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Tree-rings, a key ecological indicator of environment and climate change

Zhihua Zhang*

College of Global Change and Earth System Science, Beijing Normal University, Xinjiekouwai Street, No. 19, Beijing 100875, China

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ABSTRACT

Due to wide spatial distribution, high annual resolution, calendar-exact dating, and high climate sensitivity, tree-rings play an important role in reconstructing past environment and climate change over the past millennium at regional, hemispheric or even global scales, so tree-rings can help us to better understand climate behaviour and its mechanisms in the past and then predict variation trends for the future. In this paper, we will review latest advances in tree-ring-based climate reconstructions in China and their applications in modelling past local/regional climate change, capturing historical climatic extreme events, as well as analyzing their link to large-scale climate patterns.

1. Introduction

As a fundamental indicator for climate, ecosystem and environment, tree-rings have been widely applied in studies of environment and climate change. In China, since most reliable meteorological records are only about 60 years long and limited historical documents do not adequately examine past climate changes, tree-rings become one of the most important palaeoenvironmental and palaeoclimatic proxies in China. Not only living trees, but also dead or sub-fossil trees can be used to develop tree-ring chronologies. Since tree radial growth is always subject to complex climatic and environmental influences, tree-ring chronologies can contain key information about climate and environment. The research on tree-rings has been conducted in China since the 1930s, but until 1980s, due to increasing tree-ring sampling at each site and applying advanced statistical methods to analyze tree-rings, tree-rings become an important tool in the study of past climate and environment of China (Wu et al., 1987). The long tree-ring chronologies can be used to extend limited meteorological records, analyze interannual to multidecadal climate fluctuations, and evaluate the impacts of various climatic factors over time. Moreover, tree-ring-based reconstructions of climate and environment have significant advantages over other proxies, e.g. wide spatial distribution, high annual resolution, calendar-exact dating, and high climate sensitivity (Frank et al., 2010). All over the world, tree-rings can give long-term climate changes that occurred as far as the past approximately 2000 years, but there are only a few tree chronologies that extend back more than 1000 years. The world's longest continuous tree-ring chronology extends over more than 7000 years (Frank et al., 2010). In China, tree-ring chronologies have been already used to reconstruct historical temperature/precipitation for at least the last 1000 years on the Tibetan Plateau and for the last several hundred years in central China. For examples, Shao et al. (2010) developed a 3585-year tree-ring width chronology from the northeastern Qinghai-Tibetan Plateau. Yang et al. (2014) developed a tree-ring width chronology spanning 4500-year by using subfossil, archaeological, and living-tree juniper samples from the northeastern Tibetan Plateau.

Increased spatial distribution of tree-ring data in China provides nice opportunities to study past pan-Asian climate variability and its link to large-scale climate patterns such as the El Niño-Southern Oscillation (ENSO), the Asian monsoon variability and the North Atlantic Oscillation (NAO) (e.g. Hua et al., 2014; Chen et al., 2006, 2013; Qin et al., 2011; Lu et al., 2013; Peng and Liu, 2013; Wu et al., 2013; Cai and Liu, 2013; Sun and Liu, 2013). In this paper, we will review latest advances in Chinese tree-ring research. Since tree-ring data have been shown to have strong, linear correlations with climate variables, with the help of tree-ring width, density, or isotope data, Chinese researchers use tree-ring chronologies to reconstruct temperature, precipitation, runoff, drought, cloud cover and so on that extend back several centuries to millennia. In Section 2, we will introduce how to obtain tree-ring samples during field works. In Section 3, we will introduce main statistical methods used for analyzing tree-ring data, reconstructing various climatic factors from tree-ring data and discovering their links to large-scale climate patterns. In Sections 4–8, we will review lat-

* Tel.: +8613260299923.
E-mail address: zhangzh@bnu.edu.cn

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est tree-ring-based climate reconstructions in different regions of China and their applications in modelling past local/regional climate change, capturing historical climatic extreme events, as well as analyzing their link to large-scale climate patterns. In Section 9, we give some discussions and conclusion.

2. Field works and materials

In order to obtain tree-ring data, a lot of field work is needed to be done (Fritts, 1976; Breitenmoser et al., 2012; McCarroll and Loader, 2004; Holmes et al., 2009; Sheppard et al., 2004; Braker, 2002; Hughes, 2002; Liang et al., 2003; Palmer, 1965; Esper et al., 2002, 2003). First, we need to decide the location of sample sites carefully. In order to maximize the temperature signal, sample sites should be chosen in upper-elevation tree-line locations and cold mountain valley environments. But for precipitation, sample sites should be chosen in a steep, rocky, south facing slope. Next, we need to choose suitable trees for sampling in each sample site. Since most reliable meteorological records in China are about 60 years long, trees selected for sampling must have the age of above 60 years. After removing a cylinder of wood roughly 5 mm in diameter along the radius of a tree, core samples are collected at breast height (about 1.3 m above the ground) from trees by using an increment borer. Finally, tree-ring core samples are brought back to the laboratory and treated according the following standard process:

Step 1 (Tree-ring width measurement). Before further analysis, core samples are needed to be air dried and polished with successively finer grades of sandpaper until annual rings could be distinguished easily. In general, some samples may be discarded due to irregular rings or missing rings. After that, tee-ring widths are measured with a precision of 0.01 mm or 0.001 mm by using a LINTAB system or similar system.

Step 2 (Cross-dating). The process of tree-ring cross-dating is to match patterns of wide and narrow rings over time to ensure the exact dating of each annual ring to its calendar year of growth, If a similar pattern of wide and narrow rings in living trees could be found on the samples taken from old dead trees, then the samples would be considered cross-dated, so cross-dating can extend tree-ring chronologies based only on living trees much further back in time. It is well known that some growth rings are often missing in trees because of critical hydrological conditions. Cross-dating permits the reliable identification of “false rings” and missing or partially missing rings. Cores with any ambiguities of cross-dating are often excluded from further analysis. Finally, the cross-dated tree-ring series can be quality checked using the COFECHA software

Step 3 (Tree-ring width chronologies). In order to combine samples with differences in growth rates and eliminate nonclimatic, age-related growth trends, with the help of the negative exponential function/linear regression function and the spline function, the untreated tree-ring width data are detrended and/or standardized by using Programme ARSTAN. Finally, we obtain three kinds of tree-ring width chronologies: the standard chronology, the residual chronology and the autoregression standard chronology

Except for tree-ring widths, tree-ring isotopic data are also a powerful tool for reconstructing climatic conditions with perfect annual resolution. An important advantage of tree-ring isotopic data is that they can be used for climate reconstructions without detrending. In order to obtain isotopic information, each ring of tree core samples are cut using a scalpel blade under a binocular microscope and cellulose are extracted, then tree δ^{18}O and δ^{13}C values of cellulose are measured by using a stable isotope ratio mass spectrometer (e.g. Thermal Chemical Elemental Analyzer). Since the principal source of water for tree growth is precipitation and its oxygen isotopic ratio (δ^{18}O) is related to temperature and precipitation amount, so the tree-ring cellulose δ^{18}O may record past changes in temperature, precipitation, relative humidity, or cloud cover. For tree δ^{13}C, due to δ^{13}C depletion in atmospheric CO_2 by fossil fuel emissions, δ^{13}C tree-ring records generally show a prominent downward trend of 1–2% starting around 1850 AD. It must be removed prior to any climatic reconstruction. In addition, wood densities are also often used in climate reconstruction.

3. Statistical analysis for tree-ring chronologies

After tree-ring chronologies are obtained in tree-ring labs, various advanced statistical methods (von Storch and Zwiers, 1999; Zhang and Moore (2011, 2012); Zhang et al., 2014a,b; Marengo et al., 2013; Pascual et al., 2013) can be used to analyze these chronologies, develop tree-ring-based climate reconstruction and examine the link between local/regional climate and global climate.

Correlation analysis can be used to examine the relationships between tree-ring parameters and climate factors. Main tree-ring parameters include tree-ring width, density, and isotopic data. Main climate factors include temperature, precipitation, runoff, drought, cloud cover and so on. In tree-ring research, researchers always first compute the correlation coefficient between each tree-ring parameter and each climatic factor, then researchers find a tree-ring parameter and a climatic factor whose correlation coefficient is largest. Finally, researchers will choose this tree-ring parameter to reconstruct this climatic factor that extends back several centuries to millennia. In addition, correlation analysis is also used in examining the link between this reconstructed climatic series and global climate.

Linear regression and *curvilinear regression* are main tools to develop a tree-ring-based climate reconstruction. Since tree-ring data have been shown to have strong, linear correlations with climate factors, with the help of tree-ring width, density, or isotope data, researchers can use tree-ring chronologies to reconstruct temperature, precipitation, runoff, drought, cloud cover and so on that extend back several centuries to millennia. In detail, if researchers find a significant relationship between a tree-ring parameter and a climatic factor (e.g. temperature) in correlation analysis, with the help of linear regression, a climate reconstruction is estimated using this climatic factor as the dependent variable and the tree-ring parameter as the independent variable. Recently, in order to obtain better climate reconstruction, many researchers begin to use curvilinear regression instead of linear regression.

Principal component analysis can detect spatial pattern of tree-ring-based climate reconstructions from different regions of China and discover the dominant modes of variability.

Power Spectral Analysis, Multi-taper Method, and Wavelet Analysis can be used to analyze interannual to multi-decadal variability contained in the reconstructed climatic series. Researchers often choose red noise as climatic background noise and combine power spectral analysis/multi-taper method/wavelet analysis with *statistical significance tests*. By this way, researchers can extract significant cycles in the tree-ring-based climate reconstructions and large-scale climate patterns such as the El Niño-Southern Oscillation (ENSO), the Asian monsoon variability and the North Atlantic Oscillation (NAO). If there are some common significant cycles between the reconstructed climatic series and some large-scale climate pattern, it may suggest a link between local climate and this large-scale climate pattern.

4. Case studies in Northeast China

Northeast China consists of Liaoning province, Jilin province, Heilongjiang province and eastern Inner Mongolia autonomous region. Many parts of Northeast China are covered with undisturbed old-growth forest, so many tree-ring researches are carried out in this region. In order to obtain better climate reconstruction,