Focus Article

Dendroclimatology: extracting climate from trees

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The scientific discipline called dendrochronology is the study of tree rings and of environmental conditions and events of the past that tree growth can reflect. The beginning of scientific study of tree rings is generally ascribed to an astronomer named Andrew Ellicott Douglass, who in the early 1900s noticed not only variation in tree-ring width but also that this variability was similar between multiple trees. Dendrochronology subsequently expanded worldwide, and now over 3000 of the 12,000+ publications on dendrochronology can be classified as dendroclimatology. As a subfield of tree-ring analysis, dendroclimatology estimates climate back in time beyond the start of recorded meteorological measurements. Dendroclimatology starts with site and tree selection and continues with dating, measuring, data quality control, and chronology construction. Tree rings are associated with climate using statistical models that are then evaluated for their full length to reconstruct climate of the past. Most commonly, either precipitation or temperature is reconstructed, and reconstructions are then analyzed for frequency of extreme years, changes in mean conditions, ranges of long-term variability, and changes in interannual variability. For example, from reconstructions of Northern Hemisphere temperature based on tree rings and other natural archives of climate collected from multiple sites, it appears that current temperature (since AD 1850) exceeds the range of variability reconstructed for AD 1000-1850. Uncertainties in dendroclimatology exist, including a relatively recent issue called divergence, but dendroclimatology has played, and continues to play, a substantial role in interdisciplinary research on climate change. *WIREs Clim Change* 2010 1 343–352

The objective of this paper is to review dendroclimatology with an eye toward the role this subdiscipline plays in broader research on climate change. The scientific discipline called dendrochronology is the study of tree rings and of environmental conditions and events of the past that tree growth can reflect.[1] As a subfield of dendrochronology, dendroclimatology estimates climate back in time beyond the start of recorded meteorological measurements.[2] Dendroclimatic reconstructions can be analyzed to assess long-term departures from average climate,[3] frequency of extreme climate,[4] changes in interannual variability in climate,[5] and ranges of long-term variability in climate.[6]

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SHORT HISTORY OF DENDROCLIMATOLOGY

As long ago as the ancient Greeks, tree rings have been observed to form mostly on an annual basis, and width and other characteristics of tree rings have been noted to vary from year to year.[7] Leonardo da Vinci associated tree-ring variation with change in the environment at the time of ring formation.[8] Such observation and reasoning could be considered early dendrochronology.

The beginning of scientific study of tree rings is generally ascribed to the early 1900s and to an astronomer named Andrew Ellicott Douglass.[9] While living and working in Flagstaff, Arizona, Douglass noticed not only variation in tree-ring width but also that this variability was similar between multiple trees. Douglass surmised that the specific environmental component causing multiple trees of an area to show similar patterns of tree-ring variability was climate, probably moisture availability generally and rainfall more specifically.[10] As an astronomer, Douglass was keenly interested in the sun and in variation of its output of energy, which is a factor in variation of climate on earth.[11] By extension, Douglass hypothesized that since ring growth of trees reflected climate, perhaps they also indirectly reflected variation of the sun itself.[12] In this way, quantitative study of tree rings could lead to valuable understanding of the sun.

Alas, by the time of his passing in 1962,[13] Douglass had not fully succeeded in matching patterns of tree rings with variation in solar output.[14] Nonetheless, throughout his remarkable career, Douglass developed techniques and codified principles that underlie dendrochronological methods used today. Among other accomplishments, Douglass refined the understanding of how climate affects tree rings, ultimately publishing 75 works in dendrochronology, many of which can be classified as dendroclimatology.

From the humble beginnings of Douglass working on tree rings in near isolation in Arizona,[15] the field of dendrochronology expanded tremendously. Douglass was joined by students and colleagues by whom dendrochronology radiated throughout North America, with a particularly important work of dendroclimatology being published in 1956: Dendroclimatic Changes in Semiarid America.[16] Dendrochronological research was also initiated elsewhere, including Europe,[17] northern Asia,[18] Australasia,[19] southern South America,[20] southeast Asia,[21] and parts of Africa[22,23] (Figure 1(a)). Tree-ring sites are noticeably sparse throughout the tropics, which constitute a substantial research frontier for dendrochronology.[24]

A sizeable percentage of global dendrochronology has fallen within the subdiscipline of dendroclimatology. The rate of publication of papers on dendroclimatology was slow during the first half of the 20th century, but it increased exponentially after 1960 (Figure 2). Over 3000 of the 12,000+ scientific publications currently listed in the online bibliography of dendrochronology[26] contain some version of the word 'climate'. By sheer dint of this prodigious body of research, dendroclimatology has contributed mightily to the study of past climate and of climate change.

METHODS OF DENDROCLIMATOLOGY

A crucial first step in dendroclimatology is site selection.[28] In sites where moisture availability limits tree growth, tree rings can be used to reconstruct precipitation, whereas in sites where growing season temperature limits tree growth, tree rings can be used to reconstruct temperature.[29] Once at a dendroclimate site, trees are chosen for sampling based principally on apparent age and on the absence of evidence of disturbance by nonclimatic processes such as fire,[30] wind,[31] wildlife,[32] earthquakes,[33] volcanic eruptions,[34] or humans.[35]

A critical next step in dendrochronology is ensuring that each tree ring is dated to its year of formation. For dating, a procedure called crossdating is done whereby patterns of relatively wide and narrow rings are matched across trees.[36] Some tree-ring collections wind up not being crossdateable,[37]

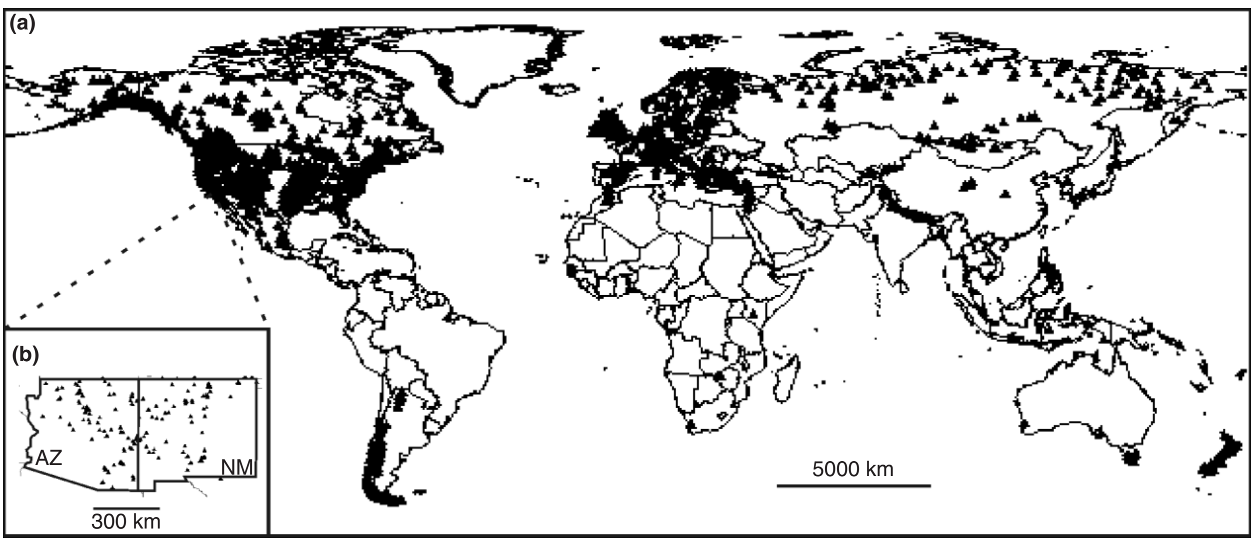

FIGURE 1 | (a) World map with tree-ring sites (triangles) archived in the International Tree-ring Data Bank, and (b) map of the American Southwest (Arizona and New Mexico) with tree-ring sites (triangles). Data from NCDC[25] as of August 2009.

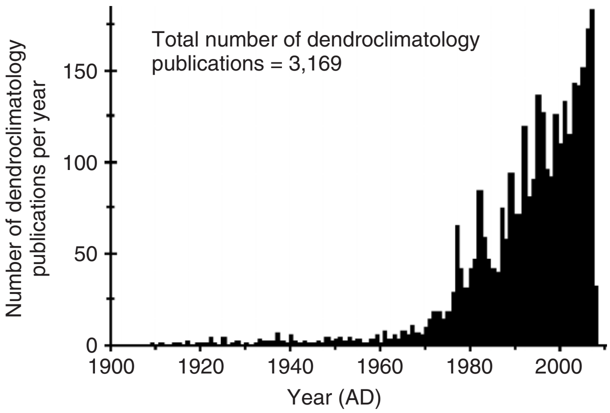

FIGURE 2 | Number of dendroclimatology publications per year listed within the online Bibliography of Dendrochronology[27].

but when patterns of ring-growth variability are strong and held synchronously across multiple trees, confidence in crossdating can be high, to the point of being essentially indisputable.[38]

In dendroclimatology, tree rings are measured. The predominant, workhorse variable of tree-ring research is total ring width,[39] with earlywood and latewood width often being measured separately.[40] When appropriate, wood density of rings might be measured,[41] with emphasis on latewood maximum density,[42] which primarily reflects temperature[43] but also occasionally precipitation.[44] Stable isotopes of carbon and oxygen have also been measured in tree rings for the purpose of reconstructing climate.[45] Another climatic feature of note in tree rings is frost damage, which indicates freezing conditions during the growing season.[46]

Next, measured values as well as crossdating itself are verified. This step is accomplished by prewhitening measurement series and then cross-correlating resultant residual series to identify misfitting and/or outlying values.[47,48] The average correlation of individual trees to a master series composed of all trees of a site amounts to a quantitative diagnostic of crossdating and signal strength of a collection.[49]

Following verification of dating and measuring, tree-ring series are detrended. In particular, ring-width series typically decline from pith to bark in a negative exponential fashion due to a geometric constraint of tree growth whereby trees add about the same amount of biomass each year to their increasingly larger selves.[50] This trend does not reflect environmental forcing and therefore should be removed prior to dendroclimatological analysis.[51] More generally, regardless of direction or exact mathematical shape, series-length trend in tree rings is not unambiguously interpretable as an environmental signal,[52] hence detrending.

Following detrending, resultant standardized series are merged into a single time series, i.e., the chronology, a fundamental product of dendrochronology. Site chronologies are well replicated, usually comprising 20+ trees. For site chronologies to demonstrate variability in common, most trees within them must have been affected the same way by some environmental factor,[53] which is usually climate.

With data reduction done, tree-ring chronologies are quantitatively associated with climate. For this step, climate data can come from individual meteorological stations or from multiple stations averaged across climatically homogeneous regions.[54] Meteorological data come in various time steps, such as hourly, daily, weekly, or monthly, but ultimately tree rings usually associate with climate on a seasonal or yearly time step.

Various statistical methods exist to quantify the relationship between tree rings and climate.[55] Basic methods of dendroclimatology include correlation[56] or response-function analysis,[57] each with confidence intervals for assessing significance.[58] Dendroclimate models can be quantified regionally, incorporating multiple sites.[59] Once calibrated, the relationship between tree rings and climate is verified on independent data not used in calibration, e.g., with split-period testing,[60] prediction sum of squares,[61] and/or comparison with climate reconstructed from other natural archive indicators of climate[62] or from qualitative indications of climate contained in historical documents.[63]

Once validated, dendroclimate models are evaluated for the entire length of their respective dendrochronologies to reconstruct climate back in time. This step assumes the same principle that underlies much of natural-geological science, uniformitarianism, i.e., that the relationship between tree growth and climate is the same now as it was in the past.[64] This assumption is questioned occasionally,[65] but to a first approximation it is sufficiently true in dendroclimatology to instill confidence in reconstructions of climate. This is because biological bases of tree growth are essentially immutable. For example, for trees whose growth is limited principally by moisture availability, below-average rainfall in any given year results in below-average width for the ring of that year. Such fundamental mechanisms should hold true through time, at least throughout the last several thousand years, which is the time covered by dendroclimatology,[66–68] with rare exceptions.[69]

EXAMPLES OF DENDROCLIMATOLOGY

Given the vast extent of published dendroclimatology, it would be impossible to show even a minor fraction of it in review. For illustration purposes, one tree-ring reconstruction of moisture availability and one of temperature are presented here. Both of these examples come from the American Southwest. After that, reconstructed Northern Hemisphere temperature, based in part on dendroclimatology, is discussed.

American Southwest: moisture availability

The American Southwest, comprising Arizona, New Mexico, and adjacent parts of neighboring states,[70] has been sampled extensively for tree-ring specimens for the purpose of reconstructing climate (Figure 1(b)). This is due to the fact that Douglass started dendrochronology in Arizona and tree-ring research has continued in the Southwest since then. Tree-ring growth at many sites of the Southwest is sensitive to moisture availability. A large-scale tree-ring analysis of the Southwest, including many hundreds of trees from many tens of sites as well as climate data from many tens of meteorological stations, has reconstructed moisture availability for the entire region (Figure 3(a)).[71] In this example, moisture availability is expressed as Palmer Drought Severity Index (PDSI), which incorporates precipitation, temperature, soil characteristics, and time lags.[72] Positive values of PDSI indicate above-average moisture availability; negative values indicate drought. In this case, PDSI is for June through August, i.e., the growing season, which is primarily affected directly by precipitation of preceding winter and spring months as well as secondarily and inversely by temperature of summer months.[73]

An obvious feature of this reconstruction is multidecadal variation that began in the mid-1800s and has increased in amplitude since that time. The period length of this variation is well shorter than the typical ages of the trees analyzed, so it is not an artifact of detrending to remove nonenvironmental variation.[77] The major ups and downs of this variation match known periods of climatic departures, such as the drought of the late 1800s corresponding to a crash of livestock grazing in the Southwest,[78] the wet period of the early 1900s corresponding to anomalously high discharge of major rivers of the Southwest,[79] and the drought of the mid-1900s corresponding to ecological and economic distress throughout the Southwest.[80]

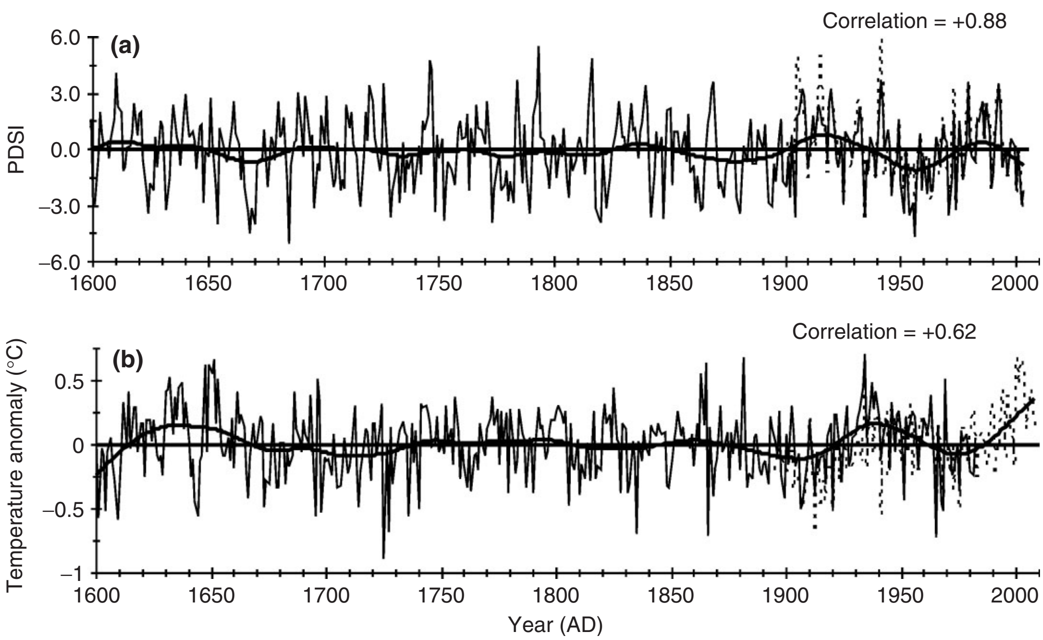

FIGURE 3 | Reconstructions from tree rings for the American Southwest of (a) June–August Palmer Drought Severity Index (PDSI) and (b) April–September temperature anomalies from the 1951 to 1970 base period. In both cases, the smooth line is a cubic spline that expresses 75% of the 40-year period.[74] Dashed lines are averages of meteorological data for Arizona and New Mexico, 1900–2003 for PDSI, and 1895–2008 for temperature. Meteorological temperatures are interpolations using the Parameter–elevation Relationships on Independent Slopes Model (PRISM),[75] and are available online from Westmap.[76] For both Arizona and New Mexico, statewide temperature averages were converted to anomalies from the 1951 to 1970 base period, adjusted to have the same variance as the temperature reconstruction, and then merged into a single series for the Southwest. For PDSI and temperature, correlation values are for reconstructed and meteorological data for respective periods of overlap.

Curiously, multidecadal variation in moisture availability is not strong in the reconstruction from 1600 to the mid-1800s. Obvious questions arise. Why has moisture availability, primarily winter precipitation, changed through time in this way? Does this reflect change in El Niño Southern Oscillation?[81] Change in Pacific Decadal Oscillation?[82] Could increased amplitude be construed as evidence of anthropogenic climate change? Will this variation continue into the future? If so, what socioeconomic–ecological ramifications might emerge due to variability in delivery of fresh water to the American Southwest by climate?[83] Such questions arise from knowing about climate of the past further back in time than existing meteorological records. Dendroclimatology provides this important view of climate into the distant past.

American Southwest: temperature

Tree rings at other sites of the American Southwest are sensitive to temperature. A separate, large-scale tree-ring analysis of the Southwest, once again including many trees from many sites as well as climate data from many stations, has reconstructed temperature for the entire region using ring density (Figure 3(b)).[84] In this case, temperature is expressed for a growing season of April through September. For the most part, this temperature reconstruction is reasonably stable since 1600. Decadal departures exist now and then, but the amplitude of departures is usually not extraordinary. A period of high temperature in the early 1600s is notable.

On the other hand, the current end of the reconstruction, which is extended to present with recorded data, shows a ramp of increasing temperature. By comparison with the rest of the reconstruction, it appears as if temperature of recent decades exceeds the range of variability established by the entire series. Yet more questions arise. Is this climate change specifically warming? Will this ramp of increasing temperature continue into the future? What socioeconomic–ecological ramifications might emerge if warming continued into the future? What might be causing this current warming? Again, questions such as these are critical, and debate on global warming is notoriously in full swing. To even know if modern climate might be anomalous, climate must be reconstructed as far back into the past as possible. Dendroclimatology serves that purpose.

Northern Hemisphere: temperature

At the global scale, climatic warming is commanding substantial research interest as well as media/political attention. The Intergovernmental Panel on Climate Change (IPCC) regularly updates the state of understanding about climate change,[85] and its recent reports consider dendrochronological reconstructions of climate. Of particular note are reconstructions of Northern Hemisphere temperature based on tree rings and other natural archives of climate collected from multiple sites. In addition to work of Mann et al.,[86–88] multiple reconstructions have been published, some based exclusively on tree-ring data,[89–92] some combining tree rings with other proxy records such as fresh water or marine sediments, speleothems, corals, and/or historical documents,[93] and others excluding tree rings completely.[94,95] Even though methods and spatial distribution and temporal extent of records vary among these reconstructions, they converge strongly in important respects, especially for the period since AD 1600, when the number of records is great and their geographic coverage is extensive.[96] The IPCC concluded that for the Northern Hemisphere there were 'relatively cool conditions in the 17th and early 19th centuries and warmth in the 11th and early 15th centuries, but the warmest conditions are apparent in the 20th century'. Moreover, the IPCC found this general picture to be very similar to the history of the past millennium as simulated by global climate models driven by the best available estimates of solar input, volcanic effects, anthropogenic particulates, and greenhouse gases.

These reconstructions of past temperature and the materials and methods used in them have been scrutinized intensely,[97–102] including by a special panel of the US National Research Council, National Academy of Sciences.[103] The 1000-year reconstruction[104] has been dubbed the 'hockey stick' and is of such importance that Wiley Interdisciplinary Reviews—Climate Change lists it as a specific topic of interest. Meanwhile, humanity is pondering options for responding to global warming, including mitigation and/or adaptation.[85] Either way, once again the importance of dendroclimatology in climate change is apparent. It is truly empowering to have an indication of climate spanning 1000+ years, resolved to the year, and representing a whole hemisphere. Tree rings contribute to that insight.

UNCERTAINTY IN DENDROCLIMATOLOGY

Model error is inevitable in dendroclimatology. By virtue of being statistical in nature, quantitative models of tree rings and climate simply cannot be perfect. Statistical models of tree rings and climate for an area cannot be any stronger than the common signal held by multiple meteorological stations of that area.[105] Still, at regional scales, trees potentially integrate and incorporate climate about as well as meteorological stations do.[106] By this rationale, even when tree rings and climate share a seemingly low amount of variation in common with climate, this might actually approach the level of variation shared by different meteorological stations. Thus, low levels of model strength, which might seem to constitute a source of uncertainty, are actually not as bad as they appear at first glance.

Recently, new uncertainty has emerged in dendroclimatic modeling. Dubbed the 'divergence problem', this is where ring growth and climate are not statistically associating with one another in the same way as before,[107] especially at the decadal scale.[108] At a bare minimum, this phenomenon casts doubt on uniformitarianism, as relationships between tree growth and climate appear to be changing through time.[109] Research is ongoing to better understand divergence and to cope with it.[110,111]

CONCLUSION

By virtue of its complexity and all-encompassing nature, climate change has spawned research that is highly interdisciplinary, including multiple facets of social, physical, chemical, biological, and environmental sciences. Underlying this broad research endeavor is a need to know just how similar or different climate of today is relative to the deep past. For this comparison, reconstructions of past climate from natural proxy archives are invaluable. Tree-ring growth is especially well suited for reconstructing climate due to multiple advantages, including reliable dating, annual resolution, ample replication, longevity up to thousands of years, widespread representation across tree species and microsites, and sensitivity to climatic conditions. Dendroclimatology has played, and continues to play, a substantial role in research on climate change.[112]

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