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Reconstruction of biological drought conditions during the past 2847 years in an alpine environment of the northeastern Tibetan Plateau, China, and possible linkages to solar forcing

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ABSTRACT

In this study we reconstructed the moisture condition of the eastern Qaidam Basin of the northeastern Tibetan Plateau based on a 3585-year tree ring chronology. The growth environment of Qilian juniper (*Sabina przewalskii* Kom.) on the mountains in the eastern Qaidam Basin was first determined by comparing precipitation and temperature estimates from two spatial datasets (PRISM and World Climate). Moisture balance was calculated as the sum of simulated moisture deficit (negative) and surplus using a modified Thornthwaite water balance model, and used as a proxy of biological drought conditions. Using data during 1956–2005, we established the transfer function to reconstruct a 2847-year series of January–June moisture balance (843 BCE–2004 CE). With an adjusted R^2 value of 0.654 of the transfer function and strong performance in validation, the reconstructed January–June moisture balance can be considered an excellent indicator of biological drought conditions for the study region. The reconstructed series showed strong correlations with reconstructed PDSI in the monsoon Asian region, representing a region of 10° latitudes by 20° longitudes. Using the reconstructed series, we identified centennial-scale dry periods since 843 BCE: 381–277 BCE, 425–520 CE, 1108–1212 CE, 1428–1516 CE, and 1634–1743 CE. Additionally it had statistically significant negative correlations with a monsoon intensity proxy based on oxygen stable isotope from southwestern China (Dongge Cave). Further analyses identified significant relationships with solar activity, especially during the last 700 years. We confirmed the ~200-year cyclic pattern in the reconstructed moisture balance series, which matched the known 210-year de Vries solar cycle and peaked during the Little Ice Age. However, the cyclic patterns of the reconstructed moisture balance series and solar activity were decoupled for the period prior to approx. 1300 CE.

1. Introduction

Studies of megadroughts in the past have attracted much attention in recent years (e.g., Cook et al., 2010a, 2010b; Routson et al., 2011; Sinha et al., 2011; Stahle et al., 2007). Assessments on the severity and frequency of occurrence of such events require long records of climatic conditions as the context, especially when variation patterns on the multi-decadal and centennial time-scales are investigated. Among the most widely used proxies of past climate, tree ring data provide information of various aspects of climate at the annual resolution (Fritts, 1976; Hughes, 2011) and millennium-length records have been found in the northeastern Tibetan Plateau (Shao et al., 2005; Sheppard et al., 2004; Zhang et al., 2003; Yang et al., 2014). The Tibetan Plateau is a region of great significance in regards of climate change. On the one hand, its mechanical and thermal dynamic effects on atmospheric circulation have far-reaching influences on the Asian monsoons (Wu et al., 2007; Yanai and Li, 1994; Yanai et al., 1992; Yeh and Gao, 1979). On the other hand, the Plateau has been regarded as a region highly sensitive to climatic change and is experiencing or will experience significant environmental changes associated with the recent warming, from atmospheric and hydrological processes (e.g., Liu and Chen, 2000; Liu et al., 2006; Wang et al., 2008; Zhao et al., 2004) to vegetation cover (e.g., Wang et al., 2011; Zhao et al., 2011) and cryosphere (Cheng and Wu, 2007; Li et al., 2008; Yao et al., 2007).

The conventional approach of using tree ring data to reconstruction of past climate is to select sampling sites with consideration of the target climatic variable for reconstruction, and then to use the instrumental data from near-by weather stations to build the transfer functions

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during the calibration period (Fritts, 1976). In some cases, however, the climatic conditions at the sampling sites can be quite different from those at the weather stations. For example, in semi-arid regions, sampling sites are often found on mountain slopes with elevations higher than the near-by weather stations and tend to have much wetter and cooler conditions than the weather stations located on the valley bottoms or foothills. Such differences in micro-environments often lead to different climatic elements to act as the limiting factors of tree growth (Fritts, 1976). When temporal variation patterns are concerned, strong associations between the tree ring data and observed climatic conditions at the near-by weather stations may indicate commonalities in regional climatic conditions, even though the exact growth conditions at the tree ring sampling sites may be quite different from the environments represented by the weather stations.

Of the moisture sensitive Qilian juniper (*S. przewalskii* Kom.) ring-width chronologies found in the eastern Qaidam Basin of the northeastern Tibetan Plateau, a common feature in the relationships between tree growth and climate variables is a strong positive correlation with precipitation in the late spring and early summer (esp. May and/or June) in conjunction with a negative correlation with temperature for the same time period (e.g., Shao et al., 2010; Shao et al., 2005; Sheppard et al., 2004; Yin et al., 2008; Zhang et al., 2003). This has also been discovered for a variety of coniferous species in other areas of the northeastern and eastern Tibetan Plateau, such as Qilian Mountains (Zhang et al., 2011, in May–June, approx. 38.81–39.04°N, 99.96–100.81°E) to the north, and Yushu (Qin et al., 2003; Shi et al., 2010), Anyemaqen Mountains (Peng et al., 2007), Changdu (Zhu et al., 2011), and central Hengduan Mountains (Fan et al., 2009) south of the eastern Qaidam Basin. Since the temperature during the early growing season would rarely reach the harmful levels for physiological processes at the sampling sites with elevations typically higher than 3000 m above sea level (a.s.l.) in these areas, strong negative correlations between tree growth and temperature indicate the effects of enhanced water-use demand under relatively warm conditions during the early growing season. This phenomenon should be particularly prominent for trees growing on steep slopes with shallow and well-drained soils and with exposure to strong wind (Fritts, 1976), which are typical of the alpine environments in the semi-arid northeastern Tibetan Plateau. In other words, early growing-season moisture condition can be considered as the ultimate factor regulating tree growth in this region. In an earlier study (Yin et al., 2008), it was found that the simulated moisture conditions in the eastern Qaidam Basin (Delingha) using a water balance model were strongly correlated with the radial growth of Qilian juniper, outperforming similar analyses using precipitation or Palmer's Drought Severity Index (PDSI, Palmer, 1965) data. However, whether the simulated moisture variables (e.g., soil moisture, and moisture deficit and surplus) represented the conditions at the weather station on the foothills or those at the tree ring sampling sites was a question unanswered.

Without in situ observational data, it is difficult to quantify the growth environments and moisture conditions at the sampling sites. For the eastern Qaidam Basin, the climatic conditions recorded at the weather stations, with mean annual total precipitation close to 200 mm (e.g., 177 mm/year for Delingha and 203 mm/year in Dulan for the period 1971–2000), are characteristic of a semi-arid region. Such climatic condition is favorable for the desert and steppe vegetation (Woodward et al., 2004) and cannot support a forest vegetation in the foothills areas of the eastern Qaidam Basin (Zheng, 1996). For the general region of the northeastern Tibetan Plateau, Wu (1990) showed that the maximum precipitation occurred at the station Jiuzhi (33° 26′ N, 101° 29′E, 3629 m a.s.l.), compared to 4 other stations with elevations ranging from 3414 m (Waisi at 34° 12′N, 101° 34′E) to 4211 m (Maqin at 34° 16′N, 99° 12′E). So elevation cannot be the only factor that determines precipitation distribution at the regional scale. At a smaller scale, however, the differences in elevation and long-term mean precipitation (1971–2000) between two nearby weather stations (Tianjun at 37° 18′ N, 99° 02′E vs. Chaka at 36° 47′N, 99° 05′E, approximately 60 km apart, Fig. 1) allowed us to obtain a precipitation gradient of 42 mm/100 m (345 mm/year at Tianjun at 3417 m vs. 208 mm/year at Chaka at 3088 m). Based on the elevation differences (~700 m or more) between the weather station in Delingha and our sampling sites, there should be a minimum increase of 294 mm in annual precipitation to 471 mm/year. In other words, precipitation at the sampling sites in Delingha might be

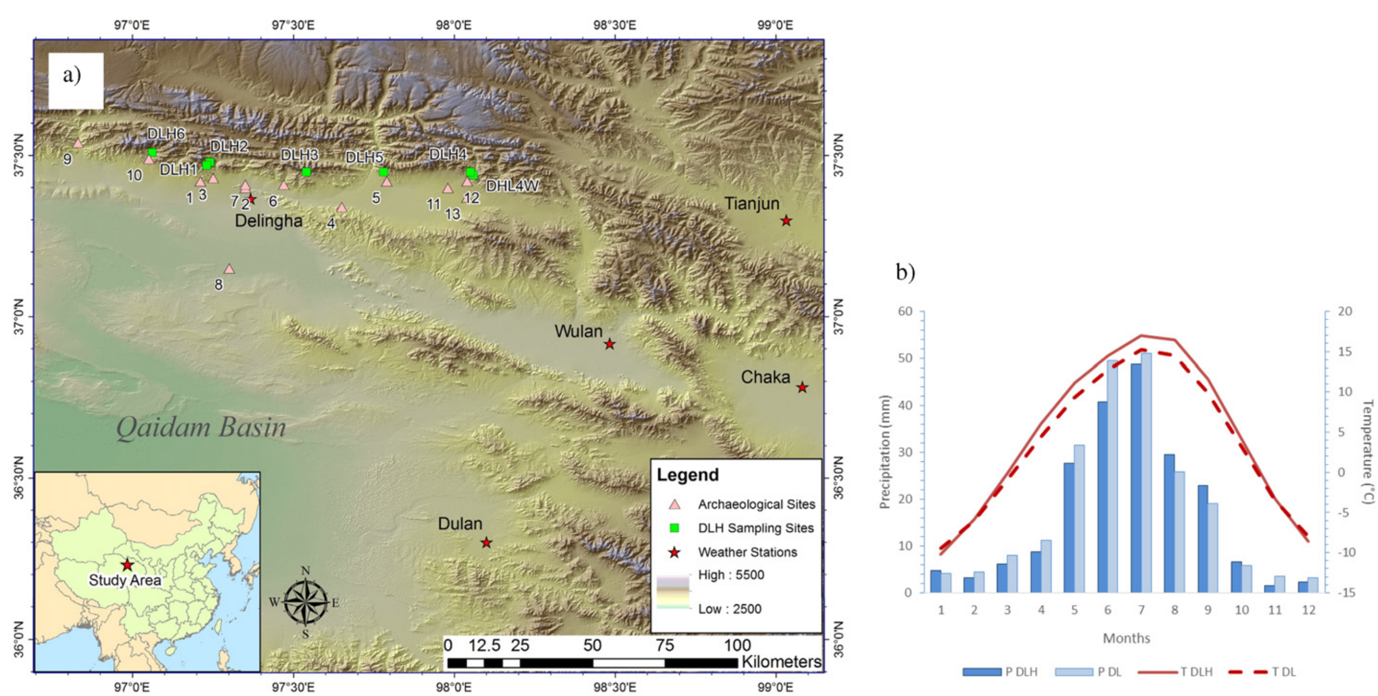

Fig. 1. Study area in the eastern Qaidam Basin, with tree ring sampling sites (DLH1–6 and DLH4W), weather stations and archaeological sites (no. 1–13) near the city of Delingha (a); and 1981–2010 mean temperature (T) and precipitation (P) for Delingha (DLH) and Dulan (DL) (b). Refer to Table 1 for additional information regarding the sampling and archaeological sites.