Two centuries of April-July temperature change in southeastern China and its influence on grain productivity

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Abstract China is a traditional agriculturally based country and one main region for crop production is southeastern China where temperature is a dominant climate variable affecting agriculture. Temperature and social disturbances both influence crop production, yet distinguishing their relative impacts is difficult due to a lack of reliable, high-resolution historical climatic records before the very recent period. Here we present the first tree-ring based warm-season temperature reconstruction for southeastern China, a core region of the East Asian monsoon, for the past 227 years. The reconstruction target was April-July mean temperature, and our model explained 60.6% of the observed temperature variance during 1953-2012. Spatial correlation analysis showed that the reconstruction is representative of April-July temperature change over most of eastern China. The reconstructed temperature series agrees well with China-scale (heavily weighted in eastern China) agricultural production index at decadal timescales. The impacts of social upheavals on food production, such as those in the late period of the Republic of China, were confirmed after climatic influences were excluded. Our study should help distinguish the influence of social disturbance and warm-season temperature on historical grain productivity in the core agricultural region of China during the past two centuries.

Keywords Temperature · Grain productivity · Social disturbance · China · Tree-rings

1 Introduction

China has a long history as a traditional agriculturally based country and crop production has played a crucial role in socioeconomic development over the past centuries to millennia [1-3]. Crop production could be influenced by both climatic change and social disturbance [4-11]. However, it is always challenging to distinguish their relative contribution, partly due to their interwoven effects on agriculture [12]. China's major grain production area lies in the eastern monsoon climate zone where temperature is one of the key factors in determining agricultural production [13], as cooling could decrease grain yields by shortening crop growing season and reducing the effective farmland area [14]. However, annually resolved, long-term warm-season temperature variability in southeastern China is poorly understood till now for three main reasons: (i) the very limited period of instrumental data, (ii) the scarcity of long-term high-resolution warm-season temperature reconstructions from natural proxies, and (iii) the scarcity of historical records that offer reliable temperature information. Even when available, the historical records tend to reflect cold-season instead of warm season temperatures [15-17].

A potential solution to the lack of reliable long-term temperature records lies in the analysis of tree-ring records. Tree-ring based studies have revealed regional temperature variations in several parts of southeastern China. Winter-spring temperatures have been reconstructed in several areas of southeastern China from tree rings [18-21]. The negative relationship between tree growth and the growing season temperature are mostly found at low elevation sites in southeastern China [22-24].

The limiting effects of precipitation on tree growth are only found at a few very dry, low elevation sites in southeastern China [25]. At high elevation sites in southeastern China, the limiting effects of temperature on tree growth may extend even into the summer period [26, 27]. It thus seems likely that tree-ring series from humid high elevation sites in eastern China may provide a basis for warm-season temperature reconstruction, and a means to evaluate the influence of climate and social disturbance on crop production.

The mountains are mostly at low to medium elevations in southeastern China (Fig. 1), which makes it hard to find clear upper tree line situation. However, trees might approach their upper limit tolerance at some relatively high elevation sites. Indeed, we found strong warm-season temperature signals in two tree-ring width chronologies 1500 m above sea level (a.s.l.), 250 km from each other, despite a relatively low sample replication [28]. Therefore, we consider taking tree-ring samples at sites higher than 1500 m a.s.l. will help develop a regional chronology that contains strong warm-season temperature signals.

In this study, we aim to understand how long-term warm-season temperature has changed in southeastern China and to what extent temperature and social disturbances have affected grain productivity in history. Our objectives are (1) to build a regional chronology based on tree-ring samples from high-elevation sites in southeastern China, (2) to reconstruct the warm-season temperatures using the regional chronology, (3) to explore its spatial representativeness by comparing with China-scale temperatures, and (4) to investigate the connections between temperature change and agricultural productivity in historical China so as to distinguish the relative influence of warm-season temperature and social disturbance.

2 Data and methods

2.1 Meteorological data

Southeastern China is an East Asian monsoon dominated region with a mild climate. Summer is hot and wet while winter is cool and dry. Generally, this type of temperature and precipitation pattern is suitable for crop growth. The average of Tunxi and Jingdezhen meteorological data indicates that the annual mean temperature in the study area is 17.0 ^{o}C, and annual total precipitation is 1747.2 mm (Supplementary Table S1). The coldest month is January with an average temperature of 4.6 ^{o}C, while the hottest month is July with an average temperature of 28.6 ^{o}C (Fig. S1). The meteorological records were obtained from the China Meteorological Data Sharing Service System. The sampling sites have a much higher elevation (Supplementary Table S2). Thus they should have experienced higher precipitation and lower temperatures than that recorded at the meteorological stations.

2.2 Tree-ring data

Tree-ring samples of *Pinus taiwanensis* Hayata were taken from three sites: SQG0204 (28^{o}55′ N, 118^{o}03′ E, 1550-1600 m a.s.l.) of Jiangxi province, JLS01 (28^{o}20′ N, 118^{o}51′ E, 1530 m a.s.l.) of Zhejiang province, and GNJ01 (30^{o}03′ N, 117^{o}27′ E, 1650-1700 m a.s.l.) of Anhui province (Fig.1 and Supplementary Table S2). SQG0204 samples were taken from the Sanqingshan National Geological Park in Shangrao, Jiangxi province. The park is part of the Huaiyu Mountains with the highest peak at 1820 m a.s.l., the fifth highest in Jiangxi province. JLS01 samples were taken from the Jiulongshan Natural Reserve with a southwest to northeast orientation in the western Suichang, Zhejiang province. It is a branch of the Xianxia Mountains, with the highest peak at 1724 m a.s.l., the fourth highest in Zhejiang province. GNJ01 samples were taken from the Guniujiang Natural Reserve in Shitai, Anhui province. The mountains extend from east to west, with the highest peak at 1728 m a.s.l., the third highest in southern Anhui province.

After crossdating the tree cores following standard dendrochronological methods [29] and deleting the ones shorter than 100 years, 114 cores from 62 trees were used in the following analyses, including 66 cores of 35 trees from SQG0204, 28 cores of 16 trees from JLS01, and 20 cores of 11 trees from GNJ01. The data of JLS01 and GNJ01 were previously used to analyze the responses of tree growth to climate [28]. Missing rings account for 0.79% of the total. The series intercorrelation is 0.53, and the average mean sensitivity is 0.30.

2.3 Methods

Age-dependent spline smoothing was used to detrend original tree-ring width series, and their ratio series were averaged using a robust Tukey biweight mean method. Signal-free detrending methods were used to build the chronologies [30]. Correlation function analyses were performed to investigate tree growth responses to climate. The dominant limiting climatic factor (i.e., April-July mean temperature) was reconstructed by a simple linear regression function [31]. The reliability of the reconstruction function was tested using the calibration-verification method [32]. The spatial representativeness of the reconstruction was explored using the KNMI climate explorer (http://climexp.knmi.nl).

3 Results and discussion

3.1 Characteristics of the tree-ring chronologies

Three site chronologies were built in this study (Figs S2a-c). They matched each other quite well at annual or decadal time scales, with a correlation of 0.61 between SQG0204 and JLS01, 0.58 between SQG04 and GNJ01, and 0.83 between JLS01 and GNJ01 over their common reliable period 1904-2008, based on the expressed population signal (EPS) value larger than 0.9. The correlations are all significant at 0.01 level. Therefore, we pooled all the 114 cores from the three sampling sites to build a regional chronology (hereafter, RGC) with the reliable period 1812-2013 (Fig. S2d). The RGC chronology could minimize local influences and strengthen the regional common climate signals.

3.2 Relationships between tree growth and climate

Pearson's correlation coefficients were calculated between tree growth and monthly total precipitation and monthly mean temperature for a two-year window for the period 1953-2013 (Fig. 2). All the monthly temperatures had a positive correlation with tree growth, while most of the monthly precipitation had a weak negative correlation. There were no significant correlations with monthly precipitation, indicating that precipitation was not a limiting factor on tree growth at these high elevation sites in southeastern China. Temperature of previous April to previous July had the highest relation with tree growth. The correlation coefficient was as high as 0.78. Physiological preconditioning from the prior year is well known to affect radial growth in the following year [31, 33, 34]. The combination of high precipitation and low temperature may produce a strong temperature signal at high elevation sites in southeastern China. Therefore, April-July mean temperature was chosen as a target for reconstruction.

3.3 Reconstruction of the April-July mean temperature

According to the tree growth responses to climatic factors, the April-July mean temperature averaged from the Tunxi and Jingdezhen meteorological data was selected as the predictand for reconstruction. The regional tree-ring chronology was chosen as the predictor. The calibration-verification tests showed that all the correlation coefficients were significant at the 0.01 level, and that the reductions of error (REs) and the coefficients of efficiency (CEs) were all positive (Table 1). Positive RE and CE values indicated that the skill of the reconstruction function is satisfactory [35]. The reconstruction explained 60.6% of the observed temperature variance over the period 1953-2013, by far the highest for tree-rings in southeastern China (Fig. 3a). Based on this function, the April-July mean temperature was reconstructed for the period of 1785 to 2013, with the reliable period covering 1811-2013 (Fig. 3b). According to our reconstruction, the temperature has been increasing since the 1880s and reached the highest level of the past two centuries in the 2000s.

3.4 Spatial representativeness of the reconstructed April-July temperature series

The KNMI Climate Explorer was used to examine the spatial representativeness of the reconstructed April-July temperature. The reconstruction represents the April-July temperature variability over most of southeastern China and North China (Fig. 4), the main crop production region in China [3]. The reconstructed April-July temperature was also compared with tree-ring-based June-August temperature for China [36] (Fig. 5). The correlation coefficient of our reconstruction with the June-August temperature was 0.21 over the period 1811-2009, significant at the 0.01 level. Visual comparisons also indicate that both records matched well in most periods. However, substantial discrepancies between them occurred in the periods of 1887-1909 and 1939-1955, during which the June-August temperatures were overall higher than our April-July reconstruction. It should be noticed that the tree-ring chronologies used for the June-August temperature reconstruction were mainly from western China, with only one from southeastern China [36]. We found that the only tree-ring chronology from southeastern China had a strong cold-season temperature signal, which might explain why the discrepancies occurred during the above two periods.

3.5 Linkage between the reconstructed temperature and historical grain production

Tree-ring based high-resolution climate reconstructions have been used to investigate the connection between social issues and climate [37-39]. In China, ten-year resolution data showed a positive connection between temperature and agricultural production, although sometimes cold-season temperatures were used for the comparison due to the absence of warm-season temperature reconstructions [5, 13].

There are mainly two harvest seasons in eastern China, including the summer harvesting and the autumn harvesting. The summer-harvesting crops are generally planted in April and harvested in July [40]. Coincidently, our temperature reconstruction period is from April to July, allowing a direct comparison to assess its impacts on crop production. Eastern China is an East Asian monsoon dominated region with more precipitation in summer and less in winter, beneficial to crop growth. Such a climate scenario places precipitation as secondary to temperature in modulating the success of crop production. We used the April-July temperature series at both spatial and temporal scales to explore the connection with China-scale crop production. The grain production index indicates the production per land unit over China in approximate terms. The database was from 66 stations of historical harvest records in China (Fig. 4). The summer grain production index was developed by Gong et al. [40], covering the period 1730-1978. It has a scale of 3 to 10, reflecting the grain yield relative to full harvest. As shown in Figure 6, our temperature reconstruction and the China-scale grain production matched well at decadal timescales. Their correlation coefficient is 0.48 during 1811-1978, and rises to 0.64 if the years 1920-1949 are excluded, both significant at 0.01 level. One obvious large deviation between the datasets occurred from 1920 to 1949, the late period of the Republic of China. The grain production index was largely lower than the temperature series, although the two records matched each other during other periods, such as the late Qing Dynasty, the early period of the Republic of China, and the early period of the People's Republic of China. Inspecting the spring and summer precipitation in

East China since 1880 [41], we found no drought or wet anomalies during 1920-1949 to explain such a long-term deviation. Thus, social factors rather than climatic factors might be the root cause of the serious agricultural recession, namely the so-called “rural crisis” or “agricultural panic” in the late period of the Republic of China [42, 43].

4 Conclusion

We developed a 228-year robust tree-ring width chronology from three sites in southeastern China, with the most reliable interval covering 1812-2013. This record explains as much as 60.6% of the observed April-July temperature variance over the period 1953-2013. Such a high value of explained variance is due to the physically homogeneous sampling sites at high elevations, all above 1500 m a.s.l. The reconstructed temperature covered important historical periods in China, including the late Qing Dynasty, the Republic of China, and the People’s Republic of China. The temperature reconstruction matched the China-scale grain production quite well over most of their common period at decadal time scales, except for the period 1920-1949 under the Republic of China, likely indicative of additional human-caused constraints on general crop productivity during this era. Our work shows that more high-elevation tree-ring sites in southeastern China should be explored to build a longer warm-season temperature reconstruction in the area. This would allow further and more detailed investigation of, and distinction between, climate change and social disturbances on agricultural productivity through time. Such investigation of the past will allow us to draw lessons for better projection of the future.

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Conflict of interest We have no conflict of interests.

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Figure legends

Fig. 1 Map showing the three tree-ring sampling sites and the two meteorological stations

Fig. 2 Correlation coefficients between the regional tree-ring width chronology and monthly total precipitation (gray bar) and monthly mean temperature (black bar) from previous January to current December. The overlapping period was from 1953 to 2013. The precipitation and temperature were the average of Tunxi and Jingdezhen meteorological data

Fig. 3 Regional April-July mean temperature reconstruction in southeastern China. (**a**) Comparison of observed (solid line) and reconstructed (dotted line) temperature for 1953-2013; (**b**) the reconstructed temperature (thin line), its 10-yr FFT smoothing (thick line) to highlight the low-frequency variability, and the mean value (horizontal line) from 1785-2013

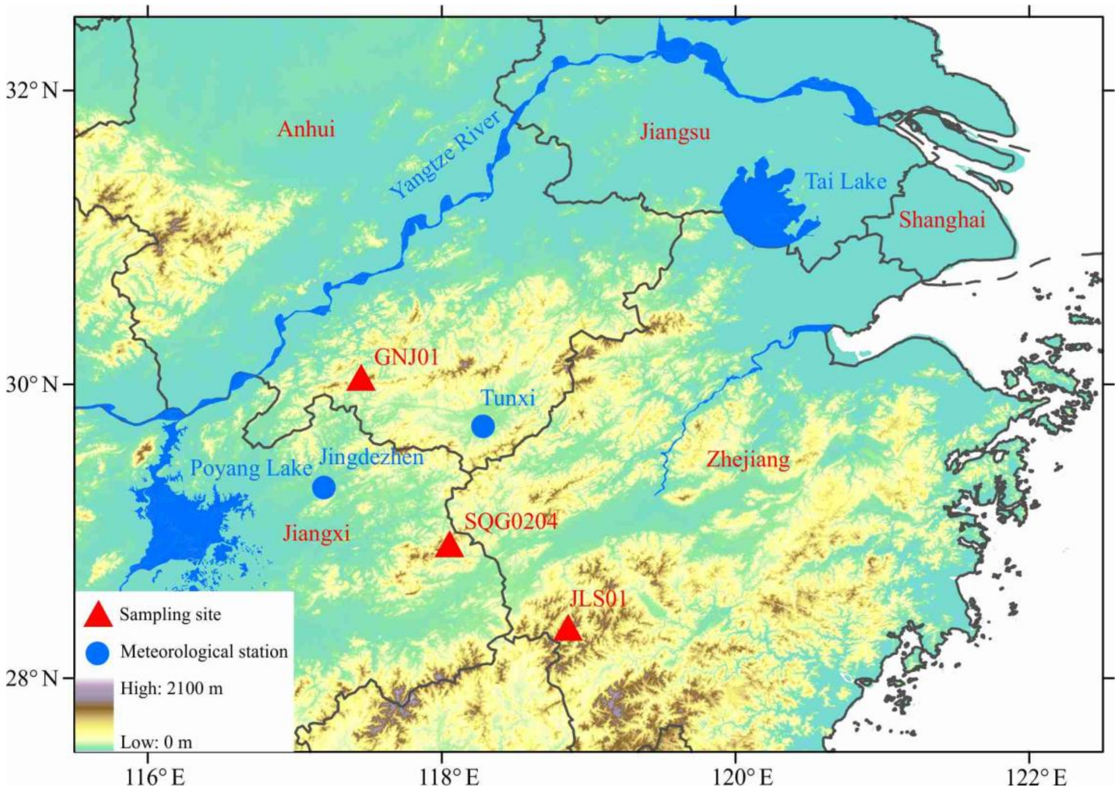
Fig. 4 Correlation pattern of the reconstructed temperature with East Asia April-July temperature from CRU TS3.22 (land) over 1953-2012 [44]. Insignificant correlations (i.e. $p >$ 10%) were masked out. The locations of 66 stations of regional harvest reports are overlapped (green circles)

Fig. 5 Comparison of the April-July mean temperature with June-August mean temperature [36]. Both series were standardized for easy visual comparison

Fig. 6 Relationship between April-July mean temperature and China-scale grain production index. (**a**) The scatter plots between April-July mean temperature and grain production. The red dots represent the period 1920-1949 in the late period of the Republic of China. (**b**) The comparison between April-July mean temperature and grain production

Table 1 Statistics of calibration and verification test results for the common period of 1953-2013. RE: reduction of error, CE: coefficient of efficiency

	Calibration (1953-1982)	Verification (1983-2012)	Calibration (1983-2012)	Verification (1953-1982)	Full calibration (1953-2012)
r	0.69	0.73	0.73	0.69	0.78
r^2	—	—	—	—	0.61
RE	—	0.72	—	0.76	—
CE	—	0.50	—	0.38	—



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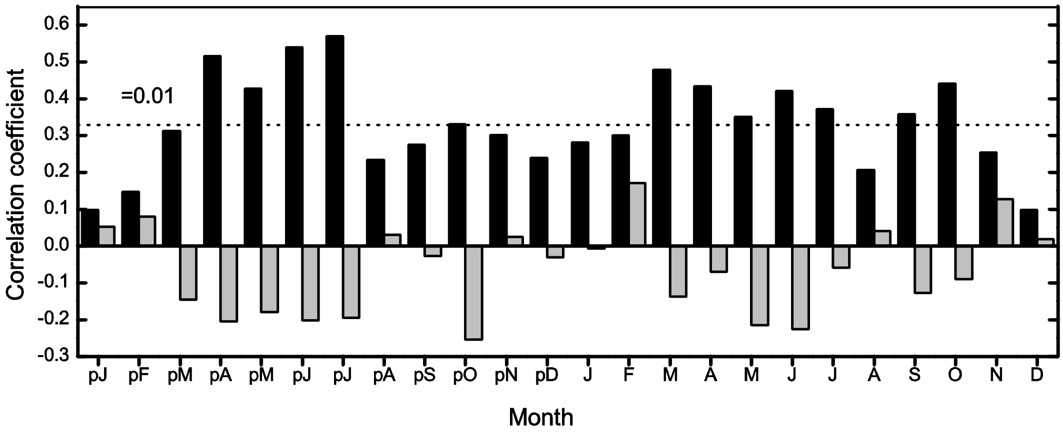

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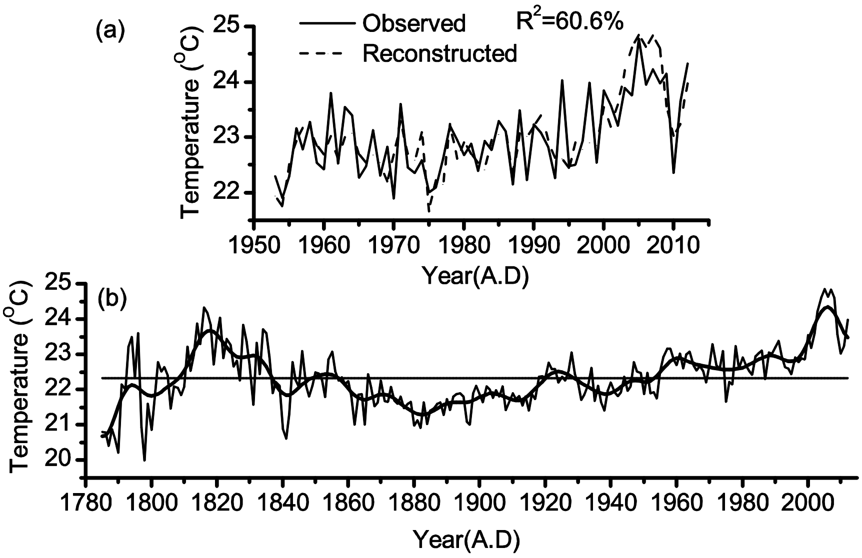

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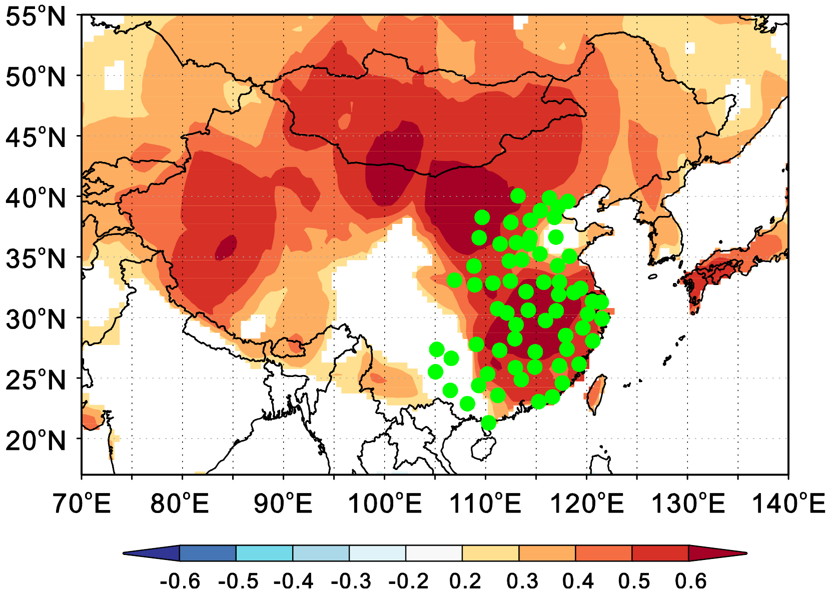

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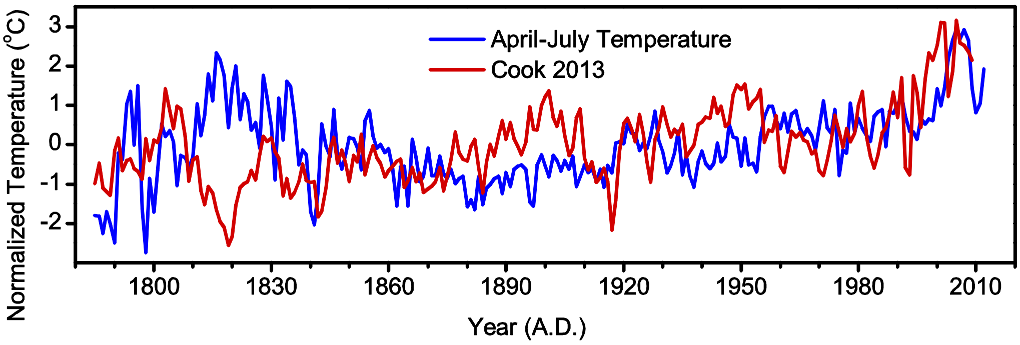

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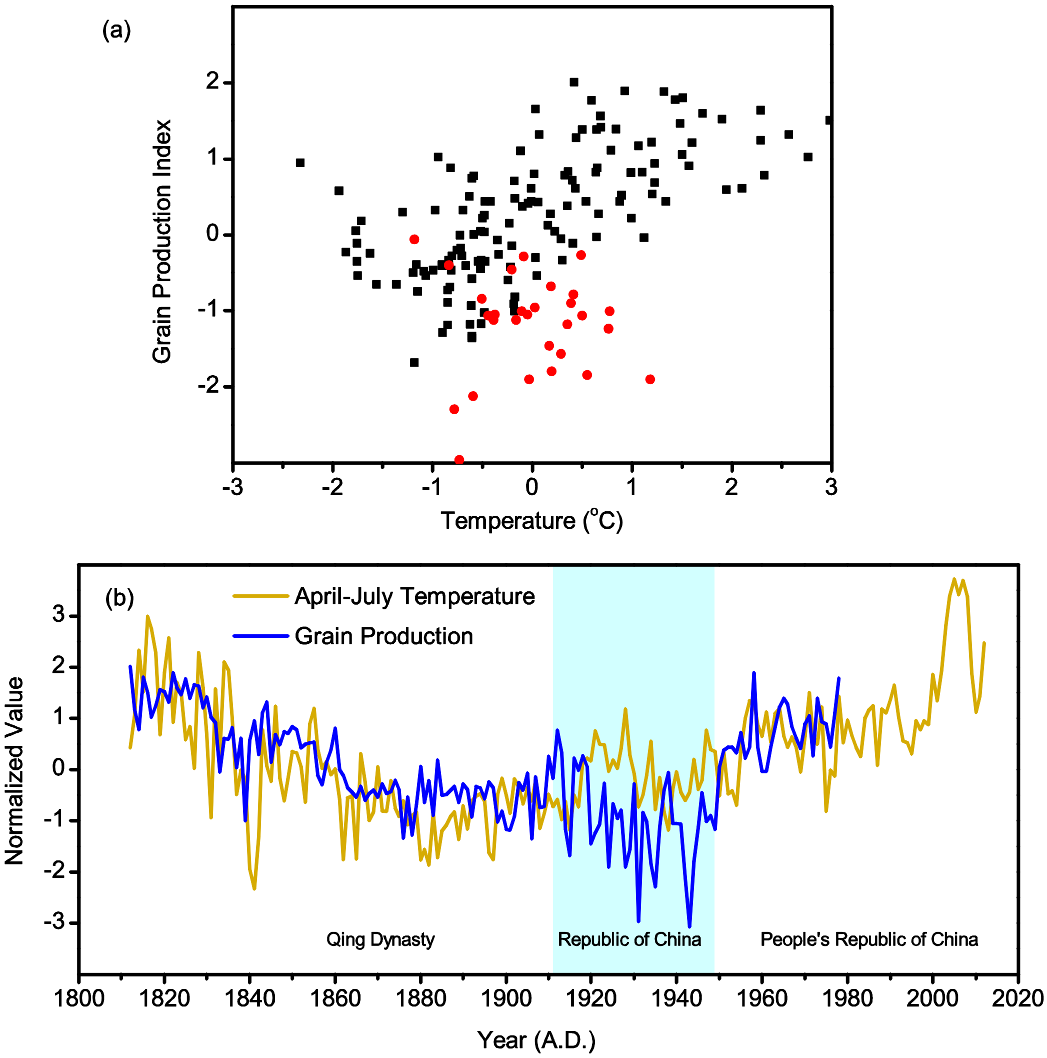

Fig. 6 Relationships between April-July temperature and China-scale grain production index. (**a**) The scatter plots between April-July mean temperature and grain production; the red dots represent the period 1920-1949 in the Republic of China. (**b**) The comparison between April-July mean temperature and grain production