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The Radial Growth of Schrenk Spruce (*Picea schrenkiana* Fisch. et Mey.) Records the Hydroclimatic Changes in the Chu River Basin over the Past 175 Years

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Abstract: The Chu River is one of the most important rivers in arid Central Asia. Its discharge is affected by climate change. Here, we establish a tree-ring chronology for the upper Chu River Basin and analyze the relationships between radial growth, climate, and discharge. The results show that the radial growth of Schrenk spruce (*Picea schrenkiana* Fisch. et Mey.) is controlled by moisture. We also reconstruct a 175-year standardized precipitation-evapotranspiration index (SPEI) for the Chu River Basin. A comparison of the reconstructed and observed indices reveal that 39.5% of the variance occurred during the calibration period of 1952–2014. The SPEI reconstruction and discharge variability of the Chu River show consistent long-term change. They also show that the Chu River Basin became increasingly dry between the 1840s and the 1960s, with a significant drought during the 1970s. A long and rapid wetting period occurred between the 1970s and the 2000s, and was followed by increasing drought since 2004. The change in the SPEI in the Chu River Basin is consistent with records of long-term precipitation, SPEI and Palmer Drought Severity Indices (PDSI) in other proximate regions of the western Tianshan Mountains. The hydroclimatic change of the Chu River Basin may be associated with westerly wind. This study is helpful for disaster prevention and water resource management in arid central Asia.

Keywords: tree rings; Schrenk spruce (*Picea schrenkiana* Fisch. et Mey.); hydroclimatology; Chu River; Tianshan Mountains; climate change; Central Asia

1. Introduction

It is widely recognized that global warming has occurred since the mid-19th century [1]. However, corresponding hydroclimatic changes demonstrate significant regional variations [2]. Arid Central Asia (ACA) covers 5×10^6 km^2, and includes Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Xinjiang in northwest China. Drought is a major climate disaster in ACA and the cause of considerable agricultural, economic and environmental damage. The Tianshan Mountains, which extend across the region, are known as the "water towers" of Central Asia, and are the largest and most important mountain system in ACA. The region is especially sensitive to climate change [3,4]. Obvious warming in the Tianshan Mountains has been detected at a rate of 0.3 °C/10 years [5], and persistent warming is exacerbating droughts and water shortages. The Chu River, which originates in the Tianshan Mountains, is one of the longest rivers in ACA. Its river basin is shared by Kyrgyzstan (where the river originates) and Kazakhstan, and its waters feed millions of people and support the social development and economic prosperity of both countries. Hence, it is particularly important to understand long-term hydroclimatic changes in the Chu River Basin. However, the sparse and unevenly distributed meteorological and hydrological stations in the region provide limited data for understanding the region's climate and water resource variations [6]. As proxy data is also limited, long-term climate change research for the region is lacking. However, Schrenk spruce (*Picea schrenkiana* Fisch. et Mey.) is distributed throughout the Tianshan Mountains, and its radial growth is an ideal proxy for past climate change [7].

Tree-ring proxies are an important source of high-resolution, absolutely dated information about the hydroclimate of the Common Era (C.E.). They are widespread and well replicated, and they can be statistically calibrated against overlapping instrumental records to produce validated reconstructions and associated estimates of uncertainty in past climate variability at an annual resolution [8]. Recent studies have increasingly shed light on the historical moisture variability of arid Central Asia [7,9,10]. However, because moisture availability is especially variable in mountains, localized hydroclimatic reconstructions are needed. The history of hydroclimatic change in the Chu River Basin is still unclear, despite the river's importance.

In this study, we established a tree-ring-width chronology using tree-ring samples collected in the Chu River Basin in 2014. We analyzed the radial growth of Schrenk spruce and its response to climate, and reconstructed the standardized precipitation-evapotranspiration index (SPEI) to understand past changes in moisture availability. We also examined the relationship between the hydroclimatic changes over the last 175 years and large-scale oscillations in the climate system.

2. Data and Methods

2.1. Study Area

The Chu River is one of the longest rivers in Central Asia (73°24′–77°04′ E, 41°45′–43°11′ N), with a length of approximately 1067 km and a drainage area of 62,500 km^2 (Figure 1). The river starts in Kyrgyzstan and runs through the country for 115 km before becoming the border between Kyrgyzstan and Kazakhstan for 221 km. The last 731 km are in Kazakhstan. It is one of the longest rivers in both Kyrgyzstan and in Kazakhstan, and is fed mainly by glaciers and melting snow; rainfall is of secondary importance.

Like most rivers in arid regions, the Chu River is an inland river, originating in the middle ranges of the Tianshan Mountains and disappearing in the desert. After passing through the narrow Boom Gorge, the river enters the comparatively flat Chu Valley, within which the Kyrgyz capital of Bishkek and the Kazakh city of Chu are located. Much of the Chu's water is diverted into a network of canals to irrigate the fertile black soils of the Chu Valley for farming, both on the Kyrgyzstan and Kazakhstan sides of the river. Finally, the Chu River disappears in the Moyynqunm Desert. The study area is located in the headwater region of Chu River Basin [11].

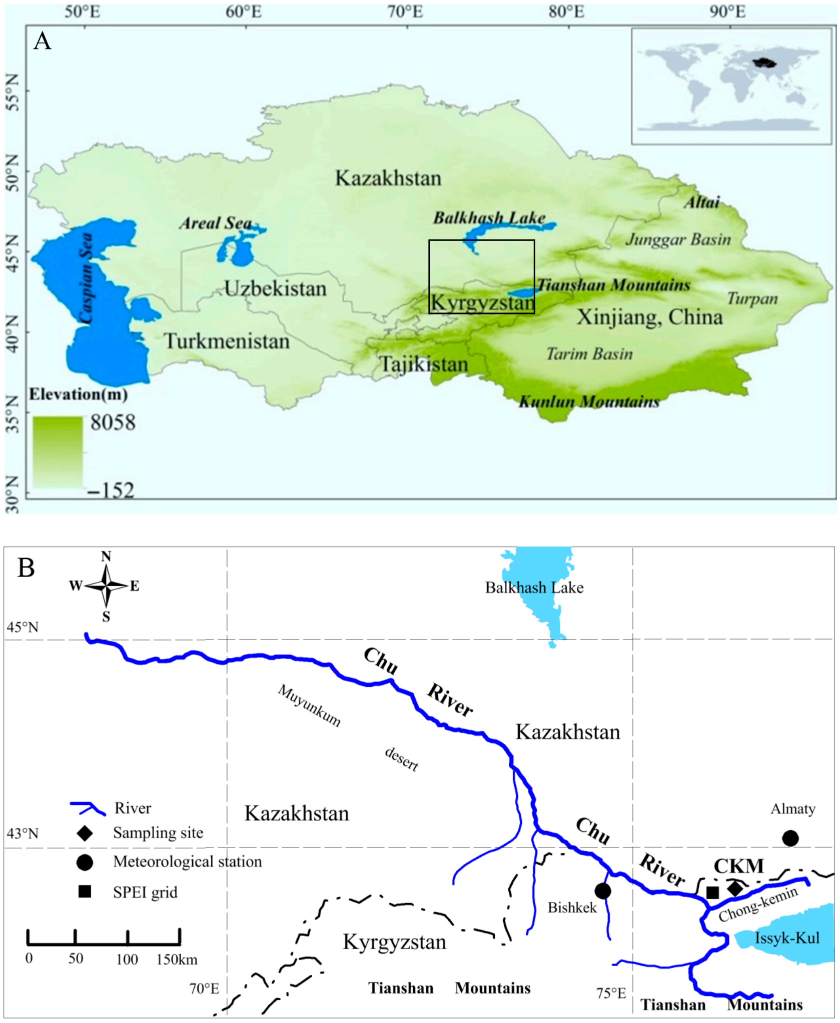

Figure 1. Map of tree-ring sample sites information. (**A**) Map of arid Central Asia; (**B**) Sketch map of tree-ring sampling site, meteorological station and SPEI grid.

2.2. Tree-Ring Data

We collected tree-ring samples on the southwestern Zailiy Alatau Range in northern Kyrgyzstan. The sampling site was located near the Chong Kemin River (76°23′ E, 42°48′ N, elevation 2400 m, designated the "CKM" group). Forty-one increment cores were collected from 21 trees in virgin forest. The pure Schrenk spruce forests distributed in the shady slopes of mountains. We chose trees with larger slopes, thinner soil layers, less competition and less interference, which radial growth is limited by the climate. The trees with no injury and disease were sampled in order to minimize the signal of non-climatic effects on tree growth.

Following standard dendrochronological methods, all tree-ring cores were brought to the Key Laboratory of Tree-ring Physical and Chemical Research of China Meteorological Administration, dried naturally, mounted, and sanded with progressively finer grains sizes until the ring structures were clear. The samples were then cross-dated with skeleton plots and measured with 0.001 mm precision using a Velmex measuring system [12]. The quality of the cross-dating was checked with the COFECHA program [13] to ensure exact dating. We developed a site chronology using established standardisation techniques with the program ARSTAN [14]. We chose the negative exponential curve (NEC) method to de-trend the growth trend. We used a subsample signal strength (SSS) of 0.85 as an appropriate cut-off criterion for climate reconstructions [15] (Figure 2). The SSS is a measure of decreasing predictive power of transfer functions due to reductions in the sample size of underlying tree-ring series back in time [16].

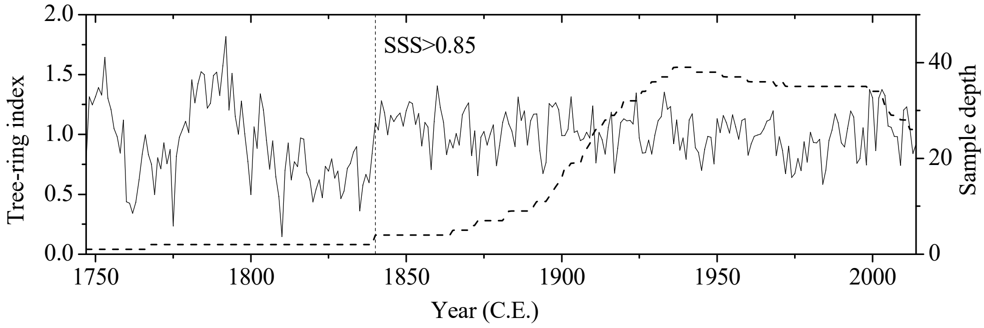

Figure 2. Tree-ring-width chronology (STD) in the Chu River Basin.

2.3. Meteorological and Hydrological Data

We collected the monthly mean temperature (1896–1988) and precipitation (1895–2004) data from the Frunze meteorological station (43.82 N, 74.58 E, 756.0 m) as a climate background analysis, because it is located in the Chu River Basin. We also used standardized precipitation-evapotranspiration index (SPEI) data (1901–2014) from the nearest grid (42.75° N, 76.25° E). The SPEI is based on monthly precipitation and potential evapotranspiration data from the Climatic Research Unit of the University of East Anglia and can represent drought intensity. The Global SPEI database offers long-term, robust information about drought conditions at the global scale, and has a 0.5 degree spatial resolution. The main advantage of the SPEI Global Drought Monitor is thus its near real-time character, a characteristic best suited for drought monitoring and early warning purposes [17]. The average annual total discharge of the Chu River is derived primarily from runoff from the Chu Valley (not including the Cochkor Valleys). We used the average annual total discharge from 1970–1999 [18].

The mean temperature from 1925 to 1988 and the total precipitation from 1950 to 2000 were analyzed because the meteorological data were discontinuous. The mean temperature was 10.3 °C and average annual precipitation was 429.0 mm over their respective periods. An analysis of the climate data indicates that both the temperature and the precipitation of the Chu River Basin have increased (Figure 3A). The amplitudes are 0.1 °C/10a and 6 mm/10a, respectively. Monthly mean temperature peaks in summer, whereas the average monthly precipitation of the Chu River Basin is bimodal and peaks in spring (March to May) and winter (October to December) (Figure 3B).

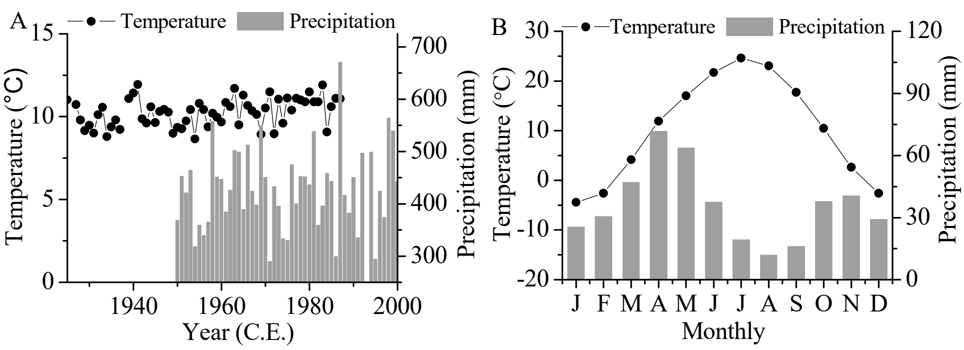

Figure 3. Annual (**A**) and monthly (**B**) changes in mean temperature (1925–1988) and total precipitation (1950–2000) at the Frunze meteorological station.

2.4. Methods

We used the Pearson correlation coefficient to analyze the relationship between the tree-ring chronologies and SPEI, and a linear regression model to perform the reconstruction [19]. The SPEI reconstruction was conducted on the basis of a split calibration-verification procedure that was designed to test the reliability of the model [20]. The length of the final reconstruction equals the longest nested regression model that still has good calibration and verification results. Spectral properties of both reconstructions were investigated using a multi-taper method (MTM), a powerful tool in spectral estimation that is particularly effective for short time series [21].

3. Results

3.1. Tree-Ring Response to Climate and the Reconstructed SPEI

Correlation and response analysis revealed significant correlations between the SPEI and tree growth during both the previous and current growing seasons. The greatest single correlation between the CKM tree-ring-width standard chronology (Figure 2) and SPEI from the previous July to current June was 0.629 ($n = 64$, $p < 0.001$). Moisture from the previous July to current June was the dominant climatic factor for tree growth in the Chu River Basin.

Based on the results of the correlation analysis, we reconstructed SPEI from the previous July to current June for the Chu River Basin. The transfer function was

$$SPEI_{p7c6} = 0.911 \times CKM - 0.753 \quad (1)$$

where $SPEI_{p7c6}$ is the SPEI from the previous July to current June, and CKM is the Chro-Kemin chronology detrended by the negative exponential curve fitting with and without application of an adaptive power transformation. For function (1) during the calibration period (1951–2014), the reconstruction explained 39.5% of the variance (38.6% after adjustment for loss of degrees of freedom) in the SPEI data, with $n = 64$, $r = 0.629$, $F_{1, 62} = 40.53$, and $p < 0.0001$ (Figure 4).

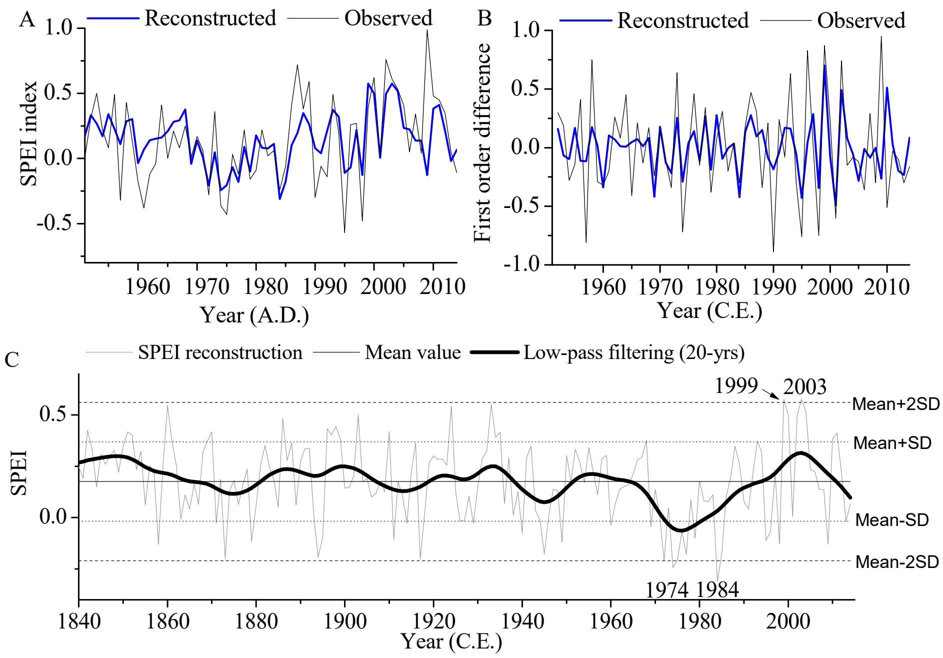

Figure 4. Reconstructed SPEI variability of the Chu River Basin. (**A**) Comparison of the reconstructed SPEI (blue line) and the SPEI recorded in grid from CRU (black line) during the common period 1951–2014. (**B**) Comparison of the first differences (year-to-year changes) between the reconstruction (blue line) and the SPEI grid (black line). (**C**) Reconstructed SPEI from the previous July to the current June for the Chu River Basin since 1840 C.E. (gray line). The bold black line shows the data smoothed with a 20-years low-pass filter to emphasize the long-term fluctuations. The solid horizontal line represents the long-term mean for the period 1840–2014; the dashed horizontal lines represent the mean value ± 1σ and the dotted horizontal lines represent the mean value ± 2σ.

A leave-one-out cross-validation test indicated that the regression model passed all verification tests (Table 1). We also verified the reliability and stability of the model using split-sample calibration-verification tests. The explained variances are relatively high during the two calibration periods. All of the correlation coefficient (r), first order difference correlation (rd), explained variance (R^2), F-test (F), product mean test (t), sign test (ST) and first order difference sign test (ST1) achieved or surpassed the 95% significance level. The reduction of error (RE) and coefficient of efficiency (CE) which are particularly rigorous indicators of reconstructed reliability, were both positive, suggest that the linear regression equation was statistically validated. Finally, we compared the first differences with the SPEI grid and obtained a correlation coefficient of 0.514 ($p < 0.001$, $n = 63$) (Figure 4B). This indicates that there is good consistency in the high frequency changes between the reconstruction and the observed. Equation (1) was therefore used successfully to reconstruct SPEI from the previous July to current June in the Chu River Basin for the period 1840–2014 (Figure 4C).

Table 1. Statistics of the leave-one-out cross-validation and the split-sample calibration-verification test model for the SPEI reconstruction.

Leave-one-out Cross-validation Test									
	r	r_d	ST	ST1	t	RE			
SPEI	0.599 **	0.470 **	47+/17− **	42+/21− *	4.803 **	0.357			
Split-sample Calibration-verification Test									
Calibration				Verification					
Period	r	R^2	F	Period	r	RE	CE	ST	ST1
1951–1982	0.653	0.426	22.33	1983–2014	0.594	0.409	0.263	22+/10−	22+/9− *
1983–2014	0.594	0.353	16.33	1951–1982	0.653	0.494	0.235	25+/7− **	19+/12−
1951–2014	0.629	0.395	40.53						

* indicate significance at the 95% level of confidence. ** indicate significance at the 99% level of confidence.

3.2. Changes in Moisture over the Past 175 Years

As shown in Figure 4C, the number of drought years and wet years are consistent: 15% (27a) of the years exceeded the mean + 1σ (standard deviation), and 16% (28a) were lower than the mean—1σ. Extreme drought years occurred in 1974 and 1984, when the SPEI was lower than the mean—2σ. Conversely, 1999 and 2003 were extremely moist years with SPEI exceeding the mean + 2σ.

The reconstruction was subjected to 20-year low-pass filtering in order to further understand the low-frequency change in SPEI over the past 175-years (Figure 4C). The results revealed five drying periods and four wetting periods. The drying periods occurred in 1840–1873, 1904–1917, 1934–1945, 1956–1974, and 2004–2014; wetting prevailed in 1874–1903, 1918–1833, 1946–1955, and 1975–2003. Notably, the climate in the Chu river basin over the past 175-years presents a slow process of drought from the 1840s to the 1960s, and a significant drought in the 1970s. Then, the SPEI change exhibited a long period of rapid wetting from the 1970s to 2000s. Since 2004, however, there has again been a strong drying trend, even dropping lower than the average value in the last 3 years.

4. Discussion

Many previous studies have confirmed that the radial growth of Schrenk spruce growing at lower elevations is limited by moisture conditions prior to the growing season [7,9,10,22–25]. Zhang et al. [26] analyzed intra-annual radial growth based on data from continuously monitored dendrometers and suggested that moisture between late May to late June is a limiting factor for the radial growth of Schrenk spruce in the Tianshan Mountains. Studies of tree-ring widths and their relation to climate for conifers in arid and semiarid sites iteratively demonstrate that ring-width growth is influenced not only by the climate during the growing season, but also by climatic conditions in the autumn, winter, and spring prior to the growing season [12].

Changes in the SPEI in the Chu River Basin over the past 175-years are consistent with the dry/wet changes in the western Tianshan Mountains (Figure 5). Numerous studies have shown a trend of increasing precipitation from the 1980s [27]. Shi et al. [28] further suggested that the climate in Xinjiang shifted from warm-dry to warm-wet in the 1980s. Several recent studies have also shown that precipitation and the PDSI have decreased since 2004 [9,10]. This study further confirms the moisture fluctuation phenomenon in recent years.

We compared the consistency of the SPEI reconstruction with other studies in the western Tianshan Mountains (Figure 5) and found that past moisture changes in the region are very consistent. The correlation coefficient between the SPEI reconstruction and southern Kazakhstan [9], Dzungarian Alatau [10], and Issyk Lake [7] are 0.596 (Pearson, $n = 175$, $p < 0.0001$), 0.482 (Pearson, $n = 175$, $p < 0.0001$), and 0.399 (Pearson, $n = 131$, $p < 0.0001$), respectively. These strong correlations confirm that the SPEI reconstruction is reliable. To determine the spatial representation of the SPEI reconstruction, we analyzed its spatial correlation with the precipitation, SPEI, and scPDSI data from the CRU-TS grid datasets. The results showed that the SPEI reconstruction successfully represents the changes in climate over the whole of Central Asia during the past century, especially in Kyrgyzstan and southeast Kazakhstan (Figure 6).

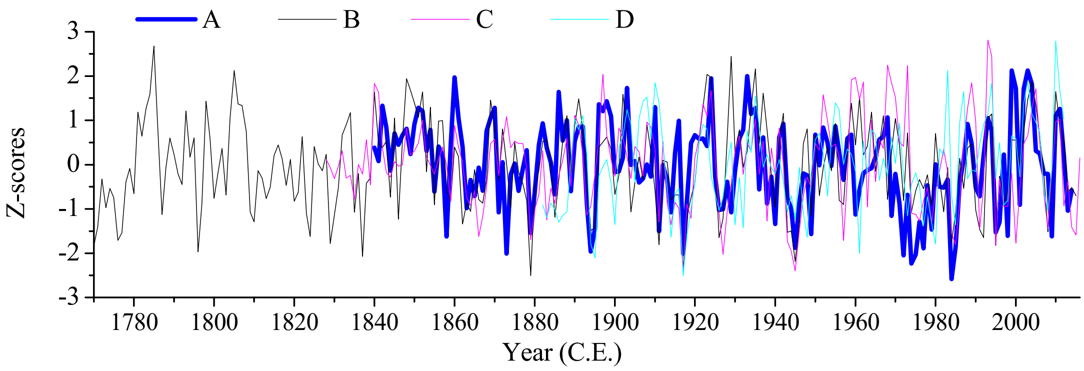

Figure 5. Comparison of SPEI reconstruction from this study and other studies in the western Tianshan Mountains. (**A**) Reconstructed SPEI in Chu River Basin (this study); (**B**) Reconstructed precipitation in southern Kazakhstan [9]; (**C**) Reconstructed PDSI in Dzungarian Alatau [10]; (**D**) Reconstructed precipitation in Issyk-Kul, Kyrgyzstan [7].

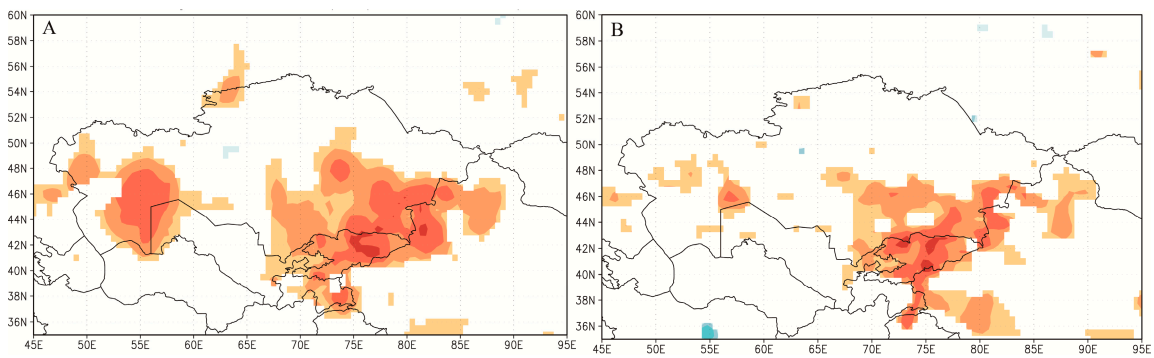

Figure 6. *Cont.*

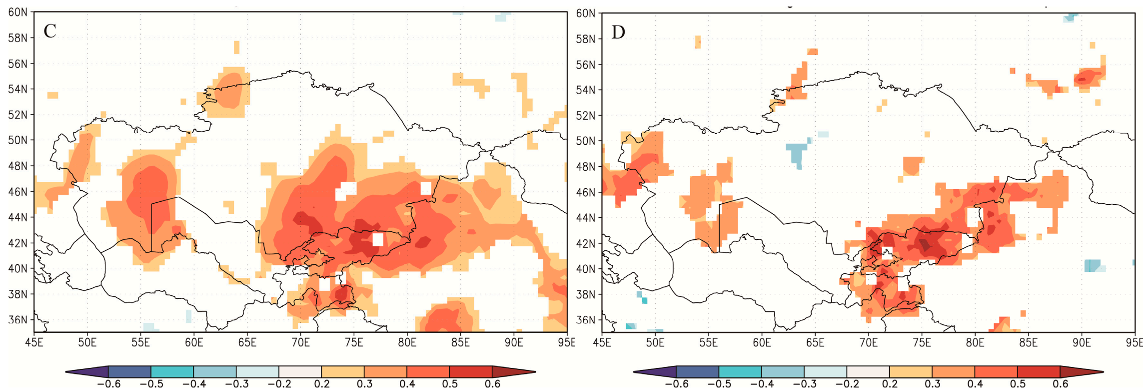

Figure 6. Spatial correlation between the reconstruction and previous July to current June grid data (1951–2012). (**A**) Precipitation data from the CRU-TS 3.22; (**B**) Precipitation data from the Global Precipitation Climatology Centre (GPCC) V7; (**C**) SPEI; (**D**) scPDSI.

A comparison of the SPEI reconstruction and discharge variability of the Chu River indicates consistent long-term change (Figure 7). The correlation coefficient between the reconstruction and discharge is 0.540 (n = 30, p < 0.01) from 1970 to 1999. Discharge out of the Tianshan Mountains is strongly influenced by climate change because moisture mainly is supplied by atmospheric precipitation and snow melt. The SPEI reconstruction is therefore representative of the long-term trend in discharge.

Strong inter-annual SPEI change was identified using the multi-taper method (MTM) [29]. There are significant 2.0-year, 2.6-year, 2.8–2.9-year and 4.4-year periods in the Chu River Basin (Figure 8). These periods suggest that the moisture of the Chu River Basin originates from the westerly circulation. In particular, a study suggested the 2–3-year period is linked to variations in the westerly circulation in the mid troposphere [30]. Other studies have found that the 2–3-year period characterizes precipitation or drought change in arid Central Asia [31–33], and suggest that the periodicity may be related to the tropospheric biennial oscillation (TBO) [34]. Because the upper stream westerly plays an important role in moisture variations in arid Central Asia by influencing the transport of water, the TBO signal is likely related to variations of the westerly.

We also compared the correlation between change in the SPEI and sea surface temperatures (HadISST1). Our results indicate that the SPEI has a significant positive correlation with North Atlantic SSTs (Figure 9). The correlation is strong for both the past 30 years and the past century. These periods have frequently been noted in other dendroclimatology and dendrohydrology studies of the Tianshan Mountains [7,9,10,35] and of other arid and semiarid regions in northern China [36,37]. We therefore posit that changes in the SPEI in the Chu River Basin may be related to westerly circulation.

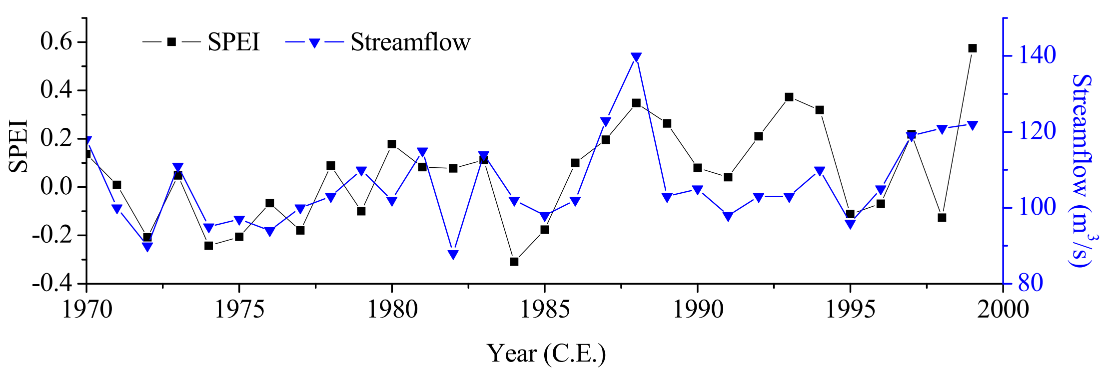

Figure 7. Comparison of the SPEI reconstruction and discharge of the Chu River.

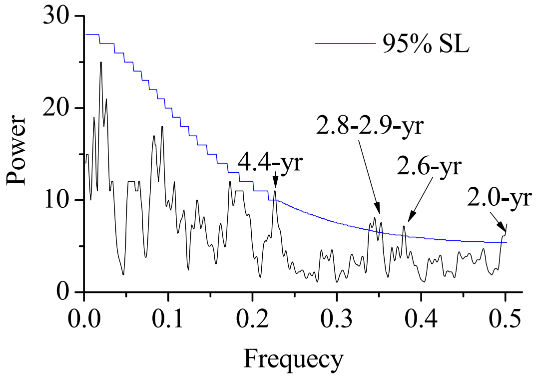

Figure 8. Multi-Taper Power spectra for the reconstructed SPEI (AD 1840–2014). 95% SL represents the 95% significance level.

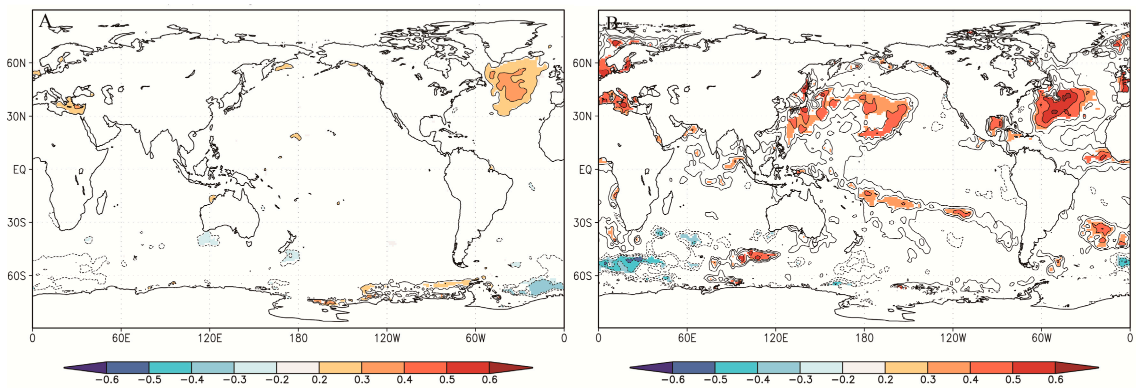

Figure 9. Correlation between the SPEI and sea surface temperature (HadISST1). (**A**) Relationship between the reconstruction and July-June HadlSST1(1870–2013) $p < 10\%$; (**B**) Relationship between the reconstruction and July-June HadlSST1(1981–2010) $p < 10\%$.

5. Conclusions

In previous dendroclimatological studies in the Tianshan Mountains, we found that long-term changes in moisture have a strong local character [7,9,10,26,38,39]. The consistency of the change decreases rapidly with increasing distance. It is therefore important to develop a more robust network of reconstruction if we are to fully understand the hydroclimatic changes in the Tianshan Mountains. To this end, we developed the first tree-ring chronology for the Chu River Basin, one of the most important basins in Central Asia. Climate-growth response results suggest that moisture before and early in the growing season is the dominant factor controlling the radial growth of Schrenk spruce in the Chu River Basin. Although moisture varies considerably in mountain areas, our research indicates that the radial growth of Schrenk spruce has a stable response to moisture in the Tianshan mountains.

We also developed a reliable 175-year SPEI reconstruction for the Chu River Basin. We found that past moisture changes in the western Tianshan Mountains are very consistent. Our reconstruction showed a slow, long-term process of drought from the 1840s to the 1960s, followed by a long and rapid wetting from the 1970s to the 2000s. Our reconstruction also provides further evidence for a drought trend since 2004. We posit that long-term changes in the SPEI in the Chu River Basin may be related to large-scale oscillations in the climate system. This study further advances dendroclimatology in the Tianshan Mountains, and is helpful for disaster prevention and water resource management in arid Central Asia.

Author Contributions: Conceptualization, R.Z.; Data curation, R.Z. and L.Q.; Formal analysis, R.Z. and L.Q.; Funding acquisition, R.Z.; Investigation, R.Z., B.E., T.Z. and M.A.; Methodology, L.Q.; Resources, R.S.; Validation, L.Q.; Writing—original draft, R.Z.; Writing—review & editing, R.Z.

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Conflicts of Interest: The authors declare no conflict of interest.

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