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Temperature variability in North-Central China during the past 231 years based on multiple proxies

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ABSTRACT

Several temperature-sensitive paleoclimate proxies, including tree rings, stalagmites, and historical documents, were employed to derive regional temperature signals for the period 1779–1985 via principal component analysis (PCA). The PCA series was significantly correlated with gridded temperature datasets for Northeast China, the Korean Peninsula, and part of Japan. Based on statistical correlation between the PCA series and observed temperature records, we regionally reconstructed May–August temperature variations for 1779 to 2009. The reconstruction explained 53.4% of the variance in observed summer temperature during the instrumental period. Intervals with persistent decadal warm and cold periods in the past 231 years were detected. The results suggest that, of the past 231 years, the past half century suffered unprecedented warming in North-Central China, which may be related to increasing human activities since the Anthropocene epoch.

1. Introduction

East Asian monsoons are regarded as one of the most important global climatic bridges between low and high latitudes and are the only subtropical/temperate monsoons on Earth (An et al., 2000). The primary source of water vapour in North-Central China (NCC) was delivered by East Asian Monsoon from the Pacific. Unfortunately, few long-term temperature reconstructions exist for NCC, which limits understanding of the relationship between the monsoons and the temperature variability. Reconstruction of temperatures through natural materials (tree rings, stalagmites, corals, ice cores, etc.) is essential to understanding how the temperature changed during non-instrumental eras (Mann, 2002). Tree rings and stalagmites play important roles in high-resolution past-climate reconstruction because they are continuous, accurate records and widely distributed throughout the world (Liu et al., 2010a,b; Tan et al., 2007). In addition, historical documents are also useful for paleoclimate study in old countries that have long periods of civilization and volumes of paper records. Historical documents have great potential in the field of climate reconstruction; however, they have some shortcomings. For instance, it is difficult to quantify the temperature and precipitation variations solely through text description. The China Meteorological Administration used a five-level classification method to estimate the yearly dryness/wetness index (DWI) (Zhang, 1988).

NCC is a very important region agriculturally and ecologically and mainly consists of the Loess Plateau and the North China Plain. NCC belongs to an environmentally sensitive region, where the climate is controlled by East Asian monsoons. Although some temperature reconstructions have been performed for NCC, most are based on a single proxy (Tan et al., 2013; Li et al., 2013; Liu et al., 2014; Yi et al., 2012). Reconstruction using a single proxy often focuses on a specific frequency of climate signals. For example, the temperature reconstruction by Li et al. (2013) was concentrated on low-frequency signals of regional temperature variations based on tree-ring width. Integrating tree-ring data and DWI data, Yi et al. (2012) reconstructed temperature variation in north-central China, which is the first multi-proxy reconstruction for NCC using

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high-resolution temperature data. However, the reconstruction by Yi et al. (2012) only contained two tree-ring sites and several DWI stations. Yet, it is necessary to integrate additional, different paleoclimate proxies to detect all aspects of past regional temperature variations in NCC.

In this study, we tried to integrate more tree ring, DWI, and stalagmite data to present a synthesized temperature reconstruction by employing principal component analysis (PCA) to reduce the high-frequency noise in order to understand regional temperature variations in NCC during the past 231 years.

2. Materials and method

2.1. Materials

In this study, we combined four different proxies (time series) to reconstruct the past temperature variations in NCC. The time series are described as follows.

2.1.1. Tree-ring widths for Yulin

Tree-ring samples were taken in Yulin (36°7′34″N, 116°17′26″E; Fig. 1) in Shandong Province, China. In September 2008, 34 cores were collected from 17 *Pinus bungeana* trees. In the laboratory, all cores were surfaced, cross-dated, and measured using standard dendrochronological processes, precisely. The tree-ring widths in Yulin have a significantly positive correlation with the average lowest temperature from the previous October to the current September, according to Liu et al. (2010a), who reconstructed the lowest temperature variations for the previous October to the current September for the time span 1616-2007 AD. Their results displayed a significant rising trend after 1960 AD, which correlated with the global SST, the global land temperature, and the global mean temperature for 1850 to 2007 AD. The reconstruction indicated that Yulin is a region sensitive to global change and the results therein are useful for our study.

2.1.2. Tree-ring widths for Ningwu

Tree-ring samples were taken in the Guancen Mountains in Ningwu (NW; 38°50′N, 112°05′E; 1600–2100 m altitude; Fig. 1) in Shanxi Province, China. In July 2004, 37 cores were collected from 17 living Chinese Pine trees (*Pinus tabulaeformis*). All samples were cross-dated precisely using the COFECHA program, and undesirable growth trends were removed via ARSTAN software. Li et al. (2013) successfully detected the May–July temperature variations during the period 1686-2003 AD. Their results showed that the NW temperature sequence is representative of large-area temperature variability in North China (including parts of the Loess Plateau and the North China Plain), and this curve could be employed for large-area climate reconstruction.

2.1.3. Stalagmite growth layer in Shihua Cave

Based on the stalagmites in Shihua Cave (115°56′E, 39°47′N, 251 m height above sea level at the cave entrance; Fig. 1) in Beijing, China, Tan et al. (2003) reconstructed the past temperature from 665 BC to 1985 AD. As a high-resolution proxy record, the stalagmite growth layer is sensitive to paleoclimate change. In this case, the thickness of the annual layer was employed to detect the temperature variations. The results showed a significant correlation with the various 1000-year Northern Hemisphere temperature recorded at the decadal time scale. That means this temperature series is dependable, and we could use this sequence for further study.

2.1.4. Yi et al.'s temperature sequence

Yi et al. (2012) reported a summer temperature sequence reconstructed by combining historical DWI and tree-ring data. Tree-ring samples were taken from Luya Mountain (38°44′N, 110°50′E, 2400–2600 m above sea level; Fig. 1) and Huashan Mountain (34°29′N, 110°05′E, 1900–2000 m above sea level; Fig. 1). All samples were measured and cross-dated precisely. The Luya tree-ring chronology was detrended using the regional curve standardization (RCS) method, and the Huashan tree-ring chronology was standardized using conservative negative-exponential or straight curve. Data from 10 DWI stations (Fig. 1) were used to analyse the climatic change. The empirical orthogonal function analysis was employed to check the regional homogeneity of temperature changes, Yi's curve was reconstructed for the period 1470 to 2002 and the result has a relatively good relationship with other temperature variations.

2.2. Method

We carried out the spatial correlations between four individual time series and CRU TS3.10 datasets by using the KNMI Climate Explorer (http://climexp.knmi.nl/). The results showed that all four time series presented significant correlation with regional temperature variations from spring to summer in NCC (Fig. 2a–d). As similar regional temperature signals existed, PCA was employed to extra and enhance the regional temperature signals from the tree-ring widths of Yulin, tree-ring widths of Ningwu, stalagmite growth layers of Shihua Cave, and Yi et al.'s temperature sequence. Prior to PCA, all four time series were *z*-score standardized. The common overlapping period of 1779–1985 was used to carry out further analysis. The first three principal components accounted for 85.23% of the explained variance of all components. Therefore, we combined the first three principal components of the PCA to carry out further analysis in this study.

3. Results and discussion

3.1. Climate responses of PCA

It is necessary to determine what the area of spatial representativeness of the PCA is. By using the KNMI Climate Explorer to explore the spatial correlation pattern between the CRU-temperature gridded dataset and the PCA, we found that the PCA could express large-scale temperature variations in north and central China. For the purpose of climate reconstruction, we extracted regional temperature (most significant in 108°–117°E, 36°-41°N) from the CRU TS3.10 dataset as instrumental data for carrying out temperature reconstruction in this study. The serial correlation was processed between the monthly reconstruction indices and the monthly temperature. The reconstruction indices had significant positive correlation with temperature in May, June, July, and August (Fig. 3). Of all the correlations, the highest occurred for the temperature from May to August (T_{58}) (R^2_{adj}=0.587), which was more robust than that for the temperature from June to August (T_{68}) (R^2_{adj}=0.448). To reconstruct the past summer temperature to the greatest extent, we considered T_{58} as the reconstructed target, which was also considerable because of the high amount of expressed variance to the instrumental temperature variations.

The temperature variations greatly influenced tree growth especially during May to August, the growing season. Theoretically, the speed of tree growth decreases and narrow rings are produced if low temperature occurs under normal precipitation conditions. However, in some special cases, tree-ring widths have a negative relationship with summer temperature (Li et al., 2013). There is a high probability that the trees would keep a memory of summer temperature information. In Shihua Cave, water drip rate is one of the most important factors for stalagmite accumulation, which normally increases during summer in response to heavier summer

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