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Process-based modeling of tree-ring formation and its relationships with climate on the Tibetan Plateau

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ABSTRACT

Response of climate warming on tree-ring formation has attracted much attention during recent years. However, most studies are based on statistical analysis, lacking understanding of tree-physiological processes, especially in the mountainous regions of the Tibetan Plateau (TP). Herein, we firstly use an updated new version of the tree-ring process-based Vaganov-Shashkin model (VS-oscilloscope) to simulate tree-ring formation and its relationships with climate factors during the past six decades. Our analyses covered 341 sampled trees growing within elevations ranging from 2750 to 4575 m a.s.l. at five sampling sites across the TP. Simulated tree-ring width series are significantly ($p < 0.01$) correlated with actual tree-ring width chronologies during their common interval periods. Starting dates of tree-ring formation are determined by temperature at all five sampling sites. After the initiation of tree stem cambial activity, soil moisture content has a significant effect on tree radial growth. Ending dates of cambial activity are driven by temperature over the whole study region. Simulated results indicate differences between wide and narrow tree-rings are mostly induced by soil moisture content, especially during the first half of the growing season, when effects from temperature variations are minor. Interestingly, we detected significantly ($p < 0.001$) increased relative growth rates due to higher soil moisture content after the year 1985 at the five sampling sites. However, the variability of mean relative growth rates due to temperature is negligible before and after that. Based on the successful application of VS-oscilloscope modeling on the high-elevation tree stands on the TP, our study provides a new perspective on tree radial growth process and their varying relationships to climate factors during the past six decades.

1. Introduction

Dendrochronology as a discipline has been developed thoroughly during the past decades. Tree-ring series have been frequently used to derive various climate parameters for hundreds to thousands of years prior to existing instrumental weather records at regional to hemispheric scales (Bunn et al., 2013; Touchan et al., 2014; Yang et al., 2014; Arsalani et al., 2015; DeRose et al., 2015; Touchan et al., 2016). Dendroclimatology has in this way contributed to a better understanding of climate variability on different spatiotemporal scales. Traditionally, most studies are based on the assumption that the relationship between tree-ring series and the reconstructed climate variable is linear and stationary (Fritts, 1976). However, during recent decades, some studies have challenged this assumption by reporting nonlinear or non-stationary proxy-climate relationships (Lebourgeois et al., 2011; Álvarez et al., 2015; Galván et al., 2015; Saladyga and Maxwell, 2015; Suarez et al., 2015). Possible causes for shifting growth-climate relationships include drought-induced stress in formerly temperature-limited trees (Galván et al., 2015; Jiao et al., 2015), changes in the timing and length of the growing season (De Grandpré et al., 2011), local industrial emissions (Wilson and Elling, 2004), and global dimming (D'Arrigo et al., 2008; Stine and Huybers, 2014). For an adequate consideration of such limitations of traditional statistical analyses in dendroclimatological applications, process-based tree physiological models (Anchukaitis et al., 2006; Tolwinski-Ward et al., 2011; Touchan et al., 2012) provide a suitable

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way to explore potentially nonlinear or non-stationary relationships between tree-ring growth and climate factors.

Among the existing process-based models of tree-ring growth (Guiot et al., 2014), the Vaganov-Shashkin (V-S) model is perhaps the most suitable one for studying the nature of tree-ring growth and its relationships with climate factors in regions where daily climate datasets are available (Shashkin and Vaganov, 1993; Vaganov et al., 2006, 2011). The V-S model was developed to quantify tree-ring formation as a function of climate and environmental variables, by using a limited number of equations relating daily temperature, precipitation, and sunlight to the kinetics of secondary xylem development (Vaganov, 1996; Vaganov et al., 2011). The model consists of two primary modules, or blocks (Vaganov et al., 2006). The Growth (or Environmental) Block calculates a daily 'external growth rate' based on climatic variability, including temperature, soil moisture and solar irradiance. The Cambial Block uses this 'external growth rate' to simulate the rate and timing of growth and division of cells in the cambium. The advantages of the V-S model mainly rely on its ability to evaluate the importance of hypothesized ecological factors that might be mostly responsible for actual tree-ring growth. Besides, it can also be used to determine whether observed variability in climate-tree growth relationships arise as a function of climate itself, as a stochastic feature without a determinant cause, or through possibly unobserved influences by biological or ecological changes not related to climate (Vaganov et al., 2006). Hence, it has been effectively verified to simulate tree-ring growth processes and their relationships with climate factors in the United States (Anchukaitis et al., 2006; Evans et al., 2006), in southern and central Siberia (Shishov et al., 2016), in the Mediterranean region (Touchan et al., 2012), and in China (Zhang et al., 2011; Zhang et al., 2015).

However, the V-S model requires a considerable number of parameters that should be re-estimated for each forest stand and therefore limit to some extent its spatiotemporal usage. Recently, a new visual approach of the process-based tree-ring model parameterization, the so-called 'VS-oscilloscope' (Shishov et al., 2016) was successfully developed. The VS-oscilloscope allows simulation of tree-ring growth by selection of parameter values in an interactive mode. The Lazarus Code of the VS-Oscilloscope and distributive package can be downloaded from the http://vs-genn.ru/downloads/

In view of the advantages of the updated model, herein we will for the first time apply it on high-elevation tree stands growing on the Tibetan Plateau, 1) to evaluate whether the parameterization of the V-S model is suitable to the study region; 2) to determine the most important climate factors for tree-ring growth during the past six decades (1953–2010); and 3) to investigate the stationarity of limiting growth factors in recent decades on a daily time scale.

2. Material and methods

2.1. Study sites and tree-ring width chronology

The study area is located on the Tibetan Plateau (TP, Fig. 1), where climate is characterized by long and cold winters and short and mild summers (Fig. S1, Table S1). During the past six decades, the mean annual temperature varies from −2.88 °C to 7.67 °C at the five sampling sites according to the records of their nearest meteorological stations. The mean annual precipitation from January to December ranges from 87 mm to 480 mm, and thus local climate can be identified as arid to semi-arid. All used tree-ring width chronologies have already been published (Table S2) and are valuable for their use in paleoclimatic reconstructions: Qifeng (QF) (Yang et al., 2010), Sidalong (SDL) (Yang et al., 2010), Qumalai (QML) (He et al., 2014), Linzhou (LZ) (He et al., 2013) and Qamdo (QD) (Wang et al., 2014). To allow unbiased comparison, we calculated all five chronologies applying the same algorithms using the ARSTAN program (Cook, 1985). Before removing biological trends, a data adaptive power transformation was applied to reduce the potential heteroscedasticity commonly found in raw ring-width measurements (Cook and Peters, 1997). The removal of the biological age trend for the individual tree-ring width series was done by calculating differences between the raw data and an exponential growth trend curve. The detrended tree-ring series were averaged to a standard site chronology using a biweight robust estimate of the mean to minimize the influence of outliers (Cook and Kairiukstis, 1990). The produced standardized (STD) chronologies were used for further analysis. Detailed information about the resulting tree-ring series is provided in Table S2.

2.2. VS-oscilloscope

The mechanism of the V-S model is based on the assumption that climatic influences are associated directly, but nonlinearly, with tree-ring growth through controls on the rates and duration of cellular processes (cell division, enlargement and maturation) in the developing wood (Vaganov et al., 2006; Vaganov et al., 2011). The simulated tree-ring growth is determined by comparing the daily temperature and soil moisture budget to a "bell-shaped" growth function, and using the most limiting factor (Fritts, 1976) to scale the component processes of tree-ring formation. The integral tree-ring growth rate Gr(t) is estimated based on the following equation:

$$\mathrm{Gr}(t) = \mathrm{GrE}(t) \times \min\{\mathrm{GrT}(t),\ \mathrm{GrW}(t)\}$$

where GrE(t), GrT(t) and GrW(t) are the partial growth rates, calculated independently from solar irradiation, temperature, and water content in soil.

The VS-Oscilloscope is used to estimate the optimal V-S parameters, which guarantee the best fitting of the actual tree-ring chronology for the certain growth conditions (Shishov et al., 2016). It contains two window sheets: one is the "Open Data" sheet, where users can upload the files of initial parameter values, i.e., climatic data, tree-ring chronology, latitude value for the study site to estimate day length, and the final value of the year before the start of calculation; the other window is the "Model parameterization" sheet, which contains scrollbars for most parameters of the model, such as minimum temperature for tree stem radial growth, critical growth rate, etc. Values of the parameters can be adjusted manually in the Model Parameterization sheet by moving scroll-bars along a value scale. Other parameters not presented in the sheet can be changed in the file of parameters directly before running the program (Shishov et al., 2016).

For model calibration, daily precipitation and temperature data from the nearest meteorological stations to the tree-ring sites (Jiuquan-QF, Yeniugou-SDL, Qumalai-QML, Dangxiong-LZ, and Qamdo-QD) were used (Fig. 1, Table S1). The skill of the model was evaluated against their actual high-quality tree-ring width chronologies during their common interval periods (QF: 1953–2009; SDL: 1961–2008; QML: 1958–2010; LZ: 1964–2009; QD: 1955–2010). Note the first simulated year from meteorological station was excluded to reduce the influence of model initialization. Model outputs of mean relative growth rates due to temperature (GrT), soil moisture variability (GrW), solar irradiance (GrE), and the integral growth rate (Gr) for each year were used for further analysis. For direct comparison of the relative growth rates at the five sampling sites, all data were analysed for their common period 1961–2008 (LZ site begins at the year 1964) as well for two equal sub-periods of 1961–1984 and 1985–2008.