Dendroclimatology

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Dendroclimatology

Progress and Prospects

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Preface

This collection is the latest of a series of efforts to evaluate the contributions of dendroclimatology, the study of past climate using tree rings, to climatology and to other fields and activities. The origins of dendroclimatology as a collaborative international field may be traced to two meetings held at the Laboratory of Tree-Ring Research (LTRR), University of Arizona, in April 1974 and June 1977. The First International Workshop on Dendroclimatology (April 1974), inspired and organized by Harold C. Fritts, set the scene for a scientific venture of remarkable ambition—the development of networks of fully dated, adequately replicated, and documented tree-ring chronologies throughout the temperate and subarctic regions of both the Northern and Southern Hemispheres. It was at this meeting, attended by scientists from ten countries, that the International Tree-Ring Data Bank (ITRDB) was established, with an interim committee chaired by Fritts and including Bernd Becker (Germany), Zdzisaw Bednarz (Poland), Jon Pilcher (UK), and Charles Stockton (USA). The foundation of the ITRDB (now part of the World Data Center for Paleoclimatology, operated by the US National Oceanic and Atmospheric Administration, NOAA), signaled the acceptance by most of the active practitioners around the world of a shared minimum set of criteria for the development and recording of dendroclimatic data. This in turn made it possible to conceive of many individual efforts, leading to the establishment of internally consistent networks at national, continental, and eventually, global scales.

The June 1977 meeting, organized with the support of the National Science Foundation (NSF), had the goal of reviewing Harold Fritts's pioneering dendroclimatic reconstruction projects. Most of the participants at the meeting were climatologists interested in a topic that had received very little attention up to that time—high-resolution paleoclimatology. Those present included Roger Barry, Ray Bradley, Henry Diaz, Mick Kelly, John Kutzbach, Murray Mitchell, Jr., and Harry van Loon. The meeting led to several productive long-term scientific collaborations, which in turn led to, among other things, the creation of baseline comprehensive instrumental climate databases for studying climatic variations over the past century and a half. From today's viewpoint, it is difficult to imagine how little was known about interannual- to century-scale variability in the climate system at that time, with published sketches of the spectrum of climatic variability exhibiting little or no power between bidecadal and millennial frequencies. Recall, the El Niño/Southern

Oscillation (ENSO) phenomenon was not as well understood then as it is now, and the view of longer fluctuations had changed little since the early twentieth-century work of Sir Gilbert Walker. The last 35 years have seen an extraordinary growth of interest in the very topics of climatology and broader environmental science to which tree-ring studies can contribute most—variability on interannual to century timescales. The tree-ring record has become more and more important to the understanding of the climate system as we learn about things like decadal and longer patterns, and it is central to the issue of whether current climate changes are extraordinary, and if so, on what scale.

This volume arose from a workshop titled, 'Tree Rings and Climate: Sharpening the Focus,' held in Tucson, Arizona, April 6–9, 2004, although it contains much material developed since the workshop. There were forty oral presentations and twenty-two poster presentations at the workshop, with participants coming from many countries, and including 'users' of dendroclimatic information, such as climatologists, as well as 'producers.' The primary aim of the meeting was to review what has been learned, by using tree rings, about natural climate variability and its environmental and social impacts. This was done by reviewing and synthesizing the results of the last 35 years, and identifying the strengths and weaknesses of dendroclimatology and the needs for and the opportunities for future work. Thanks are due to the following bodies for financial and other support for the meeting, and hence for making this volume possible: the Paleoclimatology Program in the Division of Atmospheric Sciences at the US National Science Foundation; the Climate Change Data and Detection Program, US National Oceanic and Atmospheric Administration; the Past Global Changes (PAGES) project of the International Geosphere-Biosphere Program; the Institute for the Study of Planet Earth, University of Arizona; the Office of the Vice President for Research, University of Arizona; and the Laboratory of Tree-Ring Research, University of Arizona.

We are also particularly grateful to the colleagues who kindly undertook the task of providing peer reviews for the chapters in this collection, and to the authors for their good grace in awaiting its publication. Diana Miller has done us all a great favor by her meticulous and constructive copyediting of the manuscripts.

Finally, thanks are due to those who set this ball rolling: Andrew Douglass in the early twentieth century, Edward Schulman and Bruno Huber in the mid-twentieth century, and, notably, Harold C. Fritts, who made the global venture possible, and to whom this volume is dedicated.

Tucson, Arizona Malcolm K. Hughes
Tucson, Arizona Thomas W. Swetnam
Boulder, Colorado Henry F. Diaz

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Part I
Introductory Section

Chapter 1
High-Resolution Paleoclimatology

Raymond S. Bradley

Abstract High resolution paleoclimatology involves studies of natural archives as proxies for past climate variations at a temporal scale that is comparable to that of instrumental data. In practice, this generally means annually resolved records, from tree rings, ice cores, banded corals, laminated speleothems and varved sediments. New analytical techniques offer many unexplored avenues of research in high resolution paleoclimatology. However, critical issues involving accuracy of the chronology, reproducibility of the record, frequency response to forcing and other factors, and calibration of the proxies remain. Studies of proxies at high resolution provide opportunities to examine the frequency and magnitude of extreme events over time, and their relationships to forcing, and such studies may be of particular relevance to societal concerns.

Keywords Climate dynamics · Natural archives · Paleoclimate · Proxies

1.1 Introduction

Paleoclimatology uses natural archives to reconstruct climate in the pre-instrumental period. The longest instrumental records are from Western Europe, and a few of these extend back into the early eighteenth (or even late seventeenth) century. However, for most regions, continuous instrumental measurements rarely extend beyond the early nineteenth century, with some remote (desert or polar) regions having barely 50 years of observations (Fig. 1.1). Consequently, our instrumental perspective on climate variability is extremely limited. In particular, it is unlikely

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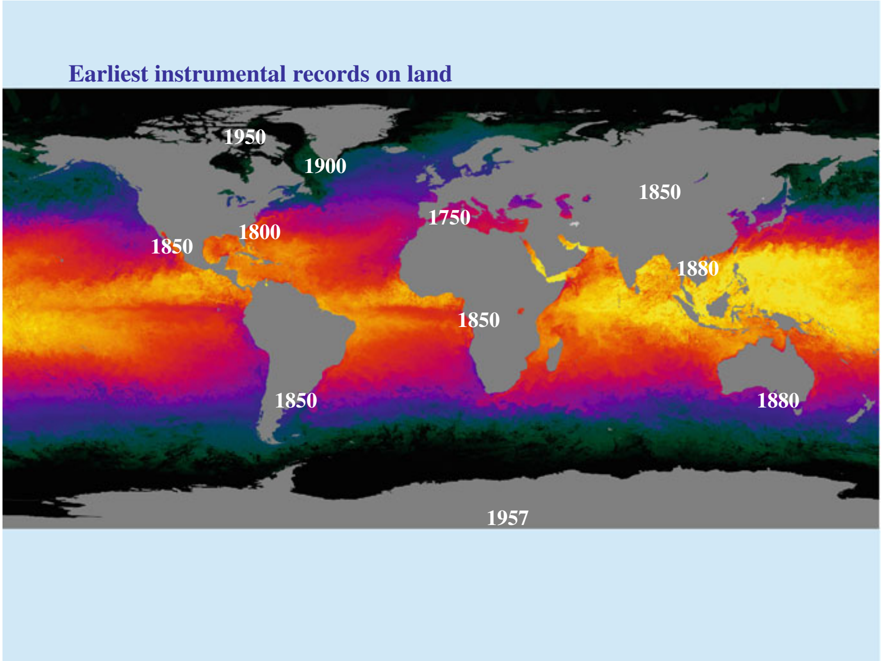


Fig. 1.1 Approximate earliest date of continuous instrumental records, which defines the need for high-resolution proxy-based data prior to these dates

that we understand the full spectrum of variability of the most important climate modes (such as the El Niño/Southern Oscillation [ENSO], Pacific Decadal Oscillation [PDO], North Atlantic Oscillation [NAO]. etc). High-resolution paleoclimatology addresses this issue by focusing on climate proxies that can be resolved at seasonal to annual resolutions. These proxy records may extend back continuously from the present, or provide discrete windows into the past, to shed light on modes of variability in earlier times. By providing data at a resolution comparable to that of the instrumental record, high-resolution paleoclimatology plays an important role in resolving anthropogenic effects on climate. Specifically, it helps to place contemporary climate variability in a long-term perspective (*detection*, in the parlance of the Intergovernmental Panel on Climate Change [IPCC]), and it enables climatic changes to be examined in terms of forcing mechanisms (*attribution*). High-resolution paleoclimatology also provides targets (either time series or maps of past climatic conditions) with which models (general circulation models [GCMs] or energy balance models [EBMs]) can be tested and validated, and it offers the opportunity to explore climate dynamics (modes of variability, abrupt climate changes, climate system feedbacks) over long periods of time. Thus, high-resolution paleoclimatology naturally interfaces with, and complements, the research priorities of the climate dynamics community.

1.2 Data Sources for High-Resolution Paleoclimatology

The critical requirements for high-resolution paleoclimatology are that:

- An accurate chronology can be established; this generally requires replication of the archive being sampled.
- The archive can be sampled in detail, ideally at seasonal to annual resolutions, but at least at the resolution of a few years.
- The parameter being measured is reasonably well understood in terms of its relationship to climate (i.e., its mechanistic and seasonal response) so that it can be calibrated in terms of climate, by using the instrumental record as a yardstick for interpreting the paleorecord.
- The relationship between the proxy and climate observed today has been similar in the past (the principle of uniformitarianism).
- The record captures variance of climate over a wide range of frequencies, or at least the window of variance that the proxy does capture is known.

In the next section, these issues are examined with reference to the main archives that are available for high-resolution paleoclimatology: tree rings, corals, speleothems, ice cores, and varved sediments. This examination is followed by a discussion of the opportunities and challenges in high-resolution paleoclimatology, with particular reference to dendroclimatology.

1.3 Chronology and Replication

An accurate timescale is essential in high-resolution paleoclimatology. A chronology is commonly obtained by counting annual increments, by using variations in some parameter to mark the passage of time. This might be the cyclical ^{18}O maximum in a coral record, registering the sea surface temperature (SST) minimum over each annual cycle; or the presence of a ‘clay cap’ in varved lacustrine sediments, marking each winter’s sediment layer; or the width of a tree ring between the large, open-walled spring cells that form each year. However, simply counting these recurrent features in a sample (even if they are counted several times by different analysts) does not guarantee an accurate chronology. The best procedure is to replicate the record by using more than one sample (core), to eliminate potential uncertainties due to ‘missing’ layers and to avoid misinterpretation of dubious sections. On this matter, dendroclimatic studies have a clear and unambiguous advantage over most other paleoclimate proxies. Duplicate cores are easily recovered, and crossdating using one or more samples is routinely done. Tree-ring chronologies are thus as good as a natural chronometer can be, at least for those regions where there is an annual cycle of temperature or rainfall and trees are selected to record such changes in their growth. However, for those vast areas of equatorial and tropical forests, where trees are not under climatic stress and so do not produce annual rings, establishing a chronology has been far more challenging. Recent analytical improvements using continuous flow isotope mass spectrometry have made feasible the almost continuous sampling of wood, so that annual changes in isotopic properties can be identified, even in wood that appears to be undifferentiated in its growth structure (Evans and Schrag 2004; Poussart et al. 2004). This technique opens up the possibility of using trees for paleoclimatic reconstruction in regions that were hitherto unavailable. However, replication of samples from nearby trees is still necessary to reduce chronological uncertainties in these newer records.

In the case of most other high-resolution proxies, replication is rarely carried out. This is generally related to the cost of sample recovery (in terms of logistics or time) or because of the analytical expense of duplicating measurements. Most coral records, for example, are based on single transects through one core, though the veracity of the chronology may be reinforced through the measurement of multiple parameters, each of which helps confirm the identification of annual layering in the coral. Similarly, in ice cores, multiparameter glaciochemical analyses can be especially useful in determining a secure chronology (McConnell et al. 2002a; Souney et al. 2002). In addition, in some locations more than one core may be recovered to provide additional ice for analysis and to help resolve uncertainties in chronology (Thompson 1993). It may also be possible to identify sulfate peaks in the ice, related to explosive volcanic eruptions of known age. Such chronostratigraphic horizons can be very helpful in confirming an annually counted chronology (Stenni et al. 2002). Varved sediments are sometimes analyzed in multiple cores, but sample preparation (such as impregnation of the sediments with epoxy, thin section preparation, etc.) is expensive and very time-consuming, so duplication is not commonly done. Where radioactive isotopes from atmospheric nuclear tests conducted in the late 1950s and 1960s can be identified in sediments (and in ice cores), such horizons can be useful time markers. Tephra layers (even finely dispersed cryptotephra) can be useful in confirming a sedimentary chronology if the tephras can be geochemically fingerprinted to a volcanic eruption of known age (e.g., Pilcher et al. 2005). Finally, where annual layer counting is not feasible—as in many speleothems—radioactive isotopes (^{210}Pb, ^{14}C, and uranium-series) can be used to obtain mean deposition/accumulation rates, though there may have been variations in those rates between dated levels.

1.4 High-Resolution Sampling

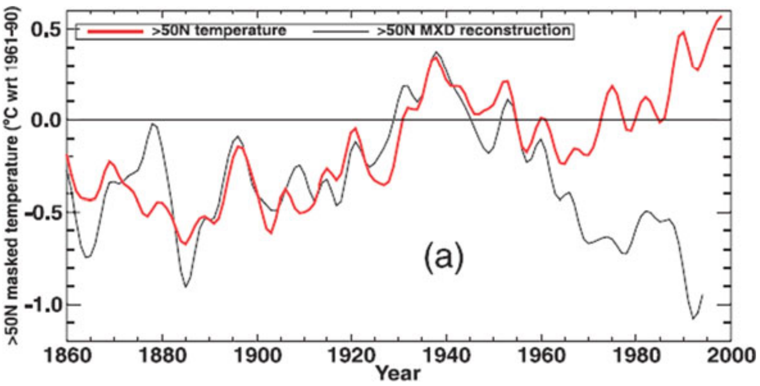
Advances in analytical techniques have now made sub-annual sampling and measurements fairly routine in most high-resolution proxies. Whereas tree rings were generally measured in terms of total annual increments, densitometry now enables measurements of wood density and incremental growth in early and latewood sections of each annual ring. Image analysis provides further options in terms of analyzing cell growth parameters (Panyushkina et al. 2003). Isotopic dendroclimatic studies require subannual sampling resolution to determine growth increments. In corals, such detailed sampling is now routine; often 10 or more samples will be obtained per annual increment (e.g., Mitsuguchi et al. 1996; Quinn and Sampson 2002). Stalagmite research has rarely achieved such detail, with sampling intervals (in most studies) of a few years at best. However, some studies have established chronologies by counting annual layers on polished sections under a microscope, and new analytical approaches (using an electron microprobe, secondary ionization mass spectrometry [SIMS], or excimer laser ablation–inductively coupled plasma–mass spectrometry [ELA-ICP-MS]) have made it feasible to identify annual layers through seasonal changes in trace elements (such as Mg, Ca, Sr, Ba, and U), along multiple transects of a sample (e.g., Fairchild et al. 2001; Desmarchelier et al. 2006). Image analysis of varved sediments (via impregnated thin sections examined under a petrographic or scanning electron microscope) can reveal intra-annual sediment variations that may be associated with seasonal diatom blooms or rainfall events (Dean et al. 1999). In ice cores, it is now possible to make continuous multiparameter measurements, providing extremely detailed time series (McConnell et al. 2002a, b). Thus, in most natural archives available for high-resolution paleoclimatology, detailed measurements can be made both to define annual layers or growth increments and to characterize changes therein. However, it is not necessarily the case that an annual layer fully represents conditions over the course of a year. Much of the sediment in a varve, for example, may result from brief periods of runoff. Similarly, annual layers in an ice core represent only those days when snowfall occurred. Indeed, they may not even do that, if snow was subsequently lost through sublimation or wind scour. Coral growth increments may result from more continuous growth, and trees may also grow more continuously, at least during the growing season. Speleothems accumulate from water that has percolated through the overlying regolith, and so short-term variations related to individual rainfall episodes are likely to be ‘smoothed out.’ Nevertheless, there is some evidence that extreme rainfall episodes can be detected in the carbon isotopes of speleothems in areas where the throughflow of water is rapid (Frappier et al. 2007).

1.5 Relationships Between Natural Archives and Climate

Extracting a climatic signal from individual archives requires an understanding of the climatic controls on them. Analysis of the temporal relationships between variables may provide a statistical basis for calibration, but a theoretical basis for such a relationship is also required, to direct some light into the statistical black box. This may require in situ process-based studies to understand the factors controlling the proxy signal. Even if such studies are short-term, they can provide valuable insights into how climate influences the system being studied, and hence improve our understanding of the paleoclimatic record. For example, studies of meteorological conditions at the ice-coring site on Sajama, Bolivia, demonstrated strong seasonality in snow accumulation, with much of the snowfall that accumulated late in the accumulation season being subsequently lost through sublimation (Hardy et al. 2003). Consequently, the ice core record is made up of sections of snow that accumulated for (at most) a few months each year, demonstrating that division of such records into 12 monthly increments is not appropriate (cf. Thompson et al. 2000a). Similarly, hydrological studies in the Arctic have shown that in some lakes, much of the runoff and associated sediment may be transferred into the lake over the course of only a few weeks. For example, measurements at Sophia Lake (Cornwallis Island, Nunavut, Canada) showed that 80% of the runoff and 88% of the annual sediment flux occurred in the first 33 days of the 1994 melt season (Braun et al. 2000). This sediment was subsequently distributed across the lake floor, forming an annual increment (varve), but the climatic conditions that mobilized the sediment were brief and perhaps unrepresentative of the summer season (and the year as a whole). Other studies of arctic lakes indicate that watersheds containing glaciers provide more continuous runoff and associated sediment flux throughout each summer, and thus provide a better proxy for summer climatic conditions (e.g., Hardy et al. 1996). Thus, understanding the environment from which the proxy archive is extracted is critically important for proper interpretation of the paleoclimate record. Process-based studies (often derided as simply 'monitoring') have also provided insights into climatic controls on corals, showing strong nonlinearities at high water temperatures (Lough 2004). In situ measurements within caves, aimed at gaining a better understanding of paleoclimate records, are now also being carried out (e.g., McDonald et al. 2004; Cruz et al. 2005). By comparison, dendroclimatology is far advanced because ecophysiological studies of tree growth have a long history. Consequently, factors influencing tree growth increments are well understood (Fritts 1996; Schweingruber 1996; Vaganov et al. 2006), providing a very strong foundation for paleoclimatic studies using tree rings.

1.6 Uniformitarianism

Perhaps because of the rapidity of recent climate change, many archives are no longer responding to climate in a manner that typifies much of the past. This phenomenon was first noted by Briffa et al. (1998), who showed that some trees that were formerly strongly influenced by temperature were no longer so influenced, or at least not to the same extent. Figure 1.2 shows the geographical distribution of this effect. Briffa et al. (2004) speculated that this response might be related to recent increases in ultraviolet radiation resulting from the loss of ozone at high elevations. Others have argued it might reflect the fact that trees in some areas have reached a threshold, perhaps now being affected more by drought stress than was formerly the case. Whatever the reason, it raises the question of whether such conditions might have occurred in the past, and if so, whether it would be possible to recognize such a 'decoupling' of the proxy archive from the ('normal') climate driver. Paleoclimate reconstruction is built on the principle of uniformitarianism, in which the present is assumed to provide a key to the past. If modern conditions (during the calibration period) are not typical of the long term, this assumption will be invalid. It is thus important to resolve the reasons for such changes and determine if additional parameters (such as cell growth features) might provide clues about when such stresses may have overwhelmed the typical climate response.



(b) **Regression with difference series (infilled)**

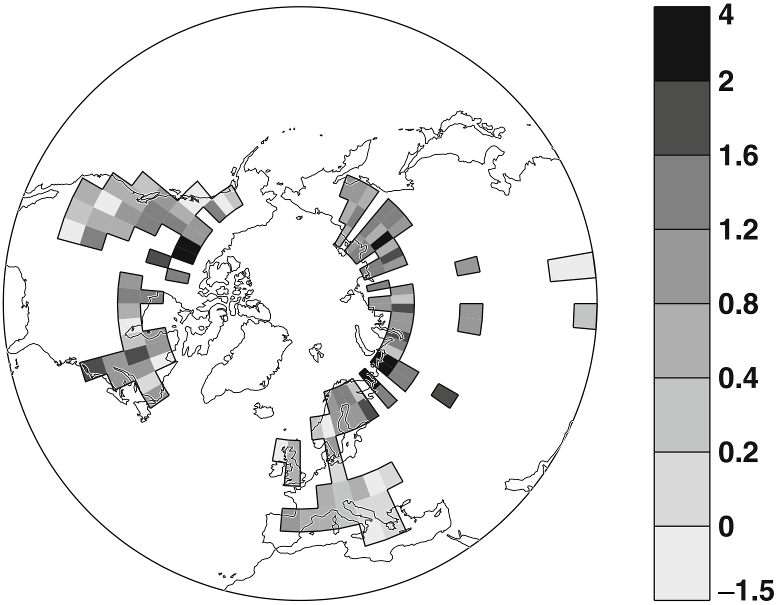


Fig. 1.2 (**a**) Instrumental temperatures (*heavier line; red in on-line version*) and tree-ring density reconstructions of temperature (*thinner line; black in on-line version*) averaged over all land grid boxes north of 50°N, smoothed with a 5-year low-pass filter. (**b**) Map showing where the average temporal pattern of divergence between tree-ring density chronologies and mean warm season temperatures is most apparent. The smoothed difference between the thin line (*black in on-line version*) and the thicker line (*red*) in (**a**) were regressed against the local difference curves produced from the averages of data in each grid box. Where the regression slope coefficients are progressively >1.0 (the increasingly darker boxes, generally the most northerly locations), the greater is the local difference between density and temperature. In the areas shown as lighter colored boxes (generally areas further south), the difference is apparent, but of lower magnitude. The areas shown in the lightest color (basically the most southern regions) do not show the divergence (redrawn from Briffa et al. 2004)

On a related point, it is clear that many natural archives are being detrimentally affected by recent changes in climate. Thus, many high-elevation ice caps in the tropics have been affected by surface melting and strong sublimation, so that the recent isotopic record has been degraded or even lost entirely (Thompson et al. 2000b). Similarly, corals in many areas were greatly affected by exceptionally high sea surface temperatures associated with the 1997–1998 El Niño (Wilkinson et al. 1999). Many century-old *Porites* colonies in the Great Barrier Reef were killed at this time.

1.7 Frequency Response

High-resolution records may have certain low-frequency characteristics that differ from the spectrum of the climatic environment in which they are situated. Such effects may be due to long-term biological growth (in the case of trees, and perhaps corals), compaction (ice, sediments), non-climatic changes in depositional environments (lake sediments, speleothems), and other proxy records. This issue is especially important as efforts are made to extend paleoclimatic reconstructions further back in time, to reveal changes in climate over thousands of years. Sediments are certainly affected by compaction, but this effect can be relatively easily corrected for by examining changes in density. This is also true in ice cores. Diffusion of isotopes within firn leads to a reduction in the amplitude of isotopic values that must also be considered. Deposition rates in speleothems are determined by radiocarbon or uranium series dates, and such analysis is generally sufficient to determine if deposition has been continuous over time. Certainly, there are no compression issues to be concerned with here, so in that sense speleothems do offer a very good option for identifying low-frequency changes in climate. This is illustrated well in the Dongge Cave record of Wang et al. (2005) (Fig. 1.3). The record shows an underlying low-frequency decline in monsoon precipitation, related to orbital forcing, on which decadal- to centennial-scale variations are superimposed, which appear to be (at least in part) related to variations in solar irradiance.

The issue of determining low-frequency changes in climate has been most problematical in dendroclimatology. The biological growth function of trees must first be removed before climatic information can be extracted. When this procedure is done, some low-frequency information may be lost. Furthermore, since most tree-ring series are short, assembling a composite long time series from many short records makes it even more problematical to obtain low-frequency information over timescales longer than the typical segment length (Cook et al. 1995). New approaches to standardization of tree-ring series have been developed, and these help to preserve more low-frequency information than do more traditional methods. However, such approaches require very large datasets and so cannot be applied in all cases. Another approach involves combining different proxies, some that may contain more low-frequency information with others that capture well higher-frequency information, so that together they cover the full spectrum of climate variability

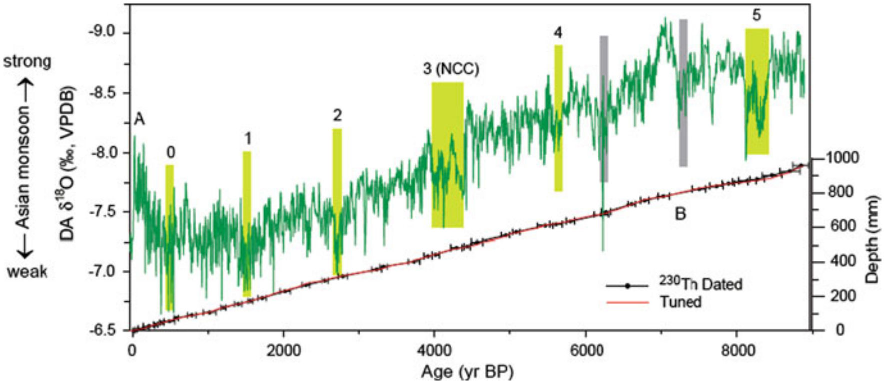


Fig. 1.3 (**a**) δ^{18}O time series of a Dongge Cave (China) stalagmite (*thin line*). Six vertical shaded bars denote the timing of Bond events 0–5 in the North Atlantic. Two *vertical gray bars* (without numbers) indicate two other notable weak Asian monsoon periods that can be correlated to ice-rafted debris events. Higher frequency variability appears to be related to solar (irradiance) forcing. NCC is the Neolithic Culture of China, which collapsed at the time indicated. (**b**) Age-depth relationship. *Black error bars* show ^{230}Th dates with 2σ errors. Two different age-depth curves are shown, one employing linear interpolation between dated depths and the second slightly modified by tuning to INTCAL98 within the ^{230}Th dating error (from Wang et al. 2005). On-line version shows this figure in color

(Moberg et al. 2005). This approach has much promise, and further fine-tuning will likely lead to a better understanding of large-scale climate variability over recent millennia.

1.8 High-Resolution Proxies: Challenges and Opportunities

High-resolution paleoclimatic records provide unique opportunities to better understand the climate system because they extend the limited sampling interval that is available from short instrumental records. This longer perspective is especially important for studies of rare events, such as explosive volcanic eruptions or the occurrence of extreme climatic conditions such as droughts or floods. Ice cores reveal (through sulfate and electrical conductivity measurements) that there have been much larger explosive volcanic eruptions in the past than during the period of instrumental records (Zielinski et al. 1994; Castellano et al. 2005); by identifying these events, it is then possible to explore the relationship between eruption size and location and the subsequent climatic effects (e.g., D'Arrigo and Jacoby 1999). Many dendroclimatic studies have recognized the connection between explosive eruptions and cold growing season conditions, which sometimes have led to frost damage in trees (e.g., LaMarche and Hirschboeck 1984; Baillie and Munro 1988; Briffa et al. 1990; D'Arrigo et al. 2001). Proxy records of volcanic forcing also provide a much larger database of eruption events than is available for the instrumental period; compositing climatic conditions following such events increases the signal-to-noise ratio, giving a clearer view of the climate system response to such events. Thus Fischer et al. (2007) were able to show that summer conditions in Europe have tended to be both cold and dry after major tropical volcanic eruptions; but in winter, a positive NAO circulation has generally been established, resulting in mild, wet conditions in northern Europe and well below average precipitation in the Alps and Mediterranean region.

Dendroclimatic research has been especially important in documenting the frequency, geographical extent, and severity of past drought episodes, as well as periods of unusually high rainfall amounts; such studies have been especially extensive in the United States (e.g., Stahle and Cleaveland 1992; Hughes and Funkhouser 1998; Cook et al. 2004). These studies have shown that there has often been a strong connection between severe droughts in the southwestern United States and the occurrence of La Niña episodes, although the precise geographical pattern of each drought has varied over time (Stahle et al. 2000; Cole et al. 2002). Tree-ring research has also been applied to reconstructing modes of circulation in the past, such as the North Atlantic Oscillation (Cook et al. 1998; Cullen et al. 2001), Pacific Decadal Oscillation (Gedalof and Smith 2001), and Atlantic Multidecadal Oscillation (AMO) (Gray et al. 2004). In all of these cases, the paleoclimatic reconstructions have expanded our understanding of the spectrum of variability of these modes of circulation and provided insight into how large-scale teleconnections (and interactions between Atlantic- and Pacific-based circulation regimes) may lead to persistent, large-amplitude anomalies over North America and other regions.

Great strides have been made in constructing hemispheric- and global-scale patterns of past climate variability by combining many different types of high-resolution paleoclimatic records, using a variety of statistical methods (Mann et al. 1998, 1999, 2005; Moberg et al. 2005; Rutherford et al. 2005). These studies have demonstrated the importance of volcanic and solar forcing, and of the increasingly dominant effects of anthropogenic forcing over the last 150 years. Nevertheless, such studies rely largely on the most extensive database of paleoclimatic reconstructions that is currently available—that provided by dendroclimatology. On the one hand, this is good because the physiological basis for how trees respond to climate is well understood, thanks to decades of careful studies, and tree rings provide the most accurate chronologies available. However, the use of tree rings in long-term paleoclimate reconstructions is dogged by questions of uniformitarianism (a question not unique to dendroclimatology, of course), but more significantly by the difficulty of resolving the full spectrum of climate variability from overlapping, relatively short, tree-ring series. This matter can be resolved by obtaining longer records where possible, expanding the tree-ring database to improve data density back in time, and developing new statistical approaches; all these methods are necessary to ensure that long-term paleoclimatic reconstructions are as reliable as possible. New isotopic and image analysis techniques applied to tree growth may add further information about past climate variations in regions that were formerly off-limits to dendroclimatologists, thereby extending the geographical domain for large-scale climate reconstruction. New proxies, especially from lake sediments and speleothems, will likely further supplement this expansion of high-resolution records, providing records with more robust low-frequency characteristics that can be combined with proxies that are exceptionally good at capturing high-frequency climate variability (e.g., Moberg et al. 2005). In this way, the next decade of high-resolution paleoclimatology will likely see paleoclimatic reconstructions with far less uncertainty, covering more geographical regions, and providing meaningful estimates of climate sensitivity before the 'Anthropocene'.

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Chapter 2
Dendroclimatology in High-Resolution Paleoclimatology

Malcolm K. Hughes

Abstract The characteristics of tree rings as natural archives of past climate are discussed. Special consideration is given to key issues affecting their robustness and reliability as sources of information on past climate. These issues include: the effects of sample design and in particular the importance of using networks of tree-ring records from many locations whenever possible; potentially complementary approaches to the identification of climate signal in tree rings, namely empirical-statistical and process-modeling approaches; statistical and mechanistic stability over time of the climate signal in tree rings; and the ongoing effort to isolate climate signal from noise, without introducing biases, in tree-ring based proxy records of climate.

Keywords Tree rings · Dendrochronology · Dendroclimatology · Climatology · Reconstructions

2.1 Introduction

Bradley (Chapter 1, this volume) has placed tree rings firmly in the context of high-resolution paleoclimatology, along with other natural archives such as coral growth bands, laminated and high-accumulation freshwater and marine sediments, speleothems, and annual bands in polar and high-elevation ice caps. He further identified a number of critical issues that must be faced in using properties of such natural archives as proxy records of climate variables. These were the precision and accuracy of the chronology applied to each record; the effective temporal resolution of each archive; the degree to which the processes producing each archive are understood and may be compared with observed climate; the consistency or inconsistency of response to climate throughout the period of interest; and the extent to which each

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type of record can capture climate variability over a wide range of timescales, from interannual to millennial. In this chapter, these critical issues will be examined, with specific reference to tree rings as natural archives of past climate.

Tree rings are uniquely widespread relative to all comparable natural archives of climate. Woody plants with reliably annual rings are formed wherever the local climate imposes a single dormant season and a single growth season each and every year. Such conditions are widespread in the boreal, temperate, and subtemperate regions, and in some parts of the tropics. At middle and high latitudes or elevations, this pattern of one dormant and one growth season per year in the formation of wood is imposed by annual day length and temperature cycles. In some tropical locations, it may be imposed by the existence of a single dry season-induced dormant period each year, as in teak through much of its range in south Asia.

The abundance of potentially useful tree-ring records and the relative ease with which they may be collected has resulted in unique approaches to their use as natural archives of past climate. In this chapter some of these specific approaches, which lead to characteristic features of tree-ring records of past climate, will be described, so as to help the reader place the chapters that follow in a wider context. Specifically, consideration will be given to four key issues:

(1) sample design in dendroclimatology and the importance of networks
(2) identifying climate signal in tree rings by empirical-statistical and process-modeling approaches
(3) stability of the climate signal
(4) the quest for unbiased chronologies

2.2 Sample Design in Dendroclimatology

2.2.1 Natural Archives and Proxy Climate Records

The layer of new xylem or wood laid down each year under the bark of a tree (the annual ring) is a natural archive of growth that year. The environmental conditions influencing that growth may leave an imprint on the properties of the ring. Thus the size, structure, and composition of the ring may contain information on those conditions; for example, climate. Estimates of those properties in turn may be used as proxy climate records.

In the case of tree rings, the most commonly used properties are structural; namely, the total ring width (TRW) and maximum latewood density (MXD). There are other structural properties of tree rings that can contain climate information; for example, earlywood and latewood width measured separately, or tracheid (conifer wood cell) dimensions. Their use will likely increase as a result of technical advances in measurement (see Vaganov et al. 2006, Chapter 2, for a basic account of these structural properties and their measurement).

Many measurements of the composition of wood in annual rings could contain climate information. In recent years considerable progress has been made in using ratios of stable isotopes, primarily of carbon and oxygen, in tree rings as proxy climate records (Gagen et al. Chapter 6, this volume). The issues of sample design, replication, removal of non-climatic variability, identification of climate signals, and the properties of networks of isotope chronologies are all being explored, and appropriate methods are emerging.

In this chapter the discussion of the four key issues mentioned in the previous section will focus on TRW and MXD because they are the subjects of most of the existing literature.

2.2.2 Single Site Chronologies

The criteria used to identify sites, species, and trees to be sampled in establishing a local reference for dating annual rings correspond to those used to capture a clear and strong climate signal. There is considerable variability in ring growth within and between trees, and so multiple samples are taken so as to 'distill' the common, presumably climatic, signal, and to 'dilute' the likely more individual non-climatic variability or noise (Fig. 2.1 shows raw data from a site where high correlations between sample series suggest a strong common climate signal). The common signal, usually expressed as some form of the mean of the individual samples' modified

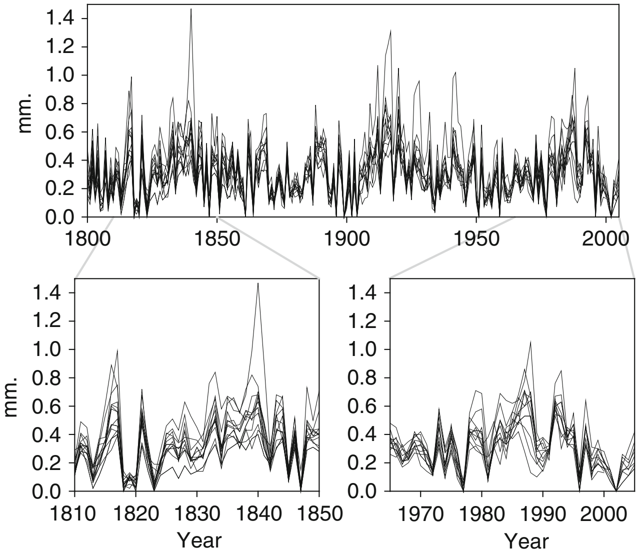

Fig. 2.1 Common pattern of variability shared by trees at one location. Raw, unmodified ring widths (millimeters) of 18 samples from Douglas-fir in Navajo Canyon, Colorado, each shown by a single fine line. Note that although absolute growth rates differ, the relative patterns of variability are similar. The *lower* panels show two 41-year periods with the horizontal scale expanded. Data provided by David M. Meko

ring series, or ‘chronology,’ is equally essential as a standard for dating local wood of unknown dates and as an estimate of ring growth as influenced by climate. In both cases, sites, species, and trees are sought in which the ratio of the climate (common) signal to non-climatic (primarily individual) noise is as great as possible.

It would make little sense to drill an ice core in a situation where stratigraphy is likely to be distorted—or even inverted—to sample lake sediments in locations where the record is prone to earthquake-induced slumps or extensive bioturbation, or indeed to use meteorological station data without the application of appropriate quality control standards and procedures for homogenization. In the same spirit, strategies have been developed for selecting the sites, species, variables, and individual trees most likely to show strong, consistent ring variability common to all trees, and hence a clear climate signal in their rings, and for rejecting those where there are a priori reasons to expect strong non-climatic influences that cannot be disentangled. The aim in this case is not to take a representative sample of the trees of the forest, but rather to maximize climate signal and minimize non-climatic noise.

A quite different sampling protocol would be used if the aim were to take a representative sample of the forest. An optimal record of summer temperature is likely to come from regions with cool, moist summers where drought influence on wood growth is minimal. Within such regions, sites at upper elevations close to the upper or poleward tree limit are likely to reflect regional temperatures, rather than the peculiar regime of a particular valley. In cases where the uppermost or highest-latitude trees have a stunted or dwarf growth form, they would not be sampled, as their wood anatomy is strongly influenced by mechanical rather than climatic forces. Individual trees with a lean, lightning damage, or other abnormal morphology would also be avoided. A site from which a chronology is to be developed should be as uniform as possible with respect to the small-scale conditions affecting tree growth, such as aspect, slope, and substrate. Tree species produce ring series with characteristic properties, and this too would be taken into account in designing a sampling program.

Differing properties of tree rings reflect different climate signals, according to the growth situation. Maximum latewood density of conifer tree rings in regions with cool, moist summers is usually a better proxy for summer temperature than is ring width from the same trees, for example. In regions of Mediterranean climate, ring width may be the best available proxy for growing season soil moisture, or for winter half-year precipitation, which is possibly the main determinant of early summer growth. These considerations concerning the location and design of tree-ring sampling are analogous to those that apply in choosing the best place to drill a lake or a glacier.

This approach to sample design is almost universally applied ‘a priori’ to the sampling of tree rings. Once the samples and data exist, the strength of the common signal within the tree-ring dataset from an individual site is analyzed by using information on the number of samples and the correlations between them (within the tree-ring data, not with a climate variable), and a decision is made whether or not to use the existing data for dendroclimatology, to reject it on the basis of a weak common signal, or to seek more samples to strengthen the signal (Wigley et al. 1984).