Palaeogeography, Palaeoclimatology, Palaeoecology 282 (2009) 81–87

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Precipitation reconstruction from Hailar pine (*Pinus sylvestris* var. *mongolica*) tree rings in the Hailar region, Inner Mongolia, China back to 1865 AD

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ARTICLE INFO

Article history:
Received 26 April 2009
Received in revised form 13 August 2009
Accepted 25 August 2009
Available online 3 September 2009

Keywords:
Hailar, China
Pinus sylvestris var. *mongolica*
Hailar pine tree-ring widths
Precipitation reconstruction
East Asian Summer Monsoon

ABSTRACT

Precipitation is the major limiting factor for the radial growth of Hailar pine (*Pinus sylvestris* var. *mongolica*) in the Hailar, northeast China. Herein, the amount of precipitation from the previous July to current June was chosen for reconstruction from 1865 to 2003 AD. This reconstruction accounts for 51% of the variance in the instrumental precipitation data during the 1952–2003 period. The reconstruction reveals the precipitation fluctuation history over the last 139 years. Some severe drought events (lasting for more than 3 years) are displayed in the series, such as 1905–1909, 1926–1929 (a severe drought event in central-northern China with tremendous losses of human lives) and 1968–1970; extreme wet events are 1867–1870, 1932–1934, 1939–1941 and 1955–1957. On the decadal scale, there are two dry periods (with precipitation lower than the mean of 1865–2003): 1888–1929 and 1963–1975, and two wet intervals (more than the mean): 1930–1962 and 1976–2003. Drought events or dry intervals correspond to weak, and wet events to strong, East Asian Summer Monsoon (EASM). The reconstructed precipitation can be well compared with the Baiyinaobao, Ortindag Sand Land in eastern Inner Mongolia and northeastern Mongolia rainfall series derived from tree rings. The four curves show similar variation related to weak/strong EASM. A power spectrum analysis shows that there are 7.67- and 7.08-year quasi-periodicities, which may be associated with ENSO activity.

1. Introduction

Tree rings are one of the most important proxies for studying past climate due to their high time resolution and precise dating. By using tree-ring data, temperature and precipitation, streamflow and drought history have been reconstructed back hundreds or even thousands of years for different regions around the world (Briffa et al., 2001; Frank et al., 2005; Rutherford et al., 2005; Esper et al., 2007; Mann et al., 2008).

Such tree-ring based reconstructions have played an important role in past climate and environment studies, which help us to better understand climate behavior and its mechanisms in the past, and then predict variation trends for the future.

In recent years, great progress has been made in dendroclimatological studies in China. Temperature and precipitation history have been reconstructed for at least the last 1000 years on the Tibetan Plateau (Shao et al., 2005; Gou et al., 2008; Liu et al., 2009), and for the last several hundred years in central China (Hughes et al., 1994; Liu and Shao, 2000; Liu et al., 2001, 2002, 2008b), in western China (Yuan et al., 2003, 2007; Liu et al., 2005, 2008a), and in eastern China (Liang et al., 2001; Liu et al., 2003, 2007). However, there are only a few dendroclimatological studies in the vast area of *ca.* 1,100,000 km^2 of northeastern China (Shao and Wu, 1997; Wang et al., 2005), Consequently, is important to carry out more dendroclimatological studies in this region to obtain climatic variation information in the past.

Hulunbuir, located in a vulnerable woodland-steppe ecotone, northeastern China, is a region sensitive to climate and environmental changes (Zhang et al., 1997; Fu et al., 1998). As an agriculture-pasture transitional zone, this region is strongly influenced by the East Asian Summer Monsoon and frequently suffers from extreme climatic factors, such as limited precipitation and low temperature. The long-term records produced by tree-ring studies could be helpful for regional planning and ecological conservation.

In this paper, we report a 139-year long rainfall reconstruction series derived from *Pinus sylvestris* tree-ring widths in Hailar, and also discuss the variations of the EASM according to the reconstruction and other results available from nearby region.

2. Materials and method

2.1. Site description and tree-ring material

Hailar, in eastern Inner Mongolia, China, belongs to a semi-arid area. It is located at the east margin of the Hulunbuir grassland, with

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doi:10.1016/j.palaeo.2009.08.012

typical monsoon climate characteristics (Wang, 1997). Annual mean temperature is −2 °C, and annual total precipitation is about 350 mm. Seasonal dry and wet conditions alternate in association with the intrusion of dry–cold air masses from high latitudes in winter and warm–humid air masses from low latitude oceans in summer (East Asian Summer Monsoon). Droughts frequently occur in each season, especially in spring and summer.

The tree samples were collected in the West Mountain (119°43′E, 49°12′N, 450~600 m a.s.l.) of west Hailar City in August, 2004 (Fig. 1). The sampling site is covered with stunted trees including sparse Hailar pine (*Pinus sylvestris* var. *mongolica*) of 20–30 m height, growing on sand dunes with poor nutrition. With their thick bark, the mature trees are relatively resistant to low temperature and drought damage. The sampling site is quite open with a discontinuous canopy. Increment cores were collected from 23 living trees, 2 cores per tree.

Tree-ring samples were treated following standard practices (Stokes and Smiley, 1996). All cores were dried, glued and mounted. After cross-dating, each individual ring was identified with an accurate calendar year, and then each annual ring was measured within 0.01 mm. The quality control of cross-dating was carried out using COFECHA (Holmes, 1983). Cores with any ambiguities of cross-dating were excluded from further analysis. The average rate of absent rings in the samples was 0.13%.

2.2. Chronology development

The individual ring-width measurement series were detrended and standardized to ring-width indices using the ARSTAN program (Cook, 1985). Undesirable growth trends, related to age and stand dynamics but unrelated to climatic variations, were removed from each series during the detrending process. To conserve the maximum common signal at the lowest frequency possible, each ring-width measurement series was standardized conservatively by fitting a negative exponential or straight line. All individual index series were combined into a single chronology by computing a bi-weight robust mean. In further analysis, the standard version (STD) of the chronology was used since it preserves much lower frequency signals (Cook and Kairiukstis, 1990).

Table 1
Statistical features of the Hailar STD chronology.

Statistical item	STD
Mean sensitivity	0.23
Standard deviation	0.36
First order autocorrelation	0.64
Mean correlation within a tree	0.68
Variance in first eigenvector (%)	34
Expressed population signal (EPS)	0.91
First year where SSS > 0.75 (number of trees)	1865 (8)

The statistical characteristics of the STD chronology are listed in Table 1. The mean sensitivity, a measure of relative difference in widths between adjacent rings, was 0.23. The first-order auto-correlations was 0.64, indicating that the tree-ring growth of Hailar pine in the current year is to a certain extent influenced by its growth in the preceding year. The expressed population signal (EPS, Wigley et al., 1984) is 0.91, which is used to represent an acceptable level of chronology confidence. Sub-sample signal strength (SSS) was used to assess the adequacy of replication in the early years of the chronologies (Wigley et al., 1984). To utilize the maximum length of the tree-ring chronology and ensure the reliability of the reconstruction, we restricted the analysis to the period with an SSS of at least 0.75. This threshold corresponds to a minimum sample depth of 9

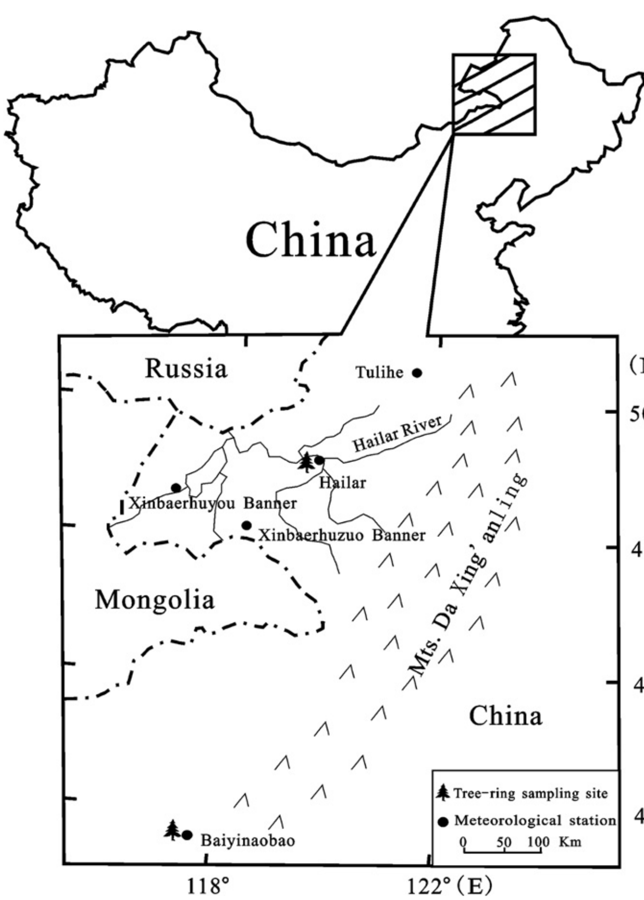

Fig. 1. Location of the sampling site and of nearby meteorological stations.

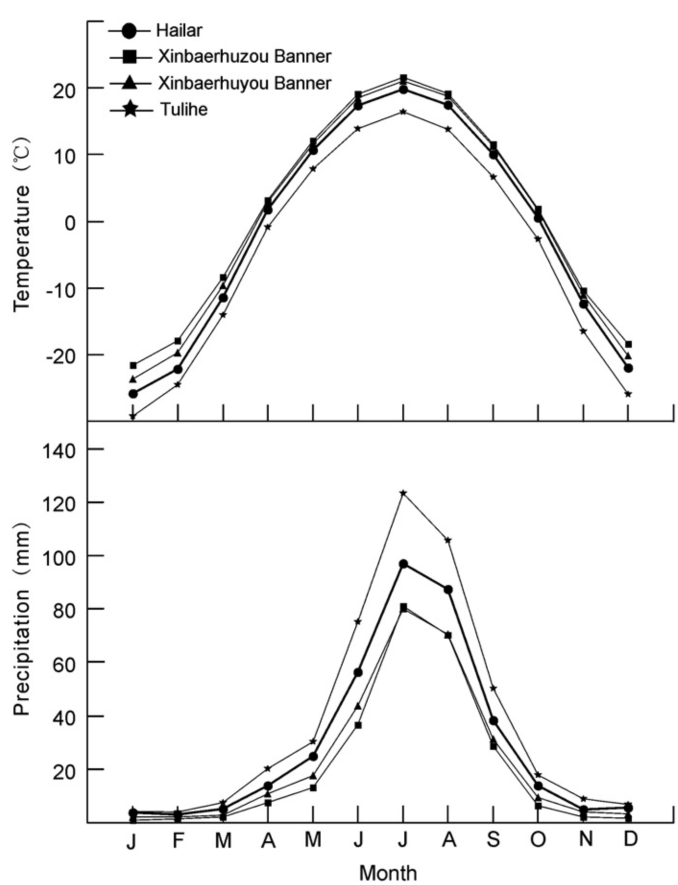

Fig. 2. Monthly mean temperature and sum of precipitation at Hailar, Xinbaerhuzuo Banner, Xinbaerhuyou Banner and Tulihe meteorological stations.

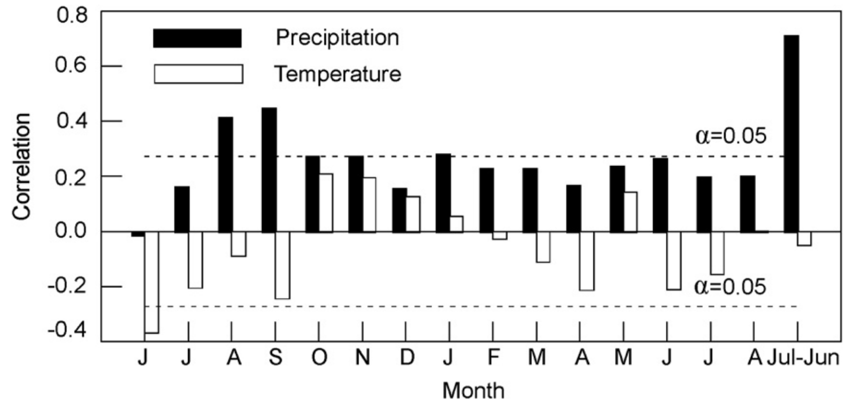

Fig. 3. Correlations between ring width and monthly sum of precipitation and mean temperature (1951–2003).

cores from 8 trees (starting from 1865). This means that the chronology is reliable after 1865.

2.3. Meteorological data

We selected four meteorological stations around the sampling site: Hailar (119°45′E, 49°13′N, 610 m a.s.l., observation interval 1951–2004), Xinbarhuzuo Banner (118°16′E, 48°13′N, 642 m a.s.l., 1958–2004), Xinbarhuyou Banner (116°49′E, 48°40′N, 554 m a.s.l., 1959–2004) and Tulihe (121°41′E, 50°29′N, 733 m a.s.l., 1957–2004). The monthly mean precipitation and temperature of each station were calculated (Fig. 2). It is clear that in this region high temperature coincides with high precipitation during summer (June to August), and *vice versa*. Hailar station, closest to the sampling site, was employed for a response analyses between ring width and climate.

2.4. Tree-ring climatic response and transfer function

Correlation function analysis was applied to investigate the relationship between tree-ring width and climate during the observation period. Monthly mean precipitation and temperature from the previous June to current August were used.

Tree-ring widths positively respond to each month's precipitation from prior July to current August (Fig. 3), the highest correlation is given to the previous September ($r = 0.45$, $p < 0.001$). In addition, ring widths are significantly related to the precipitation of August, October and November of the previous year and current January. Obviously, precipitation is the limiting factor affecting radial growth of *Pinus sylvestris* var. *mongolica* in the Hailar region in every month (where the mean annual rainfall is only 350 mm). Conversely, ring widths weakly respond to temperature, only prior June temperature significantly negatively correlates with ring widths ($r = -0.36$, $p < 0.05$).

The growing season of *Pinus sylvestris* var. *mongolica* begins in May (Wang et al., 2005). Thus in May, higher temperature and precipitation are beneficial to cambial cell divisions. However, high temperature in June and July may indirectly limit tree growth by enhancing evapotranspiration. This is why negative relationships exist between ring widths and temperature in June and July. This has a clear physiological basis.

After testing different combinations of months, we found that total precipitation from the prior July to current June (P_{76}) and ring width shows the best relationship, with $r = 0.711$ ($p < 0.0001$). Physiologically, precipitation from prior July to current June is the critical weather variable in Hailar, affecting soil moisture availability and hence tree growth.

We, therefore, reconstructed total precipitation from the previous July to current June using the STD chronology of Hailar.

The transfer function thus is designed as follows:

$$P = 222.408W_t + 133.115$$
$$\left(N = 52,\ r = 0.711,\ R^2 = 51\%,\ R^2_{\text{adj}} = 50\%,\ F = 51.18,\ p < 0.0001\right) \tag{1}$$

where P is the total precipitation from prior July to current June and W_t is the ring-width index at year t. The correlation coefficient of Eq. (1) is 0.711, the explained variance is 51% (50% after adjusted for loss of degrees of freedom) during the calibration period of 1952–2003. The F value and Durbin–Watson value are 51.18 and 1.70, respectively. Durbin–Watson statistics is a test for residual autocorrelation of the regression model. If the calculated value is larger than the significance value, it means that there is no significant autocorrelation in the model (Draper and Smith, 1981). The Durbin–Watson value is 1.70 for $n = 52$ in this study, which indicates that there is no

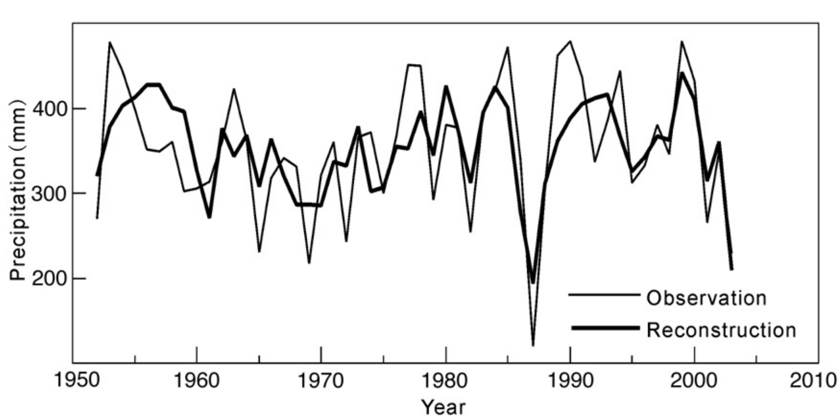

Fig. 4. Comparison between observed and reconstructed total precipitation from prior July to current June in the Hailar region (1952–2003).

Table 2
Statistical characteristics of calibration and verification of Jackknife and Bootstrap.

Statistical item	Calibration	Verification	
		Jackknife	Bootstrap (80 iterations)
		Mean (range)	Mean (range)
r	0.71	0.71 (0.65–0.73)	0.70 (0.54–0.85)
R^2	0.51	0.51 (0.42–0.53)	0.50 (0.29–0.71)
R^2_{adj}	0.50	0.50 (0.41–0.52)	0.49 (0.27–0.71)
Standard error of estimate	54.37	54.37 (53.00–54.93)	53.41 (43.09–61.71)
F	51.18	50.21 (35.47–55.76)	54.99 (20.14–124.96)
P	0.0001	0.0001 (0.0001–0.0001)	0.0001 (0.0001–0.0001)
Durbin–Watson	1.70	1.72 (1.58–1.82)	1.66 (1.28–1.74)

Table 3
Correlation between meteorological data, and comparison of reconstructed precipitation from prior July to current June in the Hailar region with meteorological data from Xinbaerhuyou Banner, Xinbaerhuzuo Banner, and Tulihe.

Station	Period	Meteorological station comparison, r (0.001)	Meteorological data vs reconstruction, r (p)
Xinbaerhuyou Banner	1960–2003	0.52	0.33 (0.027)
Xinbaerhuzou Banner	1959–2003	0.50	0.37 (0.011)
Tulihe	1958–2003	0.52	0.39 (0.007)

significant first-order autocorrelation for the period 1952–2003 in the model (1).

During the calibration period 1952–2003, the reconstructed total precipitation from prior July to current June tracked the observation very well (Fig. 4). Because of the shortness of the meteorological data set, it is not suitable to use the canonical split-sampling calibration and verification method to evaluate the quality and stability of the model (1). Instead, the Jackknife technique (Mosteller and Tukey, 1977) and Bootstrap resampling approach (Efron, 1979; Young, 1994) were applied to assess the stability and accuracy of the transfer function. Jackknife involves the calculation of the correlation coefficient for the time series after removing the values for 1 year progressively throughout the whole time period from 1952 to 2003. The idea behind the Bootstrap method is that the available observations of a variable contain the necessary information to construct an empirical probability distribution of any statistic of interest. Bootstrap can provide standard errors of statistical estimators even when no theory exists.

The statistical results including r, R^2, R^2_{adj}, standard error of estimate, F, p and Durbin–Watson value from both Jackknife and Bootstrap (with 80 interations) are quite close to those of the original regression model (1) (Table 2). These indicate that model (1) is quite stable and reliable, and can be used for the precipitation reconstruction.

The reliability of the reconstruction is also confirmed by the comparison between observed data from nearby meteorological stations not used for calibration (Table 3). This comparison could be used to better understand the regional representative of our precipitation reconstruction as well.

3. Results and discussion

The calculation shows that the total precipitation from prior July to current June is significantly correlated with the total precipitation from January to December of the previous year ($r=0.71$, $N=52$, $p<0.0001$), thus the total precipitation from prior July to current June could to a certain degree be regarded as the annual precipitation.

According to the transfer function (1), the annual precipitation from prior July to current June was reconstructed for the period from 2003 to 1865 AD (Fig. 5), with a mean of 349 mm and a standard deviation $\sigma=\pm 55$ mm. We define an extreme wet year as $>$mean$+1\sigma$, and an extreme dry year as $<$mean-1σ. The full Hailar precipitation reconstruction shows a strong interannual variability throughout the entire period 1865 to 2003 AD. In the 20th century, both the instrumental and tree-ring records are marked by extreme droughts in 1987 and 2003. Some notable dry years also occurred prior to the instrumental period (Table 4).

There are 23 dry years displayed in the Hailar rainfall reconstruction (1865–2003), accounting for 16.5% of the total. Among them, there are three severe drought events lasting more than 3 years, 1905–1909 (average precipitation 267 mm), 1926–1928 (276 mm), and 1968–1970 (286 mm). 1926–1929 is noted as experiencing a severe drought event in North China with tremendous loss of life, which has been found in many previous studies (Xu, 1997; Wang et al., 2004; Liang et al., 2006). Also 23 wet years are found in the reconstruction. Four extreme wet events lasting more than 3 years are allocated, 1867–1870 (455 mm), 1932–1934 (450 mm), 1939–1941 (424 mm) and 1955–1957 (422 mm).

In addition to the interannual fluctuations, the reconstruction also reveals that precipitation varies on the decadal time scale. When the entire reconstruction is smoothed by an 11-year moving average, two dry periods with precipitation below the mean of 349 mm are seen, 1888–1929 (324 mm) and 1963–1975 (325 mm). There are two wet

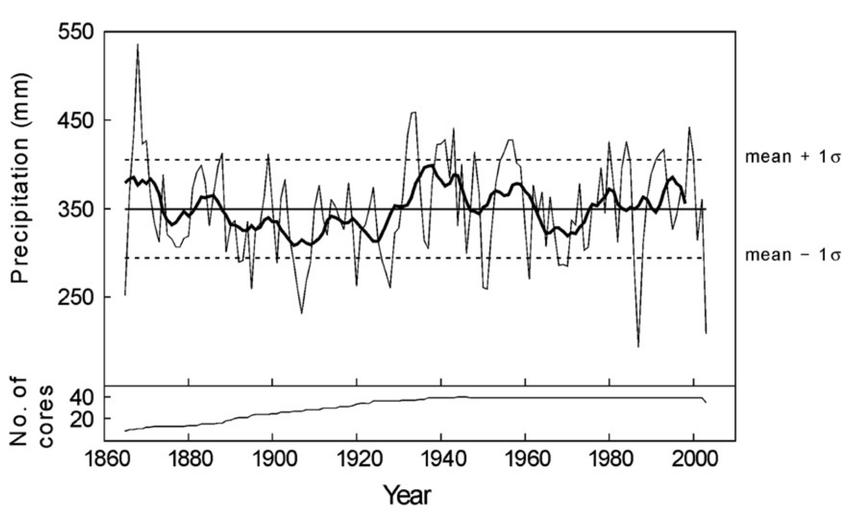

Fig. 5. (a) Reconstructed total precipitation from prior July to current June for the Hailar region during 1865–2003 AD, the smoothed line is the 11-year moving average and (b) number of cores.

Table 4
Ranking of the top ten driest and wettest years in the Hailar region annual precipitation reconstruction (from previous July to current June).

Rank	Dry year	PP_{76} (mm)	Wet year	PP_{76} (mm)
1	1987	194	1868	536
2	2003	209	1934	459
3	1907	232	1933	458
4	1865	252	1999	442
5	1906	258	1943	441
6	1895	259	1867	434
7	1951	259	1932	432
8	1928	261	1941	427
9	1950	261	1956	427
10	1920	263	1957	427

periods with precipitation above the mean, 1930–1962 (372 mm) and 1976–2003 (359 mm).

Generally speaking, the period of June to August is the summer monsoon season, and Hailar is substantially influenced by the East Asian Summer Monsoon. The calculation shows that the total precipitation from June to August accounts for 68% of the annual precipitation in the Hailar area. A strong or a weak of summer monsoon (EASM) is indicated by rainfall to a certain degree. Therefore, it is clear that the amount of annual precipitation in the Hailar region is mainly associated with the fluctuation of the strength of the East Asian Summer Monsoon (Wang, 1997). In other words, the more annual precipitation, the stronger the monsoon, and *vice versa*.

From this point of view, the above mentioned dry and wet events are related to weak or strong summer monsoons, respectively. Similarly, the dry and the wet intervals correspond to weak or strong summer monsoon periods, respectively.

To examine the temporal and spatial variations of the EASM over the northeastern region of the environment-sensitive zone, we compared our precipitation reconstruction with another precipitation curve from Baiyinaobao (see Fig. 1), 600 km south of Hailar in Inner Mongolia, a reconstruction of rainfall from April to early July was made from *Picea koraiensis* tree-ring widths in the east part of the environment-sensitive zone (Liu et al., 2003). This reconstruction could represent the early summer monsoon period. Precipitation changes at these two sites are shown in Fig. 6. After calculating the 11-year moving average, the long-term trends of the two tree-ring based precipitation reconstructions vary almost synchronously. However,

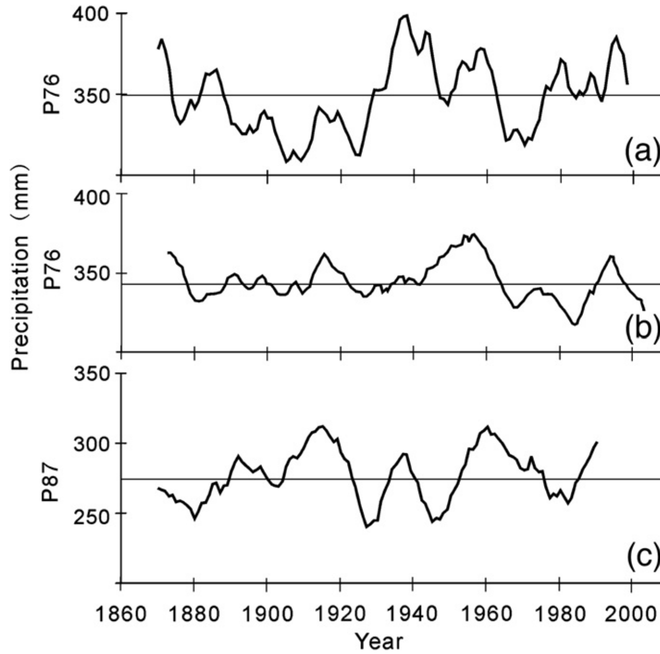

Fig. 7. Precipitation comparisons between the Hailar (a, prior July to current June, this paper), Ortindag Sand Land, east Inner Mongolia (b, prior July to current June, Liang et al., 2008), and northeastern Mongolia (c, prior August to current July, Pederson et al., 2001). All curves are smoothed by the 11-year moving average.

the precipitation reconstruction of Hailar is the annual rainfall from prior July to current June, while Baiyinaobao from April to early July. Thus we should view Baiyinaobao precipitation carefully, since it just reflects part of the monsoonal precipitation. Hailar rainfall could reflect the whole monsoonal period related precipitation.

In addition to Baiyinaobao, Hailar precipitation can be compared with other two tree-ring-width based annual precipitation reconstructions in the region (Fig. 7). One is a precipitation reconstruction from the prior August to current July (P87) for northeastern Mongolia (Pederson et al., 2001), and the other is an annual precipitation reconstruction from prior July to current June (P76) in the Ortindag Sand Land, east Inner Mongolia (Liang et al., 2008). After employing an 11-year moving average, the long-term trends of the three tree-

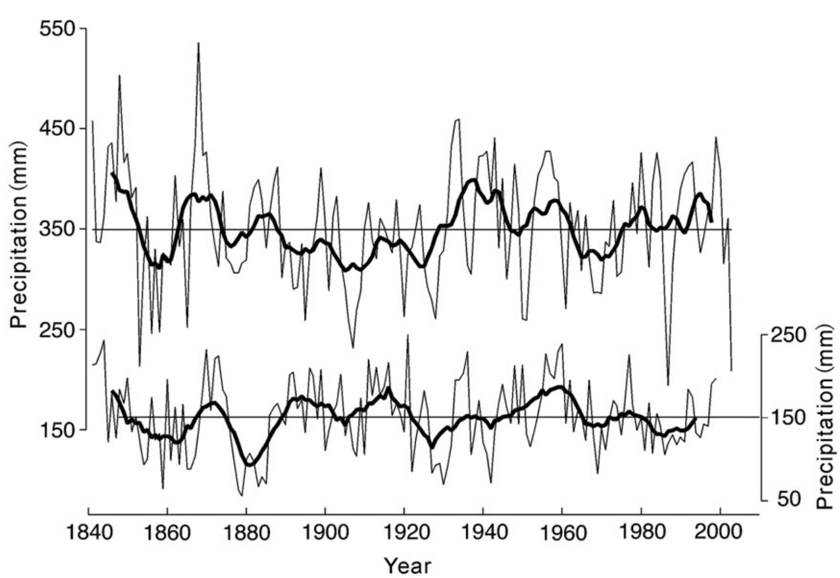

Fig. 6. Precipitation comparison between Hailar (top, prior July to current June) and Baiyinaobao (bottom, April to early July) during 1865 to 1999, the smoothed line is the 11-year moving average.

ring-width based precipitation reconstructions are quite similar. In despite of some differences, this comparison shows a spatial and temporal connection to precipitation in the eastern environment-sensitive zone, and the common trends displayed by the three time series still reveal a strong/weak fluctuation of the East Asian Summer Monsoon in these regions.

We also found that the dry period of the 1920s in Hailar corresponds well with low precipitation over northwest and northern China and the Changjiang River drainage basin at the same time span, and wet period of 1940s–1960s corresponds with more precipitation in those regions as well (Li and Zhang, 1992). Those phenomena reflect the synchronous variations of rainfall over such a large area which is controlled by the EASM.

In addition, the signal of abrupt changes of the summer monsoon from strong to weak, which was demonstrated by modern climatological analysis, is also captured by our reconstruction during the late 1960s (including the extreme dry interval from 1968 to 1970) that occurred over the whole of north China (Li and Zhang, 1992).

The precipitation reconstruction was tested for periodicities by a power spectrum analysis. The results display remarkable cycles of 7.67 and 7.08 years over the past 139 years which could be related to ENSO events (Allan et al., 1996). These periodicities imply that the precipitation of Hailar not only reflects the fluctuation of the East Asian Summer Monsoon, but also may indicate a large-scale sea–land coupling.

4. Conclusion

Precipitation is the major factor affecting the radial growth of *Pinus sylvestris* var. *mongolica* in Hailar, Inner Mongolia, northeastern China. According to the relationship between tree width and precipitation, annual precipitation has been reconstructed from prior July to current June for the period from 2003 to 1865 AD. This reconstruction accounts for 51% of the variance in instrumental data over the 1952–2003 period (50% after adjustment for loss of degrees of freedom, $N=52$, $r=0.711$, $F=51.18$, $p<0.001$). The reconstruction not only reflects the fluctuations of rainfall in the study region, but also the strong/weak variations of the East Asian Summer Monsoon to a great extent. The reconstruction agrees well with the Baiyinaobao (Liu et al., 2003), Ortindag Sand Land in Inner Mongolia (Liang et al., 2008) and Mongolia (Pederson et al., 2001) rainfall series derived from tree rings. In addition, the abrupt change of the East Asian Summer Monsoon from strong to weak during the mid-1960s to the end of 1970s was also captured. The power spectrum analysis shows that there are 7.67- and 7.08-year quasi-periodicities which may be associated with ENSO events. The results here indicate that there is a great potential to extend the tree-ring series in length in the study area, which could provide high-resolution palaeoclimatic records that span the last several centuries.

Acknowledgements

We thank Qiang Li and Lei Wang and two anonymous reviewers for their great help. This research was supported by grants from the National Natural Science Foundation of China (nos. 40525004, 40890051), the National Basic Research Program of China (nos. 2004CB720200, 2006CB400503) and State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS.

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