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Precipitation variations and possible forcing factors on the Northeastern Tibetan Plateau during the last millennium

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A B S T R A C T

Understanding precipitation variation, drought and flood history, and their associated forcing mechanisms are important to human society. In this study, five moisture-sensitive tree-ring width chronologies are used to represent variations in precipitation over the past millennium on the Northeastern Tibetan Plateau (NETP). We find a strong coherency between chronologies in the NETP, indicating a common response to regional climate during the last millennium. The first principal component of the five chronologies (PC1) correlates significantly with regional precipitation and can thus be used as an indicator of regional precipitation variations. Dry spells, even more severe than the 1920s drought, occurred during AD 1139–1152, 1294–1309, 1446–1503 and 1708–1726. Previous studies in this area using other proxies also identified these droughts. Multi-Taper spectral analysis demonstrates significant periodicities at 205 yr and 73 yr, plus a range of ~2 yr cycles, suggesting possible linkage with solar variation and the Pacific Decadal Oscillation (PDO). PC1 also shows coherent patterns with solar irradiance variation: the precipitation tends to reach low values during the well-known solar minimum.

Introduction

Global warming is expected to increase the frequency and intensity of droughts in the future (IPCC, 2007). Droughts are significant natural disasters that challenge the stability of human societies. The severe drought of the 1920s in northern China, for example, led to major economic and life losses (Liang et al., 2006). Prolonged, severe drought may not only cause damage to property and loss of life, but may also lead to social unrest, the transition of dynasties and even decline of civilization (e.g., Buckley et al., 2010; Cook et al., 2010). Making reliable predictions and optimal adaptation to drought variability requires detailed and reliable knowledge of hydroclimatic history and their possible forcing factors. However, few high-quality instrumental climate records extend back before 1900. In China, this limitation is even more severe: few of these kinds of records pre-date the 1950s. Instrumental records of this length are too short to resolve the full range of long-term natural climate variability. This limitation can be partly rectified through the use of proxies for climate that extend instrumental records several centuries prior to the beginning of recorded data. Tree-ring proxies are some of the best available methods for extending our knowledge of the hydroclimatic variability during the pre-instrumental period. This is especially true for the development of records with annual resolution spanning several hundreds to thousands of years.

The Tibetan Plateau, an area of about 2,500,000 km^2 and average elevation exceeding 4500 m, is the world's highest and largest plateau. It influences the Asian monsoon through its mechanical and thermal forcing (Wu et al., 2007). The Tibetan Plateau has also been considered as the "water tower" of Asia (Immerzeel et al., 2010). Climate change on the Tibetan Plateau may influence the water availability and food security in Asia. Located near the modern Asian summer monsoon limit, the Northeastern Tibetan Plateau (NETP) is particularly sensitive to climatic change (Henderson et al., 2010). Further, the harsh environments in the NETP make tree growth in this region sensitive to climate variability as well. It, therefore, offers the opportunity for long tree-ring records. For these reasons, the NETP has been regarded as a tree-ring study hot spot. Previous tree-ring studies have provided valuable insights on climate over the past millennium or even longer (e.g., Zhang et al., 2003; Shao et al., 2005; Liu et al., 2009; Gou et al., 2010; Zhang et al., 2011). However, there have been no tree-ring based reconstructions of regional precipitation for the NETP covering the last millennium to date. For this reason, we combine five moisture-sensitive tree-ring width chronologies archived in this area to extract the regional climate signals and discuss the regional climate mechanisms.

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Materials and methods

Study area

Our study area is located in the NETP. The main mountains in this region include the Qianlian Mountains, the Anyemaqen Mountains, and the mountains along the northeastern edge of the Qaidam Basin. The region is generally dry. NASA's Tropical Rainfall Measuring Mission data (TRMM) reveal that the northwestern part of the NETP was predominantly dry (<400 mm/yr) from 1998 to 2012, although the southeast part received more precipitation. Climate of the NETP is thought to be alternately controlled by the westerly and the Asian monsoon (Davis et al., 2005; Chen et al., 2008). As a result of the regional climate, vegetation of the study area is sparse with the dominant conifer species being Qinghai spruce (*Picea crassifolia* Kom.) and Qilian juniper (*Juniperus przewalskii* Kom.). Qinghai spruce are primarily found on moist and fertile shaded slopes at about 1600–3800 m in altitude (Fu et al., 1999a). Qilian juniper are primarily found on dry and infertile sunny slopes at about 2600–4300 m (Fu et al., 1999b). Likely because of the harsh conditions (Schulman, 1954), the junipers are long-lived and sensitive to climate. They have previously been used to reconstruct the climate of the past several thousand years (e.g., Shao et al., 2010). Shrubs and grasses, such as *Dasiphora fruticosa*, *Caragana jubata*, *Stipa przewalskii*, *Potentilla chinensis*, *Polygonum viviparum*, *Leontopodium leontopodioides*, and *Carex lansuensis*, are scattered in the understory of the forests.

Tree-ring data

We use five drought-sensitive, Qilian juniper tree-ring chronologies that have been previously used to reconstruct precipitation or streamflow variation in the NETP during the past millennium (Zhang et al., 2003; Shao et al., 2005; Gou et al., 2010; Zhang et al., 2011). All sites are located near the modern Asian summer monsoon limit (Chen et al., 2008) (Fig. 1, Table 1). Gou et al. (2007) reconstructed the stream flow of the upper reaches of the Yellow River during the past 593 yr based on tree-ring chronologies originating from the Anyemaqen Mountains. This reconstruction was extended back to AD 771 (MQB) (Gou et al., 2010). A reconstruction of precipitation in the middle Qilian Mountains over the past 1232 yr was made available using the tree-ring data at Haiyagou (HYG) (Zhang et al., 2011). The tree-ring records of Dulan (DL) (Zhang et al., 2003), Wulan (WL) (Shao et al., 2005) and Delingha (DLH) (Shao et al., 2005), which had been used to represent or reconstruct local precipitation variations, were obtained from the Tree Ring Database of China (http://ctrdb.ibcas.ac.cn/, last visited Dec. 10, 2009).

The tree-ring records of Dulan (Zhang et al., 2003), Wulan (Shao et al., 2005) and Delingha (Shao et al., 2005) were detrended using the conservative curves, such as the negative exponential function or linear regression function, during the chronology development. The tree-ring data from Anemaqin Mountain (Gou et al., 2010) and Haiyagou (Zhang et al., 2011) were mostly detrended with the conservative curve-fitting method, and with a rigid cubic-spline curve in a few cases. All the tree-ring indices were calculated as ratios between the raw measurements and fitted values. Detrended tree-ring indices were averaged to generate chronologies based on robust mean methodology (Cook and Kairiukstis, 1990).

Data analysis methods

Tree-ring chronologies were subjected to principal component analysis (PCA) to identify the common signal of climate variations in the NETP. The Multi-Taper Method (MTM: Mann and Lees, 1996) was used to estimate the periods in the precipitation record. The MTM with resolution = 2 and tapers = 3 were used. Confidence intervals were determined relative to a red-noise background. For comparison, the Pacific Decadal Oscillation (PDO) (MacDonald and Case, 2005) and the solar irradiance data (Bard et al., 2000; Lean, 2000) (http://www.ncdc.noaa.gov/paleo/, last visited Sep. 18, 2013) were also used. Because of substantial autocorrelation inherent in smoothed time series, statistical significance of the correlation was tested with the random phases method (Ebisuzaki, 1997), adopting 10,000 replications. This method is similar to bootstrap testing, but the random time series created by this method tends to preserve the autocorrelation of the original data, while the bootstrap tends to preserve the distribution.

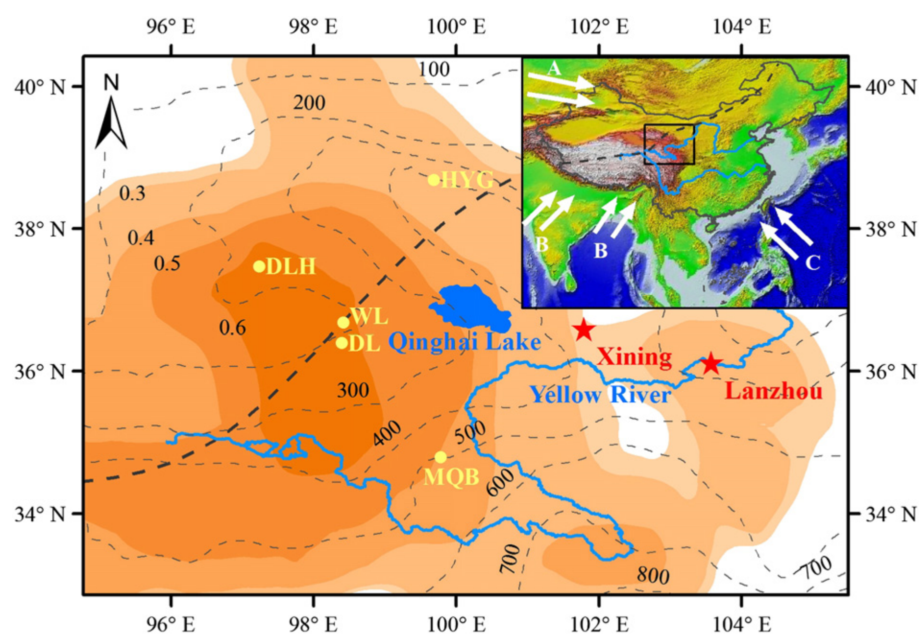

Figure 1. Tree-ring sampling sites and the contour of correlation coefficient between the PC1 of the five tree-ring width chronologies and the gridded May to June precipitation data of CRU TS 3.0 (Mitchell and Jones, 2005, http://badc.nerc.ac.uk/data/cru/) from AD 1950 to 2000. HYG, DLH, WL, DL and MQB denote tree-ring chronologies from Haiyagou (Zhang et al., 2011), Delingha (Shao et al., 2005), Wulan (Shao et al., 2005), Dulan (Zhang et al., 2003) and Anemaqin mountain (Gou et al., 2010), respectively. The thin dashed lines represent annual precipitation measured by the Tropical Rainfall Measuring Mission (TRMM) satellite (1998–2012 mean; contours are every 100 mm/yr). Large-scale air mass controls are also indicated, including the westerly (A), Indian monsoon (B), and East Asian summer monsoon (C). The modern Asian summer monsoon limit is shown by the dashed thick line (after Chen et al., 2008).