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Separating temperature from precipitation signals encoded in tree-ring widths over the past millennium on the northeastern Tibetan Plateau, China

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ABSTRACT

Tree-ring width chronologies from the upper timberline are an important material to reconstruct past temperature variability on the northeastern Tibetan Plateau (NTP). However, precipitation signals are often encoded in the upper timberline chronologies, which complicate the temperature reconstructions and should be removed properly. Here, we propose to use the chronologies from the middle to lower forest zones to remove the precipitation signals encoded in the upper timberline chronologies on the NTP, as tree growth at the two elevation zones records similar precipitation signals but has different temperature responses. We compiled a dataset of 13 Qilian juniper (*Sabina przewalskii* Kom.) tree-ring width chronologies, and employed two independent methods to develop millennial (AD 1000–2000) temperature reconstructions on the NTP. The two reconstructions are very consistent with each other over the past millennium, with a correlation of 0.97, and account for more than 50% of the observed temperature variance during 1958–2000. Both reconstructions contain little precipitation signals, suggesting that we have extracted purer temperature information than before. Our reconstructions show similar warm-cold patterns to the temperature records from the surrounding areas, indicating that they are capable of representing large-scale temperature variability during the past millennium. Comparison of our reconstructions with five millennial Northern Hemisphere (NH) temperature series indicates that temperature changes on the NTP are generally distinct from the NH temperature patterns except for the long-term trend during the past millennium, suggesting specific characteristics of regional temperature variability. The distinct variations may be related to the influence of local precipitation, which generally has inverse variations with the temperature on multi-decadal timescales. Our results also show that temperature variability on the NTP has a strong linkage with the strength of the Indian summer monsoon (ISM), with the warm and cool phases of NTP temperature associated with strong and weak ISM, respectively.

1. Introduction

The Tibetan Plateau (TP), with an area of about 2,500,000 km^2 and an average elevation exceeding 4000 m above sea level (a.s.l.), is the world's highest and largest plateau. Many studies have shown that the TP exerts profound thermal and dynamical influences on global atmospheric circulation and affects regional and global climate (Feng and Hu, 2008; Yanai et al., 1992). Temperature is one of the most important factors affecting the thermal condition. Therefore, it is important to investigate the characteristics of temperature variability on the TP and its impacts on regional and global climate.

Direct instrumental records offer valuable insights on current temperature variability. However, a complete understanding of temperature variability cannot be achieved without a long-term perspective, particularly when considering defining its current

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status and identifying possible trends and periodicities (Li et al., 2007). Tree rings are of particular value in this regard because they provide past climate conditions with precise dating and annual resolution (Fritts, 1976).

In recent two decades, many studies have demonstrated that tree-ring width chronologies from the upper timberline are an important proxy for reconstructing temperature variability of the past centuries to millennia over the TP (Fan et al., 2010; Li et al., 2012; Liang et al., 2008; Liu et al., 2005, 2009b; Shao and Fan, 1999; Wang et al., 2014; Zhang et al., 2014; Zhu et al., 2008). However, many of these chronologies also recorded strong precipitation signals, especially on the northeastern TP (NTP) (Liu et al., 2005, 2006, 2009b), where the arid climate often causes tree growth to be limited by moisture availability (Gou et al., 2015a, 2015b; Li et al., 2008; Liu et al., 2009a; Shao et al., 2005; Sheppard et al., 2004; Yang et al., 2014; Zhang et al., 2003). This suggests that there may be large uncertainties in the tree-ring width based temperature reconstructions on the NTP. Obviously, we should separate temperature from precipitation signals encoded in tree rings in order to get more reliable temperature reconstructions on the NTP.

To our knowledge, there are few valid methods to separate temperature from precipitation signals encoded in tree-ring width chronologies. Recently, the authors proposed to use the chronologies from the middle to lower forest zones to remove the precipitation signals encoded in the chronologies from the upper timberline in the Tien Shan Mountains, northwest China, because tree growth at the two elevation zones records similar precipitation signals but has different temperature responses (Liu et al., 2015b). Such climate–tree growth relationship patterns are also widely found on the NTP (Gou et al., 2015a, 2015b; Liu et al., 2005, 2006, 2009a, 2009b; Shao et al., 2005; Sheppard et al., 2004; Yang et al., 2014; Zhang et al., 2003), suggesting that it would be possible to use a similar method to extract purer temperature information from tree-ring width chronologies on the NTP. Therefore, a dataset of 13 millennial Qilian juniper (*Juniperus przewalskii* Kom.) ring-width chronologies from the low forest limit to the upper timberline over the NTP was collected to investigate such a possibility, and to produce new temperature reconstructions with precipitation signals removed.

2. Data and methods

2.1. Study area and tree-ring data

The 13 Qilian juniper ring-width chronologies (DLH1–5, TJ1, WL1–4, WLH, WDLH and DLHH) are all from the mountains on the eastern margin of the Qaidam Basin, Qinghai province (Fig. 1; Table 1). The eastern part of the Qaidam Basin, with altitudes varying from 2900 to 3000 m a.s.l., is characterized by a landscape of desert steppe. The annual mean temperature ranges from 2 °C to 4 °C and annual precipitation is about 150–200 mm, declining from east to west. Qilian juniper trees grow at the elevations of 3500 to 4000 m a.s.l. on the sunny and semi-sunny slopes of the surrounding mountains where the maximum precipitation zone is situated (Shao et al., 2005).

WLH, WDLH, and DLHH are located at the upper timberline and were developed by Zhu et al. (2008), Liu et al. (2009b; 2006), and this study, respectively. The other 10 chronologies are located at the middle and lower forest zones (Shao et al., 2005, 2006), and their raw measurement data are obtained from the International Tree-Ring Data Bank.

All the chronologies were developed using the ARSTAN program (Cook, 1985). In most cases, we used negative exponential or linear regression models with negative coefficient to fit the age trend of each tree-ring series. A few series that did not fit the negative exponential or linear models were detrended by the cubic spline models. The detrended series were then averaged into site chronologies using a bi-weight robust mean method (Cook, 1985). Because the sample size generally declines in the early portion of the tree-ring chronology, we used the expressed population signal (EPS) (Wigley et al., 1984) with a threshold value of 0.85 to determine the reliable period of the chronology. As shown in Table 1, the reliable periods of most chronologies exceed AD 1000. The variations of all the chronologies since AD 1000 are shown in Fig. 2.

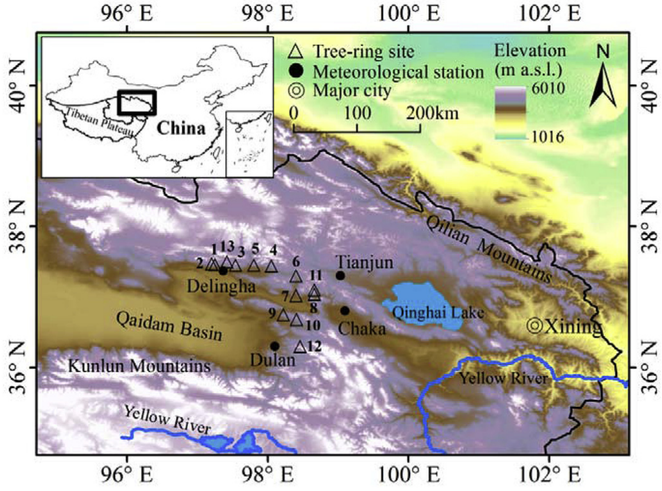

Fig. 1. Locations of tree-ring sites (the number from 1 to 13 indicates sites of DLH1–5, TJ1, WL1–4, WLH, WDLH and DLHH, respectively.) and the nearby meteorological stations (Delingha, Tianjun, Chaka and Dulan).

It should be noted that the WLH and WDLH chronologies used in this paper were directly provided by the authors, because we did not obtain the raw measurement data. In addition, the elevation of DLH3 site is closer to those of the 3 chronologies from the upper timberline, yet its chronology is more consistent with the low-elevation chronologies. Therefore, it was categorized into the low-elevation chronologies in the following study.

2.2. Climate data and statistical analysis

Monthly temperature and precipitation records were obtained from four nearby meteorological stations, including Delingha (37°22′N, 97°22′E, 2982 m a.s.l., AD, 1956–2000), Tianjun (37°18′N, 99°02′E, 3418 m a.s.l., AD, 1958–2000), Chaka (36°47′N, 99°05′E, 3088 m a.s.l., AD, 1956–2000) and Dulan (38°18′N, 98°06′E, 3191 m a.s.l., AD, 1954–2000) (Fig. 1). As most of the sampling sites are located in the middle of the four meteorological stations, the mean values of each climate variable from the four stations were calculated to better represent climate conditions in the study area.

The relationships between tree-ring chronologies and climatic records were analyzed using program SPSS. Based on the results of the climate-tree growth relationship analyses, two types of linear regression models were developed for the temperature reconstructions. The reliability of the reconstruction models was tested by the leave-one-out procedure (Mosteller and Tukey, 1977). A number of statistics were employed to evaluate model ability, including Pearson correlation (r), explained variance (R^2), explained variance after the degree of freedom is adjusted ($R^2_{aj.}$), sign test (S1, S2), product mean test (t), and reduction of error (RE). Value of RE greater than zero indicates rigorous model skill (Cook et al., 1999).

In order to demonstrate that both the observed and reconstructed temperatures reflect large-scale temperature variability, we correlated the data with the monthly gridded temperature