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Tree-ring-based reconstruction of the April to September mean temperature since 1826 AD for north-central Shaanxi Province, China

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Long-time series of high-resolution temperature record from Chinese Loess Plateau is rare. An April-September mean temperature reconstruction (1826－2004) has been developed for the north-central Shaanxi Province, China, based on tree-ring width analysis. The reconstruction captures 39.3% (p<0.001) of the variance in the instrumental data over the calibration period from 1951 to 2002. The reconstruction shows a high temperature period of 1928－1933, which coincides with the timing of the extreme drought event in 1920s in the entire northern China. The two low temperature periods in reconstruction are 1883－1888 and 1938－1942. With the global warming, the April-September mean temperature in study area has also increased since the 1970s, but has not exceeded the temperature in 1928－1933. Besides the statistical analysis, the reconstruction is also verified by the local dryness/wetness index and other dendroclimatological results.

Huanglong Mountain, Shaanxi, *Pinus tabulaeformis*, tree-ring width, April-September mean temperature

Annual growth tree rings is one of the best natural proxies to record past climate and to study climate-growth relationships[1]. Recently, studies of the northern Hemisphere temperature reconstruction for the past millennium mainly by tree-ring materials have not only recorded the global warming event in the recent decades[2−4], but also revealed that the 20th century was the warmest century in the last millennium. This conclusion drew great attention of governments and public alike. However studies in the western Himalaya showed opposite cooling trends in spring (from March to May) and spring to early summer time (from February to June) since the latter part of the 20th century[5−7], though warming trend is obvious during the winter time (from last October to current February)[7]. This may suggest that global warming in the 20th century had seasonal and regional differences.

The most part of northwestern China is environmentally sensitive region with annual precipitation less than 400 mm, while evapotranspiration is much greater than precipitation. The warm-dry trend since the 20th century in this area is obvious because of global warming, and drought occurred more frequently. Thus the investigation of the past climate change of northwestern China is necessary for the sustainable development of the region, and it is imperative to put the present climatic change in a long-term perspective. Dendroclimatological studies in this area show that precipitation is one of the climatic parameters that limits tree growth[8−11], while temperature also plays an important role in limiting tree growth by adjusting the soil moisture content[12−14]. So

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far the tree-ring-based long-time temperature reconstruction is still rare in north central China, especially on the Chinese Loess Plateau[12,15].

Shaanxi Loess Plateau is the main part of Chinese Loess Plateau, which is located in the central China, and is the foreland of the western development drive. However, natural climate change and human activity make it difficult to find suitable long-lived natural forest for dendroclimatological studies in this area except for few small mountains. In this paper we present a 180 a temperature reconstruction for the north-central Shaanxi Province by tree-ring width analysis in Huanglong Mountain. Our reconstruction not only extends the instrumental records, but also provides a background for a better understanding of the interannual and multidecadal climatic variability in north-central China.

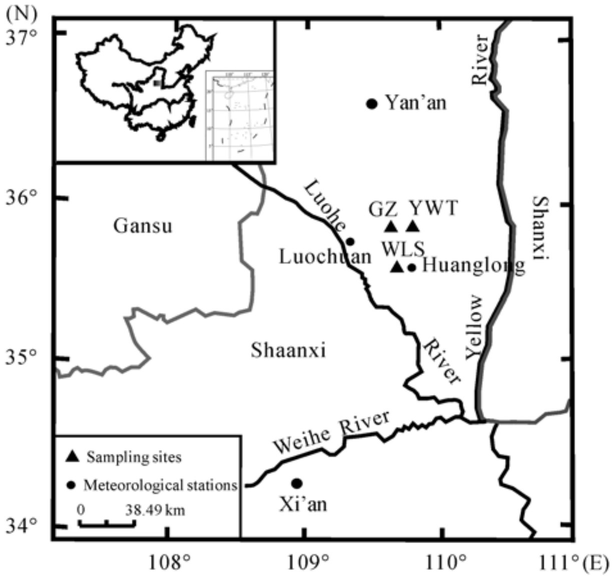

Figure 1 Location of sampling sites and meteorological stations.

1 Site description

Huanglong Mountain is located in the southeast of Shaanxi Loess Plateau (109°38′—110°12′E, 35°28′—36°2′N), which belongs to Huanglong and Yichuan. With forest coverage of 84.6%, it serves as the natural green barrier that protects the local agriculture and livestock production, known as the lung of Shaanxi Province. The predominant tree species in this mountain are *Pinus tabulaeformis*, *Quercus liaotungensis*, *Populus davidiana*, *Betula platyphylla*, *Platycladus orientalis* and *Populus simonyi.*

Samples were collected from Huanglong, which belongs to temperate continental monsoon climate region, characterized by dry spring and wet autumn, as well as long winter and short summer. The mean annual temperature of Huanglong is 8.6℃ and the mean annual precipitation is 611.8 mm, mainly concentrated from July to September. The altitude of this county is between 643.75 and 1783.5 m.

2 Materials and chronology development

A total of 59 tree-ring cores from 30 *Pinus tabulaeformis* were sampled from sites of Huanglong (GZ, YWT and WLS, Figure 1) in April, 2005. All the trees from which core samples were taken grew under organism-rich soil condition on the northern slopes of the Mountain. The tree's canopy is disconnected.

Tree-ring samples were prepared, cross-dated, and measured with a resolution of 0.01 mm following standard practices after air drying[16]. The quality of cross-dating was controlled by using COFECHA program[17]. Cores with any cross-dating ambiguity were excluded from further analysis; cores that had rings less than 50 years, or were twisted seriously were removed. The final total samples used in reconstruction are 45 cores from 24 trees, and the series intercorrelation coefficient is 0.57.

The tree-ring series were detrended and standardized to ring-width indices to remove the age-dependent growth trend as well as other low-frequency variations due to stand dynamics by using the program ARSTAN[18]. To minimize the removal of any long-term climatic variance in the process, negative exponential curve or linear regression curves were applied to each ring-width measurement series of each individual core. Tree-ring indices were calculated as the ratio of raw measurements to the fitted curve values. All tree-ring index series were then merged to develop one robust standard chronology that was retained for subsequent analysis. The statistics of samples and common period (1910—2004) analysis of series are shown in Table 1, which indicate that the tree-ring index is promising proxies for climate change studies for this area. The beginning year of the reliable index is determined by Subsample Signal Strength (SSS)[19]. To extend the length of the chronology, we restricted our analysis to the period with SSS at least 0.8, together with RBAR[20], the beginning year of tree-ring index is 1826 (Figure 2).

The value of MS, SD and correlation coefficients of different tree-ring series are lower than that of arid to

Table 1 Sample information and statistics of the tree-ring index (common period 1910—2004)

Code	Huanglong
Altitude (m)	1000—1350
All samples (trees/cores)	30/59
Sample depth (trees/cores)	24/45
Mean sensitivity (MS)	0.27
Standard deviation (SD)	0.39
First-order autocorrelation	0.65
Mean correlation among all series	0.34
Mean correlation between trees	0.31
Mean correlation within trees	0.39
Variance in first eigenvector (%)	37.52

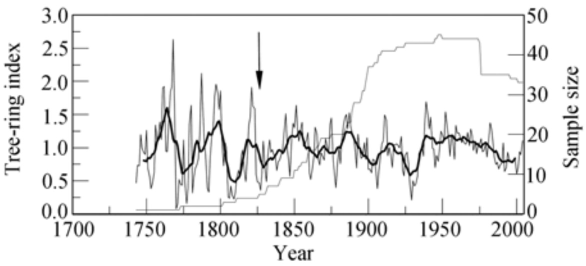

Figure 2 Tree-ring index of Huanglong Mountain. Arrow shows the beginning of the reliable index.

semi-arid area, but still similar to that of semi-humid area[13,21,22], and it can be possibly attributed to the rich precipitation of sampling site, suggesting moderately strong year-to-year growth variations that are likely caused by change of climate. The high first-order autocorrelation (0.65) is considered to be biological in origin, which means the tree-ring formation of current year uses stored photosynthates of last year.

3 Correlation analysis between tree-ring index and climatic factors

There are four meteorological observation stations around the sampling sites (Figure 1), they are Huanglong (109°50′E, 35°35′N, period of record 1957—2002), Luochuan (109°30′E, 35°49′N, period of record 1955—2002), Yan'an (109°30′E, 36°36′N, period of record 1951—2002) and Xi'an (108°56′E, 34°18′N, period of record 1951—2002) meteorological stations. Homogeneity of the monthly precipitation and monthly mean temperature data from each station was tested. We found the records from Huanglong observation station was different from the other three stations, especially the summer-half year (April to September) records, which was also the season we focused on in this paper. Considering this, the records of Huanglong observation station was excluded from further analysis. Figure 3 shows the monthly mean temperature from the three stations change simultaneously in the study area, while precipitation is slightly different.

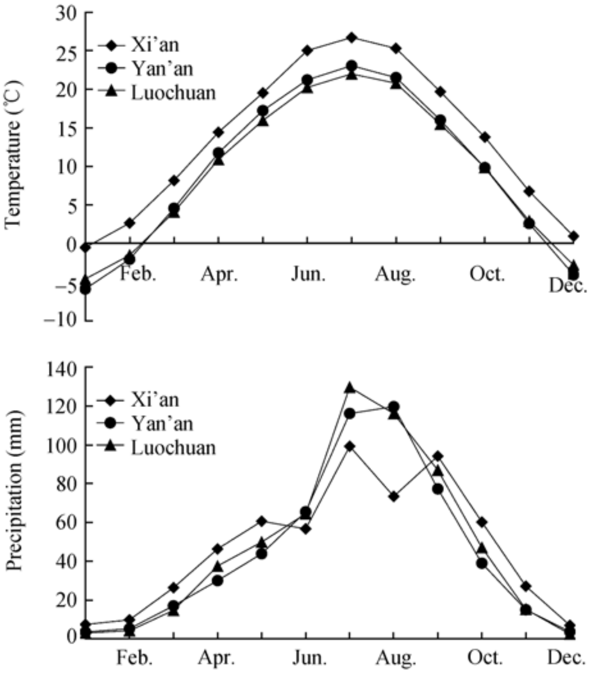

Figure 3 Monthly mean temperature and precipitation from meteorological stations.

We use simple correlation analysis to detect the relationship between tree growth and climate during the observation period. The monthly climatic data from prior October to current September from each station are used for analysis.

The primary result shows that tree-ring width negatively correlates with the monthly mean temperature of growing season, especially statistically significant with April, May and September mean temperature of each station (Table 2), with June and July mean temperature of Yan'an station as well. And it shows positive correlation with the growing-season monthly precipitation, yet statistically insignificant. To better reflect regional fluctuations, we calculated the arithmetic mean temperature and precipitation of the study area, based on the three meteorological stations (Luochuan, Xi'an, Yan'an). The correlation coefficients between tree-ring index and regional climatic data were calculated again; the highest correlation was found between tree rings and April-September mean temperature ($r=-0.63$; $p<0.001$).

The pattern of trees responding to precipitation and

Table 2 Correlation analysis between tree-ring index and the monthly mean temperature[a)]

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Luochuan	–0.17	–0.24	–0.15	–0.42**	–0.31*	–0.18	–0.09	–0.02	–0.48**
Xi'an	–0.11	–0.26	–0.34*	–0.42**	–0.40**	–0.22	–0.27	–0.15	–0.28*
Yan'an	–0.20	–0.29*	–0.21	–0.41**	–0.46**	–0.45**	–0.35*	–0.21	–0.46**

a) *, Exceed 95% confidence level; **, exceed 99% confidence level

temperature in Huanglong Mountain is similar to that of the Helan Mountain, north-central China[14] and India, western Himalaya[5,6]. Generally, the annual precipitation most suitable for *Pinus tabulaeformis* growth is above 500 mm[23]. The weak positive correlation between tree growth and precipitation in Huanglong indicates that precipitation can theoretically meet the needs of tree growth with its annual precipitation amount of 611.8 mm, and more precipitation will produce wider rings, less precipitation, narrower rings. Field experiment in the Loess Plateau[24] showed that the main period for the *Pinus*'s fast storage of dry photosynthate was from early April to June, and the main period for water usage of *Pinus* is from May to August, which means April to August are critical period for *Pinus* growing. Figure 3 indicates that the highest temperature in the study area occurred from June to August, which is earlier than the highest precipitation timing (from July to September). That is to say, the higher the temperature is in the growth season, the more intensive the soil evaporations and plant transpirations are, and this leads to worse conditions for tree growth. The negative correlation between tree-ring width and the mean temperature from April to September suggests temperature can be the most limiting climatic factor of trees in Huanglong, by accelerating soil water evaporation and tree's transpiration.

4 April-September mean temperature reconstruction and discussion

4.1 Transfer function

Simple linear regression is chosen to describe the relationship between tree-ring index and April-September mean temperature (T_{49}). Because the stored current year carbohydrate may be used in the formation of next year tree-ring width, if we consider both the current year and next year tree-ring index (I_t and $I_{t\text{-}1}$), the correlation coefficient of the equation can be increased to 0.72 ($p<0.001$). Even so, we exclude using $I_{t\text{-}1}$ in the regression model because there may be some overlapped information offered by I_t and $I_{t\text{-}1}$. The final transfer function is then designed as:

$$T_{49} = -2.432 I_t + 21.794.$$

The correlation coefficient of the equation (r) is 0.63, the estimation explained 39.3% ($p<0.001$) of the climate variation during the 1951－2002 calibration period, and the adjusted explained variance is 38.1%. Comparison of observed and reconstructed April-September mean temperature is shown in Figure 4, they show similar variation trend.

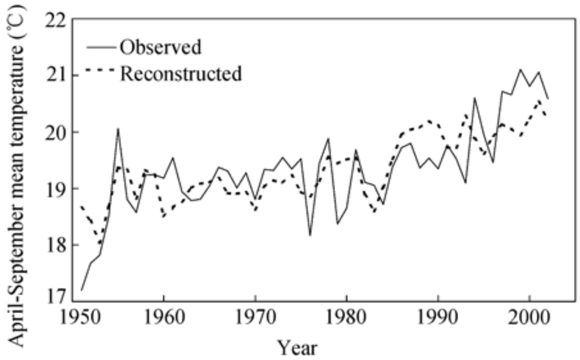

Figure 4 Comparison between the observed and reconstructed April-September mean temperature.

Because the meteorological record is short, we use Leave-one-out test to explore the stability of transfer function[25]. Since omitting any single year did not produce a large change in explained variance, the model is statistically stable. In additional, sign test (S1, S2), error reduction (RE) and product mean test (t)[1] in Table 3 also show that the reconstruction is reliable.

4.2 Results and discussion

Based on the regression model mentioned above, we reconstructed the April-September mean temperature for north-central Shaanxi Province since 1826 AD. The

Table 3 Statistical characteristics of the calibration[a)]

Period	r	R^2	R^2_{adj}	S1	S2	RE	F	t	p
1951－2002	0.63	39.3%	38.1%	35(33*, 35**)	41(34*, 36**)	0.41	32.36	5.7	<0.001

a) *, Exceed the 95% confidence level; **, exceed the 99% confidence level mean value and standard deviation (σ) of reconstructed data are 19.43 and 0.64℃, respectively.

Temperature anomaly series is shown in Figure 5(a), which can reflect the temperature changes of the study area; the smoothing line is a 10-year moving average. If we define high temperature year as the mean of temperature anomaly plus 1σ ($>1\sigma$) and low temperature year as the mean minus 1σ ($<1\sigma$), the number of the high temperature year is 28, account for 15.6% of all reconstruction, and the number of the low temperature year is 31, account for 17.3%. The year of 1929 is the warmest and 1939 is the coldest in reconstruction.

Based on the instrumental records, the mean temperature from April to September correlates negatively with the total amount of precipitation during 1951—2002 (r=–0.3; p<0.05), which means that the climate of the north-central Shaanxi Province is characterized by high temperature with low precipitation and low temperature with high precipitation. Usually high temperature with low precipitation is related with drought event in north China, and the longer-lasting high or low temperature events generally have much stronger effects on local social and agricultural activities. In our reconstruction, the positive temperature anomalies lasting over 5 years are found in 1834—1842, 1866—1870, 1900—1908, 1923—1935 and 1985—2003 (with the exception of 1991), and the negative values lasting over 5 years are in 1848—1859, 1871—1875, 1882—1890, 1938—1944, 1948—1954 and 1959—1976. Among these periods, there are only two low temperature periods ($<1\sigma$) in 1883—1888 and 1938—1942. the period of 1928—1933 is the only high temperature period ($>1\sigma$) since 1826, which is concurrent with the large-scale severe sustained drought occurred in the 1920s in North China.

The 1920s extreme drought is one of the tenth natural disasters in China in modern history[26]. It was worthy noting that drought-induced famines and disease led to the death of a total estimation of 4 million residents in five provinces including Gansu, Shaanxi, InnerMongolia, Ningxia and Qinghai, demonstrating the intensity and severity of the drought in the 1920s in north China. Tree-ring studies in other area have successfully captured this kind of extreme drought event in North China[9,27,28]. By analyzing historical document, Wang[29]

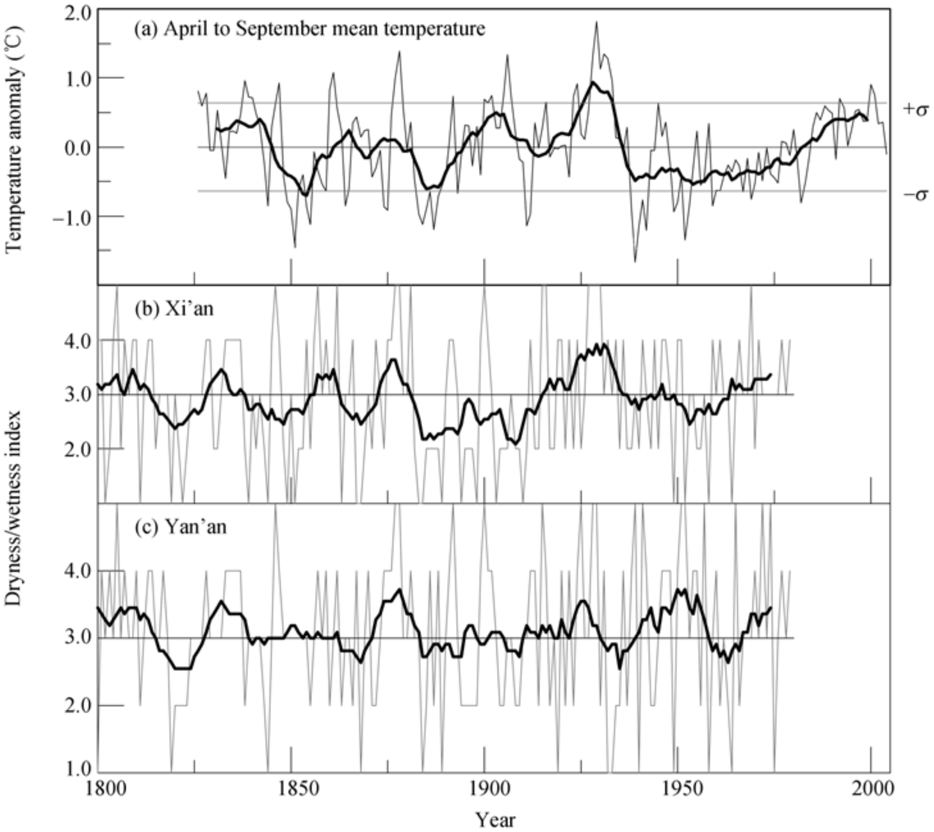

Figure 5 (a) Reconstruction of April-September mean temperature anomaly since 1826; (b) and (c) are the dryness/wetness indices from Xi'an and Yan'an, respectively.

deduced the time of this drought event in northern Shaanxi Province is from 1923 to 1932, and 1929 is the most serious year[30]. Our reconstruction also showed a high temperature period during 1923 to 1935, with 1929 as the warmest year. Undoubtedly this temperature increase contributed greatly to the 1920s drought event in local area.

The 10-year moving average curve of temperature anomaly showed the highest temperature period in the reconstruction was from the late 1920s to early 1930s (1928—1933), after that temperature decreased fast to the lowest temperature in 1939, and the low temperature persisted a longer time till the end of 1960s. After 1970s temperature in the north-central Shaanxi Province started to increase slowly up to now. The two temperature increase periods in our reconstruction in 20th century happened in the same time as the global temperature increase events[31], but difference also existed between our reconstruction and global temperature. Although the warming trend is obvious since recent decades, the temperature increase since 1970s is not the highest one in our reconstruction, it is lower than that of the 1920s, which means the temperature in Shaanxi Province not only responds to global climate change, but also has the territorial characters.

The drought event is more inclined to happen in high temperature year with low precipitation. So we use the dryness/wetness index of local area from Xi'an and Yan'an[32] to tentatively verify our reconstruction. After 10-year moving average, the dry or wet periods were clearly shown in Figures 5(b) and 5(c). By comparing the three curves in Figure 5, we can see most of the high (low) temperature periods in the April to September mean temperature series match the dry (wet) periods in the dryness/wetness indices quite well, especially with that of Xi'an.

The April-September mean temperature of north-central Shaanxi significantly correlates with the mean annual temperature with r 0.9 ($p<0.001$), so our reconstruction can be regarded as the mean annual temperature series of this area since 1826. This curve matches the nearby January-August mean temperature reconstruction of Helan mountain, north central China (which correlates significantly with mean annual temperature with r 0.74) very well[14] (Figure 6). For example, the two places are characterized by high temperature in 1900—1908 and 1923—1935; whereas the temperature in 1882—1890 and 1934—1944 showed low value. After the 1970s, temperature increased in both places. This may suggest simultaneous change of larger scale temperature of north China.

The power spectrum analysis detected 3.51, 2.63 and 2.5-year periodicity in the reconstructed temperature series. These periodicities could be likely relate with the ENSO activity[33,34], and have also been detected in other dendroclimatological studies in North China[9,22]. The dendrochronological study in Qinling Mountains, central China[35] testified that tree rings could record the ENSO

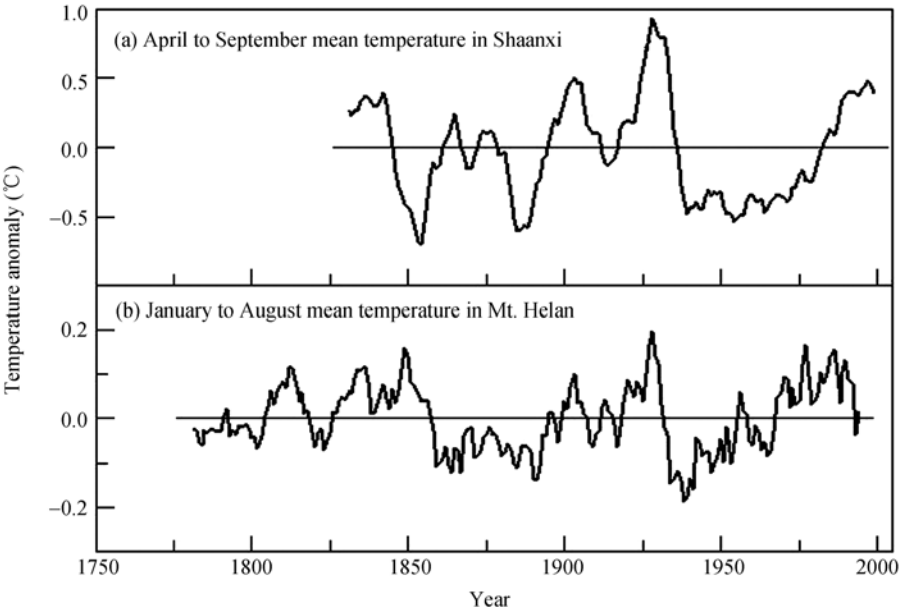

Figure 6 Temperature comparison between Shaanxi and Mt. Helan(10-year moving average).

events. Such analysis may indicate the study area is influenced not only by the local climate but also larger scope climate change.

5 Conclusions

In this paper, we reconstructed April-September mean temperature of the north-central Shaanxi Province, China, from 1826 to 2004 by tree-ring width analysis. The variation trends between the temperature reconstruction and observation is very similar, and various statistical results indicate that the reconstruction is stable and reliable. The reconstruction shows temperature increase since the 1970s, but the temperature of last decades is not the highest in the reconstruction. The highest temperature period in reconstruction is from 1928 to 1933, which is concurrent with the extreme drought event in the 1920s in North China. Beside this, the reconstruction also shows two low temperature periods in 1883—1888 and 1938—1942.

The spectral analysis detected 3.51, 2.63 and 2.5-year periodicity, which may be attributed to the influence of ENSO.

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