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Tree ring precipitation reconstruction in the Chifeng-Weichang region, China, and East Asian summer monsoon variation since A.D. 1777

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[1] The total precipitation of previous August to current July was reconstructed on the basis of the *Pinus tabulaeformis* ring widths from three sites in Chifeng and Weichang regions, China, for the past 236 years. The explained variance of reconstruction is 47.4%. The intervals with below-average precipitation (1768–2003) comprise 1779–1806, 1853–1883, 1926–1972, and 1980–1989. The intervals with above average precipitation consist of 1807–1852, 1884–1925, 1973–1979, and 1990–1999. Precipitation in the study area is dependent on the East Asian summer monsoon strength. The reconstructed series is significantly correlated with the average dryness/wetness index series of Datong and Beijing, as well as with previous results from Baiyinaobao, Helan Mountains, and even the state of Mongolia. A significant negative correlation ($r = -0.63$, $p < 0.0001$) is also found between the reconstruction and our previously reconstructed temperatures of Weichang for the period 1884–2002. Our result suggests that the variations of the East Asian summer monsoon on a decadal scale are coincident with the other regions within the environmentally sensitive zone of northern China as well as Mongolia for the past 236 years, and our reconstruction is representative of regional climate patterns.

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1. Materials and Methods

[2] An environmentally sensitive zone, with an area greater than 654,000 km^2 [*Zhao et al.*, 2002], stretches from northeast to southwest China extending along the 200–400 mm isolines of precipitation. This is a transitional zone between semiarid to arid conditions, monsoon and non-monsoon climate, forest and steppe, as well as agriculture and husbandry. The zone has a diversified variety of climatic and physiographic conditions and is extremely sensitive and vulnerable to environmental changes. The environmentally sensitive zone is closely associated with the East Asian summer monsoon variations. Strong summer monsoon might cause flooding while weak summer monsoon might bring droughts, though monsoon rainfall is a critical factor for vegetation growth. The zone has been targeted as a key area for soil erosion control in recent years. An understanding of the East Asian summer monsoon evolution, as well as of the processes and mechanisms of climate changes in the zone, serves as the basis for studying environmental issues associated with the zone. However, there is still a lack of high-resolution proxy climatic data, though tree ring records have been used in a few climatic change studies in the area [*Liu and Ma*, 1999; *Liu et al.*, 2001a, 2001b, 2002, 2003]. Therefore the study of climate change in greater depth and breadth is still needed. In this study, tree ring widths from the Chifeng and Weichang regions were used to study precipitation in connection with summer monsoon variability for the past 236 years on the east edge of the environmentally sensitive area. Furthermore, the reconstruction was compared with other studies to determine whether or not there was a connection between climatic change and the East Asian summer monsoon variability in a larger spatial and temporal context.

[3] The study area, Chifeng and Weichang, is located in southeast Inner Mongolia adjacent to the North China Plain. Controlled by continental monsoon in the area, seasonal dry and wet conditions alternate in response to intrusion of dry-cold air masses from high latitudes in winter and warm-humid air masses from low latitude oceans in summer (the East Asian summer monsoon). Droughts frequently occur in each season, especially in spring and summer. Sandstorms and dust storms frequently occur as well. The annual mean maximum temperature in the area is 11.6°C, and minimum −1.8°C, and annual mean precipitation around 300–460 mm [*Wang*, 1990; *Gu*, 1991]. Intense summer rainfall, spatial inhomogeneity, and a marked interannual variability are

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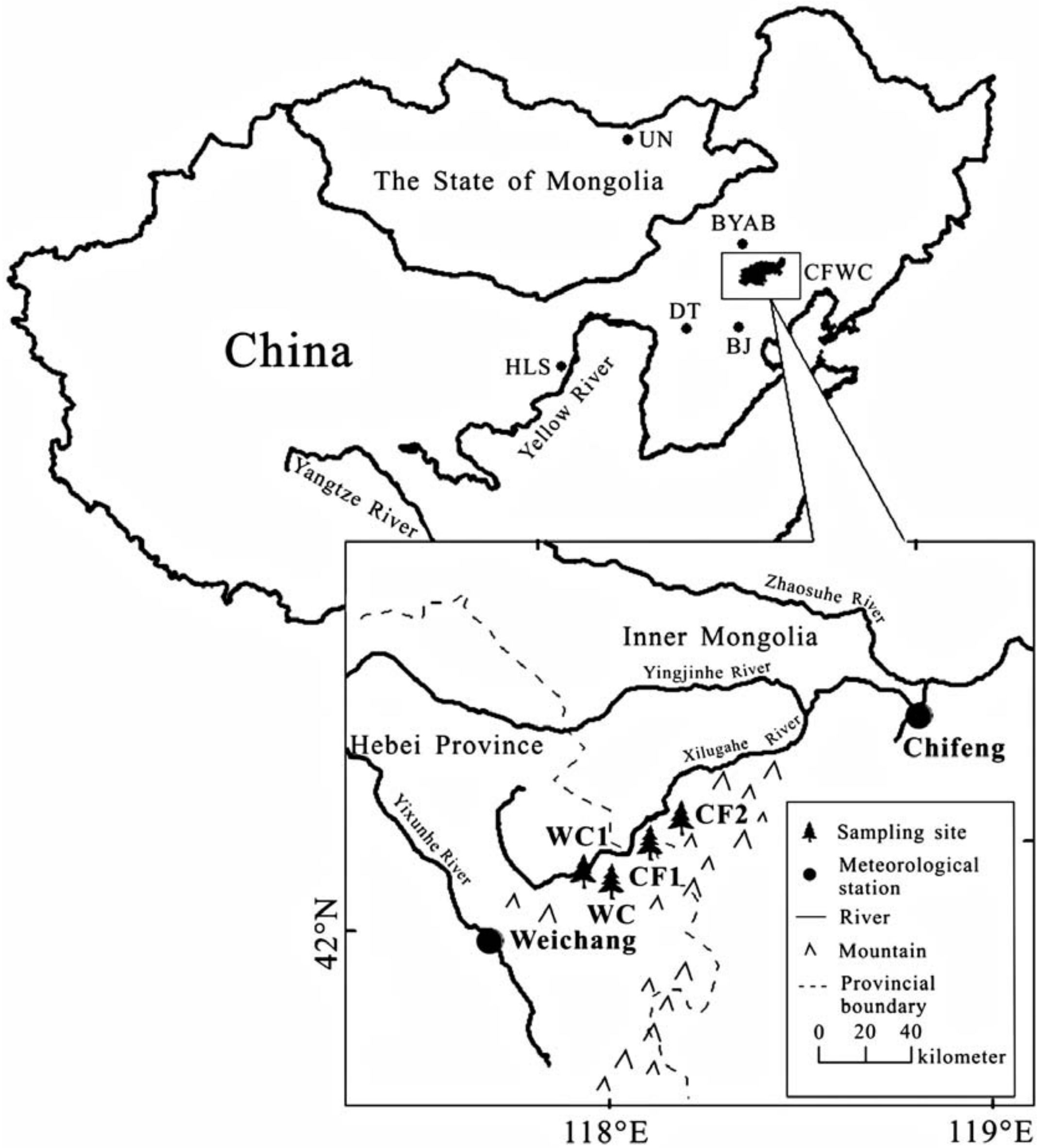

Figure 1. Sampling sites and meteorological stations. The map contains four other sampling sites in China (BYAB, Baiyinaobao; HLS, Helan Mountains), and one in the state of Mongolia (UN, Urgun Nars), all used in previous reconstructions. The average dryness/wetness indices of DT (Datong) and BJ (Beijing) were compared with the tree ring reconstructions in this paper.

characteristic of precipitation in the area, where summer rainfall accounts for 60%–70% of annual total precipitation [*Wang*, 1990; *Gu*, 1991].

[4] The sampling sites are covered with stunted trees or vegetation and sparse Chinese pine trees (*Pinus tabulaeformis* Carr.), which grow on thin soil (10–20 cm deep) with poor nutrition. These sites are very open, with 50–200 m distance between individual trees.

[5] For the study, tree ring samples of Chinese pine were collected from three sites: Chifeng 1, twenty-four trees collected (CF1, 118°09′51″E, 42°06′44″N, elevation 1000 m); Chifeng 2, nine trees (CF2, 118°08′24″E, 42°06′21″N, elevation 1100 m); and Weichang 1, ten trees (WC1, 118°02′36″E, 42°03′56″N, elevation 1000–1100 m) (Figure 1).

[6] In the laboratory, tree ring samples were surfaced, cross-dated, and measured following standard dendrochronological procedures [*Stokes and Smiley*, 1996]. The quality control of crossdating was performed with COFECHA program [*Holmes*, 1983]. Samples from all three sites contain a large number of absent rings, e.g., the percentage of absent rings for CF1 is up to 4.4%. High correlation coefficients and average mean sensitivity for all sites reveal a synchronous and a strong response to environmental factors.

Table 1. Statistical Features of CFWC Chronology

Statistic	CFWC
Mean	0.97
Skewness	0.41
Kurtosis	−0.003
Mean sensitivity	0.42
Standard deviation	0.41
First-order autocorrelation	0.29
Mean correlation between all series	0.48
Mean correlation between trees	0.46
Mean correlation within a tree	0.60
Signal-to-noise ratio	11.26
Variance in first PC (%)	50.10
Expressed population signal	0.92
Subsample signal strength (SSS) > 0.75 (trees)	1777 (3)
SSS > 0.80 (trees)	1790 (7)

[7] For each site, ARSTAN program [*Cook*, 1985] was used for detrending. In order to retain as much low-frequency signal as possible, each individual ring-width measurement series was detrended conservatively with only negative-exponential curves or linear regression curves of any slope. This procedure reduces the undesirable growth trends related to age and stand dynamics unrelated to climatic variations. After that, the individual index series were combined into a single chronology by computing a biweight robust mean.

[8] Analysis suggested that the correlation coefficient between any pair of CF1, CF2, and WC1 was significant ($r = 0.76$–0.83, $p < 0.0001$). Therefore ring-width variability of the three series was constrained by a common growth limiting factor since the tree sites are not widely separated. To capture climate change information in a larger spatial context, we considered creating a new chronology combining all ring-width measurement series from three sites (CF1, CF2, and WC1) and running the ARSTAN program again. The new chronology obtained from ARSTAN was named CFWC and is used in later analysis in this paper.

[9] Subsample signal strength (SSS) [*Wigley et al.*, 1984] was used to assess the adequacy of replication in the early years of the chronologies. SSS is a measure of the quality of the tree ring index curve, where values close to 1 are achieved when the included trees reflect a hypothetical mean curve for the population; this is achieved either if the trees display strong common growth variability or if there are a large number of samples. To utilize the maximum length of the tree ring chronologies and ensure the reliability of the reconstructions, we restricted our analysis to the period with an SSS of at least 0.75. This threshold corresponds to a minimum sample depth of three trees for the CFWC (from 1777). The statistical features of CFWC chronology are shown in Table 1.

2. Climatic Data and Correlation Analyses

[10] The observed records from the Chifeng (118°58′E, 42°16′N, elevation at 571.1 m) and Weichang (117°45′E, 41°56′N, elevation at 842.8 m) meteorological stations were employed here to analyze the effects of climate on tree growth. Both of the stations have records running from 1951 to 2003. The monthly mean precipitation and the temperature of Chifeng and Weichang are shown in Figure 2. Rainfall from June to August comprises a major proportion of annual total precipitation (about 68% of the annual total) with a peak in July. The region experiences abundant rainfall and synchronous high temperature in the summer period. Since the sampling sites are located between Chifeng and Weichang, we used the averaged climatic data from two stations for further analysis.

[11] Correlation results between the CFWC chronology and the averaged climatic data set of the two stations show that precipitation of previous August, September, and October and current May, June, and July is significantly

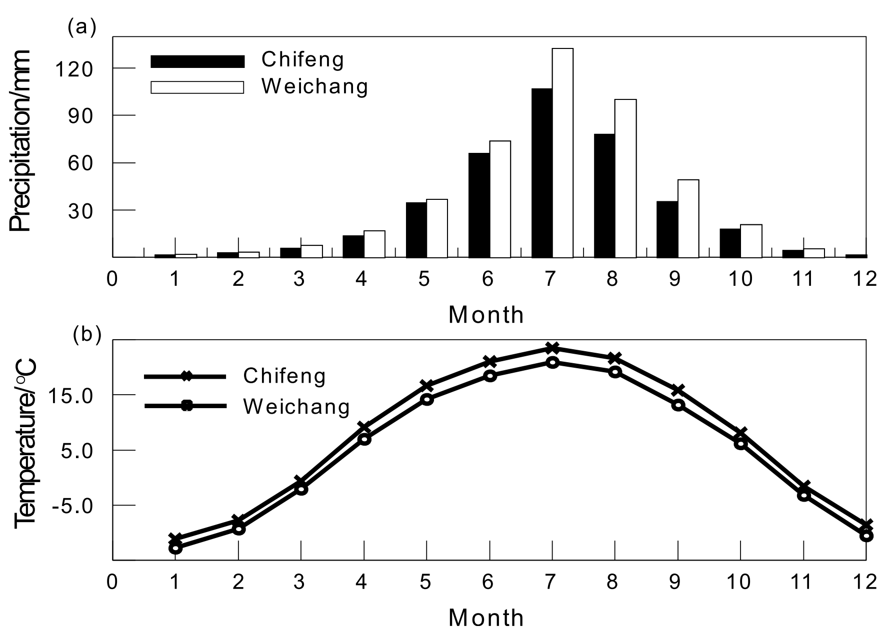

Figure 2. Monthly mean precipitation and the temperature of Chifeng and Weichang (1952–2003).

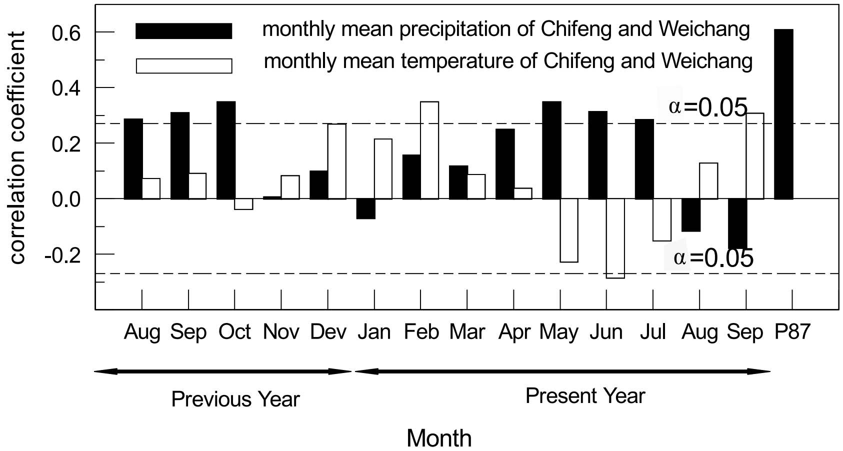

Figure 3. Correlation histogram between the meteorological data and the CFWC chronology (1952–2003).

positively correlated with CFWC ring width indices at the 95% confidence level (Figure 3). Meanwhile, the relationships between the temperature and the CFWC chronology are not so strong and only significantly correlated with current February (positively) and June (negatively).

[12] Physiologically, these correlations could be explained as follows. The precipitation from August to October in the previous year is the critical factor for nutrient storage for next year's growth. High temperatures in February could speed up root system activity, and be beneficial to nutrient absorption and transportation. In May, the presummer monsoon season with low rainfall causes dry soils and affects tree growth. And in June, accelerated evapotranspiration as temperature rises leads to water deficiency.

[13] Thus the correlations between tree growth and climatic factors have reasonable physiological meanings. In sum, tree growth in CFWC is better correlated with precipitation than with temperature (Figure 3). Therefore we used the CFWC chronology to reconstruct regional precipitation history for the period 1777–2003.

3. Transfer Function

[14] Since prior August to current July (P87) spans two growing seasons, it could be assumed that ring width of either previous year or current year were closely linked to the total precipitation P87. Therefore a multiple regression model was used to reconstruct the total precipitation of P87.

[15] The transfer function is designed as follows:

$$P = 180.838^{*} W_t - 84.127^{*} W_{t-1} + 318, \qquad (1)$$

where P is the total precipitation from previous August to current July, and W_t and W_{t-1} are the indices of the CFWC chronology at the t year and $t - 1$ year, respectively. In equation (1), $N = 52$, $r = 0.688$, $R^2 = 42.7\%$, $R^2_{\mathrm{adj}} = 40.3\%$, $F = 17.51$, standard error = 75.19, $p < 0.0001$, $t = 10.56$, Durbin-Watson = 1.94 (Durbin-Watson, D/W, is a test statistic used to detect the presence of autocorrelation in the residuals from a regression analysis. A D/W statistic close to 2 indicates no autocorrelation among residuals [*Durbin and Watson*, 1951].

[16] For the calibration period 1952–2003, the predictor variable accounts for 40.3% of the variance (adjusted for loss of degrees of freedom) of precipitation data. Figure 4 shows the comparison between observed and tree ring estimated total precipitation of previous August to current July over the Chifeng-Weichang regions for the interval of 1952–2003. The comparison suggests that the observed precipitation series during the calibration period is closely

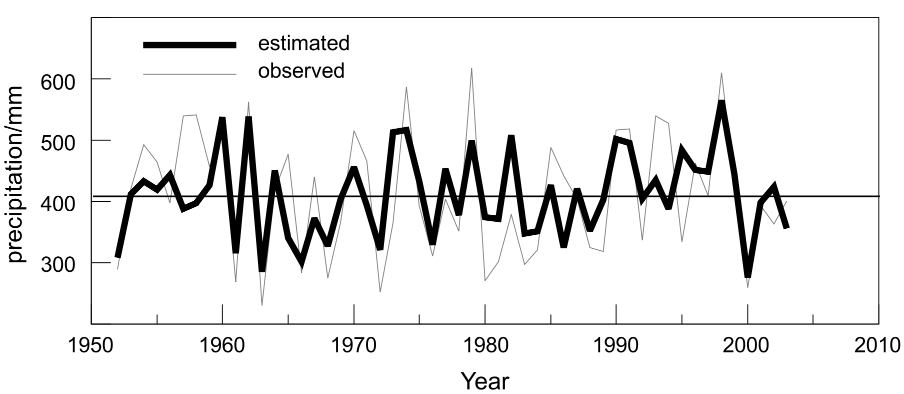

Figure 4. Comparison between the observed and tree ring estimated total precipitation from the prior August to the current July for Chifeng-Weichang regions (1952–2003). Horizontal line is the long-term mean (410 mm).

Table 2. Verification Results of Bootstrap and Jackknife

		Verification Period (A.D. 1952–2003)	
Statistic	Calibration Period (A.D. 1952–2003)	Bootstrap (80 Iterations) Mean (Range)	Jackknife Mean (Range)
r	0.69	0.68 (0.44–0.85)	0.69 (0.66–0.72)
R^2	0.47	0.47 (0.12–0.72)	0.47 (0.44–0.52)
R^2adj	0.45	0.45 (0.17–0.72)	0.45 (0.41–0.50)
SE	75.19	74.31 (57.56–90.88)	75.20 (72.59–75.97)
t	10.56	10.34 (7.19–14.31)	10.46 (9.79–11.08)
F	22.05	23.72 (6.03–65.17)	21.66 (18.44–25.75)
p	0.0001	0.0001 (0.0001–0.005)	0.0001
D/W	1.94	1.94 (1.62–2.21)	2.00 (1.79–2.17)

consistent with the reconstruction, especially for dry years, such as 1961, 1963, 1972, and 2000. Thus the reconstruction is confirmed to be reliable and further supports the proposition that tree growth is sensitive to precipitation in the Chifeng-Weichang region.

[17] Meanwhile, the bootstrap resampling technique [*Efron*, 1979] and the jackknife method [*Mosteller and Tukey*, 1977] were applied to verify the reliability and stability of our reconstruction. Proposed in 1979 by Efron, the idea behind the bootstrap resampling technique is that the available observations of a variable contain the necessary information to construct an empirical probability distribution of any statistic of interest. The bootstrap can provide standard errors of statistical estimators even when no theory exists. The jackknife method was first proposed by *Quenouille* [1949] and involves the calculation of the correlation of the time series after removing the values or one year progressively throughout the whole time period.

[18] In this paper, 80 iterations were carried out during the bootstrap resampling. The results obtained from bootstrap and jackknife analysis revealed that all values of r, R^2_{adj}, standard error, F-value, p-value, t-value, and Durbin-Watson statistics are close to the values found in the full data set (Table 2). The small differences between each statistical parameter indicate that the calibration regression model (1) for the Chifeng-Weichang regions is stable and reliable during the calibration period. Consequently, the model (1) can be employed to reconstruct precipitation for the periods devoid of instrumental meteorological records.

[19] However, we have to note that the jackknife results suggest that 1973 was an outlier from the model. If we omit this year, the explained variance of the precipitation rises to 51.7%. The observed data show that Chifeng-Weichang experienced a severe drought in 1972 (its 253 mm was the lowest P87 precipitation since the beginning of instrumental record). Its effect on tree growth might continue into the next year and led to the anomaly in reconstruction for 1973. Although 1972 is an unusual year, we did not remove it from the model (1) since we cannot discount the possibility that similar events have happened in the past.

4. Reconstruction and Analysis

4.1. Precipitation Reconstruction of Previous August to Current July in Chifeng-Weichang During A.D. 1768–2003

[20] The total precipitation of previous August to current July for 1768–2003 in Chifeng-Weichang was reconstructed on the basis of the transfer function (1) and presented in Figure 5, where the smoothed line is an 11 year moving average, and the horizontal line is the mean precipitation (412 mm for 1768–2003) with a standard deviation σ = 71.4 mm.

[21] We also have to mention that precipitation of P87 is significantly correlated with the total precipitation of current January to December (r = 0.633, N = 53, p < 0.0001), so it may to a large extent be representative of annual total precipitation.

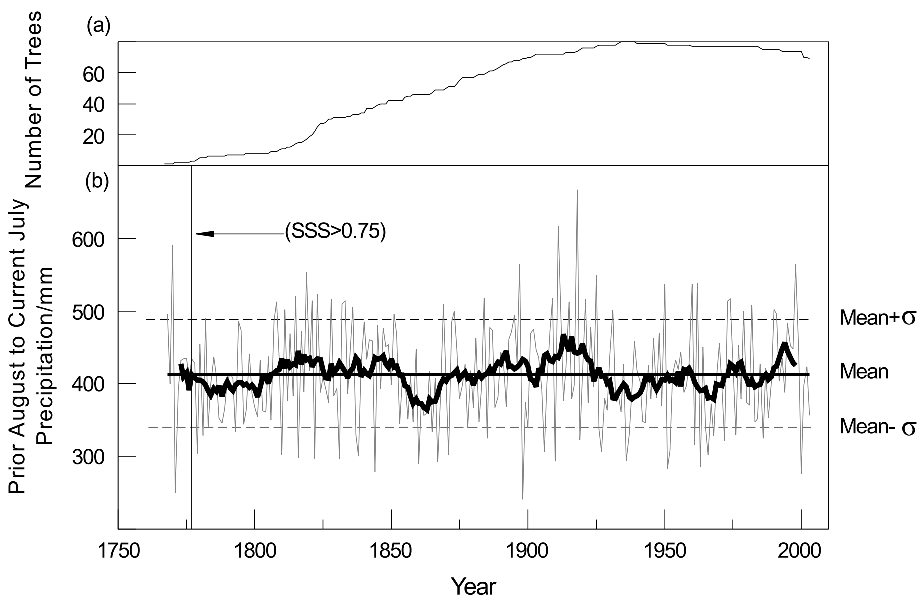

Figure 5. (top) Sample depths. (bottom) Precipitation reconstruction from prior August to current July (thin line) for Chifeng-Weichang regions, 11 year moving average (thick line), the long-term mean of A.D. 1777–2003 (horizontal solid line, 412 mm).

Table 3. Dryness/Wetness Intervals for the Chifeng-Weichang Regions During A.D. 1777–2003

Dry Intervals, Weak Monsoon (Mean Precipitation (m))	Wet Intervals, Strong Monsoon (Mean Precipitation (m))
1980–1989 (388)	1807–1852 (430)
1853–1883 (390)	1884–1925 (436)
1779–1806 (391)	1973–1979 (446)
1926–1972 (393)	1990–1999 (462)

[22] Rainfall in Chifeng-Weichang is heavily influenced by the East Asian summer monsoon [*Huang et al.*, 1999; *Yu et al.*, 2009]. The monsoon is active during June to August, and rainfall of this period is dominated by the strength of monsoon. The strength of summer monsoon is indicated by rainfall to a certain degree. As stated earlier, the rainfall from June to August accounts for 68% of annual. Therefore P87 precipitation in the study region is mainly associated with the strength variations of the East Asian summer monsoon. More annual precipitation corresponds to a stronger monsoon year, and vice versa.

[23] From this point of view, drought events are related to weak summer monsoon years, and wet years related to strong summer monsoon. Similarly, the dry (or the wet) intervals are the weak (or the strong) summer monsoon periods.

[24] In this study we define a dry year as <mean − 1σ, and a wet year as >mean + 1σ, respectively. Within the reconstructed 236 year series, 37 years are categorized as a "dry year" (accounting for 16.7% of the whole series), and 42 years are categorized as a "wet year" (accounting for 17.8%), while the remaining 157 years are categorized as a "normal year" (accounting for 64%). Analysis of frequent extreme years indicates wet years are largely concentrated during 1807–1840 (with 12 wet years) and 1895–1925 (with 9 wet years). Wet years are twice more frequent than dry years during 1807–1840 and 1895–1925. Dry years are more frequent since 1900, especially during the period of 1926–1976 (with 13 dry years).

[25] The period 1895–1925 seems extremely vulnerable to flooding (very strong monsoon period) when there were three years (1897, 1911, and 1918) with precipitation exceeding mean + 2σ, but only one year (1898, the minimum 241.2 mm over the reconstructed history) lower than mean −2σ. In contrast to conditions described earlier, dry years are twice more frequent than wet years during 1926–1976.

[26] In the entire reconstructed precipitation series (1777–2003), some intervals are below average owing to weak monsoon, such as, 1779–1806, 1853–1883, 1926–1972, and 1980–1989, while other intervals are above average owing to strong monsoon, such as, 1807–1852, 1884–1925, 1973–1979, and 1990–1999 (Table 3).

4.2. Comparison Between Precipitation Reconstruction and Dryness/Wetness Indices

[27] We compare the Chifeng-Weichang precipitation reconstruction with the historical document derived dryness/wetness indices for Chifeng [*Academy of Meteorological Science*, 1981] and found obvious discrepancies. Primarily, such discrepancies might be attributed to (1) omissions and inconsistency in historical records at Chifeng, and (2) misrepresentations of historical facts, which led to unreliable dryness/wetness grading.

[28] Then the series of average dryness/wetness indices from two cities adjacent to our sampling sites, Beijing and Datong, were compared with our reconstruction. When they are all smoothed by an 11 year moving average, a significant correlation was found between them (Spearman correlation $r = -0.318$, $N = 135$, $p < 0.0001$). The reconstructed series corresponds well to the dryness/wetness series regarding various dry/wet intervals, as well as to the extremely rainless years (Figure 6). Such a relationship is ascribed to similarity in both climate (360–450 mm with heavy rainfall during July–September) and interannual variability in precipitation between Beijing-Datong and the sampling sites, Chifeng-Weichang. In fact, Bejing-Datong and the study region are all situated in the environmentally sensitive area controlled by the East Asian summer monsoon climate. However, we should note that there are some differences between the dryness/wetness series and our reconstruction before 1840, and two kinds of series conveyed different climatic signals. For example, during 1780–1800, the reconstruction displays a dry period, but the dryness/wetness series showed a wet one. The differences between tree ring records and dryness/wetness indices are also found in other sites [*Liu et al.*, 2001a, 2001b, 2003]. We should bear in mind that tree ring records are more objective and reliable than historical documents.

4.3. Comparisons With Other Precipitation and Temperature Reconstructions

[29] To investigate whether or not there was a connection between our precipitation reconstruction in Chifeng-Weichang regions and the other East Asian summer monsoon related precipitation in a larger spatial and temporal context, we select three tree ring–based reconstructions for comparison. The first one is from the northern Helan Mountains, the second from Baiyinaobao (those two sites are within the environmentally sensitive area linked to the East Asian summer monsoon [*Liu et al.*, 2002, 2003]), and the third one from the state of Mongolia [*Pederson et al.*, 2001] (Figure 1).

[30] After applying an 11 year moving average, the reconstructed precipitation series of the study region can be compared to that of Helan Mountains and Baiyinaobao and Mongolia (Figure 7). For example, both the wet intervals (1869–1875 and 1886–1921, with the strong summer monsoon) and the dry ones (1851–1868 and 1922–1943, with the weak summer monsoon) in the Baiyinaobao reconstruction are present in our reconstruction. Meanwhile, the synchronous variations of precipitation in our reconstruction and that of Helan Mountains (located in the western part of the environmentally sensitive area) and Mongolia are also observed.

[31] The distinguished severe drought occurring in the late 1920s over the whole of northern China was commonly captured by the four precipitation curves, and this event was found in many previous studies [*Liu and Ma*, 1999; *Li and Zhang*, 1992; *Liang et al.*, 2003; *Xu*, 1997]. In the Chifeng-Weichang region since late 1920s, although the precipitation has a slowly increasing trend, the amount of rainfall is lower than the mean most of the time.

[32] The weakening of the East Asian summer monsoon circulation after the end of the 1970s [*Wang*, 2001] is pre-

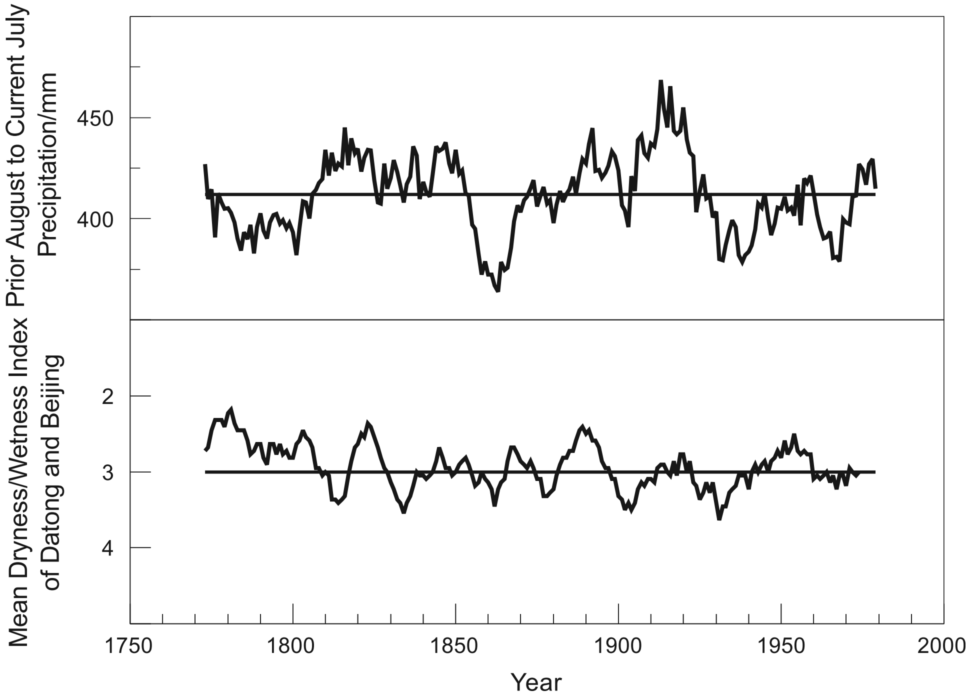

Figure 6. Comparison between the total precipitation in Chifeng-Weichang and dryness/wetness indices of Beijing-Datong. Two curves are smoothed by an 11 year moving average.

cisely captured by the precipitation reconstruction, indicating tree growth in the study region is sensitive to variability in summer monsoon to a certain degree.

[33] The great flooding of 1998, recorded in the precipitation series of Helan Mountains [*Liu et al.*, 2005], is also captured by our reconstruction (Figure 5). The amount of rainfall reconstructed in that year was up to 565 mm, which was more than mean + 2σ. In fact, 1998 was the second strongest monsoon year in more than 130 years. Twenty-two provinces, covering 89% of China's land territory, suffered from flooding disasters with 14 million people homeless and 5 million houses destroyed, with over US$20 billion in estimated damages (http://lwf.ncdc.noaa.gov/oa/reports/chinaflooding/chinaflooding.html).

[34] The comparisons suggest that variability in precipitation across the entire East Asia summer monsoon related area of northern China is consistent at larger spatial (even including the state of Mongolia) and temporal scales (on decadal).

[35] In addition, the reconstruction is also highly negatively correlated with the previous May to June temperature reconstruction of Weichang [*Liu et al.*, 2009] since 1884 ($r = -0.63$, $N = 118$, $p < 0.0001$). The correlation is even better after 1900 ($r = -0.66$, $N = 102$, $p < 0.0001$). Applying an 11 year moving average, the patterns of variation of the two curves are almost opposite (Figure 8). Therefore early summer climate in the Chifeng-Weichang region is characterized by cool/wet or warm/dry quite similar to that of Huangling [*Liu et al.*, 1996]. It is no-

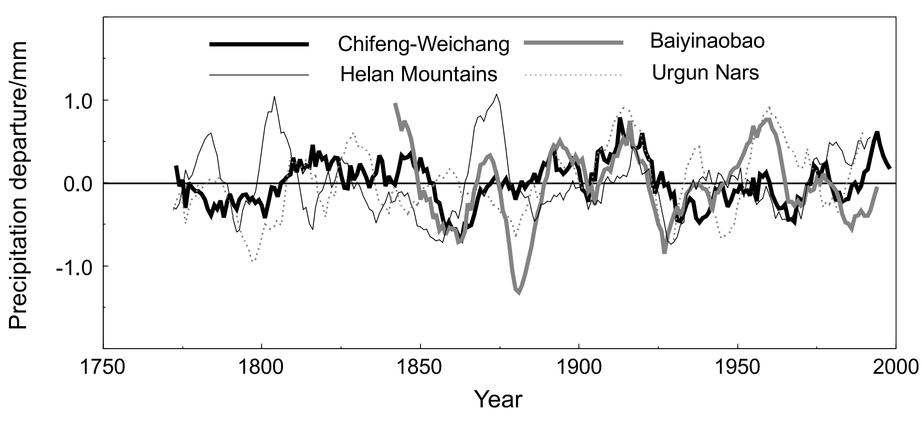

Figure 7. Comparison of the precipitation departure within Chifeng-Weichang, Helan Mountains, Baiyinaobao, and Urgun Nars (state of Mongolia). Four curves are smoothed by an 11 year moving average. The horizontal line is the zero line.

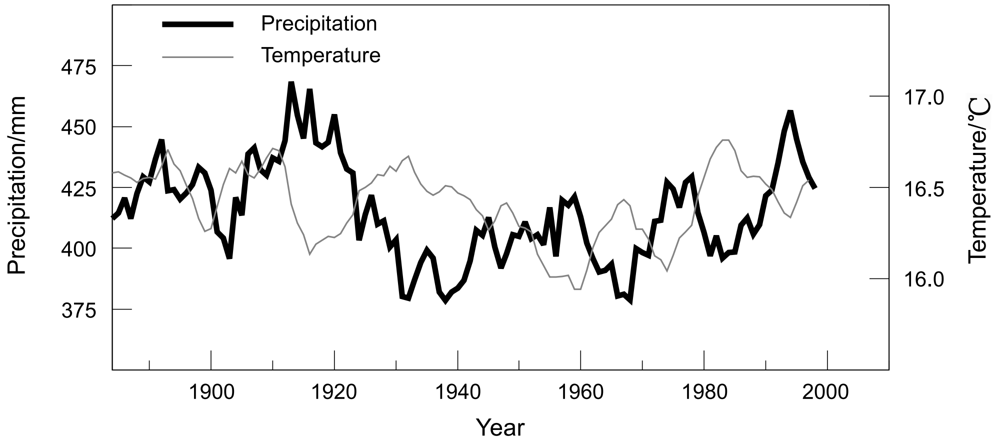

Figure 8. Comparison between the prior August to current July precipitation and May to June mean temperature of Weichang. Both curves are smoothed by an 11 year moving average.

table that both May to June temperature and precipitation are on the rise on a long-term scale since 1960s despite their negative correlation.

5. Conclusions

[36] Tree ring width series from three sites were used to reconstruct the total precipitation of previous August to current July since 1777. Variability in Chifeng-Weichang precipitation is closely linked to changes in the East Asian summer monsoon. Episodes of low precipitation, i.e., 1779–1806, 1853–1883, 1926–1972, and 1980–1989, are attributed to weak summer monsoon. On the other hand, episodes of high precipitation, i.e., 1807–1852, 1884–1925, 1973–1979, and 1990–1999, are attributed to strong summer monsoon.

[37] Monsoon rainfall in Chifeng-Weichang is in good agreement with reconstructions from Baiyinaobao, Helan Mountains, which are also within the environmentally sensitive area of northern China. The reconstruction is even comparable with that from Mongolia. The variabilities of the East Asian summer monsoon related precipitation are synchronous at larger spatial and temporal scales (on decadal) within the environmentally sensitive area of northern China.

[38] The reconstructed precipitation series is negatively correlated with our previous reconstructed temperature series in Weichang. Such a relationship suggests the dominant climate regime in the study region is either cool/wet or warm/dry.

Notation

r coefficient/multiple correlation.
p statistically significant.
SSS subsample signal strength.
N sample size.
R^2 squared multiple correlation.
R^2_{adj} adjusted squared multiple correlation.
F F ratio.
P the total precipitation from previous August to current July, in millimeters.
W_t the index of the CFWC chronology at the t year.
W_{t-1} the index of the CFWC chronology at the $t-1$ year.
σ standard deviation, in millimeters.

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