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Recent and Multicentennial Precipitation Variability and Drought Occurrence in the Uinta Mountains Region, Utah

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Abstract

We examine instrumental meteorological records to compare recent precipitation regimes in the eastern and western Uinta Mountains region of Utah. The comparison demonstrates that, although the summer monsoon contributes a higher proportion of annual precipitation in the east, the two regions are significantly correlated in terms of precipitation variations including summer precipitation. Major droughts, such as the 1930s Dustbowl event, the 1976–1977 event, and the 1987–1989 event, are largely typified by strong decreases in winter precipitation, although deficits can extend into summer. Droughts generally impact the entire region when they occur. Unlike the Southwest and the Pacific Northwest, year-to-year precipitation variability in the Uinta Mountains region does not appear correlated with the El Niño–Southern Oscillation or the Pacific Decadal Oscillation. However, severe prolonged droughts such as the 1976–1977 and 1986–1987 events are related to decreases in eastern Pacific Ocean sea surface temperatures. We extend the record of hydroclimatic variability for the Uinta Mountains by using tree-ring chronologies from *Pinus edulis* (two-needle pinyon) to reconstruct the summer Palmer Drought Severity Index (PDSI) back to A.D. 1405. The analysis demonstrates that extreme droughts (PDSI < -4) and extended multiannual to multidecadal arid periods (PDSI < 0 to < -2) are a recurrent feature of the Uinta hydroclimatic regime. Extreme droughts of PDSI < -4 typically occur two to five times per century, with an annual probability of occurrence of ~4.4%. In the context of prolonged severe droughts, the 20th century enjoyed relatively moist conditions compared to the 17th, 18th, and 19th centuries. The most prominent of these earlier arid periods was an apparent 'mega-drought' between ca. A.D. 1625 and 1670 that is evident in prolonged depression of PDSI values in the Uinta Mountains region, decreased discharge of the Ashley River, and decreased precipitation in the adjacent Uinta Basin. There was a general depression of the Pacific Decadal Oscillation during this time, suggesting some linkage between conditions in the Pacific Ocean and prolonged aridity. Wavelet analysis demonstrates the presence of multidecadal variability in aridity, but the frequency and power of long-term modes of variability are inconsistent over the past 600 years.

Introduction

Over the period of historical and instrumental records, severe to extreme drought has been a recurrent feature of the Uinta Mountains region and Utah in general. For example, during the Dust Bowl years a sharp decrease in winter precipitation centered on 1934 produced 65% to 75% declines in supplies of irrigation water in the state of Utah and necessitated large infusions of funds from the Federal Emergency Relief Administration. That drought prompted increased development of water storage infrastructure, including structures such as Pineview Dam near Ogden and Moon Lake Dam in the Uintas (Arrington, 1986). Utah was greatly affected during the 1976–1977 U.S. drought, and many municipal water districts were forced to raise water rates, restrict times of water use, and/or limit maximum water consumption (Narayanan et al., 1983). During the 1987–1989 North American drought the Uinta Mountains region was the most severely impacted area of the state, experiencing extreme drought conditions as indicated by Palmer Drought Severity Index (PDSI) values of -4 (Riebsame et al., 1991). Data from the National Drought Mitigation Center shows that the Uinta Mountains region experienced severe to extreme drought conditions (PDSI of -3 to <-4) 10% to 15% of the years between 1895 and 1995. Severe droughts, particularly multiannual episodes, affect ecological functioning through impacts on lake and stream water levels, fire regimes, plant pathogens, and plant functioning. Severe droughts also impact the availability of water for local consumption and irrigation. Finally, drought in eastern Utah decreases the supply of water to the Colorado River system, which is critical for irrigation and consumption as far away as northwestern Mexico. Resource management in the Uinta Mountains should incorporate as much information as possible on the current precipitation and drought regime of the region. It is also important to have an understanding of the potential for droughts that are more severe and prolonged than those experienced in the historical period.

In this paper we examine instrumental climate records to outline historical spatiotemporal patterns of precipitation variability in the Uinta Mountains and adjacent flanks. Specifically,

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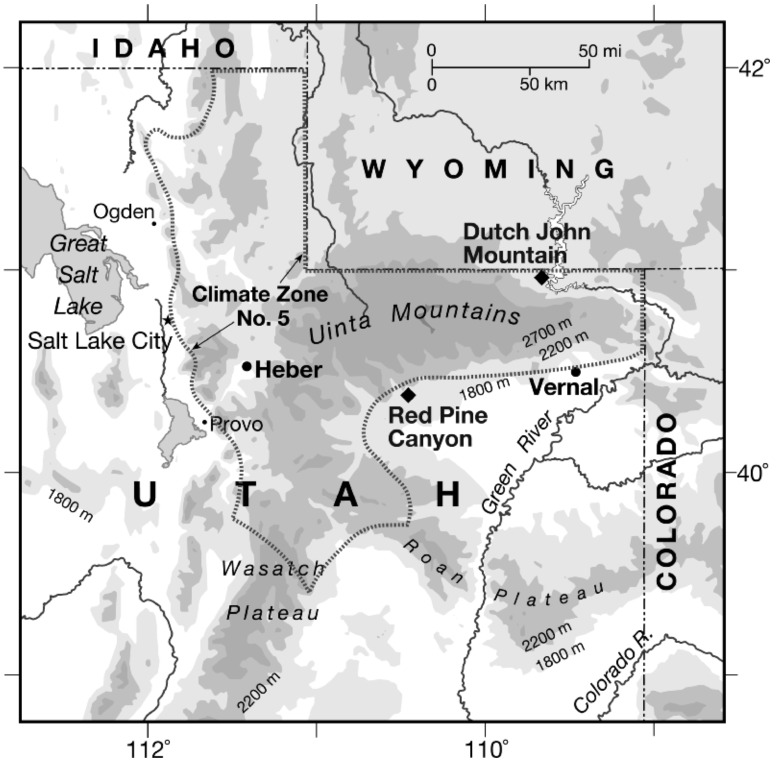

FIGURE 1. The Uinta Mountains study area, Vernal and Heber climate station sites, Climate Division 5 boundaries, and the *Pinus edulis* sites (Gray et al., 2004) used for climate reconstruction.

we explore differences in precipitation and drought between the eastern Uintas, which are sometimes considered to be more influenced by the summer monsoon, and the western Uintas. We then use recently acquired tree-ring records to produce an extended record of PDSI for Utah Climate Zone 5, which encompasses the Uinta Mountains, and further explore the range of natural severity and persistence of droughts.

Historical Patterns of Precipitation Variability and Drought

The Uinta Mountains (Fig. 1) are an east-west–trending range with maximum elevations of over 4000 m a.s.l. Although long-term meteorological records are not available from the high elevations, such records are available from the eastern flanks of the range at Vernal, Utah (~1609 m a.s.l.) and on the western flanks at Heber, Utah (~1718 m a.s.l.). The station records have a usable common period of A.D. 1928–2005. To capture the most direct picture of recent climate variability, we used the actual station records rather than reanalyzed gridded data. Years in which observations were missing for either or both stations were removed from the data set. In addition, regional composite values for monthly precipitation, temperature, and other climatic variables are available for the period A.D. 1895–2000 for Utah Climate Division 5 (Fig. 1). All historical station and climate division records used here were obtained from the United States Historical Climatology Network (http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html) and the National Climate Data Center (http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgr.html#ds).

Climagraphs from Vernal and Heber show a somewhat inverse relationship in the seasonal timing of precipitation maxima (Fig. 2). Vernal experiences highest monthly precipitation during the warm season of April–October, with lowest totals in December, January, and February. Heber experiences greatest precipitation in the cold season, with lowest values in June, July, and August. Precipitation from June through August contributes ~23% of the total annual precipitation at Vernal and only ~17% at Heber. Although northern Utah lies at the periphery of the Southwest monsoon region as defined by Mock (1996), the decrease in relative importance of summer precipitation from Vernal to Heber is consistent with a continental pattern of decreasing relative importance of monsoonal precipitation northwestward from northern Mexico. A mapped analysis by Higgins et al. (1997) shows that precipitation from July, August, and September makes up 50% of the annual total along the U.S.-

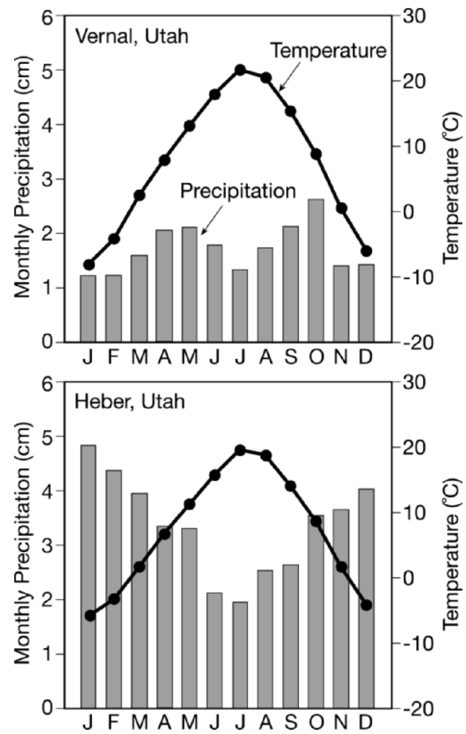

FIGURE 2. Vernal and Heber climagraphs based upon a common period of 1928–2005.

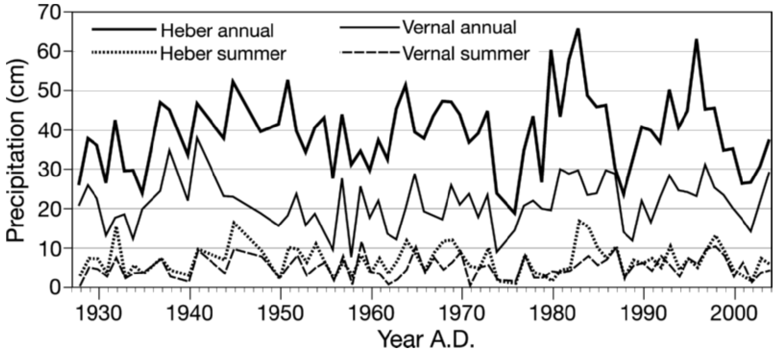

FIGURE 3. Vernal and Heber annual and summer (JJA) precipitation time-series.

Mexico border, decreases to 35% in southeastern Utah, 25% in the eastern Uinta region, and 20% in the western Uinta region.

Controls on Southwest monsoon variability, particularly in a distal region such as the Uinta Mountains, are complicated. The Gulf of California (Sea of Cortez) and Gulf of Mexico are the two sources of precipitable water for the Southwest and adjacent regions during the monsoon. The monsoon track impacting Utah and the Uinta region is generally typified by northward flow from the Gulf of California along the western flank of the Rockies (Mock, 1996; Higgins et al., 1997). However, determining the actual proximate source of moisture for Utah monsoon events is complex and linked to the vertical structure of the moisture transport. Higgins et al. (1997) found that in the Southwest, most of the moisture below 850 hPa comes from the Gulf of California, while most of the moisture above 850 hPa comes from the Gulf of Mexico. Monsoonal 'surge' events, during which precipitatable moisture increases by 50% in New Mexico and Arizona, and by as much as 25% in Utah, are typified by the convergence of moist airmasses from both the Gulf of California and the Gulf of Mexico over New Mexico and Arizona (Higgins et al., 1997). Annual variability in the strength of the Southwest monsoon can reflect a number of factors. Antecedent winter conditions of high soil moisture and large snowpack in the Southwest can decrease summer warming and lessen the strength of the monsoon. Such conditions are associated with warmth in the eastern North Pacific that enhances winter precipitation in the Southwest (Higgins and Shi, 2000). To determine if antecedent winter precipitation conditions in the Uintas produce a regular influence on the strength of summer monsoon penetration to the region, we compared winter (JFM) and summer (JJA) precipitation totals using data from both Heber and Vernal. We did not find the two seasons to have either a significant negative or positive correlation.

Several other facets of the precipitation distribution deserve consideration. First, while total annual precipitation at the eastern site is only about half as much as the western site (the average at Vernal being ~21 cm compared to ~39 cm at Heber), the summer precipitation totals (June–August) are much closer in magnitude (4.87 cm at Vernal and 6.71 cm at Heber) despite the greater relative contribution of the monsoon to total precipitation at Vernal. Therefore, the relative importance of the monsoon in the east more reflects the lack of eastward penetration of winter storm precipitation than it reflects greatly enhanced summer precipitation in the east. Second, summer precipitation totals (Fig. 3) at Heber and Vernal are more highly correlated ($r = 0.65$, $p < 0.05$) than winter or annual precipitation ($r = 0.47$, $p < 0.05$). This further suggests that failure of the monsoon to penetrate westward to Heber, while remaining strong in Vernal, is not a major feature of spatiotemporal precipitation variability. The finding that summer precipitation strongly covaries in the eastern and western Uintas is entirely consistent with the fact that most of the monsoonal flow impacting the region originates in the Southwest and follows a generally south to north trajectory (Higgins et al., 1997). Variations in the strength of the monsoon in terms of actual amounts of precipitation (rather than amounts relative to winter precipitation) should be expected to covary in the eastern and western Uintas. Finally, arid periods, including episodes of hydrologic drought where annual precipitation is >1 standard deviation below the long-term average, tend to occur synchronously in Heber and Vernal (Fig. 3) and are strongly influenced by failure of winter season precipitation. Examples include the 1934 drought, the 1977 drought, and the 1988 drought. Such synchronous droughts in the east and the west, largely driven by failure of winter precipitation, are clearly a common feature of the Uinta Mountains regional climate.

Annual precipitation variations at Vernal and Heber are significantly correlated ($r = 0.49$ and $r = 0.67$, respectively; $p \leq 0.05$) with annual variations in PDSI for Utah Climate Division Zone 5 (Fig 4). PDSI incorporates precipitation, temperature, and soil moisture deficit and the persistence of such deficits from month to month to derive a temporally integrated measure of monthly to seasonal and annual drought. The PDSI provides a more complete picture of prolonged drought severity than simple precipitation records (Palmer, 1965). Monthly PDSI values are significantly correlated with each other and with annual values in the Utah Division 5 series (average cross-correlations, $r > 0.90$, $p \leq 0.01$). The PDSI data clearly show the extreme severity of the

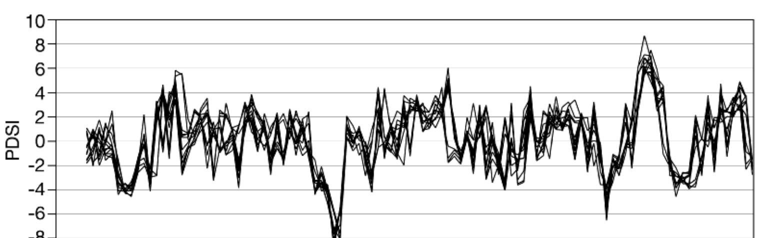

FIGURE 4. Stacked traces of all 12 months of Palmer Drought Severity Index (PDSI) from 1895–2000 for Utah Climate Division 5.

TABLE 1

Calibration and verification statistics* for June–August PDSI reconstruction model.

Model and calibration period	r^d	$r^2_{adj}{}^e$	Verification period	r^f	RE[g]	CE[h]
FULL[a]	0.65	0.40				
EARLY[b]	0.68	0.44	LATE	0.60	0.12	0.25
LATE[c]	0.68	0.42	EARLY	0.65	0.21	0.42

[a] FULL Model PDSI = −8.007 + ([4.020 × DJM] + [1.464 × DJMPriorYrRing] + [2.134 × RPC]). Calibration period extends 1895–2000.
[b] EARLY Model PDSI = −8.906 + ([2.126 × DJM] + [1.521 × DJMPriorYrRing] + [4.108 × RPC]). Calibration period extends 1895–1947; verification period extends 1948–2000.
[c] LATE Model PDSI = −7.805 + ([5.231 × DJM] + [0.434 × DJMPriorYrRing] + [1.524 × RPC]). Calibration period extends 1948–2000; verification period extends 1895–1947.
[d] r = multiple correlation coefficient.
[e] r^2_{adj} = squared multiple correlation coefficient adjusted for degrees of freedom.
[f] r = correlation coefficient between model and observational data not used to construct model.
[g] RE = Reduction of Error (values > 0 considered acceptable).
[h] CE = Coefficient of Efficiency (values > 0 considered acceptable).
* All testable statistics significant at $p \leq 0.05$.

1934 Dustbowl drought relative to the less extreme 1976–1977 and 1987–1989 droughts (Fig. 4).

Precipitation variability in subregions of western North American is often linked to the 2- to 7-year variations in sea surface temperatures in the eastern Pacific typical of El Niño/La Niña variability (Ropelewski and Halpert, 1986; Redmond and Koch,1991; Cayan, 1996). Hydrological variability is also linked at lower frequencies to the longer term bidecadal to multidecadal variability manifest in the Pacific Decadal Oscillation (PDO) (Nigam et al., 1999; Minobe, 2000; Mantua and Hare, 2002; Brown and Comrie, 2004; MacDonald and Case, 2005). In both cases, droughts in the Southwest and southern Rockies are promoted when cooler temperatures propagate from the eastern equatorial Pacific northward along the west coast of North America (La Niña conditions; negative PDO conditions). During these same periods, increased precipitation and larger snowpack are often experienced in the Pacific Northwest and northern Rockies (Cayan, 1996). However, the Uinta region lies between the two precipitation dipoles that are associated with the El Niño/La Niña and PDO modes of climatic variability. Hydroclimatic conditions in the region are generally not highly correlated with these two phenomena (Redmond and Koch, 1991; Nigam et al., 1999; Woodhouse, 2003). We found no significant correlation between annual PDSI values for Climate Division 5 (Fig. 4) and either the El Niño–Southern Oscillation (ENSO) Index or the PDO Index. We also conducted a year by year comparison of Utah Division 5 PDSI values and the occurrence and strength of individual El Niño and La Niña events from 1933 to 2000 and found no association between these events and either individual peaks or depressions in PDSI (data from the Western Regional Climate Center at http://www.wrcc.dri.edu/enso/ensodef.html). Although semicontinental droughts such as those of 1976–1977 and 1987–1989 are associated with cold water anomalies in the eastern Pacific (Namias, 1978; Trenberth et al., 1988), year-to-year precipitation variability in the Uinta Mountains region may be driven more by random variations in storm track position and frontal storm strength, and by complex interactions of variations in both the Pacific and Atlantic Oceans that impact climate in the central portions of the continent (Enfield et al., 2001; Woodhouse, 2003; Gray et al., 2004a; McCabe et al., 2004). These factors raise challenges to predicting drought occurrence and persistence in the region.

A Long-Term Record of PDSI

We used tree-ring width chronologies from *Pinus edulis* Engelm. (two-needle pinyon pine) trees growing near the northern and southern flanks of the Uinta Mountains to produce an ~600-year reconstruction (A.D. 1405–2001) of PDSI for Utah Climate Division 5. The extended PDSI record allows for the placement of 20th century droughts within the longer context of natural drought variability and also allows for the detection of long-term trends in drought. The chronologies are from the Dutch John Mountain and Red Pine Canyon sites (Fig. 1) reported by Gray et al. (2004b). Full details on the chronologies can be found in that publication. The two sites were chosen because they lie on the southern (Red Pine Canyon) and northern (Dutch John Mountain) flanks of the Uintas, unlike the other sites available from Gray et al. (2004b), which lie further south within the Uinta Basin area. The average PDSI values for Utah Climate Division 5 for the summer period (June, July, August) were used for calibration and verification of the reconstruction model. Applying standard dendroclimatological methods (Fritts, 1976; Cook and Kairiukstis, 1990), a linear multiple-regression model was developed to estimate summer PDSI back to A.D. 1405. Summer PDSI provided the best reconstruction model as it corresponds to the period when drought is most strongly represented in PDSI records and the period of tree growth. Over the period of record, summer PDSI is highly correlated with annual PDSI in the region (r = 0.94, $p \leq 0.01$) and provides a good measure of overall drought conditions (Fig. 4). The calibration-verification period for developing the model extended from A.D. 1895 to 2000. The temporal robustness of tree-ring estimates of PDSI was tested by dividing the PDSI calibration series into two halves (1895–1946 and 1947–2000), constructing multiple-regression models from each of the two shorter calibration periods, and then applying them to the tree-ring index values from the other calibration period. Each of these models had adjusted r^2 values of 0.40 or greater and had acceptable verification statistics (Table 1). The reconstruction based on the full calibration period (1895–2000) captures about 40% of the total variation in the observed PDSI values (Table 1; Fig. 5). The correlation statistics for the model are acceptable, but not as high as those obtained by Gray et al. (2004b) for the Uinta Basin study. Obtaining more tree-ring sites from Utah Climate Division 5 would potentially increase the amount of variance explained by dendroclimatic models for the

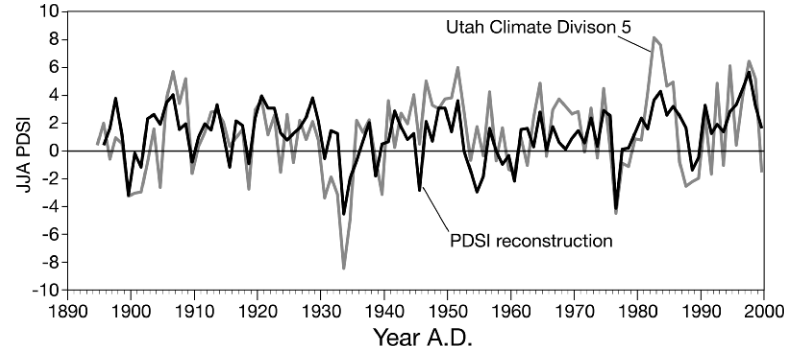

FIGURE 5. Observed summer PDSI (JJA) for Utah Climate Division 5 (gray line) compared to summer PDSI reconstructed (black) from *Pinus edulis* tree-rings from the Uinta Mountains region (tree-ring chronologies from Gray et al., 2004b).

region. As is typical in many dendrohydrological models, the reconstruction underestimates peaks in wet years and some of the troughs in PDSI during individual dry years (Fig. 5).

The PDSI reconstruction (Fig. 6) is significantly correlated with both the Uinta Basin precipitation reconstruction of Gray et al. (2004b), which is based on climate data from Utah Climate Division 6 to the southeast of the Uinta Mountains, and a reconstruction of discharge of the Ashley River, which is located in the Uinta Mountains (Carson and Munroe, 2005) (Fig. 7). The correlation with the Uinta Basin reconstruction is $r = 0.72$, $p \leq 0.01$, while the correlation with the Ashley River reconstruction is $r = 0.30$, $p \leq 0.05$. The Uinta Basin and Ashley River reconstructions are not significantly correlated with each other. The Uinta Basin reconstruction is not completely independent of our PDSI reconstruction as it also employs the Dutch John Mountain and Red Pine Creek chronologies. However, the Uinta Basin precipitation reconstruction also incorporates several other *Pinus edulis* chronologies from sites south and east of our study area. The Ashley River reconstruction uses a completely different set of chronologies and includes other species of trees. The correlation between our PDSI reconstruction and these earlier reconstructions supports the general veracity of the PDSI reconstruction. The fact that the Ashley discharge is not significantly correlated with the Uinta Basin reconstruction highlights the need for more tree-ring sites and more local and regional reconstructions to capture the spatial differences in past hydrologic variations.

In order to examine for periodic to quasi-periodic variability in drought behavior, the PDSI reconstruction was subjected to wavelet analysis (Torrence and Compo, 1998). Wavelet analysis decomposes time-series into time/frequency space simultaneously to derive information on the amplitude of repeated signals and how the amplitude varies with time. The wavelets are waveforms of a limited duration that are repeated in the series. This differs from classical Fourier analysis, which decomposes the signal into sine waves of various frequencies. Sine waves, by their very nature, are smooth and regular in periodicity. In contrast, wavelets can be irregular. The significance ($p \leq 0.10$) of peaks in the wavelet power spectrum was tested against an autoregressive red-noise background spectrum. Wavelet analysis (Fig. 8) of the period A.D. 1405–2000 indicates that overall there is significant power in the ~20- to 30-year band and the ~60- to 100-year band. This is

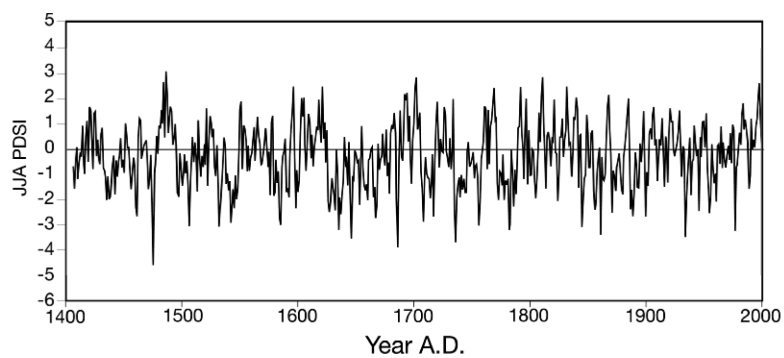

FIGURE 6. Reconstructed summer PDSI (JJA) for Utah Climate Division 5 based on *Pinus edulis* tree-ring chronologies from the Uinta Mountains region.

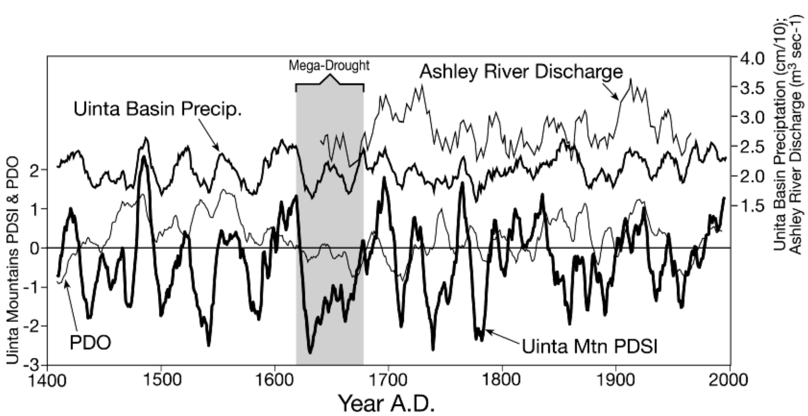

FIGURE 7. A comparison of the smoothed (11-year moving average) Summer PDSI, for Utah Climate Division 5 (Uinta Mountains), Ashley River discharge (Carson and Munroe, 2005), Utah Climate Division 6 (Unita Basin) annual (June–June) precipitation (Gray et al., 2004b), and Pacific Decadal Oscillation (PDO) (MacDonald and Case, 2005).

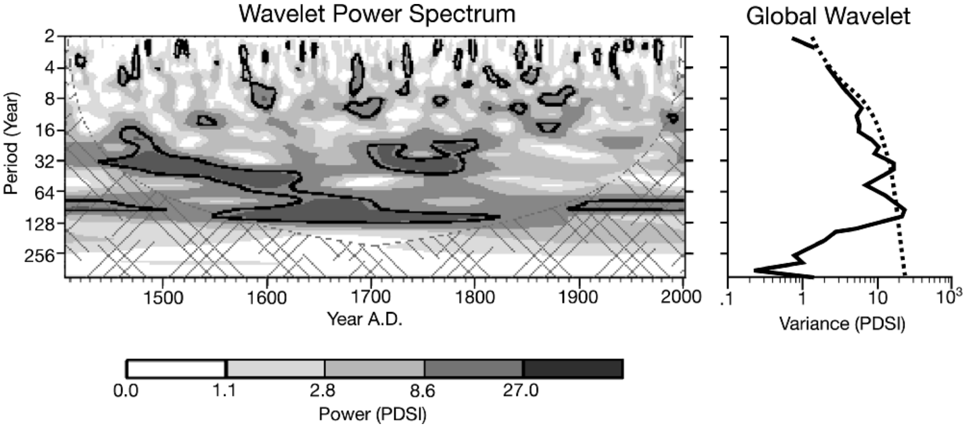

FIGURE 8. Wavelet power spectrum and global wavelet (Torrence and Compo, 1998) for the summer PDSI reconstruction for Utah Climate Division 5. The shaded contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level. The cone of influence, where edge effects due to zero padding result in decreased power, is indicated by the cross-hatched region. The 10% significance level is indicated by black outlining on the power spectrum and a dashed line on the global wavelet.

consistent with lower frequency variations observed in both North Pacific and North Atlantic SSTs and associated modes of ocean variability such as the PDO and Atlantic Multidecadal Oscillation (Gray et al., 2004a; MacDonald and Case, 2005). However, in the Uinta Mountains region significant variability in either the bidecadal and multidecadal bands is not stable and tends to shift in frequency and loses significance over some periods. There is notable weakening or absence from approximately 1800 to 1900 (Fig. 8).

We examined the correlations among the Unita Mountains PDSI reconstruction, the Uinta Basin precipitation reconstruction and the Ashley discharge reconstruction, and a reconstruction of the PDO (MacDonald and Case, 2005). In all cases, there was a weak, but significant, correlation between the PDO and the hydrological reconstructions. Over their common periods the correlations with the PDO were $r = 0.18$, $p \leq 0.05$ for the PDSI and precipitation reconstructions, and $r = 0.24$, $p \leq 0.05$ for the Ashley River discharge reconstruction. Examination of the four time-series (Fig. 7) shows that there are periods when they share common behavior and periods of time when the PDO appears to behave in an opposite fashion to the other measures. Long-term changes in the eastern Pacific as captured by the PDO appear to influence hydrology within the Uinta Mountains and Basin, but are not dominant. Therefore, direct relationships between the PDO and hydrological variability are inconsistent.

In terms of water resources and environmental management in the Uinta Mountains region, the PDSI reconstruction and spectral analysis present several important insights:

First, episodes of severe drought (PDSI < -3) and extreme drought (PDSI < -4) are a common feature of the Uinta Mountain region over the past 600 years (Figs. 6 and 7). The severity of 20th century droughts is similar to earlier periods, with the exception of a very dry period (reconstructed PDSI < -6) centered on 1475. There have been 19 episodes of single year or multiyear extreme droughts (reconstructed PDSI < -4.0) over the past 500 years. On an annual basis the probability of experiencing an extreme drought is about 4.4%. The 1934 and 1976–1977 droughts are typical of such occurrences. Four or five of such events may occur in a century.

Second, prolonged periods of multiannual to decadal aridity (sustained PDSI values < 0 to < -3) are typical features of the past 600 years. In this regard, the 20th century has been relatively moist compared to preceding centuries. Our PDSI reconstruction, along with the Ashley River discharge reconstruction and the Uinta Basin precipitation reconstruction, indicate that the early to mid 17th century in particular, and portions of the 18th and 19th centuries, experienced prolonged (>10 years) dry conditions that would be unusually severe by 20th century standards (Fig. 7). These extended periods of aridity may have contributed to the lack of neoglacial activity apparent in the Uinta Mountains during the Little Ice Age (Munroe, 2002; Carson and Munroe, 2005). The most striking example of widespread extended drought occurred during a ~45-year period between 1625 and 1670 when PDSI only rarely rose above negative values, discharge was extremely low on the Ashley River, and the Uinta Basin experienced prolonged depression of precipitation (Fig. 7). This appears to be the most extensive 'mega-drought' in the present record. Interestingly, the 17th century drought corresponds with a period when PDO index values were generally negative (Fig. 7). This suggests a potential contribution by Pacific Ocean variability in the development of this prolonged drought. A prolonged period of drought is also evident in all three hydrological records commencing in the mid 19th century and persisting to ca. 1905. The PDO, however, is depressed for only part of this drought period.

Although the 17th century and late 19th century events appear to have impacted all three hydrology indices more or less synchronously, prolonged dry periods are not always synchronous, with the Ashley River discharge reconstruction being the most out of phase with the other two Utah records. In any case, the Uinta Mountains PDSI reconstruction along with the two earlier reconstructions strongly supports the contention that the region can experience longer episodes of general aridity and more frequent prolonged drought than has been experienced in the past century. In a similar vein, Gray et al. (2004b) also cautioned that 20th century precipitation may present an overly optimistic view of water resource availability in the Uinta Basin.

Third, based on the wavelet analysis it can be concluded that quasi-cyclical variations in aridity occur in the Uinta Mountains region, but these variations have shifted in frequency and strength over the past 600 years, and a precise attribution of such variations remains to be determined. Thus, predicting the onset and duration of the next prolonged period of aridity, such as the early 17th century event, for example, remains an important goal requiring the combined efforts of climatologists and paleoclimatologists. In any case, it is important for water resource and environmental managers in the Uinta Mountains region to consider that such events (along with shorter-term severe and extreme annual droughts) are a natural part of the Uinta climate system and are likely to occur again in the future.

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