Tree Rings Reveal Climate Change Past, Present, and Future[1]

KEVIN J. ANCHUKAITIS
Associate Professor
School of Geography and Development
Laboratory of Tree-Ring Research
University of Arizona

Introduction

Earth's climate system exhibits variability in both temperature and hydroclimate across a range of spatial and temporal scales covering several orders of magnitude. However, existing observations of the climate system from weather stations and satellites are too short or too sparse to completely characterize this variability, particularly at decadal, multidecadal, and centennial time scales. And yet these modes of variability are critical for short- and medium-term natural resources management, climate policy, and economic planning. This natural variability in the climate system is also superimposed on the trends and changes caused by the anthropogenic emission of greenhouse gases, complicating straightforward detection and attribution of human modification of Earth's climate system (Solomon et al. 2011) and leaving a lacuna in our knowledge of the complete range of variability in temperature and hydroclimate. A more complete understanding of internal variability in the climate system is necessary for decadal prediction, vulnerability reduction, and long-term adaptation to climate variability and change (Meehl et al. 2009; Vera et al. 2010).

Paleoclimatology addresses the limitations of the instrumental era by extending climate information back into the past using "proxies," and tree rings are one of the most important sources of information about the climate of the last several thousand years. The various physical and chemical characteristics of the annual rings reflect past climate and environmental conditions, prior to our modern period of monitoring and measuring the Earth system, and as such effectively allow us to recover observations of the past. These proxies for pre-instrumental climate can be used to quantitatively reconstruct past temperature and hydroclimate variability prior to the advent of the instrumental,

1 Read on 28 April 2017 as part of the *Observed Climate Change* symposium.

historical, and satellite measurements of climate and weather. Tree rings have several advantages as proxies over the last few thousand years: they are widespread over the midlatitudes, particularly across the Northern Hemisphere. They are precisely dated to their year of formation, which allows not only exact chronological determinations of past climate anomalies, but also statistical comparison and calibration with corresponding instrumental records of climate where both overlap. Because they are relatively simple to collect, tree-ring data are well replicated in both space and time, increasing confidence in the accuracy of their chronology, reducing non-climatic noise associated with fine-scale ecological or forest disturbance processes, and enabling the reconstruction of entire climate fields, which can be used to identify the fingerprint of internal climate system variability and changes in the amount of energy in the Earth system.

Tree rings are therefore an archive of information about past environmental conditions, and different physical or biochemical measurements can yield complementary insights into environmental conditions in the year a ring was formed. The most common and straightforward measurement is the width of the annual ring, which reflects variability in the most limiting factor for annual growth. Subannual measurements of the ring may resolve seasonal climate variations (Meko and Baisan 2001; Griffin et al. 2013). Wood density, especially the density of the cells formed near the end of the growing season, typically reflect a strong signal of summer temperatures (Schweingruber et al. 1978; Briffa et al. 1992; Briffa, Jones, and Schweingruber 1992; Schweingruber and Briffa 1996; Esper et al. 2015; Wilson et al. 2016; Anchukaitis et al. 2017). The oxygen isotope composition of the wood can reveal the hydrological or meteorological origin of the water used by the tree, the extent of ecosystem evapotranspiration, changes in relative humidity, or the seasonal amount of rainfall itself (Roden, Lin, and Ehleringer 2000; McCarroll and Loader 2004; Gagen et al. 2011; Anchukaitis and Evans 2010). The carbon isotope ratio of wood is controlled by photosynthetic rate and the conductance of air through the leaf stomata, which can reflect soil moisture, sunlight, or the amount of carbon dioxide in the atmosphere (Leavitt and Long 1991; Saurer et al. 1997; McCarroll and Loader 2004; Gagen et al. 2007; McCarroll et al. 2009). That the visible rings in the stems of trees are both annual and reflect environmental variation has been recognized for several centuries (Sarton 1954). Leonardo da Vinci recognized both their chronological and potential climatic significance in the 15th century (Sarton 1954; Schweingruber 1996). However, the modern science of dendrochronology has its origins in the painstaking and methodical work of Andrew Ellicott Douglass, an astronomer by

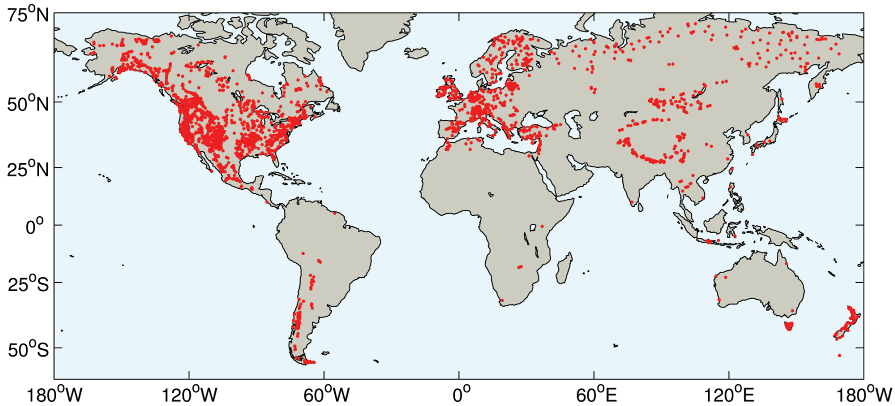

FIGURE 1. Location of all tree-ring chronology sites archived publicly in the International Tree Ring Data Bank (ITRDB).

training who established the modern basis for the field through his interest in extending the record of sunspots via their effect on weather and therefore tree growth (Douglass 1914, 1919, 1929; Webb 1983). Douglass founded the Laboratory of Tree-Ring Research at the University of Arizona in 1937 (Creasman et al. 2012). The earliest years of dendrochronology were also closely linked with archaeological research on the pre-Hispanic cultures of southwestern North America (Nash 1999), with Douglass, archaeologist Emil Haury, and their colleagues successfully matching the growth patterns from rings of living trees with those in remnant archaeological timbers to establish absolute dates for settlement and construction (Douglass 1929; Haury 1962). Douglass was also interested in using the longevity of ancient giant sequoia (*Sequoiadendron giganteum*) to link societal and climatic changes over several millennia in the ancient Americas (Huntington et al. 1914). Indeed, Douglass—a Member of the American Philosophical Society—presented on his climate investigations of sequoia at the 1922 Meeting of the Society in Philadelphia (Douglass 1922).

More than a century of dendrochronology research has now resulted in a network of tree-ring chronologies covering all the continents except Antarctica (Figure 1). This global tree-ring database is most dense in the mid- and high latitudes in the Northern Hemisphere, due to a mix of the history, location, and scholarly focus of major tree-ring laboratories and individual researchers, the location and existence of forest regions with long-lived trees, and the numerous challenges associated with tropical dendrochronology (Eckstein et al. 1981; Stahle 1999). Depending on their location, tree-ring chronologies record a diverse set of climate signals (St. George 2014; St. George and Ault 2014). In semi-arid regions, tree-ring width variation is most often controlled by precipitation or soil moisture and record information about regional hydroclimate variability. At high latitude and high elevations near tree line, temperature limitations are more likely to determine ring width and wood density. Moist temperate forests in the mid-latitudes often have trees whose growth reflects a mix of temperature and precipitation signals. Thus, sampling strategies for reconstructing past climate variability and change are guided by the metric of interest: for reconstructions of past temperature, high latitude, high altitude, and wood density chronologies contain the strongest temperature signal, while forests where moisture in the primary limiting factor on growth are the target for hydroclimate studies. This principle allows the global network of tree-ring data to be used to reconstruct different aspects of Earth's climate, depending on the geography and ecology of the proxy network.

The retrospective nature of paleoclimatology and dendroclimatology therefore offer insights into the past. But the long-term perspective afforded by tree-ring data and the climate reconstructions that can be generated from them also provide context for present climate variability and change. The paleoclimate record contains and offers for analysis a much more expansive understanding of the potential range of behaviors in Earth's climate system and the opportunity to better estimate the occurrence of rare and extreme events.

Hydroclimate Variability and Change

The majority of existing tree-ring chronologies reflect hydroclimate variability (St. George 2014; St. George and Ault 2014), although the specific monthly or seasonal climate response can vary across regions and continents (Meko et al. 1993; St. George, Meko, and Cook 2010; Touchan et al. 2014; Cook et al. 2016). For example, in winter-wet Mediterranean regions such as the American Southwest, integrated water year precipitation over several seasons usually controls annual tree-ring formation, whereas trees in forests with equitable yearly precipitation or a dominant summer wet season more often record summer or growing season precipitation. Trees in temperate mesic forests may record a mixture of monthly temperature and precipitation signals. Several superlative and highly moisture-sensitive tree species exist in the global tree-ring database, including the blue oak (*Quercus douglasii*) of California (Stahle et al. 2013; Griffin and Anchukaitis 2014), the bald cypress (*Taxodium distichum*) of the southeastern United States (, and Hehr 1988; et al. 1998), and multiple conifer species growing throughout semi-arid regions in North America and the Mediterranean (Douglass 1922, 1929; Schulman 1956; Fritts, Lofgren, and Gordon 1979; Chbouki, Stockton, and Myers 1995; Meko et al. 1993; Cook et al. 2004; Touchan et al. 2011). Tree rings also can be used to reconstruct hydroclimate phenomena such as riverflow or snowpack, as these phenomena integrate seasonal moisture balance in ecosystems and watersheds in a similar way as recorded in ring width proxies themselves.

Reconstruction of streamflow has provided important insights into the range of natural variability and potential future hydroclimate scenarios in the western United States. In the western United States, the available water resources of California, Arizona, and Nevada depend on their allocation of the annual flow of the Colorado River under the Colorado River Compact (Pulwarty, Jacobs, and Dole 2005). In the 1970s, as part of the Lake Powell Research Project, Stockton and Jacoby (1976) developed the first tree-ring reconstructions of Upper Colorado River Basin streamflow at Lee's Ferry and for other major tributaries (Stockton 1975). These reconstructions revealed that the river's flow at the time of the drafting of the Compact in 1922 was exceptionally high and not representative of the long-term average over several centuries. Moreover, their tree-ring reconstructions included periods of low flows that were both longer and more severe than any in the instrumental gauge record. The implication was clear: more water had been allocated from the river than could be consistently supplied to the Western states that were party to the Compact. Subsequent research has refined and lengthened the available tree-ring reconstructions of Colorado River streamflow, confirming that the early 20th century was exceptionally and abnormally wet and revealing past decades with severely low flows, including a 13-year period with strongly reduced flows between 1143 to 1155 CE (Figure 2; Woodhouse, Gray, and Meko 2006; Meko et al. 2007; Woodhouse et al. 2010).

Tree-ring reconstructions of past riverflow therefore demonstrate that water from the Colorado River is over-allocated compared to the long-term average flow and that extreme periods of reduced flow are possible, even without the influence of anthropogenic climate change. These reconstructions can also be used as critical quantitative information for water managers and policy-makers, since they provide more accurate information on the full range of variability in the river system. Water managers have incorporated information from paleohydrological riverflow reconstructions to model their system's vulnerability or resilience to potential future droughts similar to those discovered in the paleoclimate record (Woodhouse and Lukas 2006; Woodhouse, Lukas

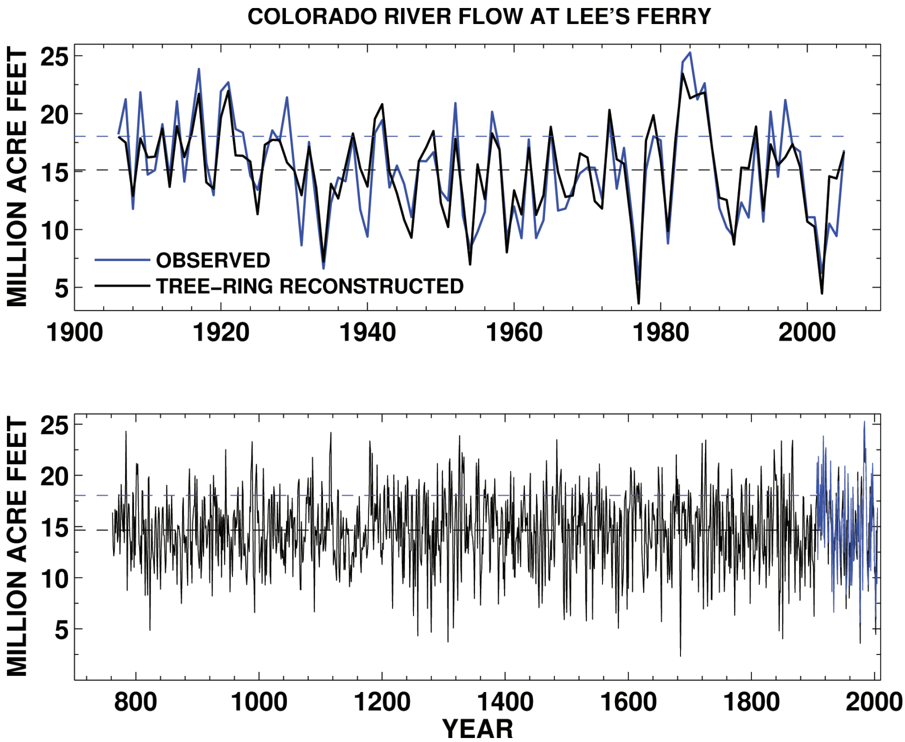

FIGURE 2. Tree-ring reconstructions of the flow of the Colorado River at Lee's Ferry (Woodhouse, Gray, and Meko 2006; Meko et al. 2007). Solid blue lines show the observed (gauge) measurements of flow, while solid black lines show the tree-ring reconstruction. Horizontal dashed lines show the average for the observed (blue) and reconstructed (black) periods.

et al. 2016). Barnett and Pierce (2009) modeled potential future water delivery scenarios for the Colorado River, using two different riverflow baselines: one from instrumental observations alone and one using tree-ring estimates of the multicentennial riverflow. They found that scenarios using the long-term tree-ring estimated flow had a higher likelihood of future and imminent shortfalls as the 21st century progressed, compared to using only recent observations of riverflow. Climate change in the Colorado River Basin exacerbated future water deficits in their simulations, but both the timing and the magnitude of simulated shortfalls depended on assumptions about the baseline conditions and differed between short instrumental and long-term tree-ring estimates. Rajagopalan et al. (2009) modeled future water supplies and reservoir status in the Colorado River Basin under future demand, management, and climate change scenarios, using the tree-ring paleoclimate record to generate stochastic natural riverflow variability. Carrier, Kalra, and Ahmad (2013) used tree-ring streamflow reconstructions to improve forecasting for western United States streamflow. Meko, Woodhouse, and Morino (2012) used a river management model to show that, if a period of Colorado River low flow similar to that reconstructed for 1143 to 1155 CE occurred today, it could lower Lake Mead to below its outlet at Hoover Dam within a few decades. The application of paleoclimate reconstruction of past riverflow within predictive models of future water resources demonstrates that while tree rings provide a long-term perspective from the past for current climate phenomena, they also can be directly and quantitatively used to manage resources and forecast the future.

Paleoclimate information also provides more robust statistics on the occurrence of rare drought events across multiple river basins (Meko and Woodhouse 2005; MacDonald, Kremenetski, and Hidalgo 2008). For example, Phoenix's Salt River Project assumed that reduced flows in Salt-Verde River Basin itself could be buffered by the addition of water supplied from the Upper Colorado River (Woodhouse, Lukas et al. 2016). Tree-ring research demonstrated that large flow deficits had a tendency to occur simultaneously in both basins and for many consecutive years (Hirschboeck and Meko 2005). Meko and Woodhouse (2005) identified joint drought years in the Upper Colorado and Sacramento River Basins since 1500 CE, which can occur several times in a century, and which may also cluster together in time, as they did in the late 16th century. MacDonald, Kremenetski, and Hidalgo (2008) also used a combination of tree-ring and instrumental data to characterize simultaneous droughts in the Sacramento and Colorado Rivers, identifying extended decadal periods of coincident reduced riverflows in both basins. The long-term and large-scale perspective offered by tree rings can therefore be used to evaluate water management strategies and their vulnerability to extreme events.

Beyond riverflow, tree-ring reconstructions of large-scale hydroclimate patterns have often focused on soil moisture, as tree growth is often linked more strongly to this than rainfall alone, and this metric also reflects agricultural drought. Pioneering work by Hal Fritts at the Laboratory of Tree-Ring Research (Fritts et al. 1971; Fritts, Lofgren, and Gordon 1979; Fritts 1991) established the statistical basis for "climate field reconstructions"—the use of continent-scale networks of paleoclimate proxies to reconstruct past climate in both space and time. Cook et al. (1999) created the first "North American Drought Atlas," an annual gridded reconstruction of the Palmer Drought Severity Index (PDSI; Palmer 1965) back to 1700 CE. An extended version of the North American Drought Atlas (Cook et al. 2004)

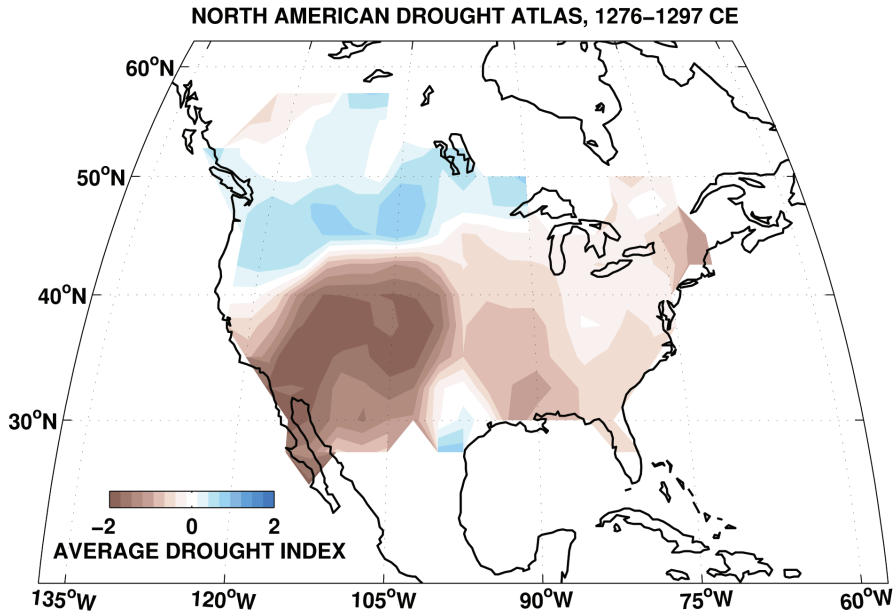

FIGURE 3. Drought intensity (reflected by the Palmer Drought Severity Index [PDSI]) for the late 13th-century "Great Drought." Tree-ring reconstruction field data from Cook, Seager et al. (2010).

revealed the spatial and temporal extent of past Medieval-era "megadroughts" (Stine 1994; Woodhouse and Overpeck 1998), including a two-decade severe dry period in the late 13th century associated with collapse, migration, and upheaval in the ancestral Pueblo cultures of the southwestern United States (Figure 3), an event first detected by Douglass during his dendroarchaeological work in the early 20th century (Douglass 1929; Nash and Dean 2005). Indeed, the Medieval period in North America had more severe and persistent droughts than observed in the 20th century, compared to even the severe "Dust Bowl" of the 1930s and the 1950s drought (Cook et al. 2004, 2013, 2014). The Medieval megadroughts included the 12th-century drought associated with a decade of reduced flow in the Colorado River (Figure 4; Meko et al. 2007). Subsequent reconstructions of annual drought patterns in Asia (Cook, Anchukaitis et al. 2010), Europe, and the Mediterranean (Cook et al. 2015) give similar findings—that past droughts even over just the last millennium were more severe and persistent than those in the recent instrumental records. Even in relatively wet environments, paleoclimate records expose the potential for the natural

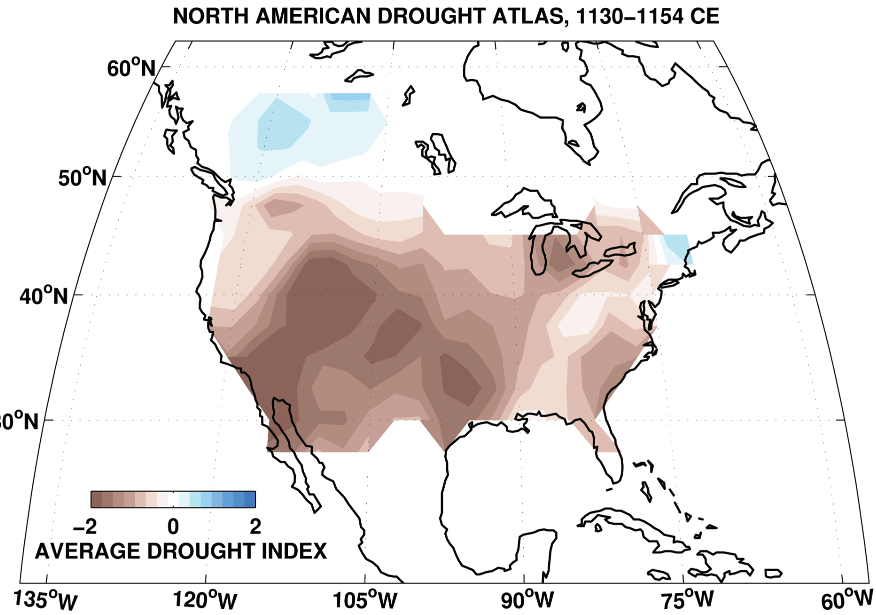

FIGURE 4. Drought intensity (reflected by the PDSI) for the late 12th-century Colorado River drought identified by Meko et al. (2007), revealing a pattern of pan-continental drought at the time. Tree-ring reconstruction field data from Cook, Seager et al. (2010).

variability in the climate system to create severe and persistent drought events (Pederson et al. 2012, 2013).

However, recent droughts in North America, the Mediterranean, and Asia have begun to challenge this paleoclimate perspective that present droughts are typically not exceptional within the longer context of past events provided by tree-ring reconstructions. Griffin and Anchukaitis (2014) used tree-ring reconstructions of southern and central California water year precipitation and a separate reconstruction of PDSI to investigate how the extremely severe 2011–2014 California drought compared to the previous millennium of hydroclimate variability in the state. Their precipitation reconstruction demonstrated that, although rainfall amounts were anomalously low, the deficit was not exceptional in the context of the last few centuries. However, the PDSI suggested that the 2011–2014 drought was the most intense short-term drought in the last 1,200 years, and 2014 amongst the driest years of the last millennium. What reconciles these two apparently disparate observations is that the record-breaking temperatures during the drought drove increased evaporative demand and soil drying, exacerbating the precipitation deficit (Griffin and Anchukaitis 2014). Subsequent analysis by Williams et al. (2015) demonstrated that this temperature contribution to the California drought was in part driven by anthropogenic climate change. Extreme value analysis by Robeson (2015) showed the California drought to be a 1-in-10,000-year event.

As temperatures increase due to human changes to the climate system from greenhouse gas emissions, the potential for "hot droughts"—driven not simply by rainfall deficits but also higher temperatures—also increases (Weiss, Castro, and Overpeck 2009; Overpeck 2013; Griffin and Anchukaitis 2014; Pederson et al. 2014). Cook et al. (2016) found that recent drought in the eastern Mediterranean is the worst drought in that region in the last 900 years, driven by declines in precipitation and increases in temperature, both related to anthropogenic climate change (Kelley et al. 2015). In Mongolia, the early 21st-century drought lasted nearly a decade and was one of the driest periods of the last millennium (Pederson et al. 2014), driven by a combination of reduced rainfall and record-breaking temperatures. Lehner et al. (2017) and Woodhouse, Pederson et al. (2016) found that recent increases in temperature are affecting riverflow in the western United States. Thus, while paleoclimatology often reveals the existence of past severe droughts or periods of reduced streamflow that arose as part of natural internal climate variability, tree-ring reconstructions are increasingly providing data that expose recent droughts as partly reflecting the influence of anthropogenic climate change, especially through the effect of rising temperatures on land surface conditions. What this means is that the consequences of anthropogenic global warming are not simply scenarios for the future, but are occurring right now in the present.

Large-scale Temperature Reconstructions and Global Warming

Variability and trends in global temperatures through time are a superposition of the broad-scale "forced" state of the climate system, due to changes or perturbations in the amount of energy in the Earth system, and the internal variability in temperatures in space and time due to natural climate system dynamics. Once again the limitations of the instrumental restrict us to a relatively short and spatially incomplete period of observation during which human modifications of the climate system have been persistent and ongoing. Paleoclimate reconstruction of past global and hemisphere-scale temperatures allow us to analyze temperature trends in the full context of the last millennium, identify the magnitude and spatial patterns associated with changes due to radiative forcing anomalies from volcanic eruptions, solar variability, and greenhouse gas emissions, and characterize patterns of internal climate system variability at timescales from decadal to centennial. These reconstructions also provide an out-of-sample opportunity to test the general circulation (climate) models used to project future changes in climate due to anthropogenic global warming.

The first tree-ring reconstruction of Northern Hemisphere temperature was developed by Jacoby and D'Arrigo (1989). Although limited in time span, their reconstruction showed that 20th-century temperatures were anomalously warm compared to the previous three centuries. Subsequent research by Mann, Bradley, and Hughes (1998, 1999) extended Northern Hemisphere reconstructions back to 1400 CE and then through the entire last millennium. The Mann, Bradley, and Hughes (1999) curve, which became known as the "Hockey Stick," showed an overall trend toward cooling temperatures from the Medieval Period until the late 19th century, and then a rapid warming (the "blade" of the hockey stick) associated with anthropogenic warming of the climate system. Esper, Cook, and Schweingruber (2002) subsequently developed a new reconstruction that preserved more low-frequency variation in their past temperature estimates, suggesting the magnitude of change over the last millennium was greater than that reconstructed by Mann, Bradley, and Hughes (1999), but generating a similar overall long-term history. Debates—often acrimonious and frequently carried out in the public and policy spheres—about data and methods for reconstructing last millennium temperature, about the true shape and magnitude of the Northern Hemisphere's Common Era temperature history, and whether present temperature were higher than those in the Medieval past, continued for the following decade (Frank, Esper, Zorita et al. 2010; Smerdon and Pollack 2016).

Recent effort to reconstruct the large-scale temperature history of the planet have built on lessons learned over the last decade. There has been an increased focus on assembling large open-access databases of proxy records (Ahmed et al. 2013; Emile-Geay et al. 2017), thorough investigation and development of statistical reconstruction methods (Esper et al. 2005; Smerdon 2011; Frank, Esper, Raible et al. 2010; Tingley and Huybers 2010; Tingley et al. 2012; Hakim et al. 2016; Smerdon and Pollack 2016), increased focus on uncertainty identification and quantification (Tingley et al. 2012; Tingley and Huybers 2013; Evans et al. 2014; Emile-Geay et al. 2013), and investigation and modeling of the proxy systems themselves (Frank, Esper, Zorita et al. 2010; Evans et al. 2013; Esper et al. 2015). Although one approach to large-scale temperature reconstruction now makes use of large multiproxy datasets (Emile-Geay et al. 2017), within dendrochronology the focus has now turned toward expert-driven assessments of well-understood tree-ring chronologies with unambiguous temperature signals. Schneider et al. (2015), Stoffel et al. (2015), and Wilson et al. (2016) all use relatively small networks of temperature-sensitive tree-ring chronologies to estimate Northern Hemisphere summer temperatures. Although global annual signals are desirable from the radiative balance and model evaluation perspective, this choice of reconstruction target reflects the extent of the temperature-sensitive network, analysis and understanding of how trees record temperature variability, and the seasonality of that response. Two recent papers move beyond large-scale mean temperatures and reconstruct summer temperature fields in both space and time (Anchukaitis et al. 2017; Guillet et al. 2017).

What do these recent temperature reconstructions from tree rings reveal? New reconstructions show a substantially improved signal of the abrupt cooling following volcanic eruptions compared to previous efforts (D'Arrigo, Wilson, and Anchukaitis 2013; Wilson et al. 2016) and field reconstruction reveal the varying magnitude of this cooling in space and time (Anchukaitis et al. 2017; Guillet et al. 2017). Recent reconstructions also have a significantly larger amplitude than early reconstructions (Figure 5). These improvements reflect better statistical techniques for retaining variance in the final reconstruction and the inclusion of more wood density data, which in many cases contains a stronger and more accurate interannual temperature signal than ring width. Multicentennial temperature variability in recent reconstructions is linked to changes in solar luminosity prior to the onset of significant anthropogenic greenhouse gas emissions, and late 20th-century summer temperatures in the Northern Hemisphere exceed those of any other period over the last 1,200 years due to anthropogenic climate change. These reconstructions provide a clear perspective on the past—of the cooling associated with decreased insolation during solar minima and following volcanic eruptions and the range of natural temperature variability at the hemisphere scale. They also reveal that recent warmth is unprecedented over the last millennium or more, driven by increasing concentrations of greenhouse gases in the atmosphere (Masson-Delmotte et al. 2013; Stocker et al. 2013).

The Past and Prospects for the Future

An important premise of the earth sciences, and dendroclimatology in particular, is that knowledge of the past is necessary for understanding the present as well as the future. As A. E. Douglass (1929) wrote, "Every year the trees in our forests show the swing of Time's pendulum

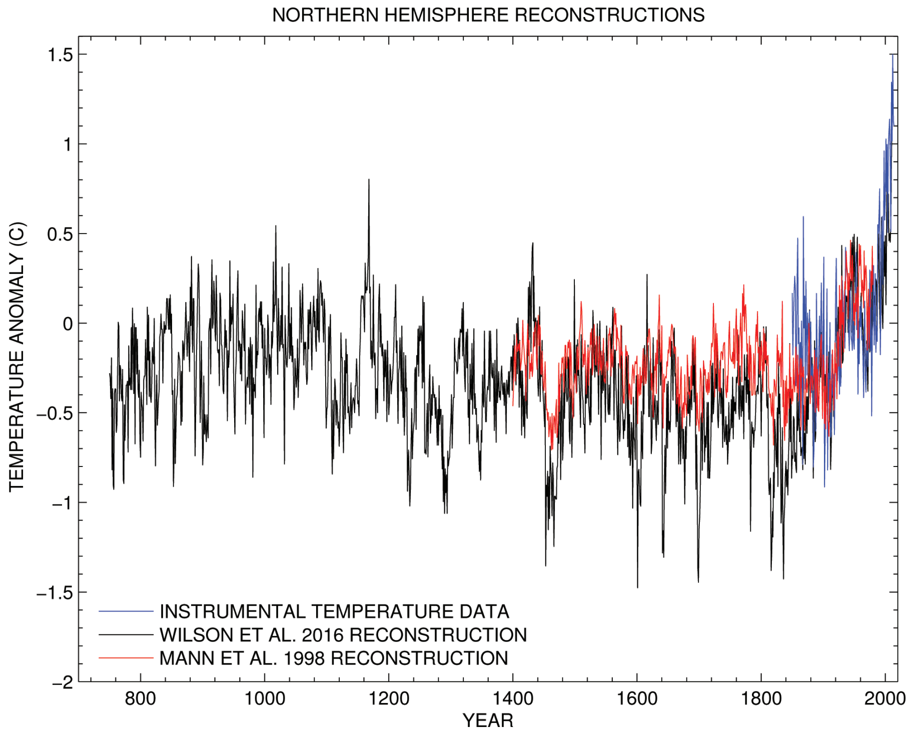

FIGURE 5. Northern Hemisphere tree-ring temperature reconstructions. Shown are the early Mann, Bradley, and Hughes (1998; in red) and the recent Wilson et al. (2016; in black) reconstructions of Northern Hemisphere temperature. Both reconstructions are scaled to the instrumental temperature estimate for the same region and season, shown in blue (Morice et al. 2012).

and put down a mark. They are chronographs, recording clocks, by which the succeeding seasons are set down through definite imprints." Tree-ring proxies provide us with the ability to precisely reconstruct both hydroclimate and temperature in the past and place the present in the longer-term context that they provide, and paleoclimate reconstructions give us the necessary perspective to identify the human fingerprint on the climate of the present and to evaluate the possible severity of future changes.

A substantial amount of work remains to be done, however. Tropical regions, whose vulnerable populations are likely to experience significant changes in both hydroclimate and temperature, are under-represented in the global tree-ring network. The Alaskan and Canadian tree lines are still under-sampled compared to similar environments in Europe and Asia, which prevents a complete understanding of the temperature history and variability of North America. Geography and ecology combine to give Southern Hemisphere dendrochronology additional challenges, while important questions remain about how radiative forcing and atmospheric dynamics shape hydroclimate and temperature variability on decadal, multidecadal, and centennial timescales there. Five hundred years after da Vinci and over a century since A. E. Douglass founded the modern science of dendrochronology, the newest generation of dendroclimatologists face both a daunting and yet critical challenge—to expand our understanding of the past in both space and time, to refine our estimates of past temperature and hydroclimate change while also improving uncertainty quantification, and to provide those observations of the past that place our present climate changes in context while generating the insights to understand and predict the future.

References

Ahmed, M., K. J. Anchukaitis, A. Asrat, H. P. Borgaonkar, M. Braida, B. M. Buckley, U. Büntgen et al. 2013. "Continental-Scale Temperature Variability during the Past Two Millennia." *Nature Geoscience* 6: 339–46.

Anchukaitis, K. J., and M. N. Evans. 2010. "Tropical Cloud Forest Climate Variability and the Demise of the Monteverde Golden Toad." *Proceedings of the National Academy of Sciences of the United States of America* 107: 5036–40.

Anchukaitis, K. J., R. Wilson, K. R. Briffa, U. Buntgen, E. R. Cook, R. D'Arrigo, N. Davi et al. 2017. "Last Millennium Northern Hemisphere Summer Temperatures from Tree Rings: Part II, Spatially Resolved Reconstructions." *Quaternary Science Reviews* 163: 1–22.

Barnett, T. P., and D. W. Pierce. 2009. "Sustainable Water Deliveries from the Colorado River in a Changing Climate." *Proceedings of the National Academy of Sciences* 106: 7334–38.

Briffa, K. R., P. D. Jones, T. S. Bartholin, D. Eckstein, F. H. Schweingruber, W. Karlen, P. Zetterberg, and M. Eronen. 1992. "Fennoscandian Summers from AD 500: Temperature Changes on Short and Long Timescales." *Climate Dynamics* 7: 111–19.

Briffa, K. R., P. D. Jones, and F. H. Schweingruber. 1992. "Tree-ring Density Reconstructions of Summer Temperature Patterns across Western North America since 1600." *Journal of Climate* 5: 735–54.

Carrier, C., A. Kalra, and S. Ahmad. 2013. "Using Paleo Reconstructions to Improve Streamflow Forecast Lead Time in the Western United States." *Journal of the American Water Resources Association* 49: 1351–66.

Chbouki, N., C. W. Stockton, and D. Myers. 1995. "Spatio-temporal Patterns of Drought in Morocco." *International Journal of Climatology* 15: 187–205.

Cook, B. I., K. J. Anchukaitis, R. Touchan, D. M. Meko, and E. R. Cook. 2016. "Spatiotemporal Drought Variability in the Mediterranean over the Last 900 Years." *Journal of Geophysical Research-Atmospheres* 121: 2060–74.

Cook, B. I., R. Seager, R. L. Miller, and J. A. Mason. 2013. "Intensification of North American Megadroughts through Surface and Dust Aerosol Forcing." *Journal of Climate* 26: 4414–30.

Cook, B. I., J. E. Smerdon, R. Seager, and E. R. Cook. 2014. "Pan-continental Droughts in North America over the Last Millennium." *Journal of Climate* 27: 383–97.

Cook, E. R., K. J. Anchukaitis, B. M. Buckley, R. D. D'Arrigo, G. C. Jacoby, and W. E. Wright. 2010. "Asian Monsoon Failure and Megadrought During the Last Millennium." *Science* 328: 486–89.

Cook, E. R., D. M. Meko, D. W. , and M. K. Cleaveland. 1999. "Drought Reconstructions for the Continental United States." *Journal of Climate* 12: 1145–62.

Cook, E. R., R. Seager, R. R. Heim, R. S. Vose, C. Herweijer, and C. A. Woodhouse. 2010. "Megadroughts in North America: Placing IPCC Projections of Hydroclimatic Change in a Long-term Paleoclimate Context." *Journal of Quaternary Science* 25: 48–61.

Cook, E. R., R. Seager, Y. Kushnir, K. R. Briffa, U. Büntgen, D. Frank, P. J. Krusic et al. 2015. "Old World Megadroughts and Pluvials during the Common Era." *Science Advances* 1: e1500561.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. Stahle. 2004. "Long-term Aridity Changes in the Western United States." *Science* 306: 1015–18.

Creasman, P. P., B. Bannister, R. H. Towner, J. S. Dean, and S. W. Leavitt. 2012. "Reflections on the Foundation, Persistence, and Growth of the Laboratory of Tree-ring Research, circa 1930–1960." *Tree-Ring Research* 68: 81–89.

D'Arrigo, R., R. Wilson, and K. J. Anchukaitis. 2013. "Volcanic Cooling Signal in Tree Ring Temperature Records for the Past Millennium." *Journal of Geophysical Research: Atmospheres* 118: 9000–10.

Douglass, A. 1919. *Climatic Cycles and Tree-growth*. Publication No. 289. Washington, D.C.: Carnegie Institution of Washington.

———. 1922. "Some Topographic and Climatic Characters in the Annual Rings of the Yellow Pines and Sequoias of the Southwest." *Proceedings of the American Philosophical Society* 61: 117–22.

Douglass, A. E. 1914. "A Method of Estimating Rainfall by the Growth of Trees." *Bulletin of the American Geographical Society* 46: 321–35.

———. 1929. "The Secret of the Southwest Solved with Talkative Tree Rings." *National Geographic* 56: 736–70.

Eckstein, D., J. Ogden, G. C. Jacoby, and J. Ash. 1981. "Age and Growth Rate Determination in Tropical Trees: The Application of Dendrochronological Methods." In *Age and Growth Rate for Tropical Trees: New Directions for Research*, edited by F. H. Bormann and G. Berlyn. School of Forestry and Environmental Studies Bulletin 94, Yale University.

Emile-Geay, J., K. M. Cobb, M. E. Mann, and A. T. Wittenberg. 2013. "Estimating Central Equatorial Pacific SST Variability over the Past Millennium. Part I: Methodology and Validation." *Journal of Climate* 26: 2302–28.

Emile-Geay, J., N. P. McKay, D. S. Kaufman, L. von Gunten, J. Wang, K. J. Anchukaitis, N. J. Abram et al. 2017. "A Global Multiproxy Database for Temperature Reconstructions of the Common Era." *Scientific Data* 4(170088).

Esper, J., E. R. Cook, and F. H. Schweingruber. 2002. "Low-frequency Signals in Long Tree-ring Chronologies for Reconstructing Past Temperature Variability." *Science* 295: 2250–53.

Esper, J., L. Schneider, J. E. Smerdon, B. R. Schöne, and U. Büntgen. 2015. "Signals and Memory in Tree-ring Width and Density Data." *Dendrochronologia* 35: 62–70.

Esper, J., R. J. S. Wilson, D. C. Frank, A. Moberg, H. Wanner, and J. Luterbacher. 2005. "Climate: Past Ranges and Future Changes." *Quaternary Science Reviews* 24: 2164–66.

Evans, M., J. E. Smerdon, A. Kaplan, S. Tolwinski-Ward, and J. González-Rouco. 2014. "Climate Field Reconstruction Uncertainty Arising from Multivariate and Nonlinear Properties of Predictors." *Geophysical Research Letters* 41: 9127–34.

Evans, M., S. Tolwinski-Ward, D. Thompson, and K. Anchukaitis. 2013. "Applications of Proxy System Modeling in High Resolution Paleoclimatology." *Quaternary Science Reviews* 76: 16–28.

Frank, D., J. Esper, E. Zorita, and R. Wilson. 2010. "A Noodle, Hockey Stick, and Spaghetti Plate: A Perspective on High-resolution Paleoclimatology." *WIREs Climate Change* 1: 507–16.

Frank, D. C., J. Esper, C. C. Raible, U. Büntgen, V. Trouet, B. Stocker, and F. Joos. 2010. "Ensemble Reconstruction Constraints on the Global Carbon Cycle Sensitivity to Climate." *Nature* 463: 527–30.

Fritts, H. C. 1991. *Reconstructing Large-scale Climatic Patterns from Tree-ring Data: A Diagnostic Analysis*. London: University of Arizona Press.

Fritts, H. C., T. J. Blasing, B. P. Hayden, and J. E. Kutzbach. 1971. "Multivariate Techniques for Specifying Tree-Growth and Climate Relationships and for Reconstructing Anomalies in Paleoclimate." *Journal of Applied Meteorology* 10: 845–64.

Fritts, H. C., G. R. Lofgren, and G. A. Gordon. 1979. "Variations in Climate since 1602 as Reconstructed from Tree Rings." *Quaternary Research* 12: 18–46.

Gagen, M., D. McCarroll, N. J. Loader, and I. Robertson. 2011. "Stable Isotopes in Dendroclimatology: Moving Beyond 'Potential.'" In *Dendroclimatology: Developments in Paleoenvironmental Research*, vol. 11, edited by M. Hughes, T. Swetnam, and H. Diaz, 147–72. New York: Springer.

Gagen, M., D. McCarroll, N. J. Loader, I. Robertson, R. Jalkanen, and K. J. Anchukaitis. 2007. "Exorcising the 'Segment Length Curse': Summer Temperature Reconstruction since AD 1640 Using Non-detrended Stable Carbon Isotope Ratios from Pine Trees in Northern Finland." *The Holocene* 17: 435.

Griffin, D., and K. J. Anchukaitis. 2014. "How Unusual Is the 2012-2014 California Drought?" *Geophysical Research Letters* 41: 9017–23.

Griffin, D., C. A. Woodhouse, D. M. Meko, D. W. Stahle, H. L. Faulstich, C. Carrillo, R. Touchan, C. L. Castro, and S. W. Leavitt. 2013. "North American Monsoon Precipitation Reconstructed from Tree-ring Latewood." *Geophysical Research Letters* 40: 954–58.

Guillet, S., C. Corona, M. Stoffel, M. Khodri, F. Lavigne, P. Ortega, N. Eckert et al. 2017. "Climate Response to the Samalas Volcanic Eruption in 1257 Revealed by Proxy Records." *Nature Geoscience* 10: 123–28.

Hakim, G. J., J. Emile-Geay, E. J. Steig, D. Noone, D. M. Anderson, R. Tardif, N. Steiger, and W. A. Perkins. 2016. "The Last Millennium Climate Reanalysis Project: Framework and First Results." *Journal of Geophysical Research: Atmospheres* 121: 6745–64.

Haury, E. W. 1962. "HH-39: Recollections of a Dramatic Moment in Southwestern Archaeology." *Tree-Ring Bulletin* 24: 11–14.

Hirschboeck, K. K., and D. M. Meko. 2005. *A Tree Ring Based Assessment of Synchronous Extreme Streamflow Episodes in the Upper Colorado and Salt-Verde-Tonto River Basins*. Tucson, AZ: University of Arizona and Salt River Project.

Huntington, E., C. Schuchert, A. E. Douglass, and C. J. Kullmer. 1914. *The Climatic Factor as Illustrated in Arid America*. Number 192. Washington, D.C.: Carnegie Institution of Washington.

Jacoby, G. C., and R. D'Arrigo. 1989. "Reconstructed Northern Hemisphere Annual Temperature since 1671 Based on High-Latitude Tree-Ring Data from North America." *Climatic Change* 14: 39–59.

Kelley, C. P., S. Mohtadi, M. A. Cane, R. Seager, and Y. Kushnir. 2015. "Climate Change in the Fertile Crescent and Implications of the Recent Syrian Drought." *Proceedings of the National Academy of Sciences* 112: 3241–46.

Leavitt, S. W., and A. Long. 1991. "Seasonal Stable-Carbon Isotope Variability in Tree Rings: Possible Paleoenvironmental Signals." *Chemical Geology* 87: 59–70.

Lehner, F., E. R. Wahl, A. W. Wood, D. B. Blatchford, and D. Llewellyn. 2017. "Assessing Recent Declines in Upper Rio Grande Runoff Efficiency from a Paleoclimate Perspective." *Geophysical Research Letters* 44: 4124–33.

MacDonald, G. M., K. V. Kremenetski, and H. G. Hidalgo. 2008. "Southern California and the Perfect Drought: Simultaneous Prolonged Drought in Southern California and the Sacramento and Colorado River Systems." *Quaternary International* 188: 11–23.

Mann, M. E., R. S. Bradley, and M. K. Hughes. 1998. "Global-scale Temperature Patterns and Climate Forcing over the Past Six Centuries." *Nature* 392: 779–87.

———. 1999. "Northern Hemisphere Temperatures during the Past Millennium: Inferences, Uncertainties, and Limitations." *Geophysical Research Letters* 26: 759–62.

Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J. González Rouco, E. Jansen et al. 2013. "Information from Paleoclimate Archives." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, 383–464. Cambridge, UK and New York: Cambridge University Press.

McCarroll, D., M. H. Gagen, N. J. Loader, I. Robertson, K. J. Anchukaitis, S. Los, G. Young et al. 2009. "Correction of Tree Ring Stable Carbon Isotope Chronologies for Changes in the Carbon Dioxide Content of the Atmosphere." *Geochimica et Cosmochimica Acta* 73: 1539–47.

McCarroll, D., and N. J. Loader. 2004. "Stable Isotopes in Tree Rings." *Quaternary Science Reviews* 23: 771–801.

Meehl, G., L. Goddard, J. Murphy, R. Stouffer, G. Boer, G. Danabasoglu, K. Dixon et al. 2009. "Decadal Prediction." *Bulletin of the American Meteorological Society* 90: 1467–85.

Meko, D., E. R. Cook, D. W. Stahle, C. W. Stockton, and M. K. Hughes. 1993. "Spatial Patterns of Tree-Growth Anomalies in the United States and Southeastern Canada." *Journal of Climate* 6: 1773–86.

Meko, D., C. Woodhouse, and K. Morino. 2012. "Dendrochronology and Links to Streamflow." *Journal of Hydrology* 412: 200–9.

Meko, D. M., and C. H. Baisan. 2001. "Pilot Study of Latewood-Width of Conifers as an Indicator of Variability of Summer Rainfall in the North American Monsoon Region." *International Journal of Climatology* 21: 697–708.

Meko, D. M., and C. A. Woodhouse. 2005. "Tree-Ring Footprint of Joint Hydrologic Drought in Sacramento and Upper Colorado River Basins, Western USA." *Journal of Hydrology* 308: 196–213.

Meko, D. M., C. A. Woodhouse, C. A. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer. 2007. "Medieval Drought in the Upper Colorado River Basin." *Geophysical Research Letters* 34: L10705.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones. 2012. "Quantifying Uncertainties in Global and Regional Temperature Change Using an Ensemble of Observational Estimates: The HadCRUT4 Data Set." *Journal of Geophysical Research: Atmospheres* 117. doi: 10.1029/2011JD017187.

Nash, S. E. 1999. *Time, Trees, and Prehistory: Tree-Ring Dating and the Development of North American Archaeology, 1914-1950*. Salt Lake City: University of Utah Press.

Nash, S. E., and J. S. Dean. 2005. "Paleoenvironmental Reconstructions and Archaeology. Uniting the Social and Natural Sciences in the American Southwest and Beyond." In *Southwest Archaeology in the Twentieth Century*, edited by L. S. Cordell and D. D. Fowler, 125–41. Salt Lake City: University of Utah Press.

Overpeck, J. T. 2013. "Climate Science: The Challenge of Hot Drought." *Nature* 503: 350–51.

Palmer, W. C. 1965. *Meteorological Drought*. Technical report, U.S. Weather Bureau Research Paper 45.

Pederson, N., A. Bell, T. Knight, C. Leland, N. Malcomb, K. Anchukaitis, K. Tackett et al. 2012. "A Long-term Perspective on a Modern Drought in the American Southeast." *Environmental Research Letters* 7.

Pederson, N., A. R. Bell, E. R. Cook, U. Lall, N. Devineni, R. Seager, K. Eggleston, and K. P. Vranes. 2013. "Is an Epic Pluvial Masking the Water Insecurity of the Greater New York City Region?" *Journal of Climate* 26: 1339–54.

Pederson, N., A. E. Hessl, N. Baatarbileg, K. J. Anchukaitis, and N. D. Cosmo. 2014. "Pluvials, Droughts, the Mongol Empire, and Modern Mongolia." *Proceedings of the National Academy of Sciences* 111: 4375–79.

Pulwarty, R. S., K. L. Jacobs, and R. M. Dole. 2005. *The Hardest Working River: Drought and Critical Water Problems in the Colorado River Basin*. Boca Raton, FL: CRC Press.

Rajagopalan, B., K. Nowak, J. Prairie, M. Hoerling, B. Harding, J. Barsugli, A. Ray, and B. Udall. 2009. "Water Supply Risk on the Colorado River: Can Management Mitigate?" *Water Resources Research* 45. doi: 10.1029/2008WR007652.

Robeson, S. M. 2015. "Revisiting the Recent California Drought as an Extreme Value." *Geophysical Research Letters* 42: 6771–79.

Roden, J. S., G. Lin, and J. R. Ehleringer. 2000. "A Mechanistic Model for Interpretation of Hydrogen and Oxygen Ratios in Tree-Ring Cellulose." *Geochimica et Cosmochimica Acta* 64: 21–35.

Sarton, G. 1954. "When Was Tree-Ring Analysis Discovered?" *Isis* 45: 383–84.

Saurer, M., S. Borella, F. Schweingruber, and R. Siegwolf. 1997. "Stable Carbon Isotopes in Tree Rings of Beech: Climatic versus Site-Related Influences." *TREES: Structure and Function* 11: 291–97.

Schneider, L., J. E. Smerdon, U. Büntgen, R. J. S. Wilson, V. S. Myglan, A. V. Kirdyanov, and J. Esper. 2015. "Revising Midlatitude Summer Temperatures Back to A.D. 600 Based on a Wood Density Network." *Geophysical Research Letters* 42: 4556–62.

Schulman, E. 1956. *Dendroclimatic Changes in Semiarid America*. Tucson, AZ: University of Arizona Press.

Schweingruber, F., H. Fritts, O. Bräker, L. Drew, and E. Schär. 1978. "The X-ray Technique as Applied to Dendroclimatology." *Tree-Ring Bulletin* 38: 61–91.

Schweingruber, F. H. 1996. *Tree Rings and Environment: Dendroecology*. Bern, Switzerland: Paul Haupt AG Bern.

Schweingruber, F. H., and K. R. Briffa. 1996. "Tree-Ring Density Networks for Climate Reconstruction." In *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, 43–66. Berlin: Springer Berlin Heidelberg.

Smerdon, J. E. 2011. "Climate Models as a Test Bed for Climate Reconstruction Methods: Pseudoproxy Experiments." *Wiley Interdisciplinary Reviews: Climate Change* 3: 63–77.

Smerdon, J. E., and H. N. Pollack. 2016. "Reconstructing Earth's Surface Temperature over the Past 2000 Years: The Science behind the Headlines." *WIREs Climate Change* 7: 746–71.

Solomon, A., L. Goddard, A. Kumar, J. Carton, C. Deser, I. Fukumori, A. Greene et al. 2011. "Distinguishing the Roles of Natural and Anthropogenically Forced Decadal Climate Variability." *Bulletin of the American Meteorological Society* 92: 141–56.

St. George, S. 2014. "An Overview of Tree-Ring Width Records across the Northern Hemisphere." *Quaternary Science Reviews* 95: 132–50.

St. George, S., and T. R. Ault. 2014. "The Imprint of Climate within Northern Hemisphere Trees." *Quaternary Science Reviews* 89: 1–4.

St. George, S., D. M. Meko, and E. R. Cook. 2010. "The Seasonality of Precipitation Signals Embedded within the North American Drought Atlas." *The Holocene* 20: 983–88.

Stahle, D., R. Griffin, D. Meko, M. Therrell, J. Edmondson, M. Cleaveland, L. Stahle et al. 2013. "The Ancient Blue Oak Woodlands of California: Longevity and Hydroclimatic History." *Earth Interactions* 17: 1–23.

Stahle, D. W. 1999. "Useful Strategies for the Development of Tropical Tree-Ring Chronologies." *IAWA Journal* 20: 249–53.

Stahle, D. W., M. K. Cleaveland, D. B. Blanton, M. D. Therrell, and D. A. Gay. 1998. "The Lost Colony and Jamestown Droughts." *Science* 280: 564–67.

Stahle, D. W., M. K. Cleaveland, and J. G. Hehr. 1988. "North Carolina Climate Changes Reconstructed from Tree Rings: AD 372 to 1985." *Science* 240: 1517–19.

Stine, S. 1994. "Extreme and Persistent Drought in California and Patagonia during Medieval Time." *Nature* 369: 546–49.

Stocker, T., D. Qin, G.-K. Plattner, L. Alexander, S. Allen, N. Bindoff, F.-M. Bréon et al. 2013. "Technical Summary." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, 33–115. Cambridge, UK and New York: Cambridge University Press.

Stockton, C. 1975. *Long-term Streamflow Records Reconstructed from Tree Rings. Papers of the Laboratory of Tree-ring Research*. Tucscon, AZ: University of Arizona Press.

Stockton, C. W., and G. C. Jacoby. 1976. "Long-term Surface-water Supply and Streamflow Trends in the Upper Colorado River Basin." *Lake Powell Research Project Bulletin* 18.

Stoffel, M., M. Khodri, C. Corona, S. Guillet, V. Poulain, S. Bekki, J. Guiot et al. 2015. "Estimates of Volcanic-induced Cooling in the Northern Hemisphere over the Past 1,500 Years." *Nature Geoscience* 8: 784–88.

Tingley, M. P., P. F. Craigmile, M. Haran, B. Li, E. Mannshardt, and B. Rajaratnam. 2012. "Piecing Together the Past: Statistical Insights into Paleoclimatic Reconstructions." *Quaternary Science Reviews* 35: 1–22.

Tingley, M. P., and P. Huybers. 2010. "A Bayesian Algorithm for Reconstructing Climate Anomalies in Space and Time. Part I: Development and Applications to Paleoclimate Reconstruction Problems." *Journal of Climate* 23: 2759–81.

———. 2013. "Recent Temperature Extremes at High Northern Latitudes Unprecedented in the Past 600 Years." *Nature* 496: 201–5.

Touchan, R., K. J. Anchukaitis, D. M. Meko, M. Sabir, S. Attalah, and A. Aloui. 2011. "Spatiotemporal Drought Variability in Northwestern Africa over the Last Nine Centuries." *Climate Dynamics* 37: 237–52.

Touchan, R., K. J. Anchukaitis, V. V. Shishov, F. Sivrikaya, J. Attieh, M. Ketmen, J. Stephan, I. Mitsopoulos, A. Christou, and D. M. Meko. 2014. "Spatial Patterns of Eastern Mediterranean Climate Influence on Tree Growth." *The Holocene* 24: 381–92.

Vera, C., M. Barange, O. Dube, L. Goddard, D. Griggs, N. Kobysheva, E. Odada et al. 2010. "Needs Assessment for Climate Information on Decadal Timescales and Longer." *Procedia Environmental Sciences* 1: 275–86.

Webb, G. E. 1983. *Tree Rings and Telescopes. The Scientific Career of A.E. Douglas*. Tucson, AZ: University of Arizona Press.

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." *Journal of Climate* 22: 5918–32.

Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook. 2015. "Contribution of Anthropogenic Warming to California Drought during 2012–2014." *Geophysical Research Letters* 42: 6819–28.

Wilson, R., K. Anchukaitis, K. R. Briffa, U. Büntgen, E. Cook, R. D'Arrigo, N. Davi et al. 2016. "Last Millennium Northern Hemisphere Summer Temperatures from Tree Rings: Part I: The Long Term Context." *Quaternary Science Reviews* 134: 1–18.

Woodhouse, C., and J. Lukas. 2006. "Drought, Tree Rings and Water Resource Management in Colorado." *Canadian Water Resources Journal* 31: 297–310.

Woodhouse, C., J. Lukas, K. Morino, D. Meko, and K. Hirschboeck. 2016. "Using the Past to Plan for the Future? The Value of Paleoclimate Reconstructions for Water Resource Planning." In *Water Policy and Planning in a Variable and Changing Climate*, 161–82. Boca Raton, FL: CRC Press.

Woodhouse, C. A., S. T. Gray, and D. M. Meko. 2006. "Updated Streamflow Reconstructions for the Upper Colorado River Basin." *Water Resources Research* 42. doi: 10.1029/2005WR004455.

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 Southwestern North America." *Proceedings of the National Academy of Sciences* 107: 21283–88.

Woodhouse, C. A., and J. T. Overpeck. 1998. "2000 Years of Drought Variability in the Central United States." *Bulletin of the American Meteorological Society* 79: 2693–714.

Woodhouse, C. A., G. T. Pederson, K. Morino, S. A. McAfee, and G. J. McCabe. 2016. "Increasing Influence of Air Temperature on Upper Colorado River Streamflow." *Geophysical Research Letters* 43: 2174–81.