Dendroclimatology

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Background

Dendroclimatology was the first application of the newly founded science of dendrochronology in the first decade of the twentieth century, based on initial findings and later principles formulated by Andrew Ellicott Douglass of the University of Arizona, United States, when analyzing tree rings from ponderosa pine trees. Douglass noted similarities in the patterns of ring widths over the years from one tree to the next, not just in trees growing next to each other in one forest stand, but also in trees growing at a considerable distance from each other. Recognizing these similar patterns across trees and across a geographic region eventually led Douglass to establish the basic principle and technique in dendrochronology known as "cross-dating" (Douglass 1941). Cross-dating exists because all trees within a region respond to the overarching climatic processes that operate from day to day, month to month, and year to year. This response will impart a common climatic signal in all trees in a pattern of wide and narrow tree rings over the years, despite some influences from other types of environmental process that also affect tree growth, such as insect herbivory, wildfires, and air pollution. The value of cross-dating lies in its ability to provide the dendroclimatologist with a precise chronology back in time with annual resolution by accounting for tree rings that may add inaccuracy, such as locally absent rings (rings that are absent from the trunk of the tree where samples are usually taken) and false rings (rings that display intra-annual density fluctuations that can often mimic a true annual ring). Such problem rings could potentially add "noise" to the climatic "signal" desired in dendroclimatology. By accounting for these problem rings, dendrochronologists minimize the noise and maximize the climatic signal, making it possible to determine which climatic factors are most responsible for that common signal in the tree rings and capitalizing on this to eventually reconstruct climate in the past for the full length of the tree-ring chronology.

Douglass recognized the importance of pushing back the climatic record from tree rings for millennia back in time using the giant sequoia trees of the western slopes of the Sierra Nevada in California, but his efforts soon turned to the dating of prehistoric structures throughout the American Southwest. After founding the first laboratory dedicated to the tree-ring sciences in 1937, the Laboratory of Tree-Ring Research (LTRR) at the University of Arizona, Douglass assisted his colleague and former student Edmund Schulman by initiating an ambitious project that would take Schulman across the Americas and elsewhere in search for old trees to extend the record of Earth's past climate. Schulman's expertise lay in climatic applications and he was the first to extrapolate precipitation patterns for the American Southwest back for 800 years. Before his unexpected death in 1958, Schulman had analyzed the climatic potential of many tree species, mainly across North America and South America. Key among his discoveries was the venerable bristlecone pine trees of the

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White Mountains in southeastern California and Nevada, which reached unprecedented ages, including many over 4000 years old (Schulman 1958). The current age record for one individual bristlecone pine is 5062 years. This particular bristlecone pine, originally discovered by Schulman in the 1950s, was later analyzed by the eminent dendrochronologist Thomas Harlan of the LTRR, who found several hundred additional tree rings to reveal the first verified 5000-year-old living tree.

Beginning in the 1930s and into the 1940s, dendroclimatology was also taking a foothold in Europe, led by Bruno Huber, then at Tharandt in Saxony, Germany, whom many consider the "father of European dendrochronology" (Liese 1978). By the 1960s, Huber and his colleagues would have laid the groundwork and developed improved quantitative methods for analyzing tree-ring chronologies throughout Europe that would eventually aid in understanding the climate of Europe for the past 10 000 years at annual resolution based on tree rings. Further, techniques developed by European dendrochronologists would eventually aid in the dating of literally thousands of historic structures from the Roman period into the Middle Ages and later all across Europe and beyond. Huber realized early in his career that the ring patterns in Europe were distinctly different in their variability across the years from ring patterns in the western United States, making visual comparisons of tree-ring patterns for cross-dating more challenging. Huber and his colleagues introduced the *Gleichläufigkeit* (percentage of agreement) statistic, the first of its kind, to help add a degree of statistical rigor in the cross-dating of tree-ring patterns.

More formal quantitative techniques for analyzing the climate signal in tree rings and for reconstructing past climate were later generated by Harold Fritts and his coworkers at the LTRR (Fritts 1976). By then, dendroclimatologists recognized the importance of sound training in botanical and biological principles to better interpret the often confounding signal contained in tree rings. These techniques first focused on generating more accurate bioclimatic models of tree growth that incorporated tree-ring data. In other words, to better understand past climate from tree rings, you must first know how trees grow by embracing a more holistic view of environmental influences on tree growth. By the 1970s, quantitative reconstructions of past climate were becoming commonplace, pushed by an emerging need to also reconstruct hydroclimatic parameters (precipitation, discharge, lake levels) from tree-ring data. By the early 1990s, statistically validated millennium-length reconstructions of regional and hemispheric temperature and precipitation patterns were becoming common, spreading from Europe and the United States to Mexico, Canada, Australia, New Zealand, Chile, Argentina, and the Middle East, later occurring also in Russia, China, Mongolia, and Southeast Asia. Recent efforts in dendroclimatology concentrate on analyzing new tree species for their climatic potential, especially in the tropics; extending our knowledge of climatically sensitive tree species into new geographic regions; evaluating the impact of nonclimatic processes on the climate signal in tree rings; establishing whether the relationship between climate and tree growth has remained stable over recent decades; and incorporating tree-ring data into larger ensembles of proxy data for reconstructing past climate. These tree-ring data and the hundreds of climate reconstructions generated from them in many regions of the world are providing valuable assessments of long-term climate patterns over the past two millennia that play a key role in understanding the probable trajectory of the Earth's climate in the future, as shown in the 2013 report by the

Intergovernmental Panel on Climate Change (IPCC) (Masson-Delmotte *et al.* 2013).

Techniques

Dendroclimatology assumes that established practices and principles have been followed when identifying and collecting tree-ring samples for understanding past climate. Key among these are the Principles of Site and Tree Selection (Speer 2010; Grissino-Mayer 2014) to ensure that climatically sensitive locations were identified during the project design and field reconnaissance phases, and that trees were carefully chosen and sampled to provide the maximum climatic information while minimizing the adverse effects of noise from confounding ecosystem (both natural and human-caused) processes. Furthermore, tree-ring data analyzed are not limited to total ring widths only. Especially useful climatic information has been obtained using maximum latewood density measurements (particularly for European tree species) and stable carbon isotopes ($^{13}C/^{12}C$ ratios) (especially in Europe and the western United States). Additional physical properties used in dendroclimatology include minimum earlywood density, average ring density, earlywood and latewood widths, latewood percentage, "light" rings (i.e., faint latewood), oxygen isotope values ($^{18}O/^{16}O$ ratios), and annual basal area increment (BAI).

Two approaches are used in dendroclimatology. The first involves the development of (mechanistic) bioclimatic models of annual tree growth by modeling growth (via annual tree-ring data) as a function of one or multiple climatic variables (usually monthly values). In this strategy, tree growth is a function of one or more climatic parameters. Basically, before tree-ring data are used to reconstruct climate in the past, we must first know to which climate variables the trees are responding, as recorded in the physical or chemical properties of tree rings. Techniques first developed by Fritts (1976) and his colleagues of the LTRR used principal components to first transform monthly climatic data (such as temperature and precipitation) and remove interdependence between the predictor climate variables, then used these transformed data in a multiple regression to determine which monthly data most influenced tree growth on an annual basis. This technique was termed response function analysis (RFA), and the models generated are especially important for (i) isolating the primary climate variable to which the trees are responding (e.g., drought or temperature); (ii) determining which months/seasons are critical for tree growth; and (iii) evaluating potential changes in tree and forest growth responses given a changing climate.

Climate variables analyzed include temperature (mean, minimum, or maximum); precipitation; drought (Palmer drought severity index, or PDSI); snowpack; streamflow; and sea-level pressure. Recent research has focused on large-scale ocean–atmosphere patterns, such as the El Niño–Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, and Atlantic Multidecadal Oscillation, among others. The months analyzed and modeled always extend back to the previous growing season because tree growth is strongly influenced by conditions set during the prior year. For example, a year of favorable climate could allow trees to fix abundant carbon in their plant tissues (e.g., tissues in the apical meristems), prior to the dormancy period, that translates to enhanced growth during the following growing season. Although such principal components-based analyses are still common, RFA as practiced today involves more the use of simple correlation functions to determine the primary variables to which the trees respond during specific months and seasons.

The second technique involves the development of (stochastic) time-series models of past climate as a function of tree growth. In this strategy, historic climate data are modeled as a function of tree-ring data (usually over the twentieth and twenty-first centuries) to develop a calibration model that predicts (or "retrodicts") climate for the full length of the tree-ring record back in time. The dendroclimatologist must first determine the one primary climate variable to which the trees are responding using RFA before the reconstruction can be accomplished. The climate variable can represent a single monthly value (e.g., July drought as modeled using the PDSI); a range of months over the current growing season and/or months prior to the current growing season (e.g., average summer temperature); or an annualized climate variable (such as water-year precipitation, common in hydrologic studies). Most tree-ring-based reconstructions of climate involve first withholding climate data for a specific period during the twentieth/twenty-first centuries and generating predicted values of climate from tree-ring data for that period. If the predicted values from the calibration model track the actual values for that period (and can be verified statistically), then the climate–tree growth relationship is considered stable enough to use the calibration equation for reconstructing climate back in time. In most cases, however, the calibration model would use the full record of climate and tree-ring data available for the twentieth/twenty-first centuries rather than just a specific calibration period.

Main findings

The response by trees to climate varies greatly across geographic regions. For example, in the American Southwest, precipitation is the primary limiting factor and the primary climate variable to which trees respond in their annual growth. Across mainland Europe and in parts of South America, (summer) temperature is the primary climate variable to which the trees respond. In the southeastern and northwestern regions of the United States, some tree species respond primarily to temperature while other species respond primarily to precipitation. Trees that grow in the tropics and subtropics experience relatively little variation in climate from month to month and season to season, such that trees that grow in lower latitudes have limited potential for climatic analyses, but recent advances demonstrate that tropical trees do harbor climate information that can be extracted. Trees that grow in higher elevations and at higher latitudes display a greater sensitivity to temperature variations, while trees that grow in more arid conditions or at the lower elevation limits for that species display greater sensitivity to variations in precipitation. Even within a specific geographic location, trees can be found that respond to one climate variable while adjacent or nearby trees can be found to respond to a different climate variable because of differences in local topography and microclimate.

Recent research has focused on evaluating whether the relationship between climate and tree growth has remained stable over time during the historic (twentieth/twenty-first centuries) period. A major concern among dendroclimatologists (and scientists in general) centers around the issue of "divergence" (D'Arrigo *et al.* 2008), which describes the diverging temporal trends between temperature records (increasing in the twentieth/twenty-first centuries) and tree growth (decreasing beginning about 1960), especially for trees in the higher latitudes of the Northern Hemisphere which have been prominently used for reconstructing past temperatures. Prior to this, temperature and tree growth showed a strong positive relationship: that is, as temperature changed, so did tree growth. The implications of a temporally unstable relationship between tree growth and climate during the twentieth/twenty-first centuries are substantial because dendroclimatology assumes that environmental processes that operate today also operated in a similar manner in the past – the so-called uniformitarianism principle. If this relationship does not hold (remain temporally stable), then tree-ring data may not be reliable indicators of past climate. Researchers have discovered that some tree-ring chronologies display unstable relationships with climate over time, but most studies have found that the tree growth–climate relationship is indeed stable over the twentieth/twenty-first centuries.

Perhaps the greatest contributions of tree-ring data to society have been the reconstructions of past climate generated for many parts of the world that extend our knowledge on seasonal and annual climate well before historical weather records were kept. Reconstructions have been developed for nearly all the climate variables analyzed, across multiple temporal scales (monthly to multidecadal), for nearly all temperate and high-latitude locations, and now extending into the tropics. For example, water-year precipitation was reconstructed for the American Southwest from 136 BCE–1992 CE and revealed several centuries-long periods of above-average and below-average rainfall, including a "megadrought" in the late sixteenth century that has since been reconstructed for other portions of North America. Reconstructed PDSI for Mesoamerica suggests a strong forcing of drought by the El Niño–Southern Oscillation and a strong influence by the Atlantic Multidecadal Oscillation on summer climate variability over Mexico. Reconstructed streamflow for the Colorado River in the western United States suggests that river discharge during the twentieth century was not representative of discharge in previous centuries, calling into question government policies that allocate water resources to various western states in the United States.

Particularly important for understanding past climate have been the reconstructions of temperature for the Northern Hemisphere generated using primarily maximum latewood density data, although ring-width data also have been used. Temperature reconstructions were first pioneered by Fritts and his colleagues (especially Valmore LaMarche) at the LTRR beginning in the 1970s, before eventually being applied in the 1980s by others in the United States (Gordon Jacoby and Edward Cook of the Tree-Ring Laboratory at Columbia University) and in Europe (specifically Dieter Eckstein, Keith Briffa, Joel Guiot, Tom Wigley, and Malcolm Hughes). These initial reconstructions pushed our knowledge on trends in past temperature back several centuries, covering the important climatic episodes known as the Little Ice Age (ca. 1400 to 1850 CE) and the Medieval Warm Period (also called various other names, including the Medieval Climatic Anomaly), which occurred from about 1000 to 1300 CE. The first well-replicated millennium-length reconstruction was developed for Fennoscandia (Briffa *et al.* 1990) but showed little evidence for either of these two climate excursions. Evidence from Huon pine trees growing in Tasmania, however, showed enhanced growth during the twentieth century that could be attributed to anomalously warm temperatures, but such enhanced growth was not revealed for long-lived alerce that grow in southern Chile which were used to develop the first multimillennial reconstruction of climate (Lara and Villalba 1993).

Beginning in the late 1990s, dendroclimatologists employed hundreds of temperature-sensitive tree-ring datasets across large portions of the Northern Hemisphere to reconstruct past temperature, based largely on ensemble methods, a strategy that focuses on the development of several different (though related) reconstructions. The ensemble strategy also occasionally uses different proxy sources of past climate (such as borehole temperatures, ice core data, and speleothem data), and averaging/combining the results of the reconstructed temperature. Such ensemble approaches are desirable because error variance in the final reconstruction can be reduced. Mann, Bradley, and Hughes (1998) focused on reconstructing temperature for the past 600 years and found that annual temperatures during several years in the late 1990s were the warmest since the 1400s, stoking an ensuing controversy surrounding the graphic that would later become known as the "hockey stick" (1998: Fig. 5b and later versions). Later independent analyses, using the original but updated tree-ring data as well as new tree-ring datasets, would later confirm that the latter part of the twentieth century was indeed warmer than at any time during the past 1000 years. Recent tree-ring studies have also confirmed that the rate at which temperatures have increased in the past 100 years has been unprecedented during the past 1000 years. New tree-ring studies, however, point to a general cooling trend over the past 2000 years since the Roman Warm Period, a period claimed to have experienced temperatures warmer than those experienced during the twentieth century.

SEE ALSO: Biologic dating techniques; Climate change and biogeography; Dendrogeomorphology; Environmental science; Global environmental change: human dimensions; Nature conservation; Paleoclimatology; Water and climate change

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