West-Wide Drought Assessment Using Paleoclimate and BCSD (Bias Corrected and Spatially Downscaled) Climate Projections

Reclamation Science and Technology Program

Fiscal Year 2012 Proposal ID 99

Summary

Research Area

- Guidance on how to jointly utilize the longer-term climate variability from observed records, paleoclimate, and projected climate information when portraying drought and surplus possibilities in planning.

Research Questions

- How different are the drought characteristics (intensity, duration or spell lengths, frequency or wet-dry transitions) estimated from paleoclimate, and projected climate information?
- Are paleohydrologic droughts prologues for future droughts, and why?
- Using projected climate information, are there differences in drought characteristics using an index that uses both precipitation and temperature such as PDSI (Palmer Drought Severity Index) versus only a precipitation based index such as SPI (Standardized Precipitation Index) at annual time scales?

Datasets Used in Analysis

- Tree-ring based similar year dataset (1400-1997) developed and used in the nonparametric reconstruction of Upper Colorado River Basin (UCRB) streamflow at Lees Ferry [*Gangopadhyay et al.*, 2009].
- US climate division boundaries. Total 138 for the western US domain.
- US climate division monthly precipitation, temperature and PDSI for climate divisions covering the western US.
- Gridded available water holding capacity (AWHC).
- *Cook et al*. [2004] gridded summertime PDSI data.
- Bias Corrected and Spatially Downscaled CMIP-3 (Coupled Model Intercomparison Project Phase 3; BCSD-CMIP3) monthly precipitation and monthly temperature for 112 climate projections at 1/8° x 1/8° (approximately [~] 12 km x 12 km) spatial resolution for the western US.

Assumption

- Ergodic hypothesis -the sequence of similar years developed for the UCRB [*Gangopadhyay et al.*, 2009] streamflow reconstruction holds for the Western United States.

Verification of Assumption

- Correlation between resampled summertime PDSI and instrumental PDSI for the 138 climate divisions is shown in Figure A (below).
- Note that instrumental PDSI was used in the resampling step of leave-one-out verification (see, *Gangopadhyay et al*. [2009] for details on developing the similar year set for the verification period, water years 1906-1997).
- Figure A shows that the correlation outside of the Upper Colorado River Basin is weak.
- The ergodic hypothesis was not valid in this case and the study was focused only on the Upper Colorado River Basin (detailed self-contained analysis below) and not the west-wide scale as originally envisioned.

Data Products

- The monthly gridded BCSD-CMIP3 precipitation and temperature data was aggregated (area-weighted) to each climate division (a total of 138) monthly precipitation and temperature for each of the 112 BCSD-CMIP3 climate projections over the period 1950-2099. For this research, the climate projection period is referred to as the years 2000-2099.
- PDSI and SPI calculation programs obtained from the University of Nebraska's Green Leaf Project (formerly, National Agricultural Decision Support System, NADSS) was run to estimate both these drought indices for the climate projection period (2000-2099).
- Ensemble of monthly precipitation and temperature over the paleo-period (water years 1400-1905) for the Upper Colorado River Basin eight digit hydrologic unit code (refer to notes below [*]).

Notes

- *Details in paper titled, *Beyond annual streamflow reconstructions for the Upper Colorado River Basin: A paleo-water-balance approach* is currently under review in the peer-reviewed journal, Geophysical Research Letters of the American Geophysical Union (AGU). A presentation (#GC41F-05) under the same title was made at the 2013 AGU Fall meeting.
- The research only analyzed PDSI and not SPI drought index.
- Reference *Gangopadhyay et al*. [2009] - Gangopadhyay S., B.L. Harding, B. Rajagopalan, J.J. Lukas, and T.J. Fulp, 2009. A non-parametric approach for paleohydrologic reconstruction of annual streamflow ensembles. Water Resources Research, 45, W06417, doi:10.1029/2008WR007201.

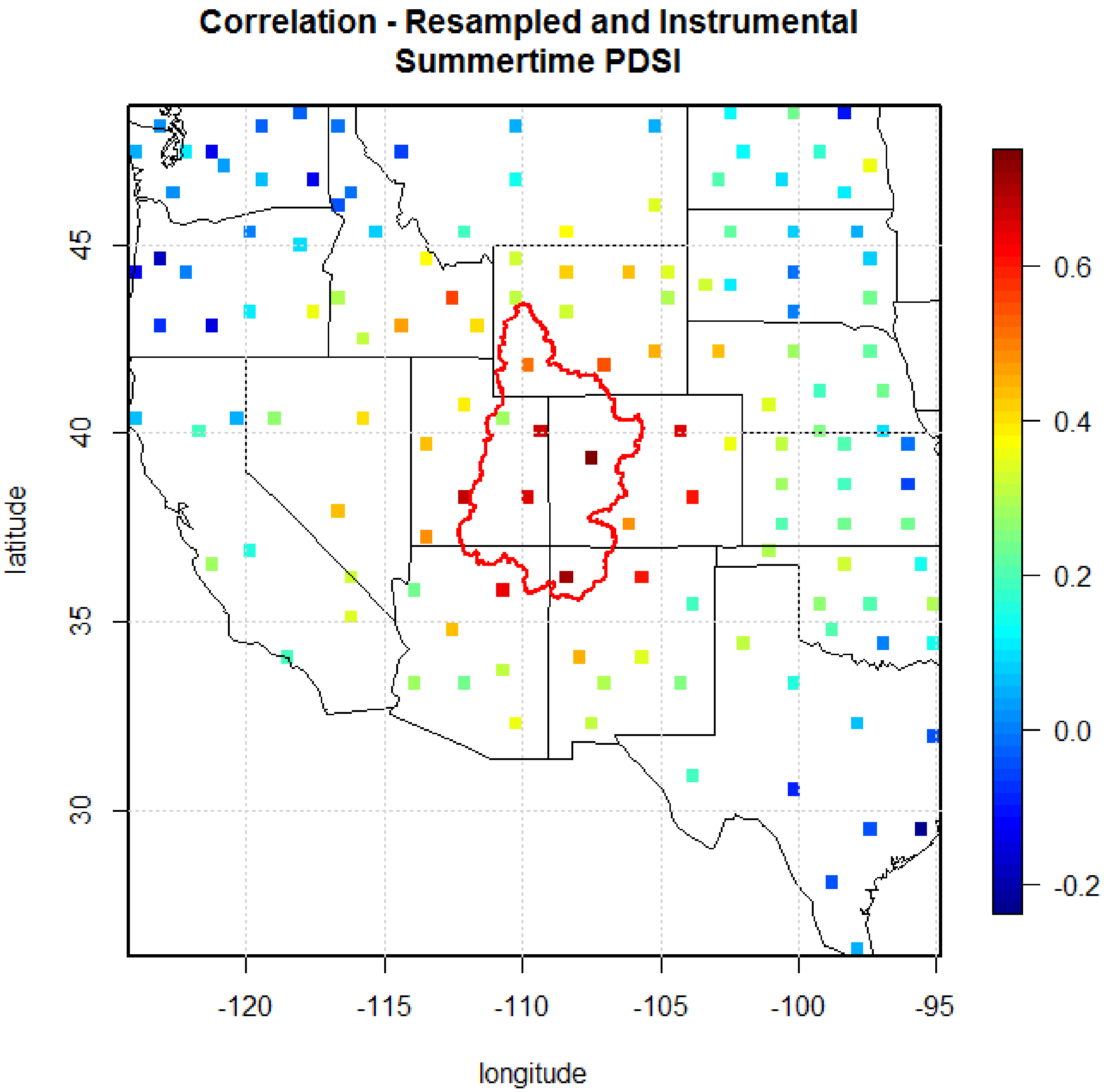

Figure A. Correlation between resampled and instrumental summer (June-July-August) PDSI over the verification period (water years 1906-1997) for the 138 climate divisions across the western United States. Colored squares at the centroids of climate divisions correspond to correlation magnitudes. The Upper Colorado River basin boundary is shown in red.

Drought Assessment Using Paleoclimate and Bias Corrected and Spatially Downscaled CMIP-3 Climate Projections for the Upper Colorado River Basin

1. Introduction

The current research addresses Priority Area 3.05 described in the long-term user needs document: Guidance on how to jointly utilize the longer-term climate variability from observed records, paleoclimate, and projected climate information when portraying drought and surplus possibilities in planning. To this end, Reclamation S&T effort 6395-Development and Comparison of Long-Term Planning Hydrologies using Alternate Climate, focused on methods to develop alternate climate data sets incorporating variability from the paleoclimate record, or projected climate changes. This research resulted in the publication of a methods report outlining methodologies for long-term planning hydrology based on various blends of instrumental records, paleoclimate, and projected climate information (Reclamation, 2009)[1].

The goal of the current research is to analyze meteorological and hydrological droughts from paleoclimate and BCSD (Bias Corrected and Spatially Downscaled) climate and hydrologic projection datasets to answer the following three research questions.

1. How different are the drought characteristics (intensity, duration or spell lengths, frequency or wet-dry transitions) estimated from paleoclimate, and projected climate information?
2. Are paleohydrologic droughts prologues for future droughts, and why?
3. Using projected climate information, are there differences in drought characteristics using an index that uses both precipitation and temperature such as PDSI (Palmer Drought Severity Index)[2] versus only a precipitation based index such as SPI (Standardized Precipitation Index)[3] at annual time scales?

Though the goal of this research was to develop a west-wide analysis, results presented in this report largely covers headwater areas of the Upper Colorado River Basin (UCRB). The development of a methodology and a proof-of-concept as to how to perform a west-wide drought assessment using paleoclimate and climate projections data along with developed datasets on weather and drought indices (PDSI and SPI) are considered key research contributions.

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[1] Reclamation, 2009. Long-term planning hydrology based on various blends of instrumental records, paleoclimate, and projected climate information, 138 pp.

[2] Palmer, W. C., 1965. Meteorological drought. Office of Climatology Research Paper 45, Weather Bureau, Washington, D.C., 58 pp.

[3] McKee, T.B., N.J. Doesken, and J. Kleist, 1993. The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, 6pp.

The report is organized as follows. A description of the datasets is given in Section 2. The research methodology is described in Section 3. Research results along with discussions are presented in Section 4. Section 5 concludes the presentation with a research summary. Section 6 outlines the next steps to address outstanding research questions.

2. Datasets

The datasets used and relied upon in this research includes the following:

1. Tree-ring based similar year dataset (1400-1997) developed and used in the nonparametric reconstruction of UCRB streamflow at Lees Ferry. The nonparametric flow reconstructions are described in Gangopadhyay et al. (2009)[4]. The similar years (a total of 10 for each year) were developed using spatial pattern matching of tree-ring chronologies for the period 1400-1905 from the years 1906-1997. Also, years similar to the period 1906-1997 was developed for methodological verification purposes.
2. US climate division boundaries. This dataset geometry as shapefile (ESRI®) is available for download from the USGS (United States Geological Survey)[5].
3. US climate division monthly precipitation, temperature and PDSI (referred to as instrumental PDSI) data for climate divisions covering the western US. This dataset is available for download from NCDC (National Climatic Data Center)[6].
4. Estimation of PDSI requires information on available water holding capacity (AWHC) or root zone water holding capacity. Gridded global AWHC data is available from the Oak Ridge National Laboratory[7]. This gridded dataset was used to develop climate division specific AWHC for all the climate divisions of the western US.
5. Cook et al. (2004)[8] gridded summertime PDSI data. This dataset is available for download from the NOAA (National Oceanic and Atmospheric Administration) Paleoclimatology Program website[9].

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[4] Gangopadhyay S., B.L. Harding, B. Rajagopalan, J.J. Lukas, and T.J. Fulp, 2009. A non-parametric approach for paleohydrologic reconstruction of annual streamflow ensembles. Water Resources Research, 45, W06417, doi:10.1029/2008WR007201.

[5] URL, http://water.usgs.gov/GIS/dsdl/climate_shpdiv_.zip. Accessed, September, 2012.

[6] FTP address, ftp://ftp.ncdc.noaa.gov/pub/data/cirs/. Precipitation filename, drd964x.pcp.txt. Temperature filename, ,drd964x.tmp.txt. PDSI filename, drd964x.pdsi.txt. README filename, divisional.README. Accessed, September, 2012.

[7] Webb, R. W., C. E. Rosenzweig, and E. R. Levine. 2000. Global Soil Texture and Derived Water-Holding Capacities (Webb et al.). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/548. Granule name, *Potential Storage of Water in the Root Zone (mm)*. Access URL, http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=548_4. Accessed, August 2012.

[8] Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W.. 2004. Long-Term Aridity Changes in the Western United States. Science, Vol. 306, No. 5698, pp. 1015-1018, 5 November 2004.

[9] URL, http://www.ncdc.noaa.gov/paleo/newpdsi.html. Accessed, September 2012.

6. Bias Corrected and Spatially Downscaled CMIP-3 (Coupled Model Intercomparison Project Phase 3)[10] monthly precipitation and monthly temperature for 112 climate projections at 1/8° x 1/8° (approximately [~] 12 km x 12 km) spatial resolution for the western US.
7. Lees Ferry natural flow data. Natural flow data on the Colorado River system is available for download from Reclamation's Lower Colorado Region website[11].

3. Methodology

For this research, the climate division was selected as the spatial unit, and analysis of droughts was done using monthly time steps. The methodological steps are described below. Also, note that, though SPI was calculated it has not been analyzed at this time in the research.

Step 1. Using the similar year dataset (Gangopadhyay et al. 2009), total monthly precipitation and average monthly temperature was sampled from the NCDC monthly climate division data to develop an archive of monthly total precipitation and monthly average temperature for each climate division of the western US (a total of 138) for the period 1400-1997. In this analysis, the paleo-period is defined as the years 1400-1905, and the verification years are 1906-1997.

Step 2. The monthly gridded BCSD precipitation and temperature data was aggregated (area-weighted) to each climate division (a total of 138) monthly precipitation and temperature for each of the 112 climate projections over the period 1950-2099. Note that, for this research, the climate projection period is referred to as the years 2000-2099.

Step 3. PDSI and SPI calculation programs obtained from the University of Nebraska's Green Leaf Project[12] (formerly, National Agricultural Decision Support System, NADSS) was run to estimate both these drought indices for the plaeo-period (1400-1905), verification period (1906-1997), and climate projection period (2000-2099).

Step 4. A correlation analysis was performed using annual instrumental PDSI and annual Lees Ferry flows for each climate division covering the UCRB to identify climate divisions that most impact the flows in the Upper Colorado Basin.

Step 5. Next, verification of wet-dry spells using PDSI estimated from resampled precipitation and temperature (Steps 1 and 3) were compared with instrumental PDSI for selected (Step 4) climate divisions.

Step 6. Finally frequency analysis of drought was performed using paleo-PDSI (1400-1905), instrumental PDSI (1906-1997), and climate change-PDSI (2000-2099) using a nonparametric approach adapted from

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[10] BCSD URL, http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html. Accessed, Septemebr 2012.

[11] Colorado River Simulation System (CRSS) natural flow dataset URL, http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html. The Lees Ferry natural flow data was obtained from the spreadsheets available through this website. Accessed, September 2012.

[12] URL for Green Leaf Project, http://greenleaf.unl.edu/. Accessed, September 2012.

Kim et al. (2003). An expanded description of the frequency analysis approach is provided in the following sub-section.

3.1 Nonparametric Frequency Analysis of Drought Duration

Frequency analysis relates properties (e.g., drought duration, drought severity and intensity or flood magnitude) of extreme events to its frequency of occurrence using a probability distribution. If a property is represented by the random variable X, and the extreme events are independent and identically distributed from a probability distribution P. Then the return period (T) of an event exceeding threshold (x_T) is given by,

$$T = \frac{1}{P(X > x_T)} = \frac{1}{1 - P(X \leq x_T)} \qquad (1)$$

Kim et al. (2003) states that because droughts persists for longer than 1 year, drought properties such as drought duration, can be analyzed as a partial duration series of independent events. Furthermore, Eagleson (1972)[13] suggests that partial duration series should be converted to an equivalent annual exceedance series using peak-over-threshold method. Then from the definition of equivalency (see, Eagleson, 1972), and following Kim et al. (2003), if the marginal cumulative distribution of drought duration, d, is given by $F_D(d)$, the return period for this drought duration (d), T_d (years) is given by Eq. (2)

$$T_d = \frac{N}{n[1 - F_D(d)]} = \frac{1}{\theta[1 - F_D(d)]} \qquad (2)$$

where $\theta = n/N$; N = total length of the observed PDSI (years); and n = total number of drought events, d, during N.

The R[14] package *sm* (Bowman and Azzalini, 1997)[15][16] was used to nonparametrically estimate the probability density function (PDFs) of drought durations for PDSI thresholds defined by PDSI < 0, PDSI < -1, PDSI < -2, PDSI < -3, and PDSI < -4. In the estimation of the PDFs, a normal bandwidth selector was used along with defaults in the function *sm.density*. Each PDF was subsequently numerically integrated using R function *integrate* to estimate $F_D(d)$.

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[13] Eagleson, P.S., 1972. Dynamics of flood frequency. *Water Resour. Res.* 8(4), 879-898.

[14] R Development Core Team (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

[15] Bowman, A., and A. Azzalini, 1997. *Applied smoothing techniques for data analysis: The kernel approach with S-Plus illustrations*. Oxford University Press, NY, 193 pp.

[16] Bowman, A. W. and Azzalini, A. (2010). R package 'sm': nonparametric smoothing methods (version 2.2-4) URL http://www.stats.gla.ac.uk/~adrian/sm, http://azzalini.stat.unipd.it/Book_sm.

4. Results and Discussions

The first step in the analysis was to develop correlation between Lees Ferry natural flow and annual instrumental PDSI for each of the climate divisions covering the Upper Colorado River Basin (HUC-2) for the period 1906-1997. Results of this analysis are summarized in Table1.

Table 1. Correlation analysis of Lees Ferry flow and annual instrumental PDSI.

Climate Division Name	Climate Division ID	State	Division	Correlation
GREEN AND BEAR DRAINAGE	WY_4803	WY	3	0.6433
UPPER PLATTE	WY_4810	WY	10	0.5450
NORTHERN MOUNTAINS	UT_4205	UT	5	0.6820
UINTA BASIN	UT_4206	UT	6	0.7682
SOUTH CENTRAL	UT_4204	UT	4	0.7798
SOUTHEAST	UT_4207	UT	7	0.6974
NORTHEAST	AZ_0202	AZ	2	0.5897
NORTHWESTERN PLATEAU	NM_2901	NM	1	0.6206
CO DRAINAGE BASIN	CO_0502	CO	2	0.8444

From Table 1 we see that the Colorado (CO) climate division 2 (CO Drainage Basin) has the highest annual PDSI correlation with Lees Ferry flow. This is not surprising because this climate division covers the headwater areas of the UCRB where most of the Basin's flow is generated from the snowpack. So, subsequent analysis is focused on this climate division (CO_0502). The flow-PDSI correlation for CO_0502 is also shown in Figure 1.

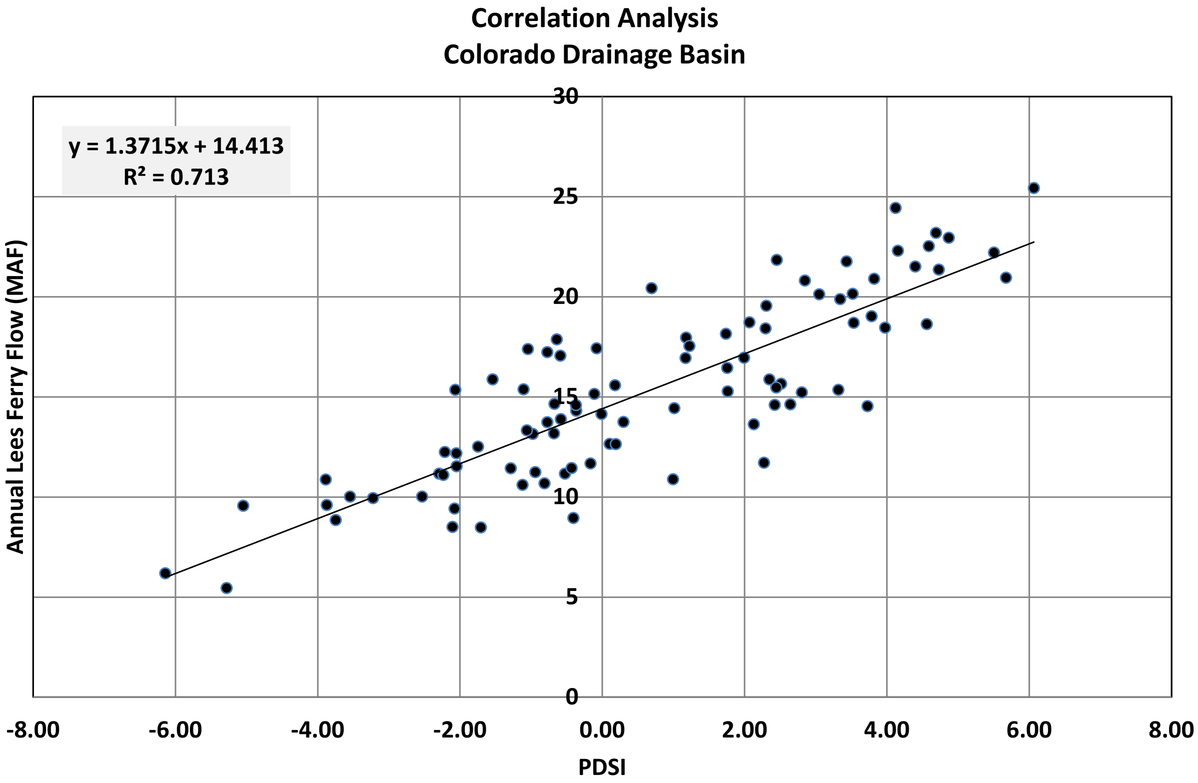

Figure 1. Correlation analysis between annual flow at Lees Ferry and annual PDSI for Colorado climate division 2 (CO Drainage Basin) over the period 1906-1997.

To see how annual PDSI generated by resampling precipitation and temperature from the nonparametric paleo-algorithm (NPP) and then subsequently calculating PDSI using the PDSI water-balance calculations matches with instrumental PDSI for CO_0502, the wet-dry states from these two time series were compared for the verification period 1906-1997. Result of this comparison is shown in Figure 2. In Figure 2, dry years (wet years) are defined as years where the annual PDSI < 0 (> 0). A comparison of the wet-dry correspondence between the two series shows a 78% correspondence. That is, in 78% of the cases (72 out of the total 92 years verification period) the wet and dry spells match between the two series. Furthermore, the known historical drought of the 1930s and 1950s shown in the instrumental PDSI data is captured well by the NPP PDSI series.

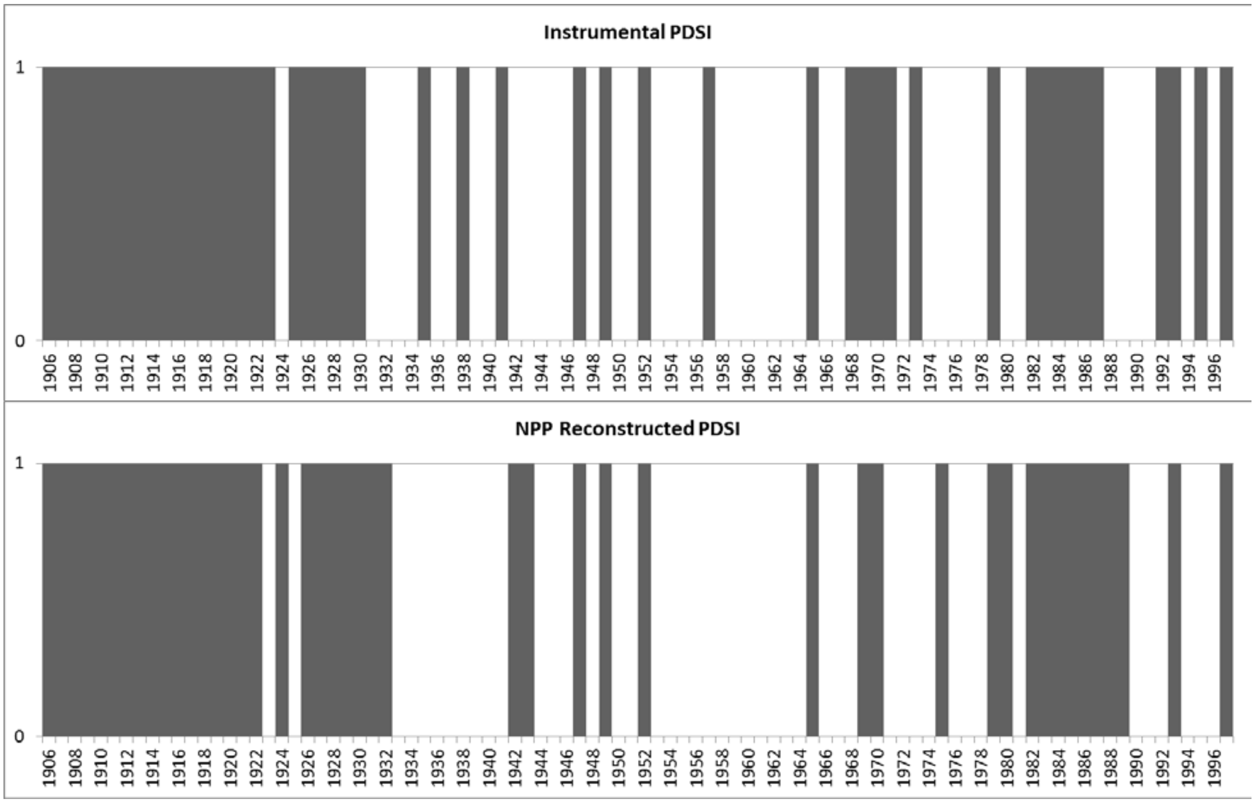

Figure 2. Comparison of wet (dark bars) and dry (white bars) periods in the Colorado Drainage Basin (climate division, CO_0502) over the period 1906-1997. Dry (wet) period is defined for years where the annual PDSI < 0 (> 0).

This analysis shows that estimating PDSI by means of the precipitation and temperature resampling, and subsequent modeling using the standard PDSI water balance model is a viable approach to estimate PDSI using the nonparametric reconstruction methodology. Having verified this methodology over the recent verification period, 1906-1997, the next step in the process was to test the performance of this methodology over the paleo-period and this is done by comparing NPP reconstructed PDSI with the Cook et al. (2004) summertime PDSI series. Two grids points, (1) longitude, 107.5W, latitude, 40.0N (grid point ID, 117); (2) longitude, 107.5W, latitude 37.5N (grid point ID, 118), fall within the climate division CO_0502. A correlation of summertime PDSI values of NPP reconstructed and Cook et al. (2004) was calculated to be around 0.60. However, a match of the wet-dry spells gave a similarity measure of 0.77. That is, in 77% of the 506 years (1400-1905), the Cook et al. (2004) reconstructed summertime PDSI wet or dry state (dry state defined as PDSI < 0, otherwise wet) matched with the NPP reconstructed PDSI state. These results suggest that the NPP reconstructions adequately represent wet or dry states in the UCRB. To further verify the NPP paleo-PDSI reconstructions a time series plot of annual PDSI for CO_0502 is shown in Figure 3.

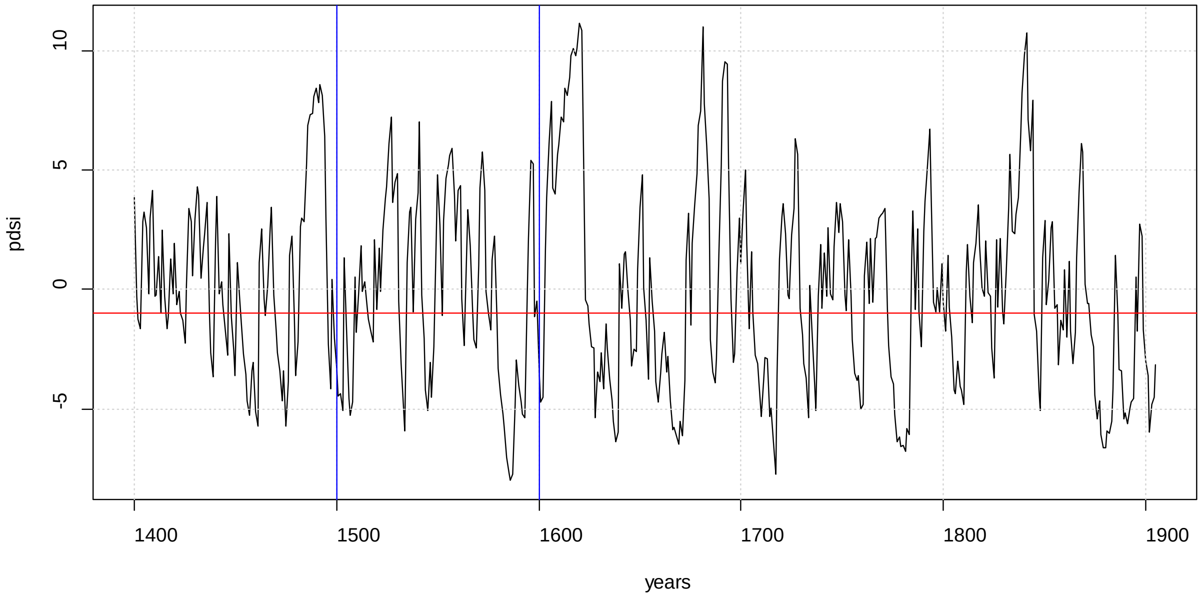

Figure 3. Time series plot of NPP paleo-PDSI (1400-1905) for the Colorado Drainage Basin climate division (CO_0502). The drought definition is PDSI < -1 (horizontal red line). The 16th century is highlighted by the vertical blue lines.

From Figure 3 we see that the late 16th century severe drought is also captured by the NPP reconstructions. This result is consistent with other tree-ring based analysis (e.g., Stahle et al., 2000)[17].

The final step in the research was to expand this methodology to develop PDSI using monthly precipitation and temperature using all the 112 BCSD-CMIP3 projections, and compare return periods of drought durations (estimated using Eq. 2) over the three periods – (1) paleo (1400-1905), (2) current/instrumental (1906-1997), and (3) climate change (2000-2099). To develop drought durations and estimate return periods, five PDSI thresholds was utilized: (1) PDSI < 0, (2) PDSI < -1, (3) PDSI < -2, (4) PDSI < -3, and (5) PDSI < -4. To analyze the paleo-PDSI data, a moving window of 100-years was used to be consistent with sample size of 92 years for the current period and 100 years in the climate change simulations. Also, in case of the climate change simulations, a median return period from the 112 projections was used to summarize the results. Finally, return periods of up to 7 years (maximum drought duration over the period, 1906-1997) was estimated using Eq. 2, and it should be noted that with more severe droughts (lower PDSI threshold values) there will not be enough events to estimate the return periods. Missing return periods arising in such cases is represented by NA in the results table, Table 2.

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[17] Stahle et al., 2000. Tree-ring data document 16th century megadrought over North America. *Eos* Transaction, AGU, 81(12), pp.121,125.

Table 2. Comparison of drought duration return periods for instrumental, plaeoclimatic and climate change PDSI using five different PDSI thresholds.

Duration	*Instrumental*	*Paleoclimatic*	*Climate Change*
PDSI < 0			
2	9.36	9.97	9.26
3	13.14	13.21	11.82
4	18.98	17.33	14.98
5	30.06	21.93	18.43
6	50.61	27.52	22.48
7	83.26	34.16	28.12
PDSI < -1			
2	15.82	14.79	11.67
3	27.47	17.13	15.56
4	44.39	20.90	20.32
5	56.67	26.36	25.45
6	65.82	32.30	33.32
7	85.54	38.36	40.45
PDSI < -2			
2	19.91	17.04	14.42
3	76.78	20.10	19.42
4	NA	24.97	25.96
5	NA	30.50	33.53
6	NA	37.49	43.18
7	NA	45.59	54.46
PDSI < -3			
2	58.55	18.59	17.60
3	NA	22.57	25.48
4	NA	30.22	34.62
5	NA	39.76	43.37
6	NA	51.40	59.03
7	NA	64.47	60.80
PDSI < -4			
2	NA	25.15	23.72
3	NA	32.26	33.26
4	NA	39.90	40.70
5	NA	48.45	45.59
6	NA	60.91	57.66
7	NA	74.17	62.58

Overall we find that the return periods of drought durations estimated from the paleoclimatic data and climate change data are very similar. Thus, droughts seen over the paleo-period are expected to be representative of future droughts at least in the Upper Colorado River Basin. These analyses aside, there are still the questions of what cause drought episodes in the paleo-record, and whether those drivers remain relevant in a warming world.

5. Summary and Conclusions

The main contributions and findings of this study are:

1. Developing and verifying a methodology to estimate paleo-PDSI at a monthly time scale using reconstructed monthly precipitation and temperature data.
2. Applying a nonparametric methodology for all the analysis thereby keeping the approach completely data driven.
3. Responding to research questions (1) and (2) by providing an analysis of drought duration return periods using paleo-PDSI and climate change PDSI extreme value analysis.