1 April 1 SWE model, and the WED ($r_{\text{ring-width,snowpack}} = 0.583$, $0 < 0.001$) chronology was used as the independent variable in the Indian Canyon April 1 SWE model. All three models passed significance and verification tests (Table 1).

Using these models, reconstructions for Duchesne River discharge (DU) since AD 1374, Lake Fork 1 April 1 SWE (LF) since AD 1500, and Indian Canyon April 1 SWE (IC) since AD 1061 were generated. Reconstructions were terminated when the number of samples in one of the predictor chronologies fell below the number needed to achieve 0.85 signal strength (Wigley *et al.*, 1984), to maximize the fidelity of the reconstructions back in time.

As each reconstruction was generated using unique tree-ring chronologies, they can be evaluated independently of one another and compared. The reconstructions correlate well with each other: the Pearson correlation coefficients are 0.734 ($p < 0.001$) for DU streamflow and LF snowpack, 0.777 ($p < 0.001$) for DU streamflow and IC snowpack, and 0.691 ($p < 0.001$) for the two snowpack reconstructions. The means over the reconstructed periods for Duchesne River water-year streamflow, April 1 SWE at Lake Fork 1, and April 1 SWE at Indian Canyon are 945.60 Mm^3, 30.93 cm, and 26.92 cm, respectively. The 1900-1999 mean is the highest of any century for all reconstructions (993.23 Mm^3 for DU streamflow, 31.43 cm for LF snowpack, and 29.42 cm for IC snowpack). The lowest centennial mean in streamflow or snowpack varies by reconstruction due to record length and possibly also location, tree-ring chronology characteristics, and time window of the

TABLE 1. Model Statistics for Duchesne River Water-Year Streamflow (DU), Lake Fork 1 April 1 SWE (LF), and Indian Canyon April 1 SWE (IC) Reconstructions.

Model	**Duchesne River Discharge (m^3) (water year) =629.290 × NUR + 570.804 × DJM − 236.987**	**Lake Fork 1 April 1 SWE (cm) =8.333 × IC + 4.009 × CG − 0.066**	**Indian Canyon April 1 SWE (cm) =17.530 × WED + 9.723**
r^2_{adj}	0.534	0.417	0.330
F-ratio	54.906	25.721	35.956
Full calibration period	1906-2000	1931-2000	1930-2001
r (full model, instrumental data)	0.738*	0.659*	0.583*
Early period	1906-1953	1931-1965	1930-1965
Late period	1954-2000	1966-2000	1966-2001
r (early model, late verification period)	0.794*	0.676*	0.585*
r (late model, early verification period)	0.689*	0.636*	0.576*
RE_{Early}	0.409	0.968	0.335
CE_{Early}	0.348	0.980	0.325
RE_{Late}	0.437	0.979	0.364
CE_{Late}	0.383	0.966	0.322

Notes: *r* represents Pearson correlation coefficients. RE is the reduction-of-error statistic, values >0 are acceptable. CE is the coefficient-of-efficiency statistic, values >0 are acceptable.
*$p < 0.001$.

reconstructed variable (i.e., annual streamflow *vs.* seasonal snowpack): 1700-1799 (875.52 Mm^3) followed by 1500-1599 (922.00 Mm^3) for DU streamflow, 1600-1699 (30.27 cm) followed by 1700-1799 (30.80 cm) for LF snowpack, and 1200-1299 (24.37 cm) followed by 1700-1799 (25.31 cm) for IC snowpack. It is notable that all reconstructions show arid conditions during the 18th Century. However, centennial differences are all within the standard error calculated for each model.

Comparison of 20th Century Hydrology With the Preinstrumental Record

Reconstructions for Duchesne River water-year streamflow, April 1 SWE at Lake Fork 1, and April 1 SWE at Indian Canyon are shown in Figure 3. The number of dry years in each century below the 0.05, 0.10, and 0.25 quantiles (Gray *et al.*, 2004a,b) were calculated for each record (Table 2). The number and average length of multiple year dry events in each reconstruction with values continuously below the 0.25 quantile were also determined (Table 3). These analyses suggest that the 20th Century was characterized by wetter conditions compared with many previous centuries in the Uinta Mountains region, which is consistent with other records from western North America (e.g., Case and MacDonald, 2003; Woodhouse, 2003; Cook *et al.*, 2004; Gray *et al.*, 2004a,b; MacDonald, 2007; Meko *et al.*, 2007; Watson *et al.*, 2009). Large concentrations of dry years and multiple dry year events occur during the 13th, 16th, 17th, and 18th Centuries.

Major dry periods in the Uinta Mountains region reconstructions generally coincide with other records from western North America. The mid to late 13th Century drought has been identified in the Colorado River Basin (e.g., Meko *et al.*, 2007; MacDonald *et al.*, 2008), the Sacramento River Basin (Meko *et al.*, 2001; MacDonald *et al.*, 2008), the Saskatchewan River Basin (Case and MacDonald, 2003), in California (e.g., Hughes and Graumlich, 1996; MacDonald, 2007; MacDonald *et al.*, 2008), and throughout the western U.S. (e.g., Cook *et al.*, 2004). A multidecadal drought in the 12th Century that has been widely found throughout western North America (e.g., Laird *et al.*, 1996; Case and MacDonald, 2003; Cook *et al.*, 2004; MacDonald, 2007; Meko *et al.*, 2007; MacDonald *et al.*, 2008) does not appear strongly in the IC record. This Megadrought may have been driven by high radiative forcing coupled with cool SST anomalies in the northeastern Pacific (MacDonald and Case, 2005; Herweijer *et al.*, 2006; MacDonald *et al.*, 2008), so the relatively mild expression of this event in the IC reconstruction may reflect a possible decoupling of Pacific Ocean SST anomalies and Uinta Mountains region hydrology during this episode. However, this could also reflect age characteristics of the samples used to construct the WED chronology and/or low sample size.

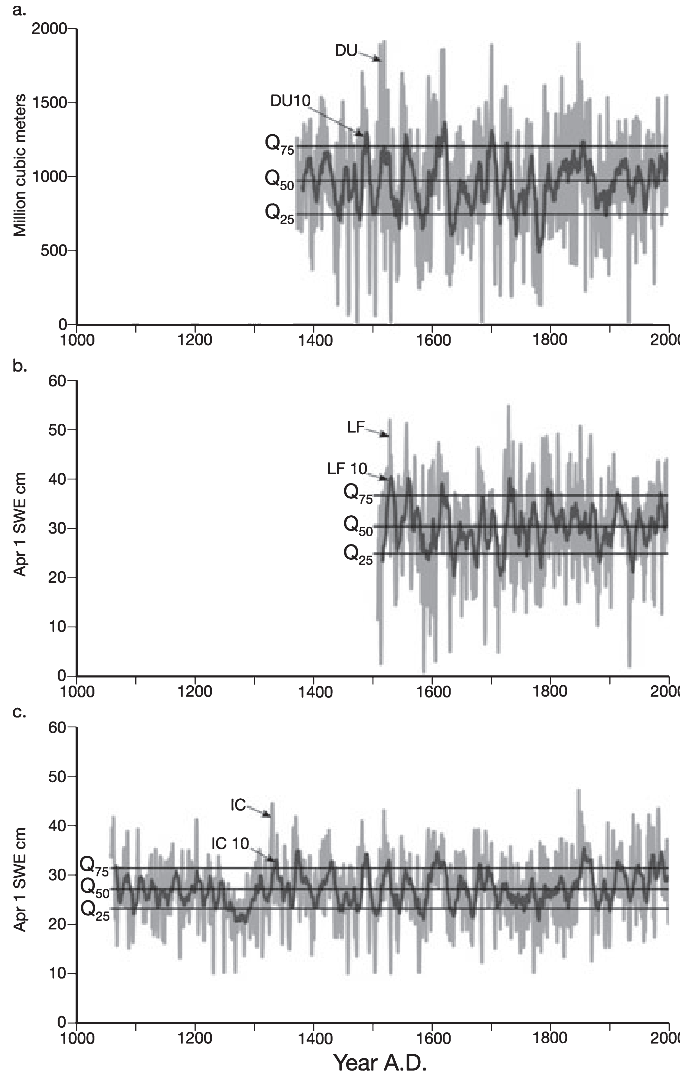

FIGURE 3. Reconstructions for (a) Duchesne River Water-Year Streamflow (DU), (b) Lake Fork 1 April 1 SWE (LF), and (c) Indian Canyon April 1 SWE (IC). Ten-year moving averages (DU-10, LF-10, and IC-10) are displayed on the charts along with the 0.25, 0.50, and 0.75 quantile values for each reconstruction. Streamflow values are expressed in millions of cubic meters and April 1 SWE values are given in centimeters.

The 16th and 17th Centuries were dry throughout the interior western U.S. (e.g., Meko *et al.*, 1995, 2007; Woodhouse and Overpeck, 1998; Stahle *et al.*, 2000; Woodhouse, 2003; Cook *et al.*, 2004; Piechota *et al.*, 2004; Meko and Woodhouse, 2005; MacDonald, 2007; Timilsena *et al.*, 2007; Watson *et al.*, 2009). A widespread drought that occurred at the end of the 16th Century was particularly prolonged and severe

TABLE 2. Number of Single Dry Year Events Below the 0.05, 0.10, and 0.25 Quantiles in DU Streamflow, LF Snowpack, and IC Snowpack Reconstructions.

Century	DU			LF			IC		
	No. < $Q(0.05)$	No. < $Q(0.10)$	No. < $Q(0.25)$	No. < $Q(0.05)$	No. < $Q(0.10)$	No. < $Q(0.25)$	No. < $Q(0.05)$	No. < $Q(0.10)$	No. < $Q(0.25)$
1100-1199	*	*	*	*	*	*	3	6	24
1200-1299	*	*	*	*	*	*	4	12	38
1300-1399	*	*	*	*	*	*	7	10	20
1400-1499	6	7	22	*	*	*	5	13	25
1500-1599	7	13	28	8	14	25	7	11	28
1600-1699	4	10	26	5	12	24	6	12	22
1700-1799	10	15	34	7	12	27	7	11	30
1800-1899	2	9	23	2	5	25	4	10	22
1900-1999	3	6	17	4	8	20	2	7	13

The asterisks (*) represent decades with no observations.

TABLE 3. Number and Average Length of Dry Events ≥2 Years in Length in DU Streamflow, LF Snowpack, and IC Snowpack Reconstructions.

Century	DU		LF		IC	
	No. ≥2 Years <$Q(0.25)$	Average Length (years)	No. ≥2 Years <$Q(0.25)$	Average Length (years)	No. ≥2 Years <$Q(0.25)$	Average Length (years)
1100-1199	*	*	*	*	7	2.0
1200-1299	*	*	*	*	9	3.6
1300-1399	*	*	*	*	5	3.2
1400-1499	5	3.0	*	*	7	2.7
1500-1599	6	2.7	8	2.4	6	3.1
1600-1699	7	2.7	6	3.5	5	2.8
1700-1799	8	2.7	6	2.7	9	2.3
1800-1899	7	2.0	6	2.2	3	3.3
1900-1999	2	3.0	3	3.7	2	3.0

The asterisks (*) represent decades with no observations.

(e.g., D'Arrigo and Jacoby, 1991; Meko *et al.*, 1995; Stahle *et al.*, 2000; Cleaveland *et al.*, 2003; Hidalgo, 2004; Piechota *et al.*, 2004). Although this drought is present in the Uinta Mountains paleohydrology reconstructions, it is not extraordinarily harsh compared with some other droughts in these records. The reasons for this are not clear, although it could indicate that the Uinta Mountains region is not as sensitive to some climatic forcing factors that produce a more uniform hydrological response in other regions, but tree-ring chronology characteristics may also play a role.

The Little Ice Age (ca. 1650-1850) was a period of near global alpine glacier advance (e.g., Jones and Bradley, 1992). However, there is no geomorphological expression of this in the Uinta Mountains (Munroe, 2002). Carson and Munroe (2005) suggest that this could be due to low precipitation in the Uinta Mountains, which appears to be confirmed by these reconstructions. In particular, the 18th Century was characterized by large concentrations of dry years and several multiple dry year events in all three reconstructions.

Pacific and Atlantic Ocean Impacts on Streamflow and Snowpack

Intermittent variability is present in wavelet power spectra for the Uinta Mountains paleohydrology reconstructions (Figure 4). The power between roughly 16 and 64 years (PDO and AMO variability) (e.g., Enfield *et al.*, 2001; Mantua and Hare, 2002) is strong in all three records from ca. 1500-1800. This largely disappears in the DU and LF records during the 19th Century, which is reflected in these records by a period of low variability. The absence of PDO/AMO frequency range variability in the IC snowpack reconstruction commences somewhat sooner, during the 18th Century, and is also associated with low variability in the record. This difference is probably related to the particular location of Indian Canyon and the tree-ring chronology used in the reconstruction. ENSO frequency range variability is present in all reconstructions in the 2- to 10-year time band (e.g., Philander, 1990), but persists intermittently.

Pearson correlation coefficients evaluated over respective periods of instrumental and reconstructed

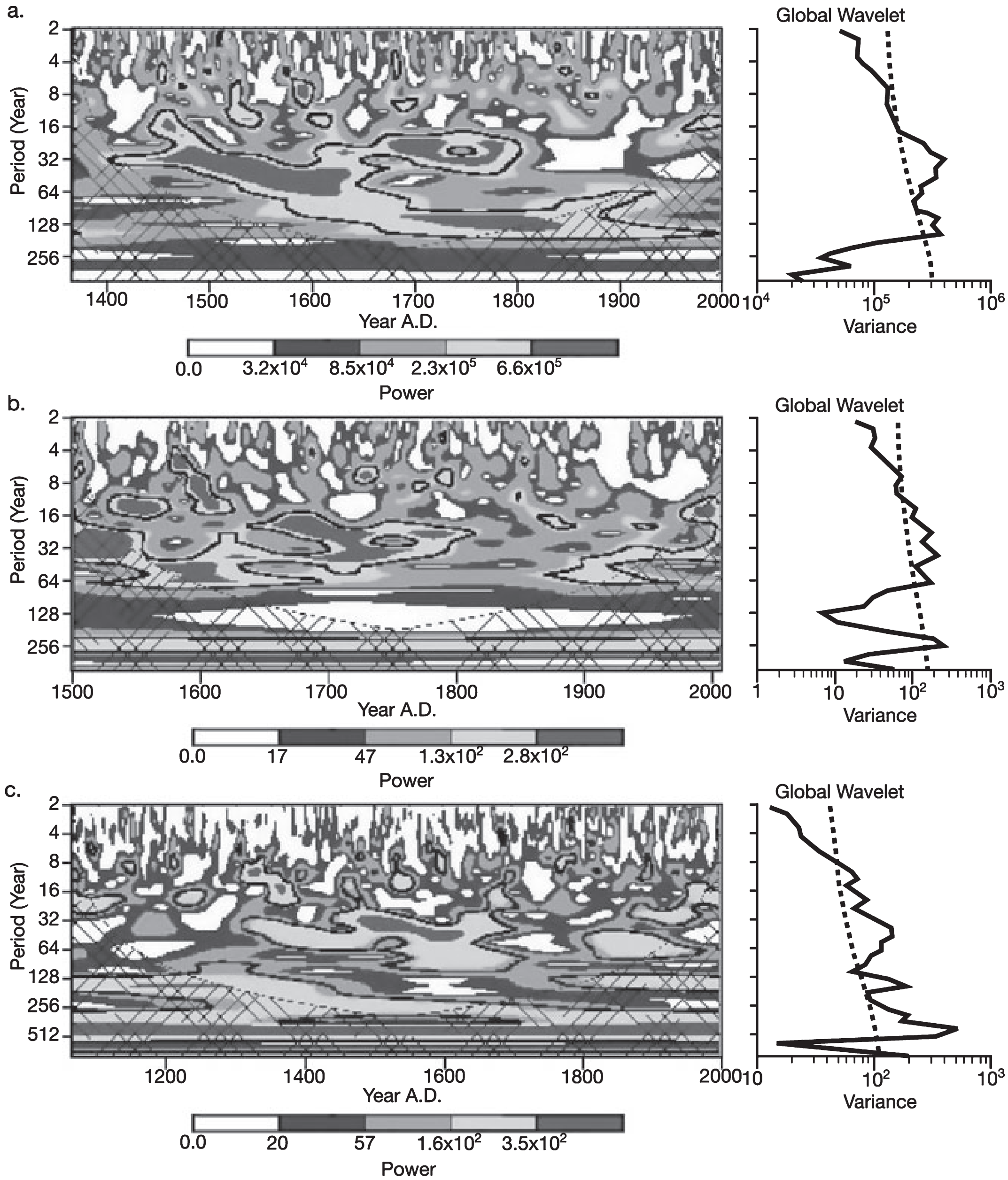

FIGURE 4. Wavelet Power Spectra for (a) DU Streamflow, (b) LF Snowpack, and (c) IC Snowpack Reconstructions. Bold black lines indicate confidence at the 5% level against a white noise background spectrum. Hatched lines delineate the cone of influence that envelops regions of the power spectrum not within the 95% confidence interval due to edge effects. The dashed line on the global wavelet plot indicates significance at the 5% level against a white noise background spectrum. Note that the time scales of each wavelet analysis differ depending on reconstruction length.

data overlap are shown in Table 4. The instrumental hydrological data appear to have the most robust relationship with SOI, but are not significantly correlated with SOI, PDO, or AMO. Correlations between reconstructed data are somewhat higher in magnitude, which could indicate the presence of stronger teleconnections prior to the start of the instrumental records and/or to regional coherence between the tree-ring chronologies. The DU and LF reconstructions are both significantly correlated with SOI and PDO. The signs of the coefficients suggest that warm eastern Pacific SSTs during El Niño and positive PDO events increase streamflow and snowpack, whereas cool eastern Pacific SSTs during La Niña and negative PDO events have the opposite impact. IC snowpack is also negatively correlated with SOI but does not have a significant correlation with PDO. The reason for this is not clear, but could be related to the location of

TABLE 4. Pearson Correlation Coefficients for DU Streamflow, LF Snowpack, and IC Snowpack With Instrumental and Reconstructed SOI, PDO, and AMO.

	SOI_I	PDO_I	AMO_I	SOI_R	PDO_R	AMO_R
DU	−0.138	0.032	−0.069	−0.242*	0.226*	−0.156
LF	−0.157	−0.079	0.121	−0.220*	0.314†	−0.168
IC	−0.209	−0.048	0.003	−0.250*	0.200	−0.043

Notes: I, instrumental data; R, reconstructed data.
*$p > 0.01$.
†$p > 0.001$.

Indian Canyon and/or the sensitivity of the chronology used in the IC reconstruction. None of the reconstructions are significantly correlated with AMO, but the consistently negative sign of the correlation coefficient suggests that there may be an association between positive AMO and drought, as suggested by Enfield *et al.* (2001).

Fifty-year moving correlations between the Uinta Mountains paleohydrology reconstructions and SOI, PDO, and AMO (Figures 5a to 5c) demonstrate that relationships between streamflow and snowpack in the Uinta Mountains region and ocean SST anomalies not only exhibit nonstationarity over the long-term, but in some cases change sign. Wavelet coherence between the DU, LF, and IC records and the SST index reconstructions (available as supplementary material online) at frequencies characteristic of ENSO (2-8 years), PDO (15-25 years), and AMO (65-80 years) suggests that these correlations do represent, at least in part, associations between Uinta Mountains hydrology and SST variability. However, coherence is not always significant at the 95% confidence level when correlations are, which may be due to occasional coherence at other timescales. Reasons for this include regional climatic coherence unrelated to the particular mode of SST variability reconstructed as well as SOI, PDO, and AMO teleconnection stability with the sites from which the tree-ring chronologies used to reconstruct them were collected.

Relationships with SOI are relatively weak and often insignificant for the Uinta Mountains paleohydrology reconstructions, which is consistent with the wavelet analysis. Although ENSO influence appears infrequent, these coefficients maintain relatively steady values and signs compared with PDO and AMO correlations. The most prolonged periods with significant correlations occurred during the early to mid 18th, mid to late 19th, and 20th Centuries. These are all associated with somewhat higher amplitude SOI variability, which may imply stronger forcing on climate. However, reconstructed data may imply periodically more robust relationships between Uinta

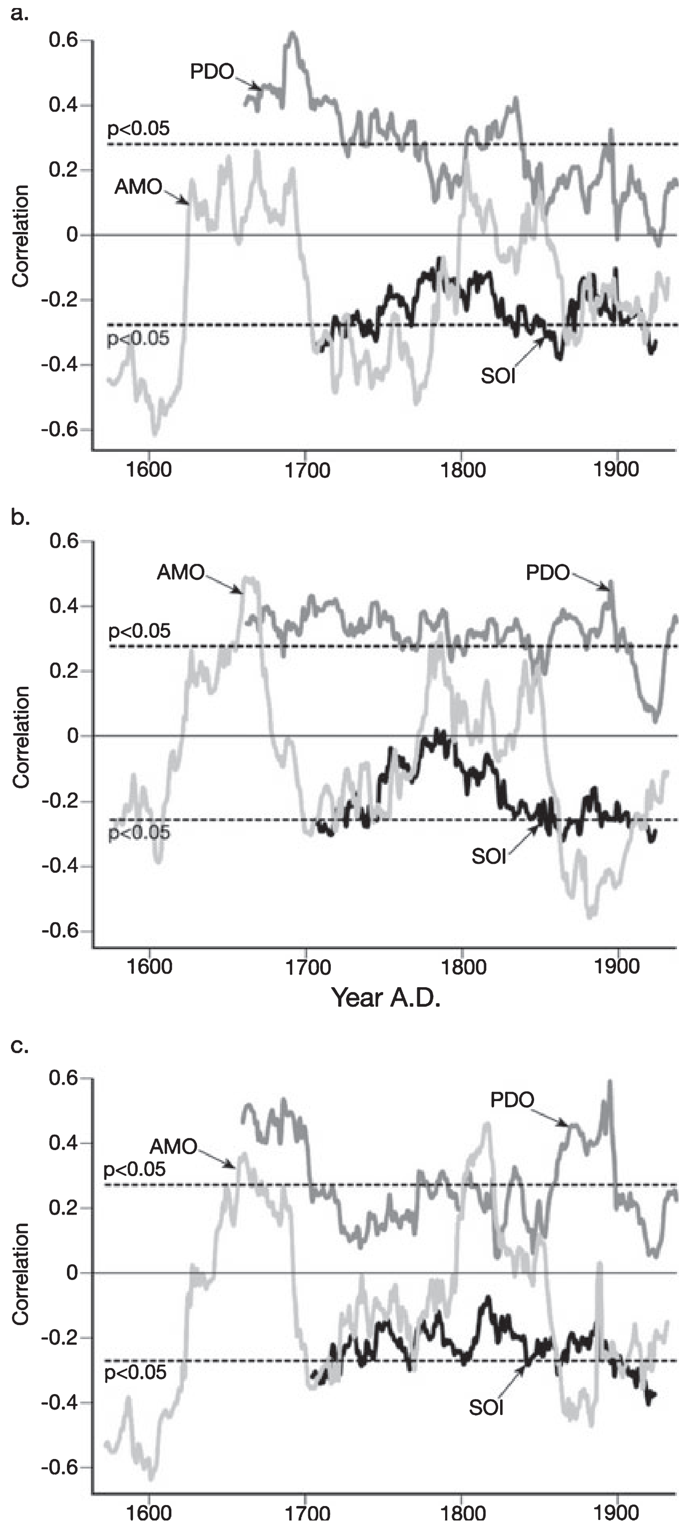

FIGURE 5. Moving 50-Year Window Pearson Correlation Coefficient Values for Reconstructed DU Streamflow (a), LF Snowpack (b), and IC Snowpack (c) With Reconstructed SOI, PDO, and AMO. Coefficients are plotted at the first year of each 50-year period. Dashed lines indicate significance at the 5% level.

Mountains paleohydrology and ENSO than instrumental records due to regional coherence between the northeastern Utah tree-ring datasets and the chronologies used to reconstruct SOI.

PDO appears to have a somewhat more continuous significant relationship with the streamflow and snowpack records. However, correlations are periodically insignificant between 1750 and 1850, when the 16- to 32-year signal was largely absent from the wavelet plots for the DU, LF, and IC reconstructions. The PDO index values display relatively strong variability during this time, so this may reflect weak teleconnections to the Uinta Mountains region. Correlations starting in the late 17th Century are notably strong, and are associated with generally negative PDO index values, indicating that droughts that occurred around this time may be linked with a relatively cool northeastern Pacific. Positive correlations beginning toward the end of the 19th Century are also coincident with cool northeastern Pacific SSTs and drought in the Uinta Mountains region. Correlations between the PDO and all three reconstructions are largely insignificant during the 20th Century, which is consistent with the analysis using instrumental data.

These seemingly inconsistent teleconnections with Pacific Ocean SST variability may have to do with the location of the Uinta Mountains region close to the center of the geographic dipole of Pacific Ocean influence on hydroclimatology. Warm phases of ENSO (El Niño) and PDO are associated with increased precipitation in the American Southwest and lower precipitation in the Pacific Northwest; cool ENSO (La Niña) and PDO have the opposite effect (Redmond and Koch, 1991; Mantua *et al.*, 1997; Nigam *et al.*, 1999; Barlow *et al.*, 2001; Mantua and Hare, 2002; Brown and Comrie, 2004). The center of this dipole lies close to the latitude of the Uinta Mountains region (Redmond and Koch, 1991; Mantua *et al.*, 1997; Nigam *et al.*, 1999), so subtle shifts in its position may have the potential to significantly alter ENSO and PDO-related impacts on northeastern Utah hydrology.

The AMO appears to have the least consistent relationship with the Uinta Mountains paleohydrology records. All three reconstructed hydrological variables exhibit significant negative correlations with AMO from the late 16th through mid 17th Centuries. These negative correlations are coincident with negative AMO index values and severe droughts in the Uinta Mountains region. DU, LF, and IC are also negatively correlated with AMO during parts of the 18th Century. This period was characterized by weak to moderately positive AMO index values and negative PDO index values. This interaction between Pacific and Atlantic Ocean conditions may have led to 18th Century aridity. The reconstructions are also negatively correlated with positive AMO index values at the end of the 19th Century, which was also characterized by drought in the Uinta Mountains region. The snowpack reconstructions also exhibit two periods of significant positive correlations with the AMO index beginning in the late 17th Century and again around the start of the 19th Century. During the former, the AMO index was consistently positive and streamflow and snowpack were elevated at times. At the time of the latter, the AMO index was generally negative and snow pack at both locations was consistently near median values.

Reasons for these unstable correlations between Uinta Mountains hydroclimate and AMO are unclear. They could be related to regional coherence, although this is unlikely because none of the tree-ring chronologies used in AMO index reconstruction are from the western U.S. Thus, these unstable correlations might reflect changes in teleconnections between Atlantic Ocean SSTs and northeastern Utah hydrology. This could be due to alterations in Pacific and Atlantic Ocean interactions and the positioning of the precipitation dipole discussed earlier. In the case of the annual streamflow record, this instability could also potentially be related to variability in a linkage between AMO and the North American Monsoon (e.g., Hu and Feng, 2008).

Overall, this analysis suggests that although connections may exist between SST variability and Uinta Mountains hydroclimate, these relationships are relatively weak and unstable over time. The lack of strong associations between SST variability and northeastern Utah hydrology over the instrumental period confirms previous work in this region (e.g., Cayan and Peterson, 1989; Cayan *et al.*, 1999; Hidalgo and Dracup, 2003; MacDonald and Tingstad, 2007; McCabe *et al.*, 2007), and could reflect particularly weak teleconnections during the 20th Century. However, this also implies that results from paleoclimate data should be interpreted with caution.

Magnitude of Impact of Ocean Variability on Uinta Mountains Region Hydrology

Ocean conditions with significantly different impacts on Uinta Mountains paleohydrology as determined through Wilcoxon rank sum tests are listed in Table 5 along with the magnitudes of resulting shifts in streamflow and snowpack as a percent of the 1706-1977 mean. ENSO and PDO both have significant individual effects on streamflow and snowpack. Although there is no added impact from combining El Niño with positive PDO over El Niño alone, La Niña and negative PDO lead to worse droughts

TABLE 5. Ocean States Associated With Significantly Different Hydrological Conditions as Determined by Wilcoxon Rank Sum Tests and Resulting Shifts in Streamflow and April 1 SWE as a Percentage of Long-Term Mean (1706-1977).

Ocean Conditions	DU Streamflow % of Mean	Ocean Conditions	LF Snowpack % of Mean	Ocean Conditions	IC Snowpack % of Mean
SOI+/PDO−/AMO+	82	SOI+/PDO−	90	SOI+/PDO−	91
SOI+/AMO+	84	SOI+/PDO−/AMO+	91	SOI+/PDO−/AMO+	92
SOI+/PDO−	86	SOI+/AMO+	93	SOI+/AMO+	93
PDO−/AMO+	89	PDO−/AMO+	93	SOI+	94
SOI+	90	PDO−	94	PDO−	94
PDO−	94	SOI+	95	PDO−/AMO+	95
AMO +	94	AMO +	96	AMO +	99
AMO−	106	AMO−	103	AMO−	101
PDO+	106	SOI−	103	SOI−/PDO+	104
SOI−/PDO+	107	SOI−/PDO+	103	SOI−	104
SOI−	107	PDO+	106	PDO+	104
PDO+/AMO−	109	SOI−/AMO−	107	PDO+/AMO−	104
SOI−/AMO−	111	PDO+/AMO−	109	SOI−/AMO−	104
SOI−/PDO+/AMO−	114	SOI−/PDO+/AMO−	112	SOI−/PDO+/AMO−	107

than either condition individually. For example, the mid-18th Century drought in the Uinta Mountains was coincident with the combination of cool eastern Pacific SSTs and La Niña events in 1748, 1752, and 1755. Differences in hydrology for AMO index values are significant for DU and LF, but not for IC. Furthermore, combining positive AMO with positive SOI or negative PDO enhances drought (e.g., AMO+/PDO− conditions prevailed during the dry period centered ca. 1780), while joining negative AMO with negative SOI or positive PDO further increases wet conditions in the DU and LF records (e.g., a wet period in the early 19th Century was characterized by cool Atlantic SSTs, warm northeastern Pacific SSTs, and fairly strong El Niño events in 1800, 1804, 1816, and 1825). There is no added AMO impact in IC, likely because the relationship between this record and the AMO index is particularly unstable as determined in the moving correlation analysis. Finally, the largest magnitude increases and decreases in streamflow and snowpack are generated by SOI−/PDO+/AMO− (warm northeastern Pacific/cool northern Atlantic) (DU streamflow: +14%, LF snowpack: +12%, IC snowpack: +7%) and SOI+/PDO−/AMO+ (cool eastern Pacific/warm northern Atlantic) for DU streamflow (−18%) and SOI+/PDO− for LF snowpack (−10%)/IC snowpack (−9%), respectively. The Great Plains Drought of the 1950s and early 1960s was associated with PDO-/AMO+ and intermittent SOI+, as were portions of the dry 18th Century. The relatively higher magnitude impacts of ocean variability (AMO in particular) on DU may reflect its representation of annual, rather than seasonal, conditions. It is also important to note here that this analysis was performed over 1706-1977, the period common between all reconstructions, while the moving correlation analysis evaluated PDO and AMO relationships with Uinta Mountains region hydrology over somewhat longer time periods. For this reason, impacts of PDO and AMO in the DU, LF, and IC reconstructions may appear more stable in the Wilcoxon rank sum test analysis than over the longer time frames investigated using moving correlations.

Comparison With Previous Work

Several studies based on instrumental data have shown that El Niño and positive PDO conditions lead to increased streamflow and snowpack in the western U.S., whereas the opposite is true during La Niña and negative PDO events (e.g., Cayan and Peterson, 1989; Redmond and Koch, 1991; Piechota and Dracup, 1996; Cayan *et al.*, 1999; Dettinger and Diaz, 2000; Hidalgo and Dracup, 2003; Tootle *et al.*, 2005; Hunter *et al.*, 2006). Other work has demonstrated that AMO influences western U.S. hydrology; in particular, the positive AMO phase has been associated with drought (Enfield *et al.*, 2001; Tootle *et al.*, 2005; McCabe *et al.*, 2007). A number of studies suggest that PDO and AMO both influence hydroclimate in the western U.S. (e.g., McCabe *et al.*, 2004, 2007; Seager *et al.*, 2007), although the relative importance reported for each varies. Furthermore, some work has indicated that different phase combinations of SST variability enhance or diminish the hydrological effects of individual modes (e.g., Gershunov and Barnett, 1998; Enfield *et al.*, 2001). Although the analysis of instrumental hydrological data from the Uinta Mountains region is inconclusive overall, it does appear to indicate a positive relationship with ENSO, which is consistent with these other studies. Furthermore, the effects of SST variability on northeastern Utah hydrology determined in the Wilcoxon rank sum test analysis using paleoclimate data are compatible with previously published results based on instrumental observations.

However, this work also affirms the results of other research that suggests weak SST teleconnections to the northeastern Utah region during the 20th Century (e.g., Cayan and Peterson, 1989; Cayan *et al.*, 1999; Gray *et al.*, 2003; Hidalgo and Dracup, 2003; MacDonald and Tingstad, 2007; McCabe *et al.*, 2007).

Paleoclimate reconstructions indicate that ENSO, PDO, and AMO likely played a role in western U.S. hydroclimate prior to the start of reliable instrumentation (e.g., D'Arrigo and Jacoby, 1991; Gray *et al.*, 2003; Hidalgo, 2004; Meko and Woodhouse, 2005; MacDonald *et al.*, 2008; Timilsena *et al.*, 2009). Although the research discussed in this article generally confirms earlier work, it also differs in some ways. For example, Uinta Mountains region streamflow and snowpack reconstructions are generally consistent with work by Hidalgo (2004), who examined tree-ring based PDSI records for the western U.S., and suggested that variability in the 32- to 64-year frequency was high from ca. 1525-1650 and ca. 1850-1975, whereas variability in the 8- to 32-year frequency was stronger from ca. 1700-1825. However, unlike this broader regional study, results from the Uinta Mountains region indicate that ENSO drives a similar amount of variability to PDO and AMO. Timilsena *et al.* (2009) found similar relationships with ENSO, PDO, and AMO to those in this article in their analysis of several Colorado River Basin streams. However, Uinta Mountains records may suggest a somewhat more important role for AMO, although fewer hydrological reconstructions were examined in this case. Whereas Timilsena *et al.* (2009) found that the largest positive shifts in mean streamflow were associated with SOI−/PDO+, this research determined that the effects of SOI− and PDO+ are more greatly enhanced by AMO− than by each other. These results agree with those of Timilsena *et al.* (2009) who indicated that SOI+/PDO− generally fosters severe drought conditions, but the relationship shown here for DU streamflow is significantly enhanced when the AMO index is positive.

CONCLUSIONS

At the beginning of this article, three questions were posed:

1. How does 20th Century hydrology compare with preinstrumental variations in streamflow and snowpack in northeastern Utah?

Uinta Mountains region streamflow and snowpack reconstructions indicate that the 20th Century was wet relative to previous centuries. Notable dry periods occurred in the 13th, 16th, 17th, and 18th Centuries.

2. Does Pacific and Atlantic Ocean SST variability impact streamflow and snowpack in northeastern Utah and are these relationships stable?

Pacific and Atlantic Ocean variability may influence Uinta Mountains region hydrology, but these relationships are not consistent over time, and appear largely insignificant during the instrumental period. Connections with the Atlantic seem particularly unstable, and Pacific Ocean influence is at times insignificant. Teleconnections with the Uinta Mountains region may be most robust when ocean variability is strong. This makes sense given the interior continental location of the Uinta Mountains region and its position near the center of the geographic dipole of Pacific Ocean influence on hydroclimatology. However, analyses based on paleoclimate data must be interpreted with caution because of the potential for regional coherence and instability in teleconnections reflected in reconstructed SST variability indices.

3. What is the mean magnitude of ENSO, PDO, and AMO influence on northeastern Utah hydrology?

Although relationships between Uinta Mountains region hydrology and SST variability have changed over time, these appear to have been consistent enough that general inferences about the sign and magnitude of ENSO, PDO, and AMO impacts can be made. Wilcoxon rank sum tests demonstrate that significant differences in streamflow and snowpack occur between certain states of ocean variability. In general, strong El Niño, positive PDO, and negative AMO appear to contribute to wet conditions in the Uinta Mountains region, whereas La Niña, negative PDO, positive AMO are associated with droughts. The largest shifts in Uinta Mountains hydrology occur during SOI−/PDO+/AMO− and SOI+/PDO−/AMO+ or SOI+/PDO−. Eighteenth Century aridity in the Uinta Mountains region is associated with generally negative PDO index values, largely positive AMO index values, and frequent La Niña events.

This research has important implications for water management within the state of Utah and the western U.S. Relatively wet conditions during the 20th Century suggests that the robustness of long-term management strategies should be evaluated against paleoclimate records as well as scenarios based on instrumental data and climate models. In addition, although prediction of future water resources based on long-term ocean variability is made difficult due to the inconsistent nature of connections between northeastern Utah climate and SST anomalies and the complexity added by the potential for both Pacific and Atlantic conditions to influence the hydroclimatology of the region, long-range water management plans should be flexible given that SST variability may periodically significantly influence hydrology. Most notably, certain configurations of Pacific and Atlantic SST variations appear to have the potential to generate long-duration aridity events.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Wavelet Coherence Between the DU, LF, and IC Records and the SST Index Reconstructions.

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