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Drought reconstruction in eastern Hulun Buir steppe, China and its linkages to the sea surface temperatures in the Pacific Ocean

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A B S T R A C T

A tree-ring width chronology covering the period 1780–2013 AD was developed from *Pinus sylvestris* var. *mongolica* for the eastern Hulun Buir steppe, a region located on the edge of the eastern Mongolian Plateau, China. Climate-growth response analysis revealed drought stress to be the primary limiting factor for tree growth. Therefore, the mean February–July standardized precipitation evapotranspiration index (SPEI) was reconstructed over the period 1819–2013, where the reconstruction could account for 32.8% of the variance in the instrumental record over the calibration period 1953–2011. Comparison with other tree-ring-based moisture sequences from nearby areas confirmed a high degree of confidence in our reconstruction. Severe drought intervals since the late 1970s in our study area consisted with the weakening East Asian summer monsoon, which modulating regional moisture conditions in semi-arid zone over northern China. Drought variations in the study area significantly correlated with sea surface temperatures (SSTs) in North Pacific Ocean, suggesting a possible connection of regional hydroclimatic variations to the Pacific Decadal Oscillation (PDO). The potential influence associated with El Niño-Southern Oscillation (ENSO) was primarily analyzed.

1. Introduction

An amplification of the hydrological cycle, including increased frequency and severity of droughts, is a likely consequence of the global warming (e.g. Cook et al., 2004; Dai et al., 2004; Dai, 2011; Liu et al., 2014; Trenberth et al., 2004; Vicente-Serrano et al., 2010a, 2010b). Severe droughts have strong influence on agriculture, water resources and ecosystems (Dai, 2011), and are affecting the livelihood of millions of people around the world each year (Wilhite, 2000). Arid and semi-arid regions tend to be affected by this climate condition, including high-latitude Asia (Li et al., 2009). A prolonged four-year extreme drought from 1999 to 2002 occurred in the Mongolian Plateau (Davi et al., 2006, 2013; Pederson et al., 2013) and its vicinity (Bao et al., 2012, 2015; Zou et al., 2005) leading to huge economic and societal losses (Batima, 2006; Zhang and Gao, 2004). For example, in Inner Mongolia, China, the yield of crops (297×10^4 ha) and pasture (5733×10^4 ha) were significantly reduced during the harsh drought in 2001 (http://www.weather.com.cn/zt/kpzt/1244064.shtml). Another massive drought appeared in 2009, affecting 10.8×10^6 acres of farmland and resulting in severe drinking water shortage for 810,000 people drinking water difficulties in northeast China including eastern Inner Mongolia (http://www.chinadaily.com.cn/cndy/2009-08/13/content_8562996.htm). In 2014, the total drought area and that of the severest in Inner Mongolia covering 720,000 and 111,000 km^2, respectively (http://nmg.sina.com.cn/z/nmggh/index.shtml).

Hulun Buir city in the northeastern Inner Mongolia, locates at the borders between China, Russia and Mongolia. Natural grassland accounts for 80% of the entire 263,953 km^2 area of Hulun Buir city, and the steppe is the largest prairie in China. The weather in winter is very dry and severe due to the influence of the Siberian High, while in summer it is very warm and moist because of the

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Asian summer monsoon (Chinese Academy of Sciences, 1984). The main extractive industry over this region includes livestock breeding and farming, which are particularly vulnerable to climate changes. The steppe ecosystems are quite fragile for cooperating effects exhibited by wind erosion, desertification, overgrazing and soil salinization (Shen, 2008; Wang et al., 2010). Like other regions in the Mongolian Plateau, the Hulun Buir steppe is also threatened by drought stress in the last decades (Bao et al., 2015; Chen et al., 2012; Li et al., 2009). However, short and sparse meteorological records (most back to 1950s) hamper us to well understand the processes and possible mechanisms of drought variations from a long perspective in this climate-sensitive region. Tree rings are one of the most useful climate proxies have proved their values of identifying the climate change characteristics according to the reliable relationships between tree-ring indices and climatic factors. Many studies based on tree rings have been conducted in Mongolia and surrounding areas, (e.g. Cook et al., 2010; D'Arrigo et al., 2000, 2001; Davi et al., 2006, 2009, 2010; Liang et al., 2007; Liu et al., 2009; Pederson et al., 2001, 2013). Nevertheless, studies obtained from the eastern edge of the Mongolian Plateau are still few (Bao, 2015; Bao et al., 2012, 2015; Chen et al., 2012; Liu et al., 2009). The purposes of our study are (1) to recover the mean February–July drought variability during the last two centuries for eastern Hulun Buir steppe, China, and (2) to identify the possible connections of drought fluctuations in eastern Mongolian Plateau with the sea surface temperatures (SSTs) in the remote Pacific Ocean.

2. Materials and methods

2.1. Study area and climate data

The study area is located in the eastern Hulun Buir steppe, China, a transitional zone between the Da Hinggan Mountains and the Mongolian Plateau (Fig. 1). This region lies in the boundary zone between arid and semi-arid conditions, monsoon and non-monsoon climate. The climate in the region is characterized by extreme temperature, strong winds, limited precipitation, high evaporation, and poor soil by wind erosion (Wang et al., 2010; Zhu et al., 2003).

Meteorological data of the monthly precipitation, monthly mean temperature and maximum temperature during the period of 1953–2012 from both Hailar (119°45′E, 49°13′N, 610 m a.s.l.) and Aershan (119°57′E, 47°10′N, 1027 m a.s.l.) stations were supplied by the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). For the reason of effectively reducing the small-scale noise or stochastic components contained in single station (Bao et al., 2015; Chen et al., 2012; Davi et al., 2006), the arithmetical averaged data of Hailar and Aershan stations were applied to stand for regional climatic conditions and further analyses. The warmest and the coldest months are July (18.4 °C) and January (−25.6 °C), respectively. Annual mean temperature and total precipitation are −2.0 °C and 398.8 mm, respectively. The sum of precipitation from May to September is 332.4 mm, accounting for 83.3% of the total annual rainfall. Average monthly temperature and precipitation for the 1953–2012 period and May–September mean temperature and total precipitation are provided in Fig. 2.

Data of the Palmer drought severity index (PDSI) on a $2.5^\circ \times 2.5^\circ$ grid (Dai et al., 2004) and the $0.5^\circ \times 0.5^\circ$ grid standardized precipitation evapotranspiration index (SPEI) version 2.2 on 1 month time-scale were utilized in this study (Vicente-Serrano et al., 2010a, 2010b). The former is based on a soil moisture supply-and-demand model, which integrating cumulative effects of precipitation and temperature, the latter is designed to combine advantages of the multitemporal nature reflected by the standardized precipitation index (SPI) and the sensitivity of the PDSI to changes in evaporation demand caused by temperature fluctuations and trends. The nearest grid data of PDSI (118°45′E, 48°45′N, 1953–2005) (Dai et al., 2004) and SPEI (119°45′E, 47°45′N; 119°45′E, 48°15′N, 1953–2011) (Vicente-Serrano et al., 2010b) were abstracted for climate-growth response analyses.

2.2. Tree-ring data

Mongolian pine (*Pinus sylvestris* var. *mongolica*) is a dominant conifer species in this region. One or two cores were sampled from each living tree, and a total of 35 cores were collected from 28 Mongolian pines at site of SSQ (48°13′07.48″–48°13′19.93″N, 119°56′02.97″–119°56′15.80″E, 773 m a.s.l.) in August 2013 (Fig. 1). In the laboratory, all the ring-width samples were treated according to standard dendrochronological procedures (Cook and Kairiukstis, 1990; Fritts, 2001), and measured with a precision of 0.01 mm using LINTAB6 measuring device. The COFECHA program (Holmes, 1983) was applied to assess the quality of the cross-dating of tree-ring series. After removing several cores with poor correlations with the master sequence, the COFECHA results showed that average correlation coefficient between individual series and the master series was 0.618, mean sensitivity was 0.208 and absent rings rate was 0.073%. The ARSTAN program (Cook, 1985) was utilized to develop the final tree-ring chronology. Apart from two cores that were treated using the cubic smoothing spline with a 50-year window (about 2/3 of the series length), most series were standardized by negative exponential curves or linear regression curves. Finally, the standard chronology of SSQ (SSQstd) was developed by averaging the index values using a biweight robust mean. (Cook and Kairiukstis, 1990). To decrease the effects of changing sample depth through time, the variance of SSQstd was stabilized following the Rbar-weighted method (Osborn et al., 1997). Subsample signal strength (SSS) was applied to assess the reliable beginning year of the chronology, and a value greater than 0.85 was acceptable (Wigley et al., 1984). The high values of Running expressed population signal (EPS, the same criterion as SSS) and Running Rbar (moving correlations between all the series) also indicated the chronology signal strength through time (Wigley et al., 1984). The entire SSQstd was 234-year in length with a span of 1780–2013, and the reliable interval (SSS > 0.85) started in 1819 and corresponded to four cores from four trees.

2.3. Statistical methods

Correlation analyses were utilized to explore the relationships between ring-width growth and climate variables during their period of overlap. Monthly total precipitation, mean and max temperature, SPEI and PDSI from the previous August to current September were used in the analysis. Correlations between climate variables of various seasons and SSQstd were also identified. Linear regression model was employed to reconstruct mean February–July SPEI. Split-sample method (Meko and Graybill, 1995) and Pearson's correlation coefficient (r) (Cook and Kairiukstis, 1990), sign test (ST), reduction of error (RE), coefficient of efficiency (CE), and product mean (t) were applied to evaluate the skills of the regression model. Positive values of RE and CE both testing the shared variance between actual and estimated series suggest that the reconstruction owns acceptable capacity (Cook et al., 1994, 1999). Regional climate signals in the tree-ring data was assessed in a spatial correlation analyses with gridded CRU TS3.22 (Harris et al., 2014), CSIC SPEI (Vicente-Serrano et al., 2010b) and NCDC ERSSTv3 (Smith et al., 2008) using the KNMI Climate Explorer (van Oldenborgh and Burgers, 2005). Period analyses were conducted using wavelet software (Torrence and Compo, 1998). The mean February–July SPEI reconstruction was evaluated