

Precipitation Reconstruction for the Khakassia Region from Tree Rings

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Abstract

A nested July-June precipitation reconstruction for the period AD 1777-2012 was developed from multi-century tree-ring records of *Pinus sylvestris* L. (Scots pine) for the Republic of Khakassia in Siberia, Russia. Calibration and verification statistics for the period 1948-2012 show a high level of skill, and account for a significant portion of the observed variance (>50%) irrespective of which period is used to develop or verify the regression model. Split-sample validation supports our use of a reconstruction model based on the full period of reliable observational data (1948-2012). Thresholds (25th and 75th percentiles) based on the empirical cumulative distribution 1948-2012 observed precipitation were used to delineate dry years and wet years of the long-term reconstruction. The longest reconstructed dry period, defined as consecutive years with less than 25th percentile of observed July-June precipitation, was 3 years (1861-1863). There was no significant difference in the number dry and wet periods during the 236 years of the reconstructed precipitation. Maps of geopotential height anomalies indicate that dry years

differ from wet years primarily in the location of an anomalous 500 mb ridge approximately over the study area.

Key words

Tree-ring, drought, climate reconstruction, Siberia.

Introduction

The Republic of Khakassia is located in the southwestern part of Eastern Siberia on the left bank of the Yenisei River, in the territories of the Altai-Sayan region and Khakass-Minusinsk Hollow (Figure 1). On a relatively small area are concentrated unique natural landscape zones ranging from semi-desert to high mountain alpine meadows and tundra. The population of the territory of Khakassia has been slightly higher than that of other regions in Siberia throughout history because of the landscape diversity and the relatively mild climate of the Minusinsk Hollow (Kyzlasov, 1984; Gumilev, 1993), a large depression with strong agricultural significance for the Republic of Khakassia.

Given the agricultural importance of the Minusinsk Hollow, it is important to understand modern climate variability of this region, such as extreme dry and wet events and to evaluate the potential for future spatiotemporal patterns. It is vital to characterize the range of potential natural climate variability over the past few centuries and develop an improved understanding of the links between large-scale climate forcing and regional extreme events. Most of the high-quality and continuous instrumental climate records in the region are short, with most records covering only the latter half of the twentieth century. Consequently, tree-ring records are particularly important as a powerful tool for developing qualitative and quantitative reconstructions of climate on seasonal to century or longer time scales.

Relatively few studies using tree rings as records of past climate (dendroclimatology) have been done in the Khakassia region when compared with many other regions of the world. Vaganov *et al.* (1985) investigated a wide range of ecological factors and climatic factors influencing tree-ring growth and formation. This work was followed by other dendroclimatological and ecological studies (Magda *et al.*, 2002, 2004, 2011; Block *et al.*, 2003; Vaganov *et al.*, 2006; Knorre *et al.*, 2010), culminating in a reconstruction of June temperature in the forest-steppe of the Republic of Khakassia by Babushkina *et al.* (2011). Shah *et al.* (2015) developed a 138-year August-July Precipitation (P) reconstruction for the Abakan region as an outcome of the 4th International Summer Course "Tree Rings, Climate, Natural Resources and Human Interaction," held in Abakan, Siberia, in 2013.

The objectives of this study were to develop the first regional nested July-June P reconstruction for the Republic of Khakassia, to quantify the drought history of the region from the reconstruction, and to diagnose the association between extreme dry and wet years and anomalies in atmospheric circulation using anomaly patterns of 500 mb geopotential height.

Site Description

The Republic of Khakassia is part of the Altai-Sayan region, and is characterized by a wide variety of physical and geographical structures and high diversity in the composition of vegetation. The western part of Khakassia is located on the eastern megaslope of the Kuznetsk Plateau (includes Kuznetsky Alatau and Abakan Range), and the southern part of the northern West Sayan megaslope: these two megaslopes account for more than half of the megaslopes throughout the republic. These mountain systems are clearly distinguished high mountain-forest belts.

The study area is characterized by *Pinus sylvestris* L. (PISY) and larch forests (*Larix sibirica* Ledeb.). The lower part of the belt is steppe characterized by forb-grass-sedge meadows: *Festuca pratensis* Huds., *Alopecurus pratensis* L., *Bromus inermis* Leyss., *Agropyron repens* (L.) P. Beauv., *Agrostis alba* auct., *Poa pratensis* L., *Deschampsia cespitosa* (L.) P. Beauv., *Sanguisorba officinalis* L., *Filipendula ulmaria* (L.) Maxim., *Carex* sp., *Vaccinium vitis-idaea* L., *Pyrola rotundifolia* L., *Calamagrostis arundinacea* (L.) Roth., *Poa sibirica* Roshev., *Aquilegia sibirica* Lam., *Anemone crinite* Juz.

Three PISY tree-ring sites were sampled in the forest-steppe zones in Khakassia (Figure 1 and Table 1). They are Berenzhak (BER) (Babushkina *et al.*, 2011), Bidzha (BID), Kazanovka (KAZ).

The soil is similar at all three sites and is sandy with 15-20 cm deep humus layer. The KAZ site is characterized by protruding rocks and heterogeneous relief. The Minusinsk (MIN) tree-ring site is located in the southern part of Krasnoyarsk Territory in a belt of conifer forests.

The climate is continental, characterized by short summers and long cold winters. The average annual temperature (T) is +0.8° C (Figure 2). The coldest month is January with a mean average of -18.6° C. The warmest month is July with a mean average of +18.7° C. Most of the annual precipitation (75-90%) falls in the summer. The highest annual P is observed in the mountains (up to 2000 mm), with only 250 mm of P on the leeward slopes and interior hollows. The precipitation pattern is due to the westerlies, the dominant circulation feature, transporting water from the Atlantic into the Siberian interior.

Methods and data processing

Chronology Development

Samples were taken from four sites including cores taken from living trees using increment borers and full cross sections taken from stumps (Table 1). Samples were sanded to a high polish and crossdated using standard dendrochronological techniques (e.g. Stokes and Smiley, 1968; Swetnam, 1985). The width of each annual ring was measured to the nearest 0.01 mm using TSAP-LINTAB (Rinntech, 2012). Crossdating and measurement accuracy were verified using COFECHA (Holmes, 1983; Grissino-Mayer, 2001).

Each series of measured ring width was fit with a cubic smoothing spline with a frequency response of 0.50 at 67% of the series length to remove biological trends, trends potentially caused by age, size, or stand dynamics (Cook and Kairiukstis, 1990). The detrended series were then prewhitened with low-order autoregressive models to remove persistence, which was observed to be higher in the tree-ring series than in seasonal and annual precipitation. The resulting series is called a “residual” index, consisting of only the interannual changes in each time series. The individual indices were combined into single averaged chronologies for each combination of site and species using a bi-weight robust estimate of the mean (Cook and Holmes 1999; Cook and Krusic 2005). The expressed population signal, or EPS (Wigley *et al.*, 1984; Cook and Kairiukstis, 1990) was used to identify the period over which the available data from the tree-ring time series have a signal that is strong enough to capture a large percentage of the common population tree-ring signal at a site (Table 2).

Climate Data Analysis

Monthly P and T data from four stations were obtained from the Russian Institute for Hydrometeorological Information – World Data Center (Bulygina *et al.*, 2017a, Bulygina *et al.*, 2017b) (Figure 1). They are Shira (N 54.50° E 89.93°, 477 m a.s.l.), Abakan (N 53.77°, E 91.32°, 254 m a.s.l.), Minusinsk (N 53.70°, E 91.70°, 254 m a.s.l.), and Tashtyp (N 52.72°, E 89.88°, 449 m a.s.l.) (Figure 1). A regional monthly P and T series, 1948-2012, for use in calibration of tree-ring reconstruction models, was computed from the four stations by the method of averaged standardized anomalies (Jones and Hulme, 1996).

Precipitation Reconstruction

The relationships between the tree-ring chronologies and the regional monthly P and T were investigated with the program Seascorr, which computes correlations and partial correlations between tree-ring data and monthly precipitation and temperature data integrated over seasons of variable length (Meko *et al.*, 2011).

The reconstruction model was developed by principal component analysis (PCA), using linear regression of the climate variable on the principal components (PCs) of three tree-ring chronologies (MIN, BID, and KAZ). Scores of the three PCs were retained for use as predictors in the first reconstruction (AD 1849-2012) and two residual chronologies (KAZ and BER) were used for the second reconstruction (AD 1777-2008). Regression equations were calibrated on the period 1948-2012. Nested reconstruction models (Touchan *et al.*, 2008, 2011, 2016) were estimated to generate a long-term reconstruction. Such nested models allow use of long chronologies for early parts of the reconstruction, while taking advantage of dense chronology coverage for later parts. While the earliest part of the

reconstruction may have lower accuracy because of low site coverage, the procedure allows for a maximum length reconstruction. Predictors for models were selected by stepwise regression. The predictor pool for stepwise comprised the full pool of available PCs. Adjusted R^2 and Mallows's C_p statistic (Mallows, 1973) statistics were used as guides to guard against overfitting. Models for the two reconstructions were validated with a split-sample procedure (Snee, 1977; Meko and Graybill, 1995; Touchan, 2014) that divides the full period (1948–2012) into two subsets to verify the stability of the model. Calibration accuracy was measured by the adjusted R^2 , and validation skill by the Pearson correlation coefficient (r), the reduction of error (RE) and the coefficient of efficiency (CE) (Cook et al., 1994). The strength of the model for the final reconstructions was calibrated on the full period (1948–2012) and further validated using the PRESS procedure (Weisberg, 1985; Fritts *et al.*, 1990; Meko, 1997; Touchan *et al.*, 2011, 2014, 2016).

Analysis of Extreme Events

Runs analysis (Dracup et al., 1980), was used on the reconstructions to study extreme dry and wet events. Empirical thresholds for the dry and wet events were defined as 25th and 75th percentiles of instrumental measurements of precipitation for the period 1932–2012. Low-frequency time series variations in reconstructed precipitation were summarized with moving averages (5-year). Composites of April–July 500 hPa geopotential height anomalies from the 1948–2012 mean were created using National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data (Kalnay *et al.*, 1996) to illustrate atmospheric circulation contrasts between extremely dry years and extremely wet years in the period 1948–2012.

Results and Discussion

Chronology Development

The length of the four chronologies ranges from 257 (BER) to 164 years (BID) (Table 1). Statistical analyses of each chronology are summarized in Table 2. The mean correlation among individual radii at each site represents the strength of their common signal and ranges from 0.48 (MIN) to 0.60 (BID). The mean sample segment length (MSSL) of the four chronologies ranges from 117 to 193 years and is adequate to investigate multidecadal climate variability (Cook and Peters 1997).

Principal component analysis (PCA) applied to the three chronologies showed a strong common statistical growth signal for their overlapping years. Principal component 1 for the three chronologies accounts for 65% of the tree-ring variance.

Precipitation Reconstruction

Seascorr identified July to June total P as the most appropriate seasonal predictand for reconstruction (Figure 3). T influence, summarized by partial correlations in Seascorr, is significant for the single month of July. The negative sign of partial correlations for this month indicates that high T during the growing season has a negative effect on the radial growth. High T is associated with increased evapotranspiration from the soil surface, and drought stress on the trees (Babushkina *et al.*, 2011; Shah *et al.*, 2015).

Two nested reconstruction models, with total P as a predictand, were estimated. Time coverage by these models is 1849-2012 and 1777-2012. The 1777-2012 model relies on just two chronologies. The year 1777 was identified by the EPS statistic (Wigley *et al.*

1984). The stepwise regression process, with adjusted R^2 and Mallows' C_p (Mallow, 1973) as selection cutoff criteria, resulted in selection of a simple model with just PC1 as a predictor for the 1849-2012 model. The same statistics applied to the earliest model (1777-2012) allowed both available chronologies to enter as predictors. Nested models calibrated on 1948-2012 explain 54-67 percent of the calibration-period variance, according to the regression adjusted R^2 (Figure 3).

Time plots of reconstructed and observed P for the calibration periods of the two models are included in the Figure 4. The split-sample validation supports use of the reconstructions based on the full period of reliable observational data (1948-2012). The nested reconstruction utilized the two models to take advantage of the robustness derived from the models that incorporated a greater number of chronologies. The beginning years of the nested reconstructions are 1777 and 1849; the number of chronologies contributing to those models is 2 and 3 respectively. For brevity, we refer to the models by beginning year: M1777, and M1849. Cross-validation using the PRESS procedure (Weisberg, 1985) indicated that the two models can adequately estimate P data not used to fit the model (Figure 4 and Table 3). Split-sample validation likewise supported temporal stability of the relationship between P and the tree-ring data, and application of reconstruction models calibrated over the full climate-overlap 1948-2012.

Analysis of Extreme Events

The July-June reconstruction time series is plotted in Figure 5. The long-term reconstruction contains 48 drought events with a mean interval of 6 years. The number of events classified by duration is as follows: durations of 1, 2, and 3 years have 27, 9, and 1 events, respectively. The maximum interval between events is 15 years (1918-1932). The longest

drought is a three-year event in 1861-1863. The driest year in the reconstruction is 1974 (224 mm), while the driest year in the instrumental P data is 1965 (215 mm). The frequency of dry years is higher in the 19th century, the same century with the extreme three-year event.

The July-June reconstruction contained 49 wet events with a mean interval of 5.7 years. The number of events classified by duration 1 and 2 years is 31 and 9 events respectively. The maximum interval between wet events is 19 years (1799-1817). The wettest year in the reconstruction is 1970 (467 mm), while the wettest year in the observed P data is 2003 (544 mm). The frequency of wet years is similar in the 19th and 20th centuries.

Our July-June precipitation reconstruction is significantly correlated ($r=0.85, n=138, p \leq 0.0001$) with the August-June P reconstruction (AD 1875-2012) developed by Santosh et al. (2015) for Minusinsk Hollow. The two reconstructions correlate highly in part because Santosh et al. (2015) used a subset of the chronologies used in this new reconstruction. Our addition of new chronology KAZ, developed in 2013, and chronology BER, developed in 2008, strengthen the tree-ring signal for P and allow extension of P reconstruction for the region to AD 1777.

A five year moving average of the reconstruction demonstrates multi-annual to decadal variation in July-June P and suggests several prolonged wet and dry events (Figure 6). The driest five-year reconstructed period is 1942-1946 (303 mm). The wettest five-year reconstructed period is 1969-1973 (408 mm), a period of exceptionally high tree-growth.

Several major historical events coincide with extreme dry periods seen in the July-June precipitation reconstruction. Vatin (1916) reported that the dry period from 1836-1837 reduced the summer crop production. Kostrov (1858) stated that the dry years of 1830 and 1849 affected crop production, caused a decline in the export of agricultural products to the

Krasnoyarsk district and caused negative impact on the economy of the region. Butanaev (2002) reported that the dry period from 1900-1902 caused shortage in forage production and forced the Abakan and Askiz regions to cut in half the size of their herds of horses.

The composite April-July mean difference (dry-wet) 500 mb anomaly map based on three of the driest and wettest years shows a strong anomalous ridge centered at about 90° W, at the approximate longitude of the study area (Figure 7). The pattern is consistent with increased stability and low storm activity and precipitation. The pattern, with the core of the anomalous ridge to the south over western China and southwestern Mongolia, suggests strengthening of the westerlies and anticyclonic curvature over the study region as a signature during dry years.

Conclusion

This is the first July-June P reconstruction for the period AD 1777-2012 developed from multi-century tree-ring records for the Republic of Khakassia in Siberia, Russia. This P reconstruction provides a baseline for studying past climate variability in the region. Calibration and verification of the statistical analyses indicate high accuracy for this tree-ring reconstruction of P. The longest period of reconstructed drought during the last century is 3 years, defined in this study as consecutive years below the 25th percentile. There was no significant difference in the number of dry and wet periods during the 236 years of the reconstructed precipitation.

The strong association of dry and wet years with distinct patterns of 500 mb geopotential height anomaly suggests that expanded tree-ring coverage could yield several centuries of reliable information on variations in trough and ridge behavior over southern Siberia for the important spring to early summer precipitation season.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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Figure Captions

Figure 1. Location of tree-ring sites and climate stations.

Figure 2. Climogram of regional monthly mean P and T for the Khakassia region, 1948-2012. P and T series of four stations developed by standardized anomaly method.

Figure 3. Program Seascorr summary of seasonal climatic signal in *Pinus sylvestris* residual chronology data. Climatic variables are regional monthly anomalies for P and temperature of four meteorological stations. (Top Figure) Correlations for precipitation. (Bottom Figure) Partial correlations for T. Colors indicate Monte-Carlo-derived significance of correlation or partial correlation (Meko *et al.*, 2011) for α -levels 0.01 and 0.05. Analysis period is years 1948–2012.

Figure 4. Time plots of reconstructed and instrumental P for the calibration periods of the two models. The start years of the nested reconstructions are 1777 and 1849; the number of chronologies contributing to those models is 2 and 3.

Figure 5. Time series plot of reconstructed July-June precipitation, AD 1777-2012. Horizontal solid line is the mean of the instrumental P data. Horizontal short-dashed line is the empirical threshold of 75th percentile of the regional July-June P of 1948-2012. Horizontal long-dashed line is the empirical threshold of 25th percentile of the regional July-June P of 1948-2012.. Uncertainty in reconstructed values is shown by an 80% confidence interval (shaded).

Figure 6. Five-year moving average. Values are plotted at the center year of each 5 year period for the 1777–2017 reconstruction. Uncertainty in reconstructed values is shown by an 80% confidence interval (shaded).

Figure 7. Composite map of difference in April-July 500 mb height anomalies in dry years and wet years. Years represented in the composites are among the driest (or wettest) ten years in April-July observed precipitation in the Khakassia region. Dry years are 1965, 1974, and 1981. Wet years are 1967, 1972 and 2003. Anomalies (color bar) are departures (m) from 1981–2010 climatology. Circle indicates approximate location of tree-ring sites. Map drawn with online mapping tool from the NOAA Earth System Research Laboratory (<http://www.esrl.noaa.gov/psd/cgi-bin/data/getpage.pl>).

Table 1. Site information for the four tree-ring sites.

Site Name	Site Code	Species	Lat.	Long.	Elev. (m)	Time Span	Total No. Of Years	No. of Trees/ Cores
Berenzhak	BER	PISY ¹	N54.32°	E89.68°	742	1752-2008	257	14/14
Bidzha	BID	PISY	N54.00°	E91.01°	691	1849-2012	164	15/15
Kazanovka	KAZ	PISY	N53.23°	E90.05°	600	1767-2013	247	47/67
Minusinsk	MIN	PISY	N53.71°	E91.84°	380	1847-2013	167	123/198

¹ *Pinus sylvestris* L.

Table 2. Summary statistics for the four chronologies from program ARSTAN (Cook and Holmes, 1999; Cook and Krusic, 2005).

Site Code	MSSL ^a	Total Chronology Std ^b	SK ^c	KU ^d	1 st Year EPS ^e >0.85	No. of Trees	Common Interval of Time Span	MCAR ^f	EV ^g PC1(%)
BER	193	0.2439	- 0.1090	0.4202	1836	6	1752-2008	0.527	57.389
BID	120	0.3007	0.2301	0.9989	1903	4	1849-2012	0.601	63.317
KAZ	179	0.3144	- 0.0158	- 0.128	1777	5	1767-2013	0.585	59.834
MIN	117	0.2017	- 0.1360	0.0735	1879	6	1847-2013	0.489	51.322

^aMSSL is Mean Sample Segment Length

^bStd is Standard Deviation

^cSK is Skewness

^dKU is Kurtosis

^eEPS is Expressed Population Statistic (Wigely et al., 1984)

^fMCAR is Mean Correlation Among Radii

^gEV is Explained Variance by 1st PC

Table 3. Split-sample calibration and validation statistics of the two reconstruction models

Reconstruction Models	Calibration Period	Verification Period	Adjusted-R ² Calibration	r- Verification	Reduction of Error, RE	Coefficient of Efficiency
1777-2008	1948-1978	1979-2008	0.55	0.71	0.49	0.41
1849-2012	1948-1980	1981-2012	0.63	0.72	0.68	0.65
1777-2008	1979-2008	1948-1978	0.57	0.72	0.42	0.33
1849-2012	1981-2012	1948-1980	0.72	0.80	0.59	0.54

Figure 1

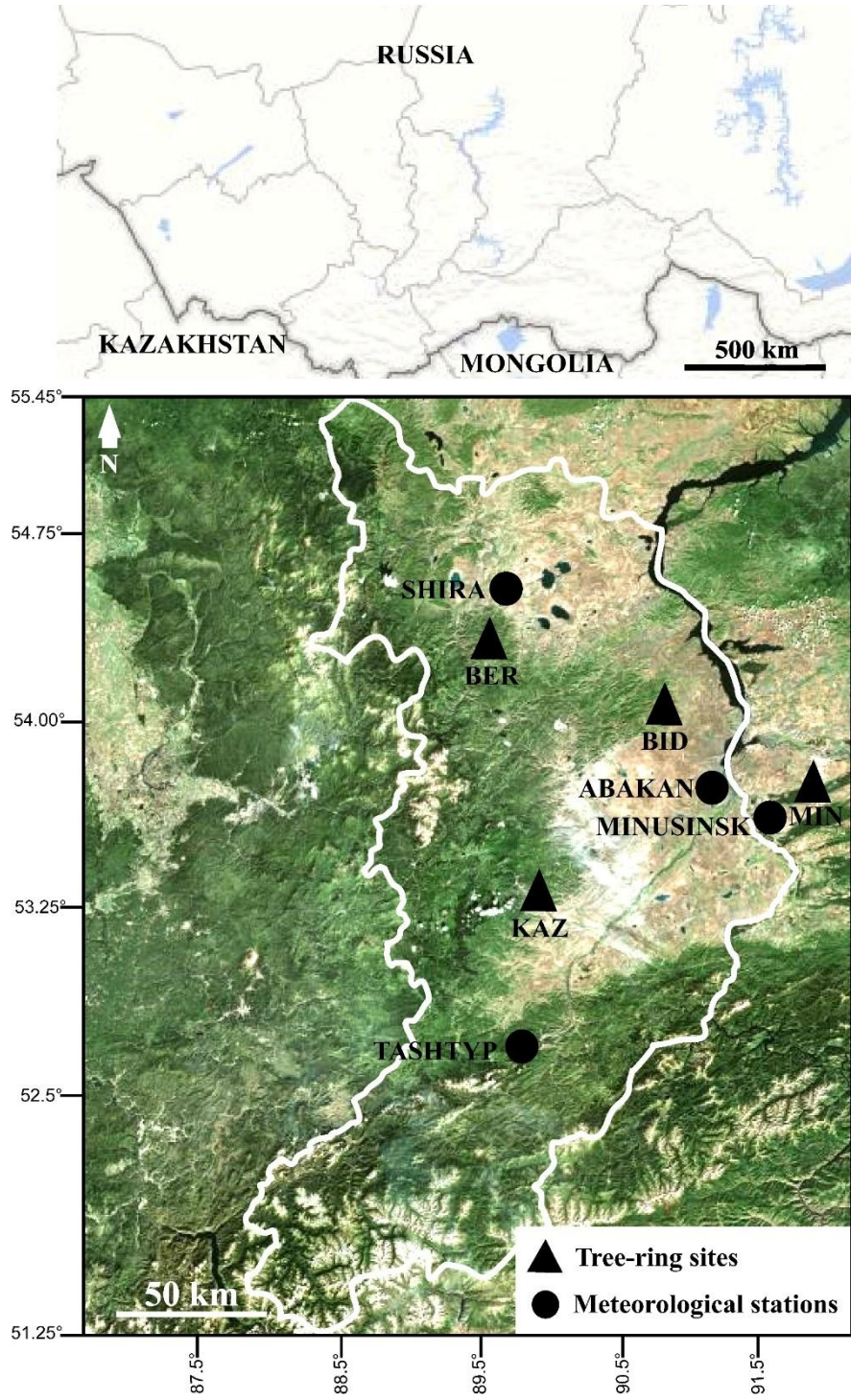


Figure 2

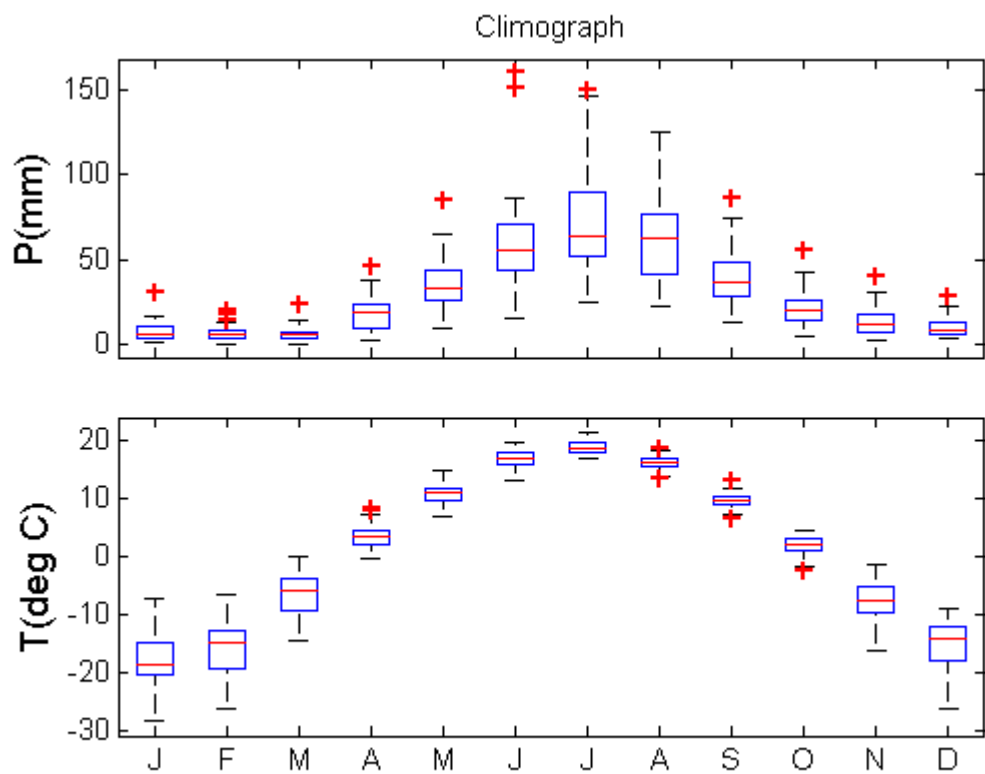


Figure 3

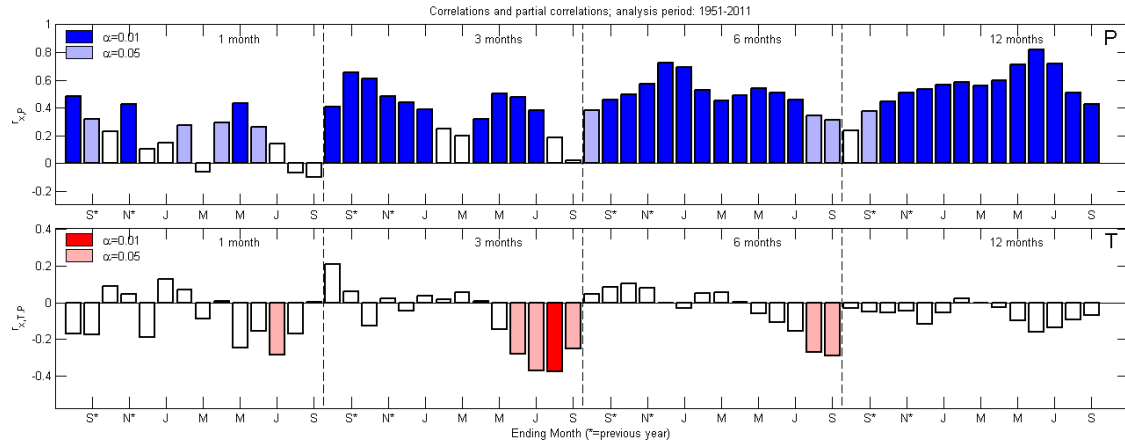


Figure 4

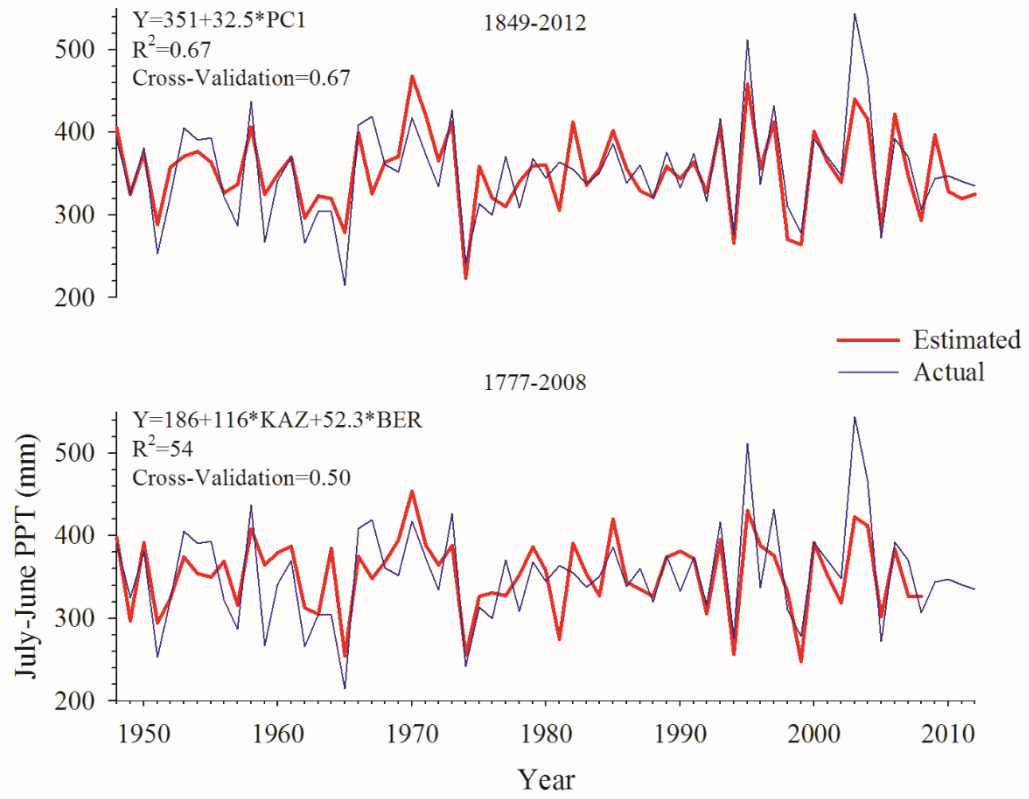


Figure 5

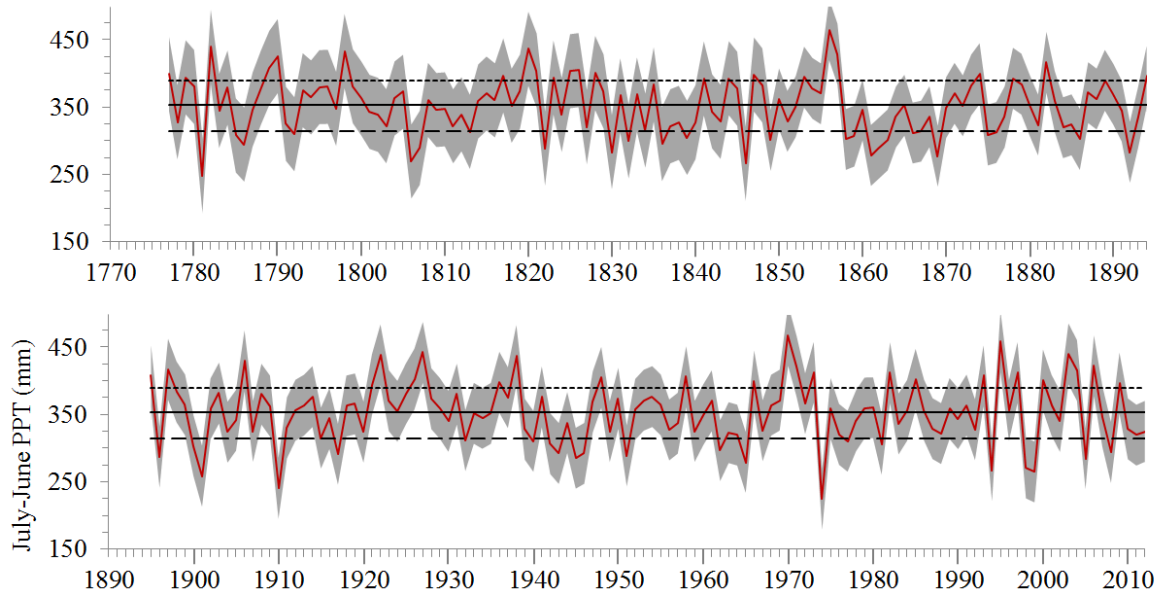


Figure 6

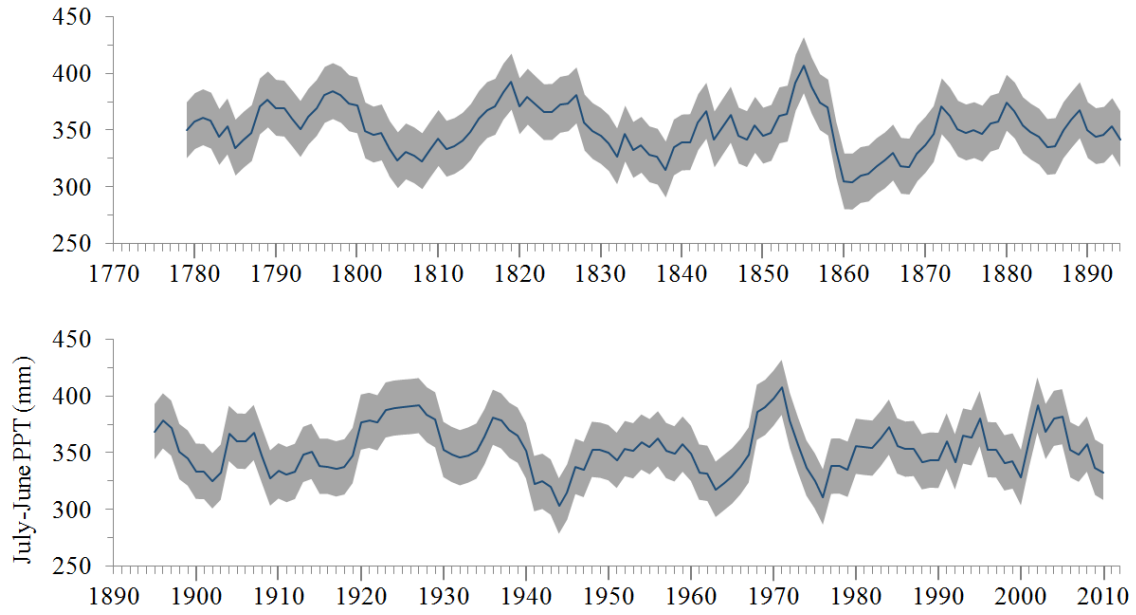


Figure 7

NCEP/NCAR Renanalysis
500mb Geopotential Height (m) Composite Anomaly 1981-2010 climo

