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ORIGINAL PAPER

Climatic change in southern Kazakhstan since 1850 C.E. inferred from tree rings

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Abstract

Although global warming is an indisputable fact, there is still uncertainty about how climate change will occur at regional levels. Kazakhstan is the largest landlocked country in the world. To best manage this country's limited water resources, socio-economic development and environmental protection, a solid understanding of regional climate change impacts is needed. In this study, tree-ring width and $\delta^{13}C$ chronologies were established based on 99 tree-ring samples of Schrenk spruce (*Picea schrenkiana Fisch.* et Mey.) collected in Almaty, Kazakhstan. Climate response analysis between the tree-ring chronologies and climate data indicates that summer mean temperature is the strongest climate signal recorded by tree-ring $\delta^{13}C$. We reconstructed temperature change in southern Kazakhstan since 1850 C.E. using the tree-ring $\delta^{13}C_{corr}$ chronology. The results show that the temperatures in southern Kazakhstan have risen at a rate of about 0.27 °C per decade over the past 166 years. However, the rate has increased by as much as 0.44 °C per decade over the past 30 years. Analyses of temperature and precipitation data show that the climate has alternated between warm-dry and cold-humid periods over the past 166 years. The extreme droughts of 1879, 1917 and 1945 were caused by the combination of continuously high temperatures and reduced precipitation.

Keywords Dendroclimatology · Temperature reconstruction · Tree-ring · $\delta^{13}C$ · Tianshan Mountains

Introduction

Global warming since the mid-nineteenth century has been widely recognised (Karl et al. 2009), and the associated changes in climate are currently an issue of scientific challenge and political debate. However, climate changes have strong regional expression. Central Asia is an arid inland region that is quite sensitive to climate change (Unger-Shayesteh et al. 2013). Analyses of instrumental observations in Kazakhstan show increasing trends in temperature and weak, decreasing trends in precipitation from 1941 to 2011 (Salnikov et al. 2015). The temperature of southern Kazakhstan exhibits an overall increasing trend since 1913, which has accelerated since 1982 (Cherednichenko et al.

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2015). However, it remains unclear how the climate of this region has changed over the long-term, i.e., prior to the instrumental period. This uncertainty restricts our ability to understand how climate change has affected this region in a long-term context. To overcome this limitation, we must use proxy data.

Tree rings are a well-established proxy for climate data and play a central role in providing information about the last several millennia of global climate change (Briffa et al. 2001; Esper et al. 2002; Palmer et al. 2006; Cook et al. 2010; Büntgen et al. 2011). Numerous drought reconstructions (e.g., precipitation, PDSI, SPEI, streamflow and snow cover) have been developed for arid Central Asia (Yuan et al. 2001, 2003; Cook et al. 2010; Solomina et al. 2012, 2014; Zhang et al. 2016a, c, d, 2017a, b, c; Qin et al. 2016; Panyushkina et al. 2018) because the radial growth of Schrenk spruce (*Picea schrenkiana Fisch.* et Mey.), a dominant species in this region, is driven by moisture. However, long-term changes in temperature remain unclear. To reconstruct temperature in the Tianshan Mountains and determine how temperature is changing in the context of global warming, we have to use a different proxy.

Stable carbon isotopes of tree rings are also proxies of past climate change. As a key part of the terrestrial carbon cycle, trees assimilate atmospheric carbon and allocate it during growth processes (Locosselli 2017). Trees are therefore both important terrestrial carbon sinks and large potential carbon pools (Malhi et al. 2011). Temperature controls carbon isotope fractionation by affecting stomatal conductance and photosynthetic rate. Based on stable carbon isotopes in tree rings, many studies have been conducted to reconstruct the historical temperature changes in the region (Helle et al. 2002; Treydte et al. 2009; Gagen et al. 2007; Young et al. 2010), including arid and semi-arid regions (Liu et al. 2002; Xu et al. 2011; Wang et al. 2015). Xu et al. (2014) suggested that the tree-ring $\delta^{13}C$ of Schrenk spruce has a positive response to temperature in the Urumqi River basin of Xinjiang, China.

In this study, we developed tree-ring width and stable carbon isotope chronologies for southern Kazakhstan and analyse the response of trees in this region to climate change. We then reconstructed summer temperatures over the past 166 years for southern Kazakhstan based on the tree-ring carbon isotope chronology. Finally, we discuss how climate change has affected and will continue to impact the region.

Data and methods

Study sites

The study area is located near Almaty in southern Kazakhstan. Almaty is the largest city in Kazakhstan, with a population of 1,801,713 people, about 8% of the country's total population. It is located on the north slope of the western Tianshan Mountains (Fig. 1). Schrenk spruce is widely distributed at elevations between 1200 and 3500 m a.s.l. and forms pure forests unique to the Tianshan Mountains. Schrenk spruce has become the preferred tree species for dendroclimatology research in arid Central Asia thanks to its characteristics of long age, clear rings and sensitivity to climate.

We collected tree-ring samples of living Schrenk spruce on the northern slope of the western Tianshan Mountains. Samples were collected above the Chimbulak Ski Resort, near the timberline of the Medeu Mountains (CSR, 43° 07′ N, 77° 05′ E, 2525 m a.s.l.) (Fig. 1). We collected 44 cores from 26 trees at breast height using Swedish increment borers with 12-mm diameter.

Establishment of the tree-ring width and $\delta^{13}C$ chronologies

Samples were pre-treated using standard dendrochronology procedures in the China Meteorological Administration's Key Laboratory of Tree-ring Physical and Chemical Research. Ring widths were measured to a precision of 0.001 mm using a Velmex system (Velmex Inc., Bloomfield, NY, USA), following visual cross dating (Fritts 1976). Ring width series were crossdated visually with plots, and dating was checked using the COFECHA program (Holmes 1983). Tree-ring width chronologies were developed using the ARSTAN program (Cook 1985; Cook and Krusic 2011). To retain low-frequency variability within the tree ring data, we used standard chronology (STD) for further analyses (Cook and Holmes 1986).

The process of extracting stable carbon isotope data was introduced in a previous paper (Zhang et al. 2019). Twelve cores from the CSR site were used for the $\delta^{13}C$ analysis after the first 30 years of each core were removed to avoid the growth signal of young trees (Porte and Loustau 2001; Gagen et al. 2007; Liu et al. 2014). We extracted the α cellulose following the method of Brendel et al. (2000). An aliquot of the samples was weighed into tin capsules, then combusted in an Elemental Analyser (Flash EA 1112; Thermo Fisher Scientific, Waltham, MA, USA). The resulting CO_2 was passed in continuous flow mode to the isotope ratio mass spectrometer (MAT253) (Zhang et al. 2019). The repeated analysis of internal standards yielded a standard deviation (SD) of about 0.05‰. We measured standard values of the graphite, glycine and soil alternately after every seven measurements in order to calibrate vs. PDB. The laboratory $\delta^{13}C$ standards of the graphite, glycine and soil are − 16.0‰, − 33.3‰, and − 27.46‰, respectively.

Coal and oil are of organic origin and hence depleted in ^{13}C, so anthropogenic increases in the concentration of CO_2 in the atmosphere have resulted in a lowering of the $\delta^{13}C$ value of air by about 1.5% since industrialisation. Since

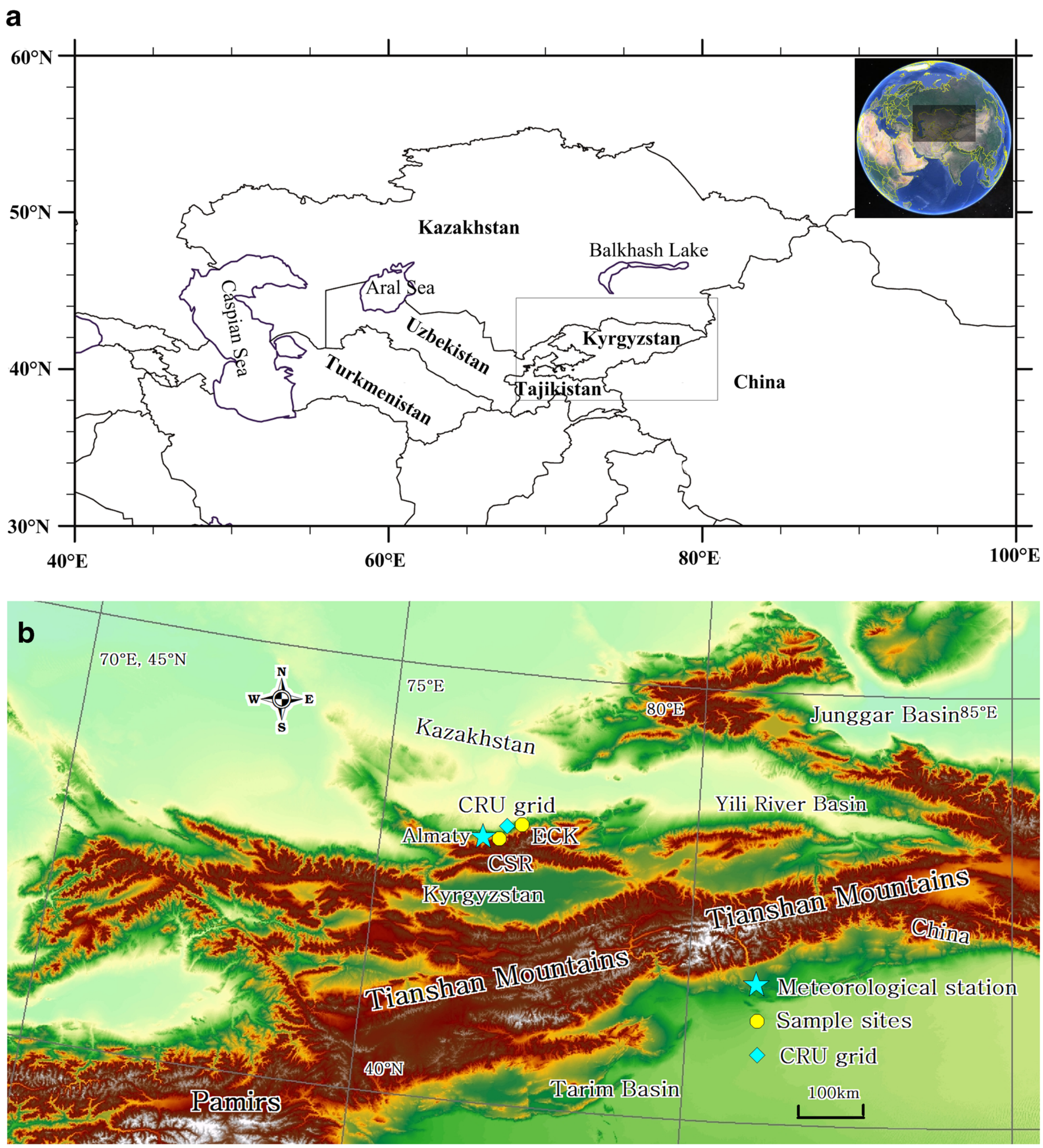


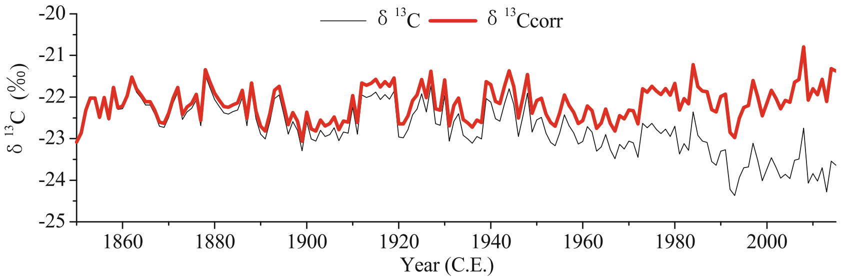
Fig. 1 (A) Map of Central Asia and its global position; (B) locations of the tree-ring sampling sites (yellow circles) and the meteorological station (blue star). The point (43° 15′ N, 77° 15′ E) of CRU grid (blue diamond) from Climate Research Unit TS 4.03

fractionation is additive, this trend should be reflected in tree rings (McCarroll and Loader 2004; Epstein and Krishnamurthy 1990; Feng and Epstein 1995a, b; February and Stock 1999; Treydte et al. 2009). This reducing trend is also reflected in our tree ring $\delta^{13}C$ series (Fig. 2). We removed the trend using the high precision record of atmospheric $\delta^{13}C$ compiled by Francey et al. (1999), which is based on Antarctic ice cores. McCarroll and Loader (2004) suggest that these data are sufficiently precise to provide a standard method for removing the atmospheric decline in $\delta^{13}C$ from tree-ring data. Thus, the signal of atmospheric $\delta^{13}C$ decline has been removed in the corrected $\delta^{13}C_{corr}$ chronology (Fig. 2).

Climate data

Monthly temperature (1930–2015) and precipitation (1967–2010) data were collected from the Almaty meteorological station (43.23 N, 76.93 E, 851.0 m), which is located about 20 km from the sampling site and is the nearest available station. The climatological data from this station have been described (Zhang et al. 2017b). Climatic Research Unit (CRU) TS 4.03 data

Fig. 2 $\delta^{13}C$ and $\delta^{13}C_{corr}$ change at CSR over the past 166 years



(1901–2017) (Harris et al. 2014) are also used to compare the spatial representation of the reconstruction.

Statistical analyses

We use conventional mathematical statistical methods of dendroclimatology studies to reconstruct and analyse long-term temperature change (Cook and Kairiukstis 1990). The relationships between climatic factors and tree-ring widths were analysed using Pearson correlation analysis with the Statistical Product and Service Solutions (SPSS) program.

Results

Relationship between ring width, $\delta^{13}C_{corr}$ and climate

We compare the CSR chronology with the low treeline site (ECK) chronology that was developed and analysed by Zhang et al. (2017b) in order to understand the response of radial tree growth to climate at different elevations (Fig. 1). The straight line distance between the two sampling sites is about 35 km, and the altitude difference is 375 m. The correlations and response analysis show that radial growth responds more strongly to climate at the low treeline site (ECK, elevation 1850 m) than that at the high elevation sampling site (CSR, elevation 2525 m). However, the ECK ring-width chronology can only be used to reconstruct precipitation, not temperature (Zhang et al. 2017b). The CO_2-corrected stable carbon isotope chronology ($\delta^{13}C_{corr}$) has a significant positive correlation with the mean temperature during the growing season, especially in summer. The correlation coefficients are as high as + 0.477 ($p < 0.01$, $n = 83$) in May, + 0.411 ($p < 0.01$, $n = 85$) in June, + 0.619 ($p < 0.01$, $n = 86$) in July and + 0.507 ($p < 0.01$, $n = 83$) in August (Fig. 3). At the same time, there is a weak negative correlation between $\delta^{13}C_{corr}$ and precipitation in July ($r = -0.335$, $p < 0.05$, $n = 44$) and August ($r = -0.318$, $p < 0.05$, $n = 42$) (Fig. 3). Further analysis showed a strong positive correlation between the $\delta^{13}C_{corr}$ and mean temperature from June to August ($r = +0.707$, $p < 0.01$, $n = 86$). These results indicate that summer mean temperature is the main factor limiting the stable carbon isotope changes of Schrenk spruce in the timberline.

Reconstruction of summer temperatures

Based on the results of the correlation analysis, we reconstructed June to August mean temperature for southern Kazakhstan. The transfer function was

$$T_{6\text{–}8} = 59.331 + 1.666 \times \delta^{13}C_{corr}, \tag{1}$$

where $T_{6\text{–}8}$ is the June to August mean temperature and $\delta^{13}C_{corr}$ is the $\delta^{13}C_{corr}$ of Schrenk spruce at the CSR sampling site. The reconstruction is able to explain 50.0% of the variance (49.4% after adjusting for the loss of degrees of freedom) in summer mean temperature during the calibration period (1930–2015; $n = 86$, $r = +0.707$, $F_{1,\ 84} = 84.13$, and $p < 0.0001$).

We used split-sample calibration-verification tests to validate the reliability and stability of the model. The F-test value and sign test (ST) are both significant at the 99% confidence level. The Reduction of Error (RE) and Coefficient of Efficiency (CE) values are not only greater than zero, they are also close to the calibration r^2 value, suggesting that the linear regression model is statistically validated (Table 1). We also compared the first differences (year-to-year changes) between reconstructed and observed summer temperature ($r = +0.690$, $p < 0.0001$, $n = 85$) (Fig. 4). All parameters showed that the reconstructed equation is stable and reliable. We can therefore reconstruct the summer mean temperature of the southern Kazakhstan since 1850 C.E. (Fig. 4).

Summer temperature change in southern Kazakhstan since 1850 C.E.

As shown in Fig. 5, 1899 was identified as an extreme cold year because the mean summer temperature of this year was lower than the mean−2σ. The extreme high temperature years were 1984, 2008 and 2014, because the mean summer temperature was greater than the mean+2σ. At 2.27 °C above the mean, 2008 was the hottest summer, with an average temperature of 24.68 °C (Fig. 4).

We calculated the 20-year low-pass filtering of the reconstruction in order to understand the low-frequency change in summer temperature in southern Kazakhstan since 1850 C.E. (Fig. 4). The results indicate two colder periods (1887–1910, 1951–1972) and three warmer ones (1858–1886, 1911–1950,

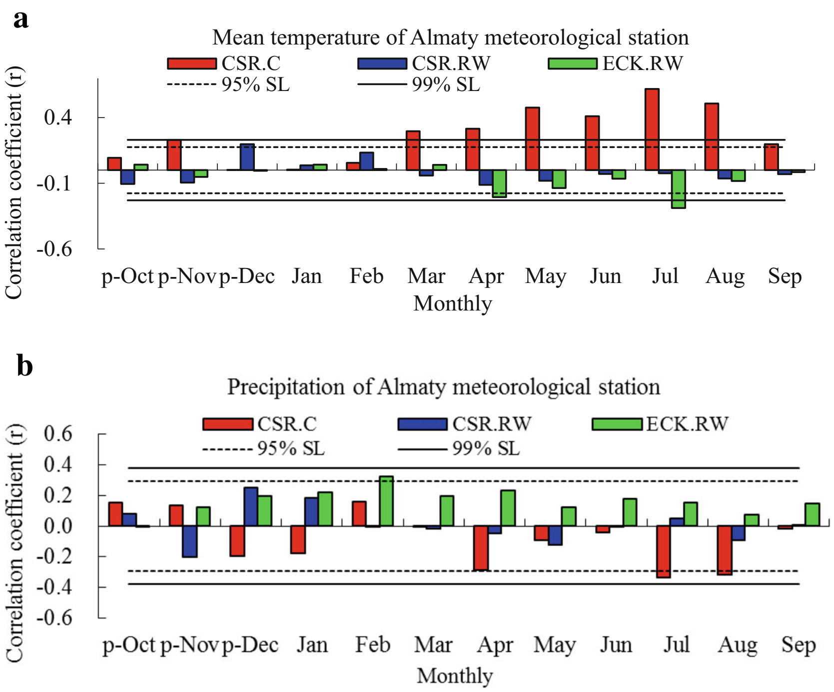


Fig. 3 The relationship between tree rings and climate in southern Kazakhstan. (A) Correlation between the tree-ring width standard chronology (CSR.RW and ECK.RW), the de-trended stable carbon isotope chronology (CSR.C), and monthly mean temperature (1930–2015) at the Almaty meteorological station. (B) Correlation between the tree-ring width standard chronology (CSR.RW and ECK.RW), the CO_2-corrected stable carbon isotope chronology (CSR.C) and monthly precipitation (1967–2010). 99% SL represents passing the 99% significance test, 95% SL represents passing the 95% significance test. The p-Oct, p-Nov and p-Dec represent October, November and December of the previous year, respectively

1973–present). Since the 1990s, the climate of southern Kazakhstan has experienced the longest, most significant, and most rapid period of warming since 1850. This result is generally consistent with temperature changes observed in the inland arid regions of Asia (Shi et al. 2007; Salnikov et al. 2015).

In comparing our temperature change results with those from other studies in the Tianshan Mountains (Chen et al. 2009, 2012; Yu et al. 2013), we found that changes in summer temperature are consistent across sites and studies (Fig. 5). Spatial correlations between the summer temperature reconstruction and the CRU-TS 4.03 temperature datasets show that our reconstruction has a wide range of spatial representativeness (Fig. 6). Our temperature reconstruction represents changes in summer temperature over the past century (1901–2015) in the arid interior of Asia (Fig. 6A). In addition, it clearly demonstrates that global warming has been rapid and sustained over the past 30 years (1986–2015) (Fig. 6B).

Table 1 Statistics of the split-sample calibration-verification test model for the summer temperature reconstruction

Calibration				Verification					
Period	*r*	R^2	*F*	Period	*r*	RE	CE	ST	ST_1
1930–1972	0.633	0.401	27.387	1973–2015	0.672	0.636	0.363	36+/7-**	29+/13-*
1973–2015	0.672	0.452	33.757	1930–1972	0.633	0.601	0.308	34+/9-**	32+/10-**
1930–2015	0.665	0.442	66.557						

ST and ST_1, sign test and the first-order difference sign test, respectively

*Significance at the 95% level of confidence

**Significance at the 99% level of confidence

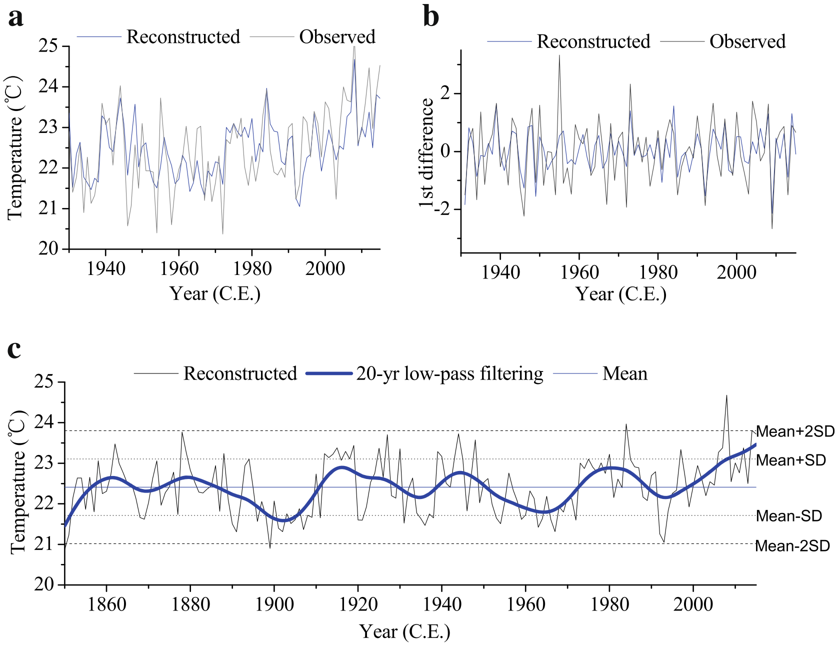


Fig. 4 (A) Comparison of the reconstructed temperature (blue line) and the observed June–August temperature from the Almaty Meteorological Station (grey line) for the common period 1930–2015. (B) Comparison of the first differences (year-to-year changes) of the reconstructed temperature and the June–August temperature from the Almaty Meteorological Station (dark grey line). (C) Reconstructed June–August temperature for southern Kazakhstan since 1850 C.E. (thin line). The thick blue line shows the data smoothed with a 20-year low-pass filter to emphasise the long-term fluctuations

Discussion

Tree-ring $\delta^{13}C_{corr}$ response to climate

Because the factor limiting radial growth near the low treeline is moisture (Zhang et al. 2016a, b, 2017a, b, c), the radial growth of trees near the timberline has a weak response to temperature. We therefore need to use other parameters to extract temperature information. In some cases, tree-ring stable isotopes can capture a better climate signal than tree ring width.

The stable carbon isotopic ratios in tree rings are affected by stomatal conductance and photosynthetic rate (Farquhar and Sharkey 1982; McCarroll and Loader 2004). At high-elevation site, there is a weak negative correlation between $\delta^{13}C_{corr}$ and precipitation in July and August, and a much stronger relationship between $\delta^{13}C_{corr}$ and temperature. This may imply that the CO_2 concentration in the leaves is mainly controlled by the carboxylation efficiency of the photosynthetic active enzyme Rubisco during the vegetation period. Meanwhile, changes in stomatal conductance affected the stable isotope fractionation process (Treydte et al. 2009).

McCarroll and Loader (2004) suggested that the dominant factor controlling stable carbon isotope fractionation may be the photosynthetic rate (which is mainly controlled by irradiance and temperature) in places where trees are less subject to water stress. The Tianshan Mountains are Central Asia's main water source and ecological barrier. The climate of the western Tianshan Mountains is mainly affected by the westerlies. When vapour-laden air from the Atlantic or the Arctic reaches the northern slope of the Tianshan Mountains, considerable precipitation occurs. In this study area, the average total annual precipitation is 650.9 mm. Hence, tree growth in this region is not affected by water stress in summer. The tree-ring $\delta^{13}C$ record shows a strong summer temperature signal for all sites in northern Pakistan (Treydte et al. 2009). In the Altai Mountains of Central Asia, the tree-ring $\delta^{13}C$ record for pine

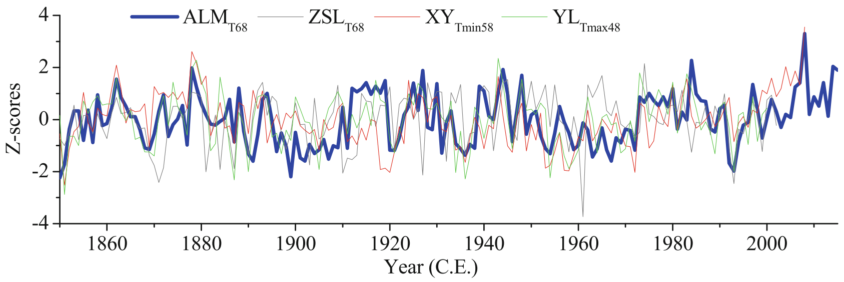


Fig. 5 Comparisons of temperature changes in the Tianshan Mountains over the past 166 years. $\mathrm{ALM}_{\mathrm{T68}}$ represents the reconstructed summer temperatures of this study; ZSLT68 represents the reconstructed summer temperatures for Zajsan Lake, Kazakhstan (Chen et al. 2012); $\mathrm{XY}_{\mathrm{Tmin58}}$ represents the reconstructed mean minimum temperatures of May to August in Xinyuan, China (Yu et al. 2013); $\mathrm{XY}_{\mathrm{Tmax48}}$ represents the reconstructed mean maximum temperatures of April to August in Yili, China (Chen et al. 2009)

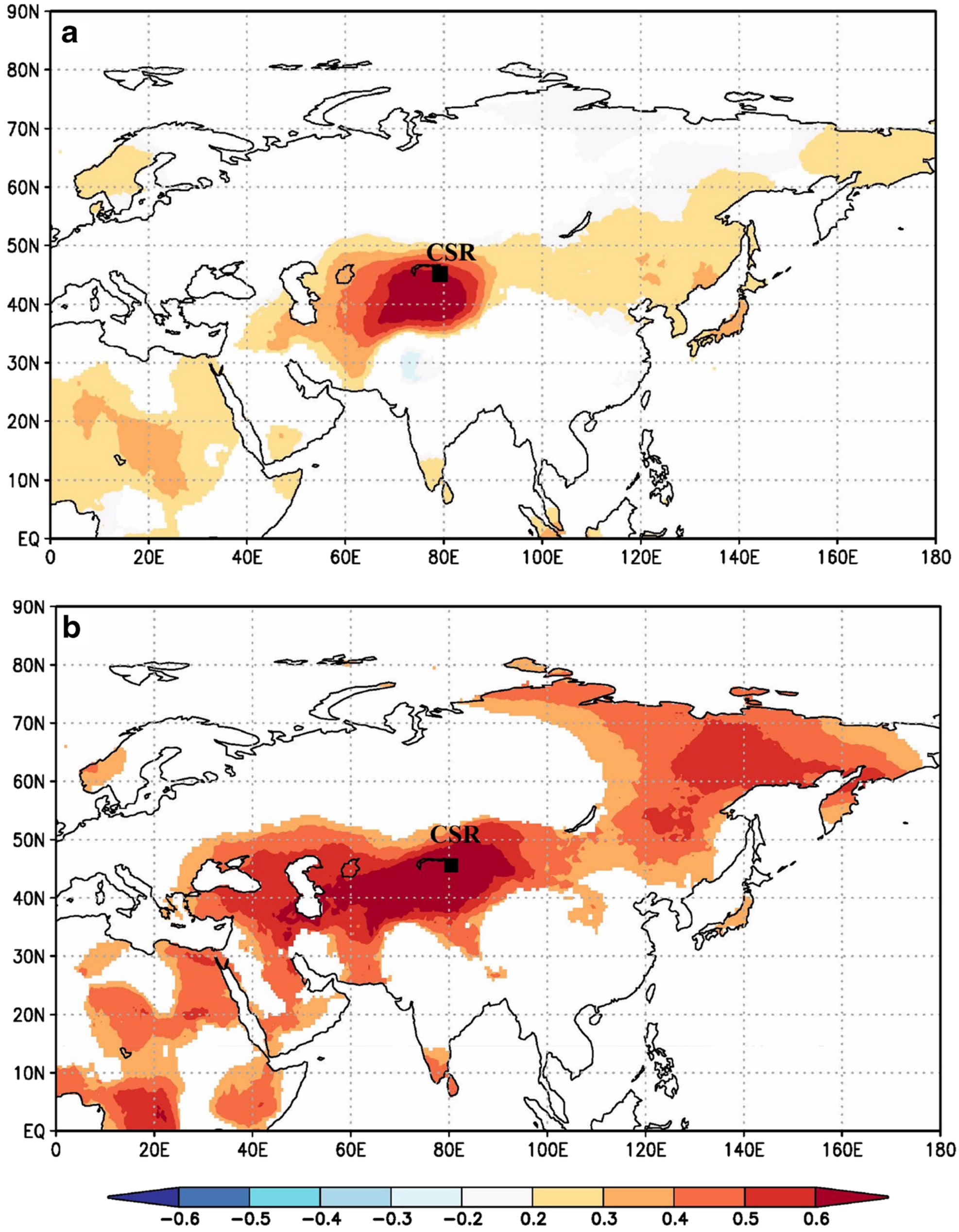


Fig. 6 Spatial correlation of the reconstructed summer temperature series with CRU TS 4.03 summer temperature data for 1901–2015 ($p < 0.1$) (A) and for 1986–2015 ($p < 0.1$) (B)

also includes a strong summer temperature signal (Sidorova et al. 2013), as is the case in most regions of Scandinavia (Seftigen et al. 2011). Konter et al. (2014) noted that δ^{13}C records from *Pinus uncinata* tree-ring data in the Spanish Pyrenees correlate negatively with summer precipitation, and positively with summer temperatures. Similar results were reported for other areas (Liu et al. 1996, 2002; Helle et al. 2002; Treydte et al. 2009; Xu et al. 2011; Wang et al. 2015; McCarroll and Pawellek 2001; Gagen et al. 2007; Hilasvuori et al. 2009; Young et al. 2010). These studies demonstrate that there can be a stronger link between δ^{13}C variability and irradiance and growing season temperatures than between δ^{13}C and air humidity or precipitation.

Natural forcing of summer temperature changes

The volcanic aerosols emitted into the atmosphere during large eruptions decrease temperatures on hemispheric and global scales for several years following the eruption (Self et al. 1981; Robock 2000; Adams et al. 2003; Ning et al. 2017; Briffa et al. 1992, 1995, 1998; Yamaguchi et al. 1993; Jones et al. 1995; Hantemirov et al. 2004). The volcanic eruptions can also be recorded in tree rings by changing the climate (Salzer and Hughes 2007; Liang et al. 2019). The volcanic explosivity index (VEI) (Newhall and Stephen 1982) is widely used to denote the climatological impact of volcanic eruptions (Simkin et al. 1981; Robock 1991; Simkin and Siebert

Table 2 Largest explosive volcanic eruptions since 1850 and low temperatures in southern Kazakhstan

Volcano name	Volcanic subregion	Year	Volcanic explosivity index (VEI)	Temperature anomaly value (°C)
Hudson, Pinatubo	Southern Chile, Philippines	1991	5+,6	− 1.04 (1992–1994)
El Chichon	México	1982	5	− 0.01 (1983)
St. Helens	Washington (USA)	1980	5	− 0.25 (1981)
Agung	Lesser Sunda Islands (Indonesia)	1963	5	− 0.88 (1963–1964)
Bezymianny	Kamchatka Peninsula (Russia)	1956	5	− 0.47 (1957–1960)
Cerro Azul, Kharimkotan	Central Chile, Kuril Islands	1932, 1933	5+, 5	− 0.75 (1934–1938)
Ksudach	Kamchatka Peninsula (Russia)	1907	5	− 0.83 (1907–1909)
Santa Maria	Guatemala	1902	6	− 0.86 (1902–1905)
Okataina	New Zealand	1886	5	− 0.59 (1887)
Krakatau	Indonesia	1883	6	− 0.15 (1883)
Askja	Northeastern Iceland	1875	5	− 0.15 (1876–1877)
Shiveluch	Kamchatka Peninsula (Russia)	1854	5	− 0.55 (1855)

1994). To determine the impact of volcanic eruptions on the climate in the Tianshan Mountains, we compared the reconstructed temperature record with the VEI, focusing on eruptions with an index ≥ 5 (Table 2). The results show that most years with strong volcanic eruptions correspond to years with low temperatures. In particular, two volcanic eruptions in 1991 directly affected the process of global warming. Hansen et al. (1996) showed that the global temperature fell by about 0.5 °C during the 2 years following the Mount Pinatubo eruption. Our results suggest that the average summer temperature in southern Kazakhstan from 1992 to 1994 is 1 °C lower than the average summer temperature over the past 166 years. The unusually low temperatures may have been closely linked to two explosive volcanic eruptions (Hudson and Pinatubo) in 1991. These results suggest that summer temperatures in southern Kazakhstan can be influenced by strong volcanic eruptions.

Climatic changes in southern Kazakhstan over the past 166 years

To further analyse the history of climate change in southern Kazakhstan, we compared changes in temperature and precipitation over the past 166 years. Precipitation in southern Kazakhstan was reconstructed by Zhang et al. (2017b) using tree-ring widths. Analyses of temperature and precipitation show that the climate has alternated between warm-dry and cold-humid phases in southern Kazakhstan since 1850 C. E. on inter-decadal scales. However, there has been a significant warming-wetting process since the 1990s (Fig. 7). This corresponds with the warming-wetting process noted for Xinjiang, China, since 1987 (Shi et al. 2007).

We also found that the extreme drought years of 1870s, 1910s and 1940s correspond not only with reduced precipitation but also with continuous warming. The drought of 1870s corresponds with a continuous rise in temperature and decrease in precipitation. The drought of 1910s corresponds with the consistently higher temperatures and lower precipitation between 1913 and 1919. Similarly, the drought of 1940s followed a period of higher temperatures and reduced precipitation. The extreme drought years in 1879, 1919 and 1945 have been noted in many dendroclimatology studies of northern China and Central Asia (Yuan et al. 2001, 2003; Li et al. 2006, 2010; Zhang et al. 2016a, 2017a, b, c). However, previous studies focus only on the relationship between drought and precipitation. This study shows that these extreme drought events are linked with continuous warming and drying.

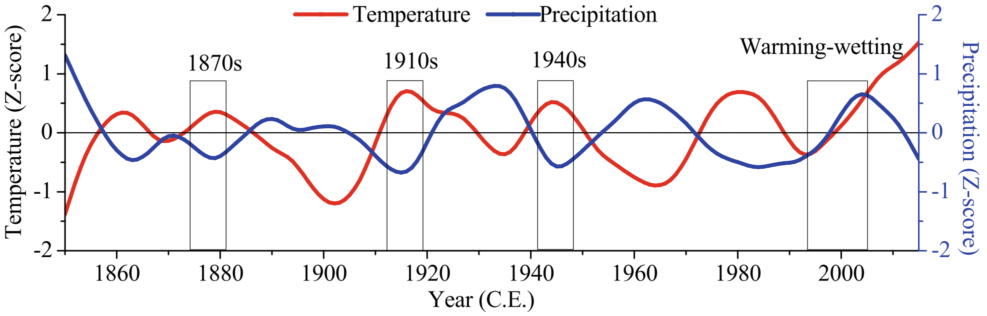


Fig. 7 Climatic change in southern Kazakhstan over the past 166 years. Precipitation was reconstructed by Zhang et al. (2017), and the temperature was reconstructed in the study

Conclusions

Our research shows that summer mean temperatures have increased at a rate of about 0.27 °C/decade over the past 166 years in southern Kazakhstan, and by as much as 0.44 °C/decade over the past 30 years. Analysis of temperature and precipitation shows that the climate in southern Kazakhstan has alternated between warm-dry and cold-humid over the past 166 years. The coldest decade was in the 1900s, and the driest decade was in the 1910s. Since the 1990s, southern Kazakhstan has experienced particularly strong warming and wetting process. The extreme droughts of 1879, 1917 and 1945 were caused by a combination of continuously higher temperature and reduction in precipitation. This study fills a spatial gap in our understanding of past temperature changes, and contributes to a better understanding of climate change and its effects on the social and ecological systems of Central Asia.

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