The Second Century Drought in the Upper Colorado River Basin

Connie Woodhouse[1,1,1], Cody Routson[2,2,2], David Meko[1,1,1], Subhrendu Gangopadhyay[3,3,3], and Gregory McCabe[4,4,4]

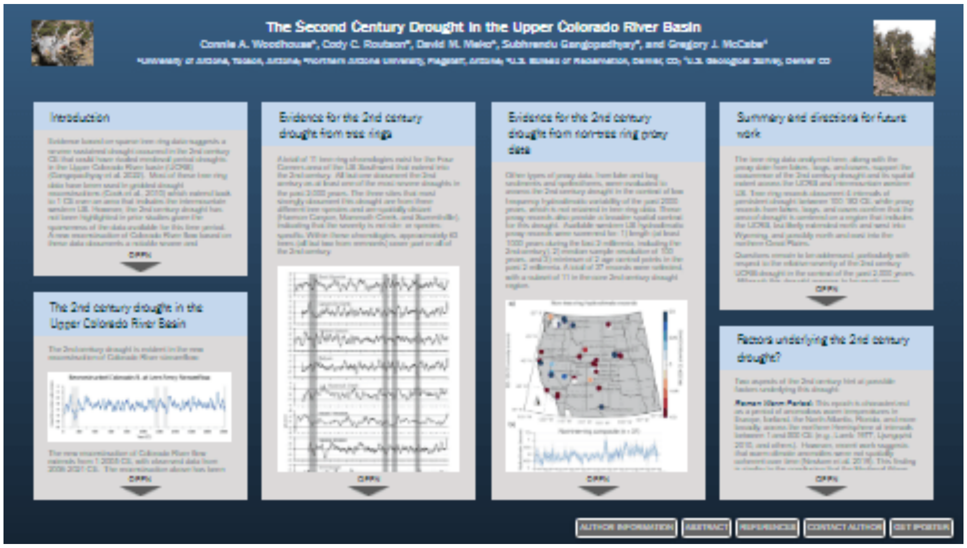
[1]University of Arizona
[2]Northern Arizona University
[3]U.S. Bureau of Reclamation, Denver, Colorado
[4]U.S. Geological Survey, Denver, Colorado

November 30, 2022

Abstract

Evidence based on sparse tree-ring data suggests a severe sustained drought occurred in the 2nd century CE that could have rivaled medieval period droughts in the Colorado River basin (Gangopadhyay et al. 2022). Most of these tree-ring data have been used in gridded drought reconstructions (Cook et al., 2010) which extend back to 1 CE over an area that includes the intermountain western US. However, the 2nd century drought has not been highlighted in prior studies given the sparseness of the data available for this time period. A new reconstruction of Colorado River flow based on these data documents a notably severe and sustained drought over much of the 2nd century (Gangopadhyay et al. 2022). While this reconstruction suggests that the drought exceeds the severity and duration of any drought in the past 2000 years, a complete assessment of the 2nd century drought is challenging due to the sparseness of data. In this poster presentation, we describe the tree-ring data available, along with other proxy data that provide evidence for the 2nd century drought and support its severity. In our conclusions, we discuss outstanding questions and thoughts for further work.

The Second Century Drought in the Upper Colorado River Basin



Connie A. Woodhouse[1], Cody C. Routson[2], David M. Meko[1], Subhrendu Gangopadhyay[3], and Gregory J. McCabe[4]

[1]University of Arizona, Tucson, Arizona; [2]Northern Arizona University, Flagstaff, Arizona; [3]U.S. Bureau of Reclamation, Denver, CO; [4]U.S. Geological Survey, Denver CO

PRESENTED AT:

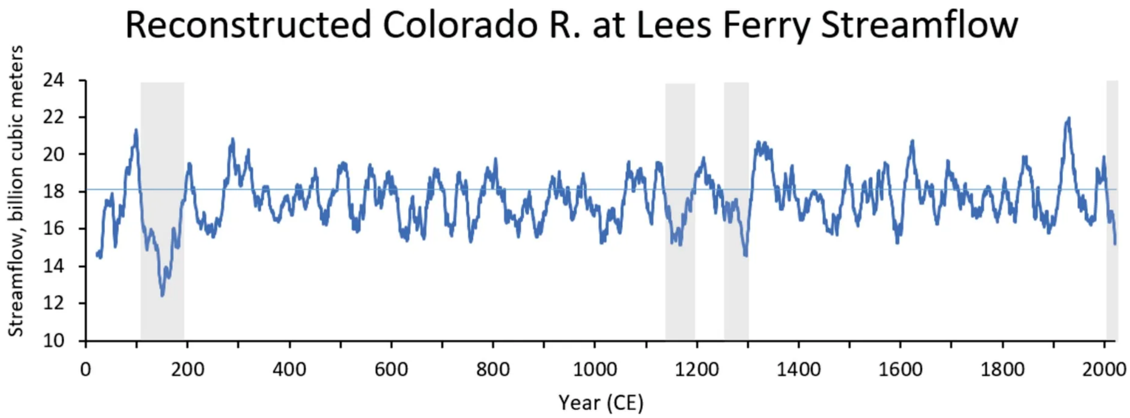
Frontiers in Hydrology

INTRODUCTION

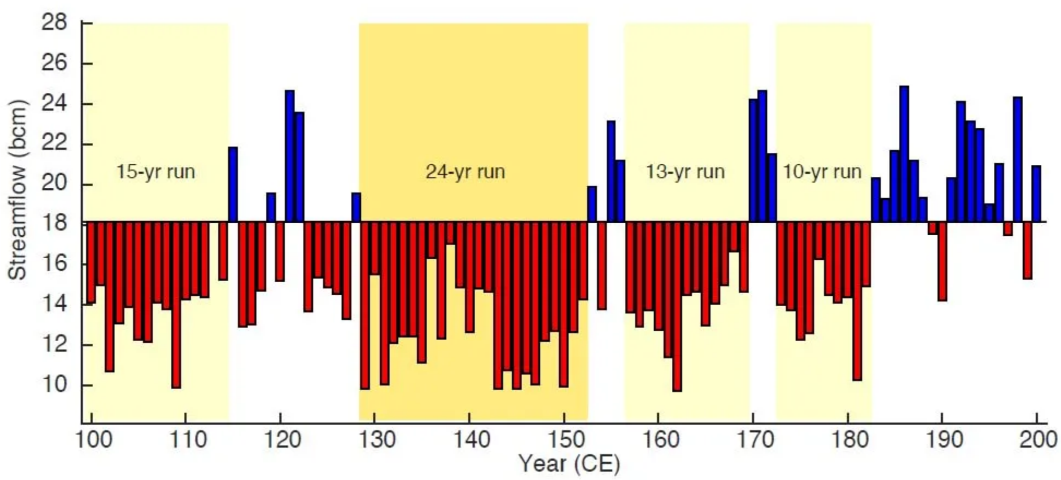
Evidence based on sparse tree-ring data suggests a severe sustained drought occurred in the 2nd century CE that could have rivaled medieval period droughts in the Upper Colorado River basin (UCRB) (Gangopadhyay et al. 2022). Most of these tree-ring data have been used in gridded drought reconstructions (Cook et al., 2010) which extend back to 1 CE over an area that includes the intermountain western US. However, the 2nd century drought has not been highlighted in prior studies given the sparseness of the data available for this time period. A new reconstruction of Colorado River flow based on these data documents a notably severe and sustained drought over much of the 2nd century (Gangopadhyay et al. 2022). While this reconstruction suggests that the drought exceeded the severity and duration of any drought in the past 2000 years, a complete assessment of the 2nd century drought is challenging due to the sparseness of data. In this poster presentation, we describe the tree-ring data available, along with other proxy data, that provide evidence for the 2nd century drought and support its severity. Following our summary and directions for future work, we speculate on two possible underlying factors that may be associated with the 2nd century drought and have yet to be explored. The findings reported here are largely taken from Gangopadhyay et al. (2022) and the associated supporting information.

THE 2ND CENTURY DROUGHT IN THE UPPER COLORADO RIVER BASIN

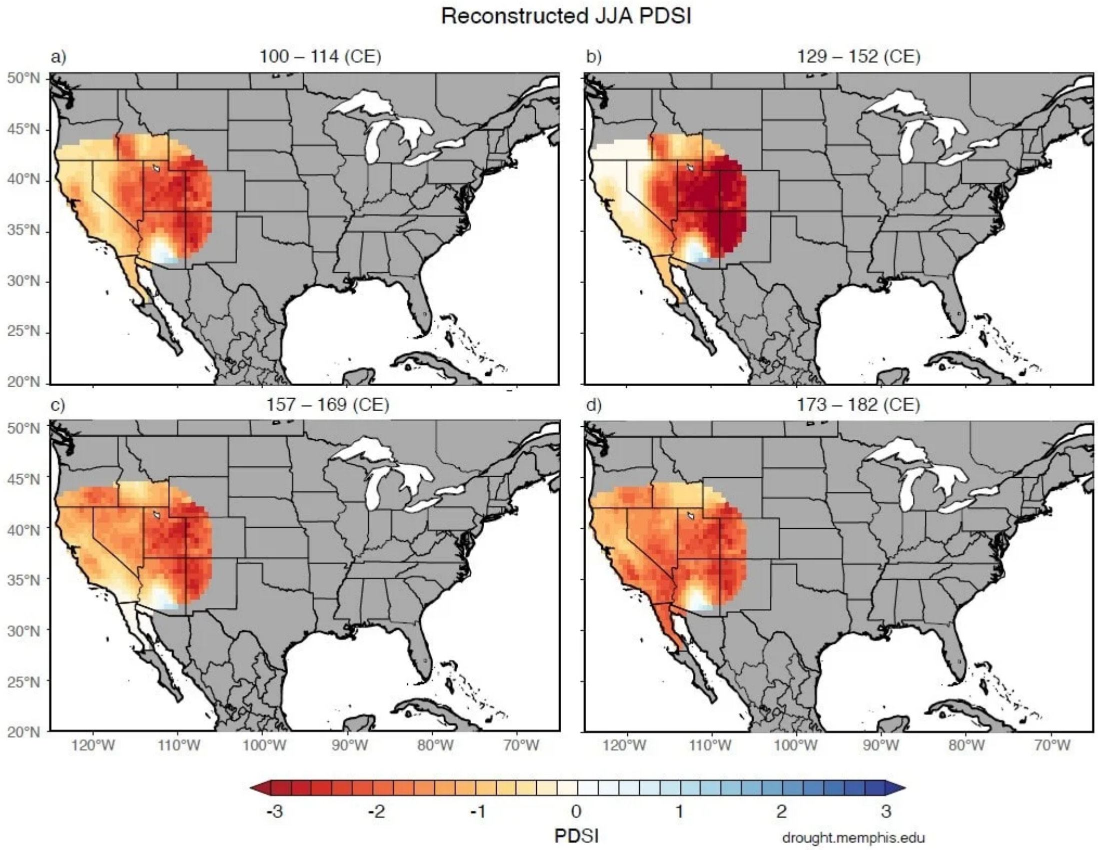
The 2nd century drought is evident in the new reconstruction of Colorado River streamflow:



The new reconstruction of Colorado River flow extends from 1-2005 CE, with observed data from 1906-2021 CE. The reconstruction above has been smoothed with a 22-year moving average (plotted on last year). The horizontal line is the 1906-2021 mean. The vertical shading highlights the 2nd century drought, two droughts in the medieval period, and the current drought, 2000-2021.



The bar graph above shows the annual Colorado River streamflow departures (in billion cubic meters, based on 1906-2021) for the 2nd century. The yellow shading highlights four sustained sequences of below average streamflow: 15 years (100-114 CE), 24 years (129-152 CE), 13 years (157-169 CE), and 10 years (173-182 CE).

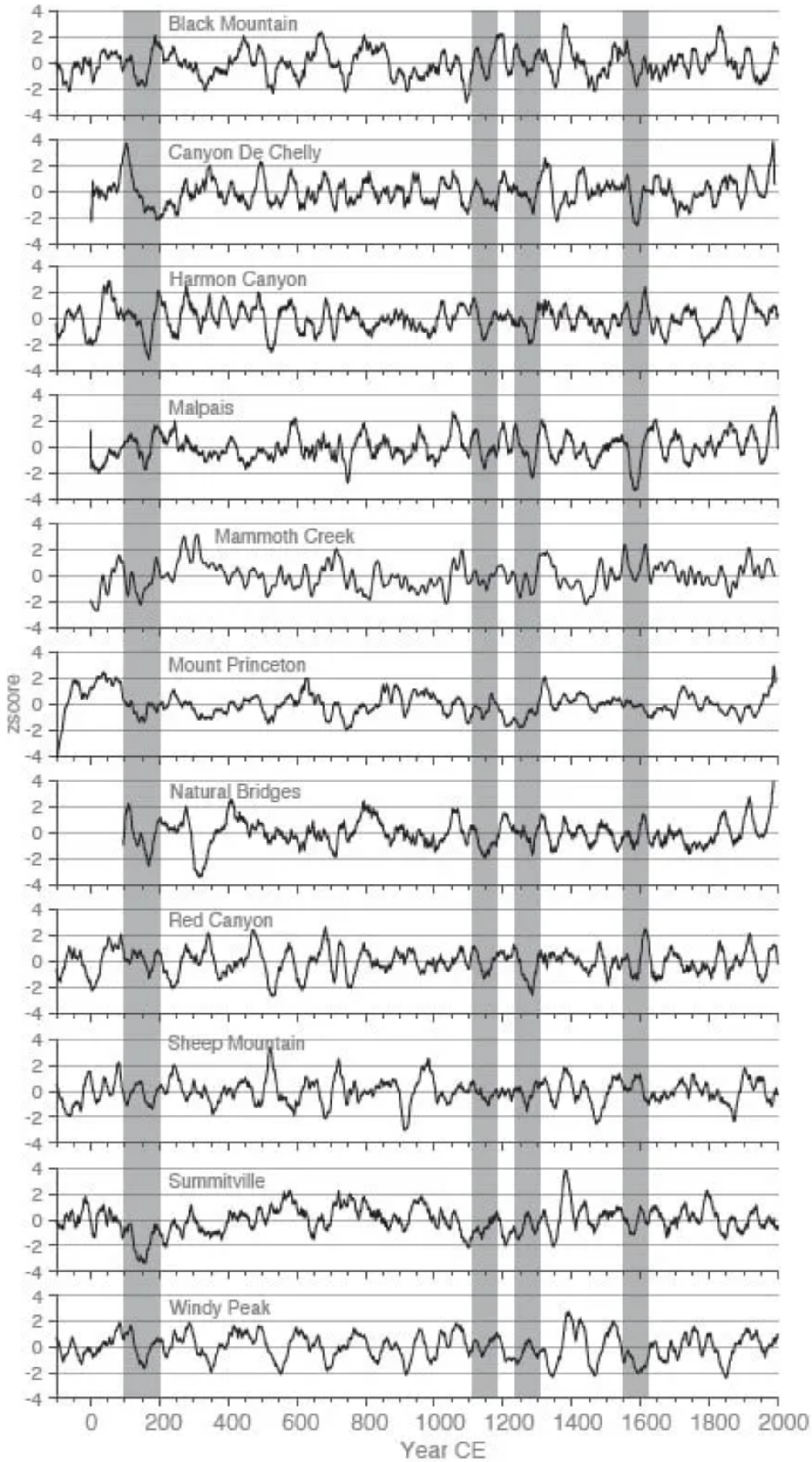


The maps show the spatial coverage of the 2nd century droughts based on reconstructed PDSI, averaged for the four periods; a) 100-114 CE, b) 129-152 CE, c) 157-169 CE, and d) 173-182 CE (Cook et al., 2010). The drought extent shown is limited by the availability of tree-ring data. Gray areas indicate no data available.

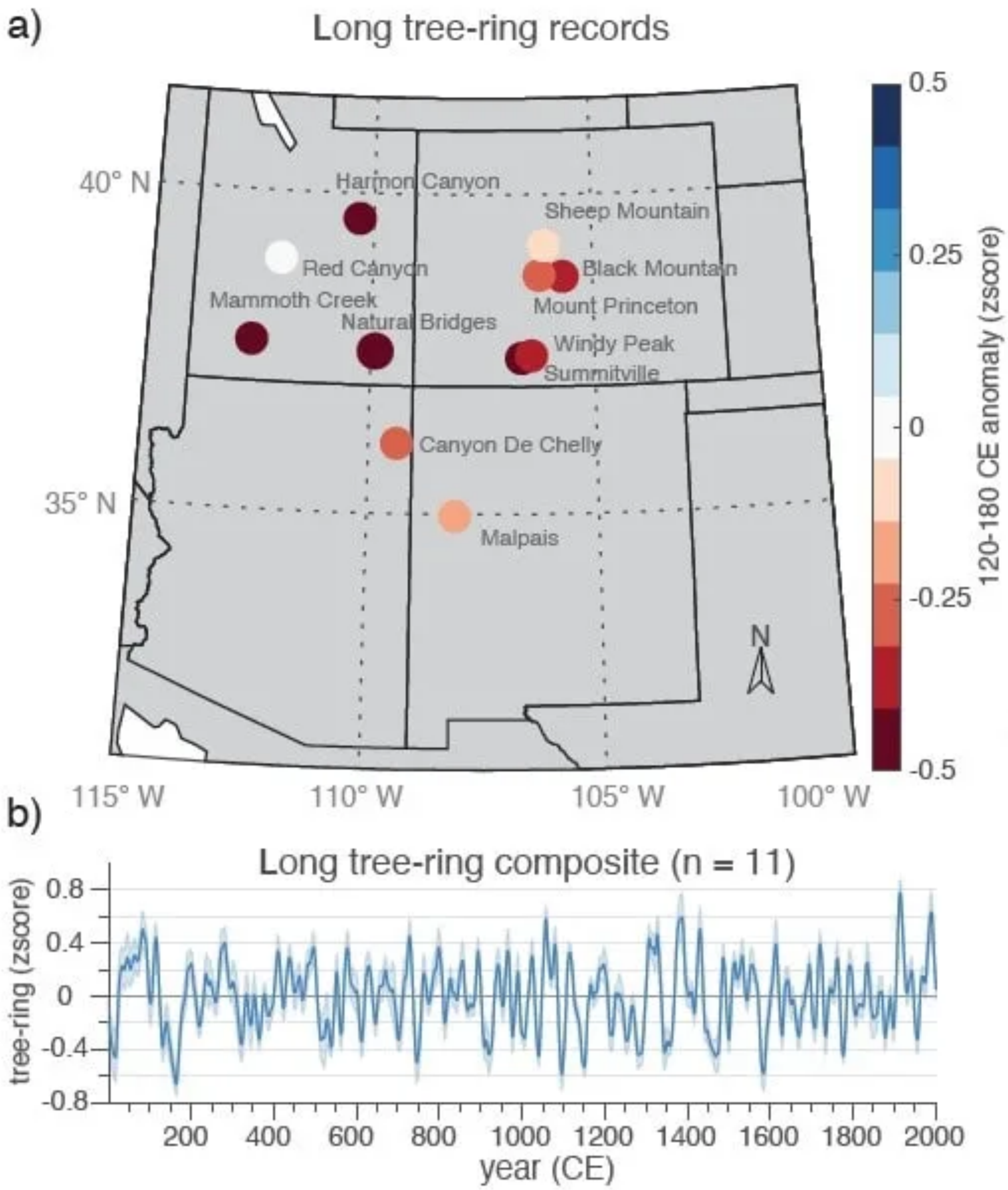
Generated from http://drought.memphis.edu/NADA/Default.aspx (http://drought.memphis.edu/NADA/Default.aspx).

EVIDENCE FOR THE 2ND CENTURY DROUGHT FROM TREE RINGS

A total of 11 tree-ring chronologies exist for the Four Corners area of the US Southwest that extend into the 2nd century. All but one document the 2nd century as at least one of the most severe droughts in the past 2,000 years. The three sites that most strongly document this drought are from three different tree species and are spatially distant (Harmon Canyon, Mammoth Creek, and Summitville), indicating that the severity is not site- or species-specific. Within these chronologies, approximately 63 trees (all but two from remnants) cover part or all of the 2nd century.



The 11 tree-ring chronologies are plotted above. Values are zscores; time series were smoothed with a 25-year moving average. Vertical gray shading indicates the 2nd century drought period, with two medieval period droughts and a late 16th century drought for comparison. In some cases, there are other droughts that are more severe, but all but the Red Canyon chronology reflect drought conditions in the 2nd century. Drought conditions in the 2nd century are particularly severe in the Harmon Canyon, Mammoth Creek, and Summitville sites.

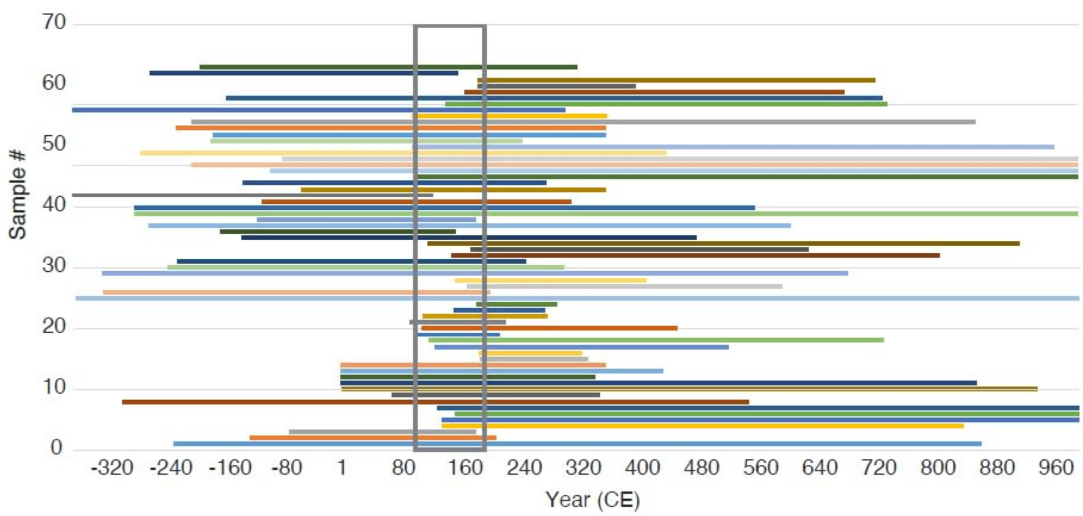


In the figure above, the locations of the 11 tree-ring chronologies are indicated (a). Dots are color-coded to reflect tree-growth anomalies (in z-scores) for 120–180 CE. All but Red Canyon reflect negative anomalies over this time period. The time series (b) is a composite record of 11 tree-ring chronologies, 1-2000 CE. The 2nd century drought is a distintive feature of this composite record.

Site	ITRDB code	species	dates	# trees*
Black Mountain##	CO689	PIAR	-452-2012	13
Summitville	CO656	PIAR	-268-2009	6
Windy Pk	CO691	PIAR	-364-2007	6
Sheep Mt##	CO690	PIAR	-260-2006	5
Harmon Cny	UT530	PSME	-322-2005	5
Princeton	CO672	PIAR	-357-1992	4
Natural Bridges	UT543	PIED	94-1998	4
El Malpais	NM615	PSME	1-2004	4
Canyon de Chelly	AZ570	PIED	1-1990	3
Mammoth Ck	UT509	PILO	1-1989	3
Red Canyon##	UT550	PILO	-504-2014	10

not included in PDSI reconstructions (Cook et al., 2010)
*estimated number of trees that contain at least three years in the 2nd century

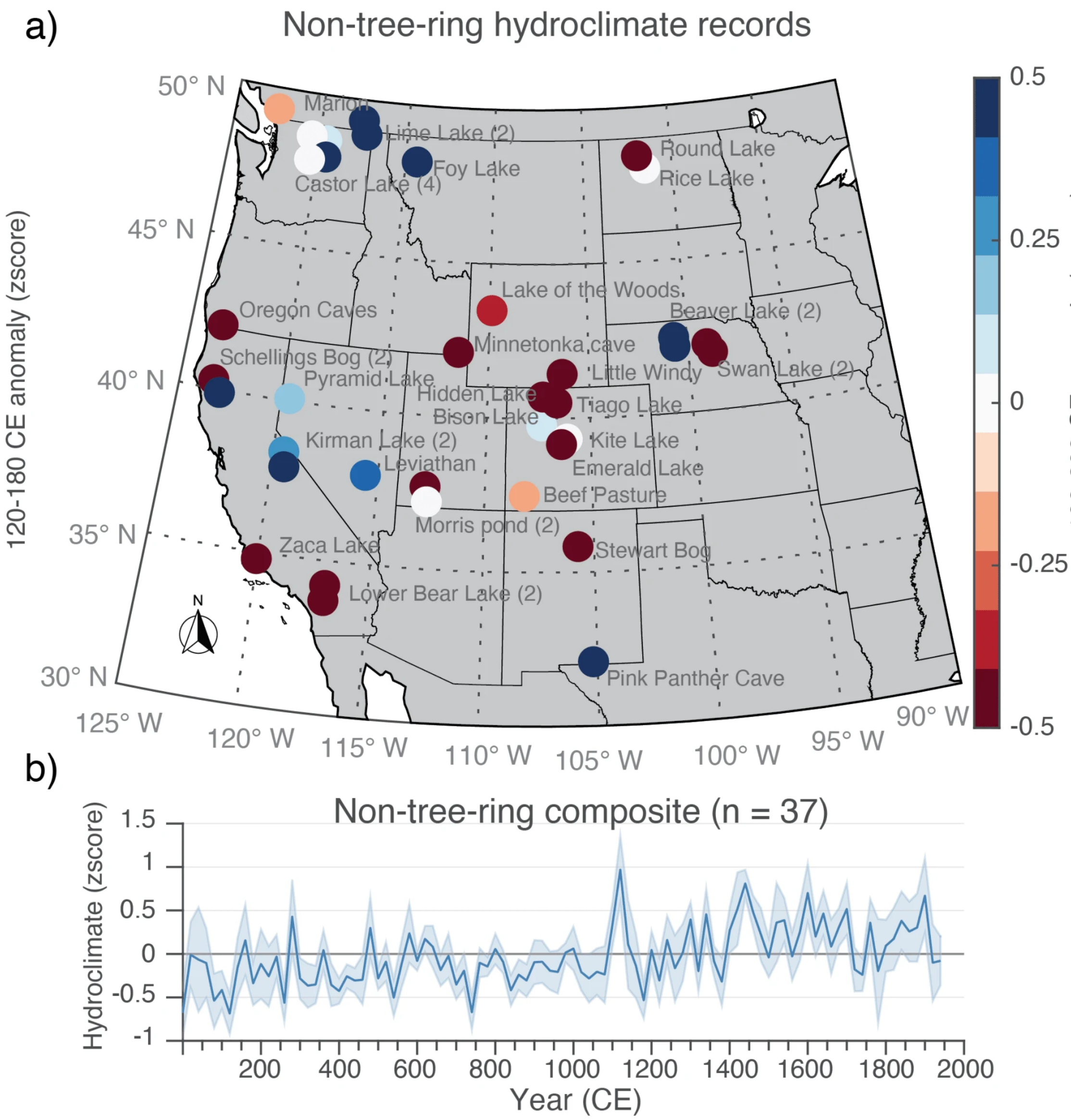
The table above lists the 11 tree-ring chronologies available that include coverage in the 2nd century. Note that most of these chronologies (all but 3) have been used in the North American Drought Atlas (NADA, Cook et al. 2010) so do not provide independent documentation of drought. Chronologies contain a mix of species, and with three to 13 trees in each that include three or more years in the 2nd century period of drought (100-183 CE).



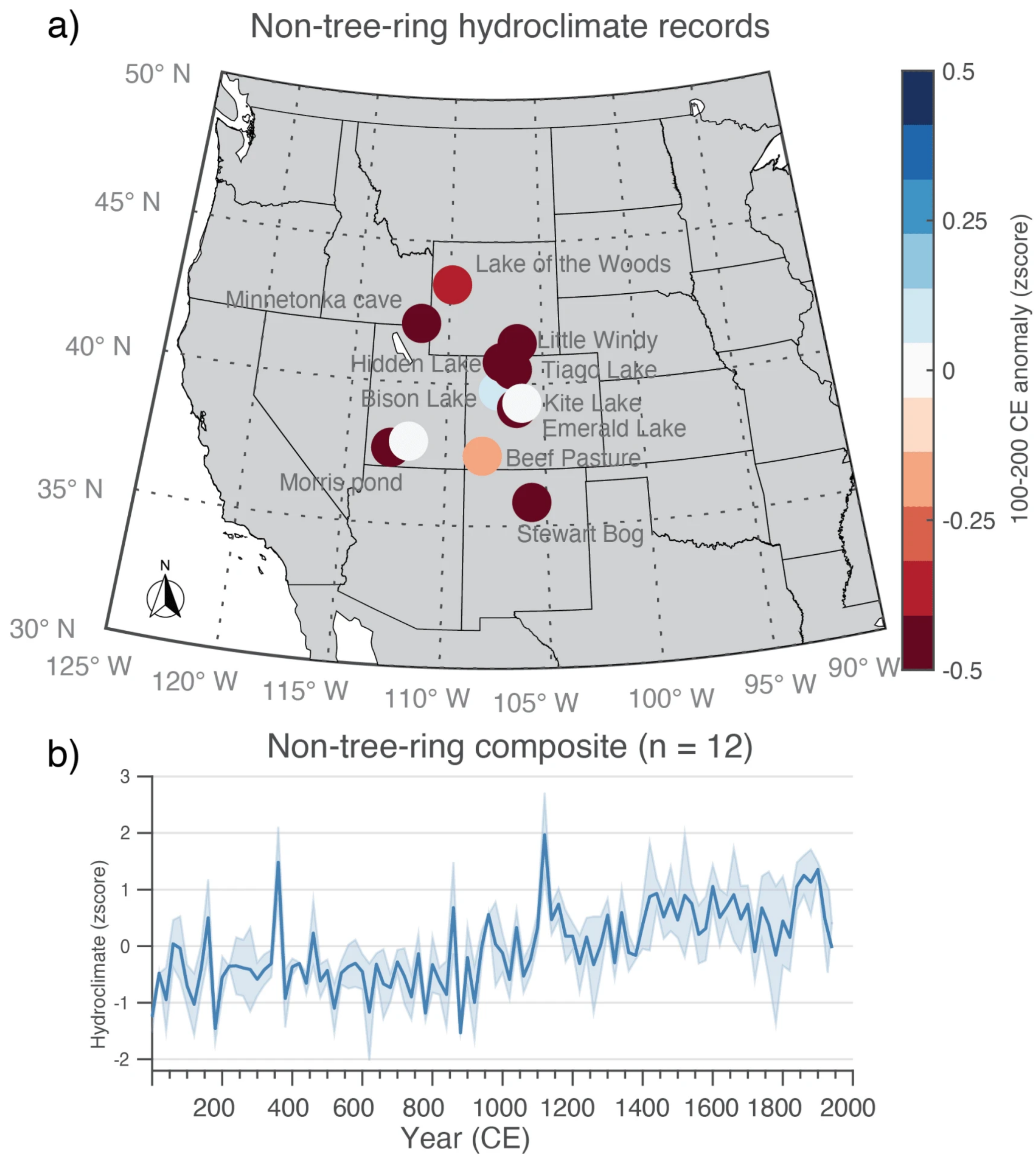
There are approximately 63 individual tree samples from the 11 sites that include at least 4 years in the 2nd century. The time coverage of each of these samples is shown above (each line is one tree). Samples are numbered consecutively from Red Canyon (bottom) to Black Mt. (top) following the order in the table. The box outlines the years 120–200 CE (total span shown is 360–999 CE). All of these samples come from dead trees, except for two trees at the Red Canyon site. While the number of samples is not large, these data provide evidence that site chronologies are reflecting tree-growth patterns from multiple trees (3-13) at these sites.

EVIDENCE FOR THE 2ND CENTURY DROUGHT FROM NON-TREE RING PROXY DATA

Other types of proxy data, from lake and bog sediments and speleothems, were evaluated to assess the 2nd century drought in the context of low frequency hydroclimatic variability of the past 2000 years, which is not retained in tree-ring data. These proxy records also provide a broader spatial context for this drought. Available western US hydroclimatic proxy records were screened for: 1) length (at least 1000 years during the last 2 millennia, including the 2nd century), 2) median sample resolution of 100 years, and 3) minimum of 2 age control points in the past 2 millennia. A total of 37 records were selected, with a subset of 11 in the core 2nd century drought region.



The figure above shows the location of the 37 hydroclimatic proxy records (a), color-coded to reflect anomalies (in z-score values) for the period 100-200 CE. Note that there is a core region reflecting drought, centered in the UCRB, and extending north and east. Drought is also reflected in some of the US west coast records as well. The time series (b) is a composite of the 37 records, 1-2000 CE. Note the negative departures in the 2nd century and the positive trend over the past 2000 years.



The figure above shows a subset of 11 of the 37 non-tree-ring proxy records for the core drought region (a), along with the composite record (b). The 2nd century drought is less marked here, reflecting more noise in this smaller subset. The long-term trend is evident, but is less smooth.

Other hydroclimate records evaluated for the 2nd century drought

Site Name	Lat	Long	Proxy	Author
Beaver Lake	42.46	-100.67	diatom	Schmieder et al., 2011
Beaver Lake	42.46	-100.67	diatom	Schmieder et al., 2011
Beef Pasture	37.47	-108.16	pollen	Petersen, 1985
Bison Lake	39.76	-107.35	d18O	Anderson et al., 2011
Castor Lake	48.54	-119.56	reflectance	Nelson et al., 2011
Castor Lake	48.54	-119.56	reflectance	Nelson et al., 2011
Castor Lake	48.54	-119.56	d18O	Nelson et al., 2011
Castor Lake	48.54	-119.56	d18O	Nelson et al., 2011
Emerald Lake	39.15	-106.41	stratigraphy	Shuman et al., 2014
Foy Lake	48.17	-114.35	d18O	Stevens et al., 2006
Hidden Lake CO	40.51	-106.61	stratigraphy	Shuman et al., 2009
Kirman Lake	38.34	-119.50	diatom	MacDonald et al., 2016
Kirman Lake	38.34	-119.50	diatom	MacDonald et al., 2016
Kite Lake	39.33	-106.13	Pinyon pollen	Jimenez-Moreno et al., 2012
Lake of the Woods	43.48	-109.89	stratigraphy	Pribyl and Shuman, 2014
Leviathan	37.89	-115.58	d13C	Lachniet et al., 2014
Lime Lake	48.87	-117.34	d18O	Steinman et al., 2016
Lime Lake	48.87	-117.34	d13C	Steinman et al., 2016
Little Windy	41.43	-106.33	stratigraphy	Minckley et al., 2012
Lower Bear Lake	34.20	-116.90	TOC	Kirby et al., 2012
Lower Bear Lake	34.20	-116.90	C/N	Kirby et al., 2012
Marion	49.31	-122.55	pollen	Mathewes et al., 1973
Minnetonka cave	42.09	-111.52	d13C	Lundeen et al., 2013
Morris pond	37.67	-112.77	art/amb pollen	Morris et al., 2013
Morris pond	37.67	-112.77	art/cheno pollen	Morris et al., 2013
Oregon Caves	42.08	-123.42	d13C	Ersek et al., 2012
Pink Panther	32.08	-105.17	d18O	Asmerom et al., 2001
Pyramid Lake	40.07	-119.58	d18O	Benson et al., 2002
Rice Lake	48.01	-101.53	Mg/Ca	Yu and Ito, 1999
Round Lake	48.42	-101.50	diatom	Schmieder et al., 2011
Schellings Bog	40.28	-123.36	Fir pollen	Barron et al., 2004
Schellings Bog	40.28	-123.36	Quercus pollen	Barron et al., 2004
Stewart Bog	35.83	-105.72	Pinyon pollen	Jimenez-Moreno et al., 2008
Swan Lake	42.16	-99.03	mineral	Schmieder et al., 2011
Swan Lake	42.16	-99.03	diatom	Schmieder et al., 2011
Tiago Lake	40.58	-106.61	Pinyon pollen	Jimenez-Moreno et al., 2011
Zaca Lake	34.78	-120.04	partical size	Kirby et al., 2014

The details of the 37 non-tree-ring proxy records are in the table, above.

SUMMARY AND DIRECTIONS FOR FUTURE WORK

The tree-ring data analyzed here, along with the proxy date from lakes, bogs, and caves, support the occurrence of the 2nd century drought and its spatial extent across the UCRB and intermountain western US. Tree-ring records document 4 intervals of persistent drought between 100-182 CE, while proxy records from lakes, bogs, and caves confirm that the area of drought is centered on a region that includes the UCRB, but likely extended north and west into Wyoming, and possibly north and east into the northern Great Plains.

Questions remain to be addressed, particularly with respect to the relative severity of the 2nd century UCRB drought in the context of the past 2,000 years. Although this drought appears to be much more severe that the previously documented droughts of the medieval period, the difference in tree-ring sample numbers available for the two periods cannot be ruled out as a possible influence. Sensitivity to individual tree-ring series length and detrending approach also need to be examined more closely. Ultimately, additional collections of samples from trees that lived through both the 2nd century and medieval period droughts are needed to more accurately compare these two drought periods. An additional challenge for future work is determining how best to combine the low-frequency information from the long proxy records with the high-frequency information from the tree-ring data to better understand how millennial-scale trends may be influencing the character of drought over the past 2000 years. Although the combining of proxy records has been undertaken for temperature proxy records (e.g., Moberg et al. 2005, Trouet et al.2013, Salzer et al. 2013), it has not been undertaken for hydroclimatic proxy data.

FACTORS UNDERLYING THE 2ND CENTURY DROUGHT?

Two aspects of the 2nd century hint at possible factors underlying this drought:

Roman Warm Period: This period is characterized as a period of anomalous warm temperatures in Europe, Iceland, the North Atlantic, Florida, and more broadly, across the northern Hemisphere at intervals between 1 and 500 CE (e.g., Lamb 1977, Ljungqvist 2010, and others). However, recent work suggests that warm climate anomalies were not spatially coherent over time (Neukom et al. 2019). This finding is similar to the conclusion that the Medieval Warm Period (~800–1300 CE) most well documented in Western Europe and the North Atlantic, was not a spatially coherent period of warmth (Hughes & Diaz 1994). Perhaps it is not a coincidence that during both of these periods, persistent and severe drought occurred across large parts of the western US. However, possible underlying causal factors for these climate periods have yet to be investigated

Holocene wetting: Hydroclimate proxy records from lakes, bogs, and caves suggest that the 2nd century drought was at the dry end of a 2000-year trend in wetness. Even longer records suggest that this 2000-year trend may be part of a trend in wetting across North America starting in the mid-Holocene (Shuman et al. 2018). Similarly, using paleoclimatic data and modeling, Routson et al. (2019) found an increasing trend in mid-latitude precipitation over the Holocene due to a decreasing Northern Hemisphere latitudinal temperature gradient. Given these Holocene-scale trends in moisture, it is possible that the climate in the UCRB could have been more predisposed to persistent and severe drought in the 2nd century, and to a lesser extent, in the medieval period, than in the more recent centuries. More work is needed to further explore this intriguing idea.

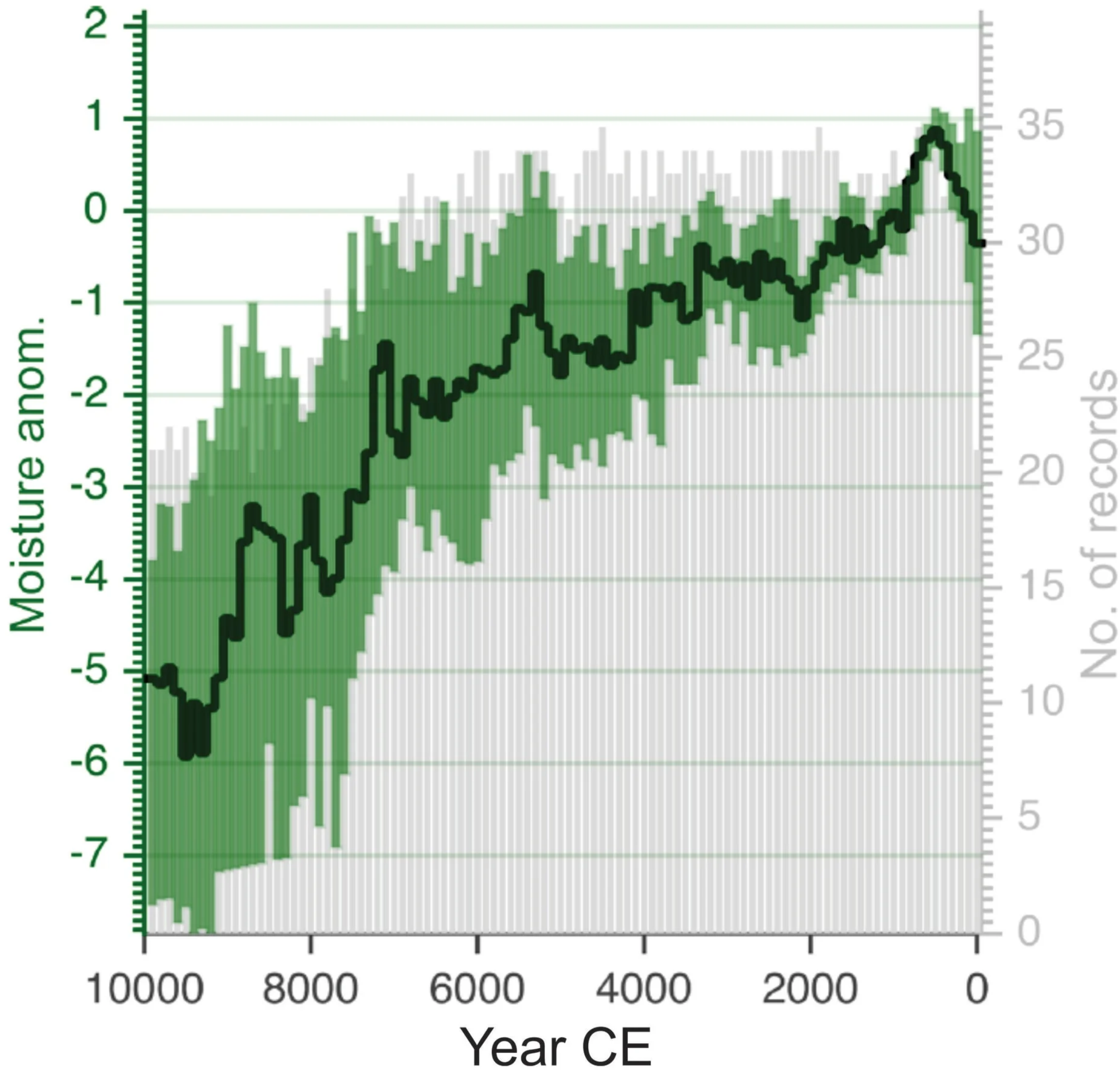


Figure from Shuman et al. 2018 (Figure 7b). The time series is the median composite record of moisture anomalies for a set of North American hydroclimatic proxy records, 6000 years or longer (black line with 95% bootstrapped confidence intervals in green shading). Grey bars show the number of records available, 10000 to 0 BP.

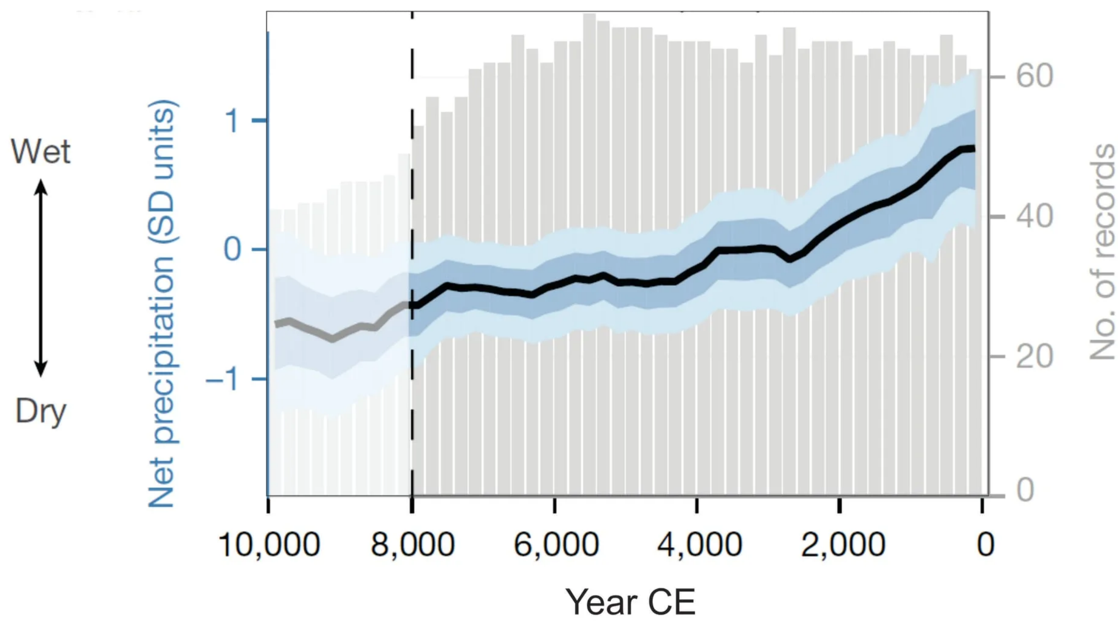


Figure from Routson et al. 2019 (Figure 3h). Northern hemisphere mid-latitude net precipitation (black line with shading representing one and two standard deviation sample, age and calibration bootstrapped uncertainty intervals), 10000-0 BP. The number of contributing records is shown in grey (200-year bins).

CV

Author Information

Connie A. Woodhouse, School of Geography, Development, and Environment, and Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona

Cody C. Routson, Northern Arizona University, School of Earth and Sustainability, Flagstaff, Arizona

David M. Meko, Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona

Subhrendu Gangopadhyay, Bureau of Reclamation, Denver, Colorado

Gregory J. McCabe, U.S. Geological Survey, Water Mission Area - Integrated Modeling and Prediction Division, Denver, Colorado

ABSTRACT

Evidence based on sparse tree-ring data suggests a severe sustained drought in the 2nd century CE that could have rivaled medieval period droughts in the Colorado River basin. A dozen tree-ring chronologies exist for the Four Corners area of the US Southwest that extend into the 2^{nd} century. Within these chronologies, approximately 65 trees (all wood remnants) document conditions during part or all of the 2^{nd} century. These tree-ring data have been used in several gridded climate reconstruction products (drought and precipitation) which extend back to 1 CE over an area that includes the intermountain western US. However, the 2^{nd} century drought has never been highlighted given the sparseness of the data available for this time period. A recently developed reconstruction of Colorado River flow based on these data documents a notably severe and sustained drought over much of the 2^{nd} century, particularly from 100-182 CE. While this reconstruction suggests that the drought exceeds the severity and duration of any drought in the past 2000 years, a complete assessment of the 2^{nd} century drought is challenging due to the sparseness of data. In this study, we use existing tree-ring data and other types of proxy data (e.g. from lake sediments and speleothems) to evaluate the temporal patterns of this drought in the upper Colorado River basin region and to provide a broader spatial context. In addition, we evaluate this drought relative to the 6-decade 12^{th} century drought identified in a previous reconstruction of Colorado River flow to determine if the 2^{nd} century drought may indeed be the new worst-case scenario over the past two millennia.

REFERENCES

Cook, E. R., Seager, R., Heim, R. R., Vose, R. S., Herweijer, C., & Woodhouse, C. (2010). Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. Journal of Quaternary Science 25, 48–61. https://doi.org/10.1002/jqs.1303.

Gangopadhyay, S., Woodhouse, C. A., McCabe, G. J., Routson, C. C., & Meko, D. M. 2022. Tree rings reveal unmatched 2nd century drought in the Colorado River Basin. Geophysical Research Letters, 49, e2022GL098781. https://doi.org/10.1029/2022GL098781

Hughes, M. K., & Diaz, H. F. 1994. Was there a “medieval warm period” and if so, where and when? Climatic Change 26, 109–142. https://doi.org/10.1007/BF01092410

Lamb, H. H. 1977. Climate: Present, past and future. Climatic history and the future, 2, 835.

Ljungqvist, F. C. 2010. A new reconstruction of temperature variability in the extra-tropical northern hemisphere during the last two millennia. Geografiska Annaler - Series A: Physical Geography 92, 339–351. https://doi.org/10.1111/j.1468-0459.2010.00399.x

Moberg, A., Sonechkin, D., Holmgren, K. et al. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433, 613–617. https://doi.org/10.1038/nature03265

Neukom, R., Steiger, N., Gómez-Navarro, J. J., Wang, J., & Werner, J. P. 2019. No evidence for globally coherent warm and cold periods over the preindustrial Common Era. Nature 71, 550–554. https://doi.org/10.1038/s41586-019-1401-2

Routson, C.C. et al. 2019. Mid-latitude net precipitation decreased with Arctic warming during the Holocene. Nature 568, 83-87. https://doi.org/10.1038/s41586-019-1060-3

Salzer, M. W., Bunn, A. G., Graham, N. E., & Hughes, M. K. 2013. Five millennia of paleotemperature from tree-rings in the Great Basin, USA. Climate Dynamics 42, 1517–1526. https://doi.org/10.1007/s00382-013-1911-9

Schuman B. N. et al. 2018. Placing the Common Era in a Holocene context: millennial to centennial patterns and trends in the hydroclimate of North America over the past 2000 years. Clim. Past 14, 665–686. https://doi.org/10.5194/cp-14-665-2018

Trouet, V. et al. 2013. A 1500-year reconstruction of annual mean temperature for temperate North America on decadal-to-multidecadal time scales. Environ. Res. Lett. 8, 024008. http://dx.doi.org/10.1088/1748-9326/8/2/024008

Photo credits (in top banner): Jeffrey J. Lukas