Second century megadrought in the Rio Grande headwaters, Colorado: How unusual was medieval drought?

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[1] A new tree-ring record from living and remnant bristlecone pine (*Pinus aristata*) wood from the headwaters region of the Rio Grande River, Colorado is used in conjunction with other regional records to evaluate periods of unusually severe drought over the past two millennia (B.C. 268 to A.D. 2009). Our new record contains a multi-century period of unusual dryness between 1 and 400 A.D., including an extreme drought during the 2nd century. Characterized by almost five decades of drought (below average ring width), we hypothesize this megadrought is equally, if not more severe than medieval period megadroughts in this region. Published paleoclimate time series help define the spatial extent, severity, and potential causes of the 2nd century megadrought. Furthermore, this early period of unusual dryness has intriguing similarities to later medieval period aridity. Our findings suggest we should anticipate similar severe drought conditions in an even warmer and drier future. **Citation:** Routson, C. C., C. A. Woodhouse, and J. T. Overpeck (2011), Second century megadrought in the Rio Grande headwaters, Colorado: How unusual was medieval drought?, *Geophys. Res. Lett.*, *38*, LXXXXX, doi:10.1029/2011GL050015.

1. Introduction

[2] A better understanding of the range of long-term moisture variability is critical for anticipation of, and adaptation to, projected increases in aridity and drought frequency in the southwestern US (henceforth referred to as the Southwest) [*Overpeck and Udall*, 2010]. Many Southwestern high-resolution proxy records show numerous droughts over the past millennium, including droughts far more severe than we have experienced during the historical period [e.g., *Woodhouse and Overpeck*, 1998; *Cook et al.*, 2004, 2010; *Meko et al.*, 2007]. The medieval interval (ca. A.D. 900 to 1400), a period with relatively warm Northern Hemisphere temperatures [e.g., *Mann et al.*, 2008], has been highlighted as a period in western North America with increased drought severity, duration, and extent [e.g., *Stine*, 1994; *Cook et al.*, 2004, 2010; *Meko et al.*, 2007; *Woodhouse et al.*, 2010]. Iconic decades-long "megadroughts," including Mono Lake low-stands [*Stine*, 1994], the mid-12th century drought associated with dramatic decreases in Colorado River flow [*Meko et al.*, 2007], and the "Great Drought" associated with the abandonment of Ancient Pueblo civilization in the Colorado Plateau region [*Douglass*, 1929], all occur during the medieval period.

[3] Were medieval drought magnitude, severity, frequency, and extent unique? New longer paleoclimate records indicate that medieval droughts were not entirely matchless in prior centuries [i.e., *Knight et al.*, 2010]. Medieval drought was likely influenced by numerous factors including warmer Northern Hemisphere temperatures, warmer regional temperatures, cold eastern equatorial Pacific sea surface temperatures (SSTs), and warm North Atlantic SSTs [*Seager et al.*, 2007; *Conroy et al.*, 2009a; *Graham et al.*, 2010; *Cook et al.*, 2010]. Did these same factors influence extreme drought before medieval time? In this paper we compare a new 2200 year long moisture sensitive bristlecone (*Pinus aristata*) tree-ring chronology from the southern San Juan Mountains, Colorado, with existing records in the broader Four-Corners region (Colorado, Utah, Arizona, and New Mexico). We selected this region because it serves as a key headwaters region for the Southwest (e.g., Colorado and Rio Grande Rivers) and because it was located in the epicenter of known medieval megadroughts [*Cook et al.*, 2008]. We find evidence that indicates centuries-long periods of aridity and Southwestern megadrought were not just a medieval phenomenon. Comparing the possible drivers of medieval drought with potential drivers during the 2nd century suggests that similar factors could have influenced drought during the two periods, helping us understand fundamental causes of severe and persistent drought.

2. Tree Ring and Climate Analysis

[4] Our new chronology was developed from living and remnant samples of moisture sensitive Rocky Mountain bristlecone pine (*Pinus aristata*) growing near Summitville in the southern San Juan Mountains, Colorado (Figure 1). Increment cores were taken from living trees and cross-sections were obtained from dead remnant wood within the stand. Cores and cross-sections were dated to the calendar year using skeleton plots and crossdating [*Stokes and Smiley*, 1968]. Individual growth rings were measured to the nearest 0.01 mm, and crossdating accuracy was checked statistically [*Holmes*, 1983]. Negative exponential detrending was employed to preserve the most low frequency variance while removing biological growth trends and generating standardized tree-ring indices [*Cook*, 1985]. To further preserve low frequency climate related variability, only tree-ring series longer than 470 years were included in the final chronology [*Cook et al.*, 1995]. The final composite chronology (Figure 2) includes 28 trees and extends from B.C. 268 to A.D. 2009. Sample depth drops steadily before A.D. 700 to one tree

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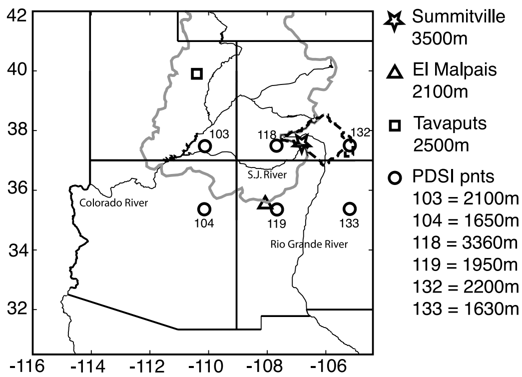

Figure 1. Regional map showing locations and elevations of moisture records employed. PDSI points 132 and 133 only extend back to A.D. 210 and do not cover the 2nd century drought. The upper Colorado River basin is outlined in grey. The Rio Grande headwaters hydrologic unit is outlined in dashed black.

prior to B.C. 200. Six trees span the 2nd century drought. Subsample signal, a measure of common variance between trees, is 0.85 or greater after 10 B.C. (0.85 is a general threshold used to indicate good signal strength [*Wigley et al.*, 1984]).

[5] Bristlecone pine grows on high elevation mountain slopes and growth has a notoriously complex relationship between temperature and moisture [e.g., *Fritts*, 1969; *LaMarche and Stockton*, 1974]. Here, we have used a set of methods designed to define the tree growth/climate response of this site and its consistency over time (details in the auxiliary material).[1] Correlation analysis with instrumental gridded PRISM data (monthly precipitation and temperature) [*Daly et al.*, 2002] spanning A.D. 1895-2009 from the Rio Grande headwaters hydrologic unit (WestMap, 2010, accessed 31 August 2010, available at http://www.cefa.dri.edu/Westmap/) was used to evaluate the climate sensitivity of our new bristlecone chronology during the period covered by instrumental records. The Rio Grande headwaters hydrologic unit (Figure 1) was used because it encompasses Summitville and the San Luis Valley, through which the Rio Grande flows. Seasonal correlation analysis and partial correlation analysis [*Meko et al.*, 2011] with the PRISM data show tree growth has a significant positive relationship with March through July precipitation ($r = 0.47$, $p < 0.01$) and has an independent significant negative relationship with March through July temperature ($r = -0.37$, $p < 0.01$). A positive relationship with late winter through early summer precipitation suggests snowpack influences on soil moisture at the beginning of the growing season, as well as early growing season precipitation both promote tree growth. A negative relationship with March through July temperature suggests that warm spring and early summer months hasten the timing of snowmelt in addition to driving increased evaporation contributing to moisture stress in the trees. The inset in Figure 2 shows the relationship of March through July precipitation and ring-width from 1895 to the present. We also evaluated potential relationships between growth and late summer temperature, which are sometimes important to high elevation tree growth, using PRISM data. We found that tree-growth responded positively to warm August temperature during years with wet spring months, but August temperatures had no influence on spring moisture sensitivity (see auxiliary material). Moving correlation analysis between our bristlecone chronology and regional PDSI and temperature reconstructions [*Salzer and Kipfmueller*, 2005; *Cook et al.*, 2008] indicates our chronology has a consistent moisture balance signal over the past 2000 years (see auxiliary material). Although the climate signal is not as strong as that found in lower elevation species, bristlecone pine allow us to develop a much longer record than possible using lower elevation species.

3. Second Century Droughts

[6] Our new record smoothed with a 25-year running mean shows how moisture balance in the southern San Juan Mountains has varied on decadal time-scales over the past 2200 years (Figure 2). The smoothed chronology reveals two periods of enhanced drought frequency and severity relative to the rest of the record. The later period, A.D. ~1050–1350, corresponds with medieval aridity well documented in other records [*Woodhouse and Overpeck*, 1998; *Cook et al.*, 2004; *Meko et al.*, 2007]. The earlier period is more persistent (A.D. ~1–400), and includes the most pronounced event in the Summitville chronology: a multi-decadal-length drought during the 2nd century. This drought includes the unsmoothed record's driest 25-year interval (A.D. 148 to A.D. 173) as well as a longer 51-year period, A.D.

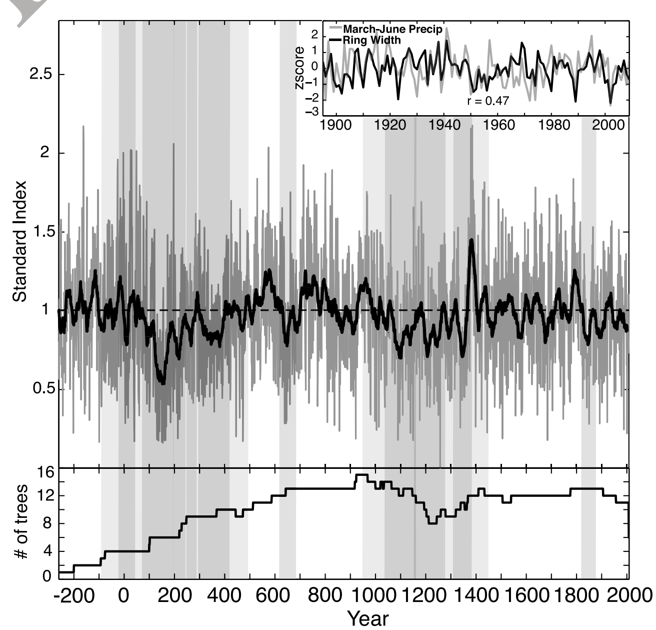

Figure 2. Summitville bristlecone chronology standard index (grey) smoothed with a 25-yr moving average (black) and number of trees (bottom). Narrow shaded bars are the 10 driest 25-yr periods defined by the Summitville chronology. Wide shaded bars highlight multicentury periods of increased aridity and drought frequency. Upper right inset: ring width (black) with March-July PRISM precipitation data from Rio Grande headwaters hydrologic unit (grey).

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050015.

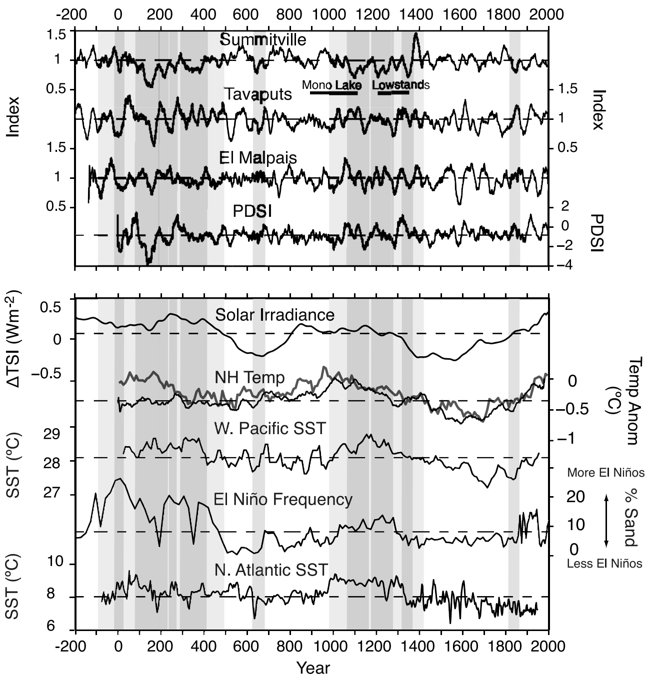

Figure 3. (top) Colorado Plateau region moisture records including Summitville CO, Tavaputs UT [*Knight et al.*, 2010], El Malpais NM [*Grissino-Mayor*, 1996], PDSI [*Cook et al.*, 2008] showing the timing and severity of the 2nd century megadrought. (bottom) Records of variables that may influence drought in the Four Corners region: inferred total solar irradiance (smoothed with a 50 yr MA) [*Steinhilber et al.*, 2009], Northern Hemisphere temperature (smoothed with a 50 yr MA) [*Moberg et al.*, 2005] (black) and [*Ljunqvist*, 2010] (grey), west Pacific warm-pool sea surface temperature [*Oppo et al.*, 2010], El Niño frequency [*Conroy et al.*, 2008], and Northern Iceland SST [*Sicre et al.*, 2008]. Shaded bars are the same as in Figure 2.

122–172, that has only two years with ring width slightly above the long-term mean. The smoothed chronology shows the periods A.D. 77–282 and A.D. 301–400 are the longest (206 and 100 years, respectively, below the long-term average) droughts of the entire 2276-yr record.

[7] Because the climate response of bristlecone pine is not as robust as lower elevation species, and because the new Summitville chronology only includes six trees during the 2nd century drought interval, we assessed the reliability of our record using other moisture-sensitive reconstructions from the region. Comparing the Summitville chronology with reconstructed Colorado Plateau PDSI [*Cook et al.*, 2008], annual precipitation from El Malpais, New Mexico (included in PDSI, so not strictly an independent record) [*Grissino-Mayor*, 1996] and Tavaputs, Utah [*Knight et al.*, 2010] (Figure 3, top) highlights the regional significance of the 2nd century drought. Consistent severity of the 2nd century drought among the records, across elevation (1630 m–3500 m), space (Figure 1), and tree species (*Pinus aristata*, *Pseudotsuga menziesii*, and *Pinus edulis*) gives us more confidence in the timing and severity of this drought. Medieval megadroughts, including the 1150's and late 1200's droughts are not as pronounced in the high-elevation Summitville chronology. The 2nd century drought, however, appears to have been equal to, or more extreme, than the iconic medieval megadroughts in these other proxy records. Sample size and climate response of the Summitville chronology limits the conclusions we can make. However, with limitations in mind and the support of the other records, we hypothesize the 2nd century drought may be one of the most severe and persistent droughts the Colorado Plateau region has experienced during the last 2000 years (Table 1). Assessing the spatial extent of the drought with composite maps of gridded PDSI reconstructions for the years A.D. 148–173 (Figure S1 in the auxiliary material) [*Cook et al.*, 2008] indicates that the 2nd century drought impacted a region that extends from southern New Mexico north and west into Idaho. The drought was less severe in Nevada and California, and no PDSI data are available for the 2nd century in the central and eastern United States. The spatial pattern of the 2nd century megadrought appears similar to the mid-12th century megadrought highlighted in PDSI and Colorado River flow reconstructions [*Meko et al.*, 2007; *Cook et al.*, 2008].

[8] We investigated potential broad-scale climatic influences on Four Corners hydroclimate by comparing our new drought record with published records from regions hypothesized to have influenced Southwestern drought. Due to a limited number of available records during the 2nd century which all contain uncertainties; the following analyses should be viewed as exploratory.

[9] Warm regional temperatures exacerbated recent drought severity [e.g., *Breshears et al.*, 2005; *Weiss et al.*, 2009; *Woodhouse et al.*, 2010], and a Colorado Plateau temperature reconstruction [*Salzer and Kipfmueller*, 2005] indicates that medieval period droughts during the mid 12th and late 13th centuries were potentially influenced by warmer than average temperatures as well. A small positive temperature anomaly on the Colorado Plateau also occurs during the 2nd century, indicating that local temperature anomalies may be a common influence on megadrought in the region. Warm global or hemispheric temperatures can also influence Southwest drought through changes in circulation [*Cook et al.*, 2010]. Few hemispheric temperature reconstructions extend back to the 2nd century, making a comparison between medieval and 2nd century temperature difficult. A multiproxy Northern Hemisphere temperature reconstruction

Table 1. Drought Persistence (Years AD) Assessed Using a 25-Year Running Mean[a]

Summitville	PDSI[b]	El Malpais	Tavaputs
77–282	**97–181**	979–1039	938–1006
301–400	426–481	1441–1500	1762–1830
1067–1160	347–399	−8–46	782–842
1192–1263	979–1017	349–395	**132–184**
1876–1914	222–257	895–936	−23–27
1326–1364	1438–1473	443–483	633–676
1447–1478	1130–1163	−99–60	1254–1297
1561–1591	505–537	1335–1373	−243–202
1828–1858	1261–1292	1567–1604	507–545
1668–1697	1568–1596	**138–174**	1130–1168

[a]Drought initiation and termination are defined by when the smoothed series drops below or rises above the long-term mean. The ten most persistent droughts in each record are shown from top to bottom. The second century drought is bolded.

[b]PDSI points 103, 104, 118, 119, 132, 133 averaged to represent four corners region.

[*Moberg et al.*, 2005] shows no anomalous warming during the 2nd century (Figure 3). A more recent multiproxy Northern Hemisphere temperature reconstruction however, shows a "Roman Warm Period" spanning 1–300 A.D. [*Ljungqvist*, 2010] that could be analogous to warmth associated with Southwestern megadroughts during medieval times. Both *Moberg et al.* [2005] and *Ljungqvist* [2010] show warm Northern Hemisphere temperatures during the medieval period. In addition, both megadrought periods may have occurred under somewhat elevated levels of solar irradiance that were above the past 2200 year average (Figure 3).

[10] Although elevated temperatures may have accompanied this drought, other factors were likely important as well. Sea surface temperature (SST) can have a significant impact on Southwestern hydroclimate through changes in oceanic and atmospheric circulation. Tropical Pacific SST, modulated by the El Niño/Southern Oscillation (ENSO), has an important influence on Southwestern precipitation. The tropical Pacific warm phase (El Niño) is typically associated with increased regional precipitation, whereas the cool phase (La Niña) is typically associated with decreased regional precipitation and drought [e.g., *Hoerling and Kumar*, 2003; *Seager et al.*, 2005]. Atlantic SST's have a less well understood, but important correspondence with Southwestern hydroclimate, whereby warm North Atlantic SST's are thought to influence the rainfall and drought severity, most strongly in summer [*Hoerling and Kumar*, 2003; *McCabe et al.*, 2004; *Kushnir et al.*, 2010]. Medieval megadroughts were likely associated with persistent "La Niña like" conditions, and warm North Atlantic SST [*Seager et al.*, 2007; *Conroy et al.*, 2009a; *Graham et al.*, 2010].

[11] Again limited records are available to evaluate potential SST influences on 2nd century megadrought. An ocean sediment record reflecting western equatorial Pacific SST shows positive anomalies during both the medieval period and the 2nd century [*Oppo et al.*, 2009], suggesting that persistent or stronger La Niña-like conditions may have forced both 2nd century and medieval drought. The 2nd century and late medieval period aridity also coincide with intervals of increased El Niño frequency in the eastern tropical Pacific inferred from changes in grain size in sediment cores from Lake El Junco in the Galapagos Islands [*Conroy et al.*, 2008]. Changes in El Junco grain size are a function of precipitation, which is closely connected in the Galapagos with some types of strong El Niño events, suggesting that strong El Niño events may have punctuated the persistent La Niña-like conditions. An SST record also from Lake El Junco shows La Niña-like background conditions spanning the medieval period, supporting our interpretation [*Conroy et al.*, 2009b]. The coincidence of heightened El Niño frequency within a La Niña-like background state corresponds closely to one mode of ENSO variance characterized by *Fedorov and Philander* [2000]. On the other hand, the extended period of increased El Niño frequency, as inferred from El Junco, contains two abrupt decreases that correspond fairly well to the two droughts in the early part of the Summitville record (Figure 3) supportive of strong La Niña conditions. Dating uncertainty and limited other records make these assessments less than robust, and it is clear that more work is needed to understand the equatorial Pacific conditions that may promote megadrought. The influence of North Atlantic SST on the 2nd century is even more uncertain due to the scarcity of high-resolution paleodata available. Northern Iceland SSTs [*Sicre et al.*, 2008] have a positive anomaly during the medieval period, but are equivocal with respect to the 2nd century period, although modest warmth spans most of the period characterized by drought. The equatorial North Atlantic appears however to be more important for influencing Southwestern drought, at least during the instrumental period [*Kushnir et al.*, 2010], and unfortunately, no proxy records that could resolve this period of drought are currently available.

4. Conclusions and Implications

[12] A new millennial-length moisture-sensitive bristlecone pine chronology from the San Juan River (a major tributary of the Colorado River) and Rio Grande headwaters region of southern Colorado provides insight on droughts and changes in aridity over the past two millennia in the Southwest. Our new record extends back 2200 years and shows a broader range of drought variability, including a drought that persisted from A.D. 122 to A.D. 172. Based on our findings, we hypothesize that megadroughts are not unique to the medieval period. Available regional moisture records indicate the 2nd century likely extended from southern New Mexico to Idaho, possibly comparable in extent to the mid 12th century drought. More high-resolution moisture records are needed to evaluate both the severity and full extent of the 2nd century drought. Additional bristlecone pine chronologies in the southern Colorado region would allow a calibrated reconstruction of moisture variability.

[13] Attributing potential causes of megadrought is challenging due to scarcity of millennial-length records. Reconstructed Colorado Plateau temperature suggests warmer than average temperature could have influenced both 2nd century and medieval drought severity. Available data also suggest that the Northern Hemisphere may have been warm during both intervals. Tropical Pacific SST and El Niño frequency reconstructions indicate similar conditions could have prevailed during the medieval and 2nd century periods, potentially contributing to drought severity and duration. Warm North Atlantic SST likely prevailed during the medieval period, but possible connections with the Atlantic remain ambiguous with respect to the 2nd century.

[14] Given the effects of recent drought on water resources and ecosystems in the Southwest [*Breshears et al.*, 2005; *Overpeck and Udall*, 2010], it will be important to test our hypothesis that 2nd century drought severity rivaled medieval megadroughts and more closely examine potential relationships with hemispheric climate patterns. Testing our hypothesis will require a better network of millennial length moisture proxy records that retain both short and long time-scale climate variability in addition to more high-resolution reconstructions of global climate patterns. Until the climate dynamics of megadrought are thoroughly understood, managers of water and natural resources in the Four Corners, Rio Grande, and Colorado regions should take note that megadroughts as long, or longer, than 50 years could reoccur with the caveat that future droughts will likely be even warmer than those in the past [*Karl et al.*, 2009; *Weiss et al.*, 2009; *Overpeck and Udall*, 2010].

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References

Breshears, D. D., et al. (2005), Regional vegetation die-off in response to global-change-type drought, *Proc. Natl. Acad. Sci. U. S. A.*, *102*(42), 15,144–15,148, doi:10.1073/pnas.0505734102.

Conroy, J. L., J. T. Overpeck, J. E. Cole, T. M. Shanahan, and M. Steinitz-Kannan (2008), Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record, *Quat. Sci. Rev.*, *27*, 1166–1180, doi:10.1016/j.quascirev.2008.02.015.

Conroy, J. L., J. T. Overpeck, J. E. Cole, and M. Steinitz-Kannan (2009a), Variable oceanic influences on western North American drought over the last 1200 years, *Geophys. Res. Lett.*, *36*, L17703, doi:10.1029/2009GL039558.

Conroy, J. L., et al. (2009b), Unprecedented recent warming of surface temperatures in the eastern tropical Pacific Ocean, *Nat. Geosci.*, *2*, 46–50, doi:10.1038/ngeo390.

Cook, E. R. (1985) A time series analysis approach to tree-ring standardization, Ph.D. dissertation, Univ. of Ariz., Tucson.

Cook, E. R., K. R. Briffa, D. M. Meko, D. A. Graybill, and G. Funkhouser (1995), The "segment length curse" in long tree-ring chronology development for palaeolclimatic studies, *Holocene*, *5*(2), 229–237, doi:10.1177/095968369500500211.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle (2004), Long-term aridity changes in the western United States, *Science*, *306*(5698), 1015–1018, doi:10.1126/science.1102586.

Cook, E. R., et al. (2008), North American summer PDSI reconstructions, version 2a, *IGBP PAGES World Data Cent. Paleoclimatol. Data Contrib. Ser. 2008-046*, Paleoclimatol. Program, *NGDC, NOAA*, Boulder, Colo.

Cook, E. R., et al. (2010), Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context, *J. Quat. Sci.*, *25*, 48–61, doi:10.1002/jqs.1303.

Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris (2002), A knowledge-based approach to the statistical mapping of climate, *Clim. Res.*, *22*, 99–113, doi:10.3354/cr022099.

Douglass, A. E. (1929), *The Secret of the Southwest Solved With Talkative Tree Rings*, pp. 736–770, Judd and Detweiler, Washington, D. C.

Fedorov, A. V., and S. G. Philander (2000), Is El Niño changing?, *Science*, *288*, 1997–2002, doi:10.1126/science.288.5473.1997.

Fritts, H. C. (1969), Bristlecone pine in the White Mountains of California. Growth and ring-width characteristics, *Pap. Lab. Tree Ring Res.*, *4*, 1–44.

Graham, N. E., C. M. Ammann, D. Fleitmann, K. M. Cobb, and J. Luterbacher (2010), Support for global climate reorganization during the Medieval Climate Anomaly, *Clim. Dyn.*, doi:10.1007/s00382-010-0914-z.

Grissino-Mayor, H. (1996), A 2129-year reconstruction of precipitation for northwestern New Mexico, USA, in *Tree Rings, Environment, and Humanity*, edited by J. S. Dean, D. M. Meko, and T. W. Swetnam, pp. 191–204, Radiocarbon, Tucson, Ariz.

Hoerling, M., and A. Kumar (2003), The perfect ocean for drought, *Science*, *299*, 691–694, doi:10.1126/science.1079053.

Holmes, R. L. (1983), Computer-assisted quality control in tree-ring dating and measurement, *Tree Ring Bull.*, *43*, 69–78.

Karl, T. R., J. M. Melillo, and T. C. Peterson (Eds.) (2009), *Global Climate Change Impacts in the United States*, Cambridge Univ. Press, Cambridge, U. K.

Knight, T. A., D. M. Meko, and C. H. Baisan (2010), A bimillennial-length tree-ring reconstruction of precipitation for the Tavaputs Plateau, northeastern Utah, *Quat. Res.*, *73*, 107–117, doi:10.1016/j.yqres.2009.08.002.

Kushnir, Y., et al. (2010), Mechanisms of tropical Atlantic SST influence on North American hydroclimate variability, *J. Clim.*, *23*, 5610–5628, doi:10.1175/2010JCLI3172.1.

LaMarche, V. C., and C. W. Stockton (1974), Chronologies from temperature-sensitive bristlecone pines at upper treeline in western United States, *Tree Ring Bull.*, *34*, 21–45.

Ljungqvist, F. C. (2010), A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia, *Geogr. Ann.*, *92*, 339–351, doi:10.1111/j.1468-0459.2010.00399.x.

Mann, M. E., Z. Zhang, M. K. Hughes, R. S. Bradley, S. K. Miller, S. Ruthford, and F. Ni (2008), Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia, *Proc. Natl. Acad. Sci. U. S. A.*, *105*(36), 13,252–13,257, doi:10.1073/pnas.0805721105.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U. S. A.*, *101*(12), 4136–4141, doi:10.1073/pnas.0306738101.

Meko, D. M., C. A. Woodhouse, C. H. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and W. Salzer (2007), Medieval drought in the Upper Colorado River Basin, *Geophys. Res. Lett.*, *34*, L10705, doi:10.1029/2007GL029988.

Meko, D. M., R. Touchan, and K. J. Anchukaitis (2011), Seascorr: A MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series, *Comput. Geosci.*, *37*, 1234–1241, doi:10.1016/j.cageo.2011.01.013.

Moberg, A., et al. (2005), Highly variable Northern Hemisphere temperatures reconstructed from low-and high-resolution proxy data, *Nature*, *433*, 613–617, doi:10.1038/nature03265.

Oppo, D. W., Y. Rosenthal, and B. K. Linsley (2009), 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool, *Nature*, *460*, 1113–1116, doi:10.1038/nature08233.

Overpeck, J. T., and B. Udall (2010), Dry times ahead, *Science*, *328*, 1642–1643, doi:10.1126/science.1186591.

Salzer, M. W., and K. F. Kipfmueller (2005), Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, *Clim. Change*, *70*, 465–487, doi:10.1007/s10584-005-5922-3.

Salzer, M. W., M. K. Hughes, A. G. Bunn, and K. F. Kipfmueller (2009), Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(48), 20,348–20,353, doi:10.1073/pnas.0903029106.

Seager, R., Y. Kushnir, C. Herweijer, N. Naik, and J. Velez (2005), Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000, *J. Clim.*, *18*(19), 4065–4088, doi:10.1175/JCLI3522.1.

Seager, R., et al. (2007), Blueprints for Medieval hydroclimate, *Quat. Sci. Rev.*, *26*, 2322–2336, doi:10.1016/j.quascirev.2007.04.020.

Sicre, M. A., et al. (2008), Decadal variability of sea surface temperatures off North Iceland over the last 2000 yrs, *Earth Planet. Sci. Lett.*, *268*, 137–142, doi:10.1016/j.epsl.2008.01.011.

Steinhilber, F., J. Beer, and C. Fröhlich (2009), Total solar irradiance during the Holocene, *Geophys. Res. Lett.*, *36*, L19704, doi:10.1029/2009GL040142.

Stine, S. (1994), Extreme and persistent drought in California and Patagonia during medieval time, *Nature*, *369*(6481), 546–549, doi:10.1038/369546a0.

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

Weiss, J. L., C. L. Castro, and J. T. Overpeck (2009), Distinguishing pronounced droughts in the southwestern United States: Seasonality and effects of warmer temperatures, *J. Clim.*, *22*, 5918–5932, doi:10.1175/2009JCLI2905.1.

Wigley, T. M. L., K. R. Briffa, and P. D. Jones (1984), On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *J. Clim. Appl. Meteorol.*, *23*, 201–213, doi:10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2.

Woodhouse, C. A., and J. T. Overpeck (1998), 2000 years of drought variability in the central United States, *Bull. Am. Meteorol. Soc.*, *79*, 2693–2714, doi:10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2.

Woodhouse, C. A., D. M. Meko, G. M. MacDonald, D. W. Stahle, and E. R. Cook (2010), A 1,200-year perspective of 21st century drought in the southwestern North America, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(50), 21,283–21,288, doi:10.1073/pnas.0911197107.

Woodhouse, C. A., G. Pederson, and S. Gray (2011), Using Bristlcone Pine to investigate long-term hydroclimatic variability of the Arkansas River, *Quat. Res.*, in press.

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