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A dendroclimatic reconstruction of June–July mean temperature in the northern Canadian Rocky Mountains

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ABSTRACT

A white spruce ring-width chronology was used to reconstruct June–July mean temperatures in the northern Canadian Rocky Mountains back to 1772 A.D. Samples were collected in an old growth subalpine forest in the remote Kwadacha Wilderness Provincial Park. Two chronologies were created, one using standard dendroclimatological methods and one through the use of principal components analysis. The ring-width chronologies both showed a strong positive relationship with minimum, maximum, and mean temperatures during the current growing season. The principal component based chronology was deemed superior for use as a proxy record due to its greater ability to explain the variance in the instrumental temperature record and stronger performance during reconstruction verification. Comparison of this reconstruction with other dendroclimatological reconstructions from western Canada revealed a coherent pattern of low-frequency variability, whereas comparisons at annual times-scales showed considerable temporal and spatial variability in the level of agreement between reconstructions. The northern Canadian Rocky Mountains reconstruction showed no evidence of the reduction in sensitivity to climatic variability that has been found in many other northern spruce chronologies during the late 20th century.

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Introduction

Dendroclimatological research methods utilize the information contained in tree-rings to produce annually resolved proxy records of climatic variability (Fritts, 1976). These dendroclimatic reconstructions are used extensively as important sources of evidence in global climate research and policy papers (Hughes, 2002). By extending the limited instrumental climate record, they offer insight into long-term natural climate variability and provide annually resolved proxy historical records to which modern climate conditions can be compared.

Climate records have been reconstructed from tree-rings at numerous sites in western Canada, including the British Columbia Coast Mountains (Larocque and Smith, 2005), the southern interior of British Columbia (Wilson and Luckman, 2003), the southern Canadian Rocky Mountains (Wig and Smith, 1994; St. George and Luckman, 2001; Luckman and Wilson, 2005), and the Northwest Territories and the Yukon Territory (Jacoby and Cook, 1981; Szeicz and MacDonald, 1994; Youngblut and Luckman, 2008). Greater spa-

tial coverage of dendroclimatic reconstructions is desirable because significant regional variations exist in the overall patterns of climate fluctuations (St. George and Luckman, 2001). Within the cordillera of western Canada, one notable spatial gap in the regional coverage of dendroclimatic reconstructions exists in the mountains of northeastern British Columbia, where only limited dendroclimatological research has been completed (Schweingruber, 1988; Briffa et al., 1994).

This paper presents the findings of a tree-ring investigation at a remote site in the northern Canadian Rocky Mountains, where dendroclimatological techniques were used to develop a proxy record of summer (June–July) mean surface air temperatures. This is the first annually resolved temperature reconstruction completed in northern interior British Columbia.

Methods

Site and sampling

A ring-width chronology was developed using increment cores extracted from white spruce (*Picea glauca* [Moench] Voss) trees growing in the remote Kwadacha Wilderness Provincial Park (Fig. 1). The Kwadacha Wilderness Provincial Park's rugged, mountainous topography is part of the Muskwa Range and reflects a history of extensive glacial activity (Bednarski and Smith, 2007).

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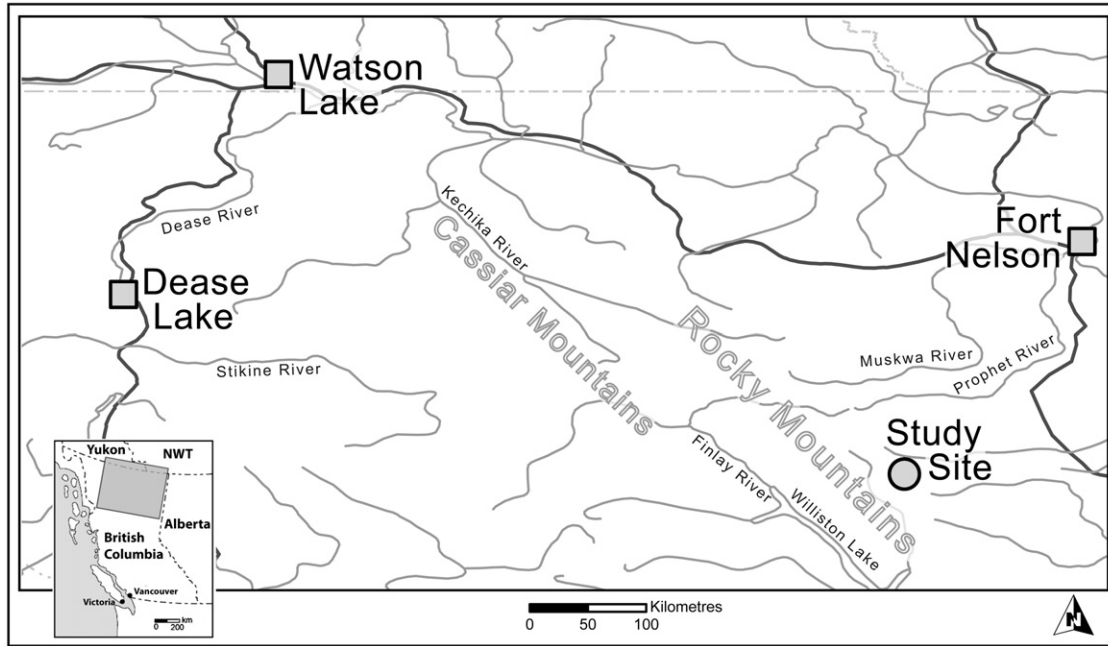


Fig. 1. Location of study site and climate stations.

The park is one of the few sites where glaciers can be found in the Canadian Rocky Mountains north of the Peace River (Ommanney, 2002) and is the source of the glacial meltwater draining into the headwaters of the Muskwa and Kechika rivers.

Samples were collected from trees found growing in a subalpine forest located between 1150 and 1400 m asl on south-east and east-facing slopes adjacent to Haworth Lake (57.8° lat N; 125.1° long W; Fig. 1). The dominant tree species at the sampling site were mature white spruce and subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) trees, with younger cohorts dominated by subalpine fir. The understorey was sparsely populated with forbs and dwarf shrubs growing out of a deep layer of step moss (*Hylocomium splendens*). Nearby swampy areas were populated by black spruce (*Picea mariana* (Mill.) B.S.P) and dense thickets of *Salix* species.

Mature, dominant trees with no obvious signs of crown damage or rot were selected for sampling. Two increment cores were taken near breast height to pith with 18 inch borers from each tree at positions $\geq 90^\circ$ apart.

Data preparation

The cores were prepared for measurement following standard dendrochronological methods (Stokes and Smiley, 1968; Fritts, 1976; Pilcher, 1990). After being air dried and glued to boards with slotted mounts, the cores were sanded with progressively finer grades of sandpaper to enhance the visibility of the annual tree-ring boundaries. Ring-widths were measured to the nearest 0.01 mm using a WinDENDRO 2006 digital image measurement and analysis system (Regent Instruments Inc., 2006).

Visual cross-dating of the ring-width series was checked using the International Tree-Ring Data Bank software program COFECHA (Holmes, 1983). Ring-width series that exhibited low correlations with the other series due to the presence of very narrow rings with faint boundaries, which hampered the accurate measurement of some of the annual rings, were removed from further analysis. Only cores older than 160 years, and with no obvious signs of damage, were included in further analyses.

Standardization and chronology construction

The ring-width series were standardized using the program ARSTAN (Cook and Krusic, 2005). A double-detrending method was used to enhance the climate signal contained in the ring-width series by reducing the noise caused by biological growth trends and endogenous disturbance events (Cook, 1985). The initial detrending was completed by fitting a growth curve to each individual ring-width series. These growth curves consisted of either a modified negative exponential curve, a linear regression line with a negative slope, or a horizontal line passing through the mean. A secondary detrending was accomplished by fitting a smoothing spline with a 67% frequency-response cutoff to each series. These splines preserve 50% of the variance in the ring-width series at a frequency equal to two-thirds of the length of each series, and therefore offer a good compromise between the risk of removing an excessive amount of low-frequency climatic variability and the danger of retaining too much low-frequency noise caused by disturbance events (Cook, 1985). Individual ring-width series were divided by the values of the fitted curves for each year to calculate the index value of each ring. Auto Regressive Moving Average (ARMA) modeling was employed to remove autocorrelation in the ring-width series (Cook, 1985). Individual ARMA models of the order determined using Akaike's Information Criterion were fit to each ring-width series in ARSTAN. Only the prewhitened residual ring-width series were used in further analysis.

The individual ring-width series were combined using a biweight robust mean function to create a master ring-width chronology (hereafter referred to as the RW chronology). The Expressed Population Signal (EPS) statistic was used to determine the change in chronology quality that occurs as sample size varies through time (Wigley et al., 1984; Briffa and Jones, 1990). EPS values were calculated for the master chronology using a 20-year moving window. The RW chronology was truncated at the decade in which the running EPS fell below the standard value of 0.85 proposed by Wigley et al. (1984).

A second master chronology was created using an unrotated principal components analysis (PCA) of the individual trees (here-

Table 1

Location, elevation (m asl), record length (years), and straight-line distance (km) from the study site of the three climate stations used in this analysis.

Station	Latitude	Longitude	Years	Elevation	Distance
Fort Nelson	58° 50.4'N	122° 36.0'W	1937–2006	382	185
Dease Lake	58° 25.8'N	130° 0.6'W	1944–2003	807	296
Watson Lake	60° 7.2'N	128° 49.2'W	1938–2006	687	333

after referred to as the PC chronology). PCA is frequently used in dendroclimatological studies as a data reduction tool, a solution for multicollinearity issues, and a method for assessing homogeneity within a set of time series. The principal components extracted during a PCA are orthogonal linear recombinations of the input series, with the first principal component representing the maximum amount of shared variance that can be extracted from the set of input series. In the case of ring-width series, the first principal component is therefore usually interpreted as representing the shared climate signal (Peters et al., 1981). PCA is commonly used in response function analysis (Fritts, 1976) and as a method for extracting shared variance from multiple master chronologies in multi-site climate reconstructions (Briffa et al., 1994; Meko, 1997). PCA has also been used as an alternative to standardization and averaging functions when creating master chronologies, using the first principal component extracted from individual unstandardized ring-width series from a single site (Jacoby and Cook, 1981; Peters et al., 1981; Enright, 1984). In this study a slightly different approach was taken in which the PCA was carried out on standardized residual ring-width series from individual trees instead of on raw ring-width series. The standardized ring-width series from each tree were combined by simple averaging to create a single series for each of the 29 individual trees. The first principal component was then extracted from the ring-width series of the oldest 15 trees and used as the second master chronology.

Climate data

Climate data from regional stations with long-term monthly precipitation and air temperature records were obtained from the Adjusted Historical Canadian Climate Database (Mekis and Hogg, 1999; Vincent and Gullet, 1999; Environment Canada, 2006). Due to the remote location of the study site, 185 km away from the nearest long-term climate station, no single climate station could be assumed to be representative of the local climatic conditions. The site's position near the crest of a major mountain range further complicated the choice of an appropriate instrumental climate record, as the local climatic conditions were likely influenced by air masses from both east and west of the mountain range (Raphael, 2002). To address this problem, monthly mean temperature records from Dease Lake, Watson Lake, and Fort Nelson (Fig. 1, Table 1) were merged to create a regionally representative record for the stations' 1944–2003 common period. The individual climate records were merged according to the procedures outlined in Jones and Hulme (1996). The monthly records from each station were first converted to z-scores using the 1944–2003 mean and standard deviation. The monthly z-scores from the three stations were averaged to create a regional series and converted back to absolute temperature values using the average of the stations' means and standard deviations. Simple averaging was used to calculate the mean temperature values from the regional climate series for each month.

Analysis of climate-growth responses

Pearson's correlation analyses were used to explore the climate-growth relationships. A 95% confidence level criterion was used to determine the statistical significance of the correlations. Partial

correlation analysis was also used to detect spurious correlations. Partial correlation analysis controls for, or holds constant, one of a pair of correlated climate variables while determining the correlation between the second climate variable and a ring-width series. The ring-width chronologies were compared with a 15-month window of climate data spanning the period from May of the previous year through July of the current growing season.

Reconstruction and verification

Transfer functions were used to reconstruct records of the climate variable with the strongest relationships with each ring-width chronology. Linear regression models were used to predict the past values of the climate variable based on the ring-width chronologies. The transfer function models were calibrated using the full 1944–2003 instrumental climate record.

Leave-one-out verification was chosen as the most appropriate technique for evaluating the strength of the reconstruction (Blasing et al., 1981; Gordon, 1982; Michaelsen, 1987). A split period verification analysis (Fritts, 1976) was deemed inappropriate due to the short length of the instrumental climate record (Gordon, 1982; Michaelsen, 1987). Additionally, comparing the earlier and latter halves of the instrumental climate record would have involved splitting the data in the mid 1970s, near the shift from a warm-phase to a cool-phase of the Pacific Decadal Oscillation (PDO). This could seriously bias the validation results, as the PDO has a significant impact on temperature in western Canada (Minobe, 1997; Bonsal et al., 2001; D'Arrigo et al., 2001; Mantua and Hare, 2002).

To complete the leave-one-out-verification, a separate linear regression model was created for each of the 60 years of the instrumental climate record. One year was left out of the calibration dataset for each model, and the model was used to predict the climate variable of interest for that year. The values predicted for each left-out year were merged into a single climate record and compared to the instrumental climate record to verify the reconstruction. This procedure was repeated for each reconstruction. The ability of the models to reconstruct climatic variability accurately was assessed using correlation coefficients, the reduction of error statistic (RE) and the sign-product statistic (Fritts, 1976; Fritts et al., 1990).

Results and discussion

Chronologies

Fifty-three ring-width series from 29 individual trees were included in the final analysis. The ring-width series have a mean inter-series correlation of 0.567 and a mean sensitivity of 0.161 (Table 2), results similar to those reported from dendroclimatic studies of Engelmann spruce (*Picea engelmannii* Parry ex Engelm var. *engelmannii*) in the central Canadian Rocky Mountains (St. George and Luckman, 2001). The first principal component extracted from the ring-width series belonging to the 15 oldest individual trees explained 44% of the variability within the series. Based on the EPS statistic, the RW chronology is significant back to 1770. The PC chronology is limited to the common period of all the series used in the PCA, in this case 1772–2003.

Table 2
Chronology statistics for the residual ring-width (RW) chronology.

Number of trees	29
Number of series	53
Start date	1723
0.85 EPS threshold	1770
Mean series length	220
Interseries correlation	0.567
Mean sensitivity	0.161
Mean ring width (mm)	0.84
Standard deviation	0.439
ARMA model	3
Variance due to autocorrelation	33%

Climate-growth responses

The chronologies were compared to mean monthly total precipitation records and monthly records of mean, minimum, and maximum temperature. This paper is focused solely on the relationship between ring-width and temperature, as the correlations between ring-width and monthly precipitation totals were relatively weak. Furthermore, partial correlation analysis revealed the few months of statistically significant correlations with precipitation to be spurious (results not shown) when temperature during the same months was held constant. The lack of a strong, consistent relationship with precipitation may be due to the absence of moisture stress in this subalpine forest, or it may be due to high levels of spatial heterogeneity in local precipitation patterns caused by the diverse and mountainous terrain in this region. The only available long-term precipitation records were from climate stations located in markedly different topographic settings than the study site, and thus may reflect very different precipitation regimes.

The two chronologies show similar responses to monthly temperature variability (Table 3). Both chronologies exhibit a strong positive correlation with mean monthly temperatures in the early summer. The chronologies were most strongly correlated with maximum temperatures during June and minimum temperatures in July. Previous dendroclimatic studies in British Columbia (Wilson and Luckman, 2003) and the Yukon Territory (Youngblut and Luckman, 2008) found stronger, more stable correlations between spruce chronologies and maximum temperature than with minimum temperature. In this case, the correlation with July minimum temperature is in fact the strongest correlation with any single monthly climate variable for the RW chronology. Partial correlation analysis revealed that the correlation between ring-width and July

Table 3
Monthly correlations between the ring-width (RW) and principal component (PC) chronologies and minimum, maximum, and mean monthly temperature. Bolded correlations are statistically significant at the 0.05 level. Correlations in italics were shown to be spurious by partial correlation analysis.

Month	RW chronology			PC chronology		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
May	-0.103	-0.147	-0.137	-0.155	-0.204	-0.194
June	-0.036	-0.139	-0.111	-0.091	-0.218	-0.187
July	-0.090	-0.197	-0.174	-0.155	-0.238	-0.229
August	0.100	0.166	0.155	0.091	0.154	0.143
September	0.184	0.063	0.120	0.186	0.091	0.141
October	0.144	0.101	0.127	0.105	0.082	0.097
November	0.000	-0.023	-0.012	0.011	-0.002	0.005
December	0.238	0.239	0.240	0.230	0.228	0.230
January	0.088	0.038	0.067	0.059	0.021	0.043
February	-0.053	-0.046	-0.050	-0.014	-0.010	-0.012
March	-0.208	-0.166	-0.192	-0.292	-0.267	-0.286
April	-0.324	-0.154	-0.248	-0.311	-0.105	-0.216
May	0.106	0.260	0.210	0.097	0.248	0.199
June	0.255	0.493	0.441	0.286	0.555	0.497
July	0.504	0.325	0.427	0.485	0.298	0.401

Table 4
Verification statistics. All statistics are significant at the 0.05 level. See text for further explanation.

Chronology	<i>r</i>	<i>R</i> ²	<i>aR</i> ²	RE	Sign products
RW	0.572	0.327	0.315	0.8807	8
PC	0.597	0.356	0.345	0.8848	11

maximum temperature is no longer statistically significant when July minimum temperature was held constant. The correlation with June minimum temperature was also deemed spurious based on a partial correlation analysis in which June maximum temperature was held constant. Overall, the climate variable most strongly correlated with both chronologies is the averaged June–July mean temperature ($r=0.572$ for the RW chronology; $r=0.597$ for the PC chronology).

The correlation analysis results indicate that warmer temperatures during the growing season lead to increased radial growth, as is typical for high-elevation and high-latitude forests (Fritts, 1976; Tranquillini, 1979). Warmer temperatures during May, June, and July allow for increased rates of photosynthesis, and thus more rapid radial growth (Kramer and Kozlowski, 1960). Higher daytime temperatures at the beginning of the growing season also melt lingering snow, thereby increasing the length of the growing season. Warmer night-time temperatures reduce the risk of frost damage and low-temperature photoinhibition (Germino and Smith, 1999; Johnson et al., 2004; Danby and Hik, 2007).

Reconstruction

June–July mean temperature was selected as the optimum climate variable for reconstruction based on the results of the correlation analyses and preliminary regression analyses. Two transfer function models were developed, one based on the PC chronology and one based on the RW chronology. Both were simple linear regression models, as no lagged values of the chronologies were statistically significantly correlated with the temperature record. The RW chronology model explained 32% of the variance in the mean June–July temperature record and passed all verification tests (Table 4). The PC chronology model explained 35% of the variance in the mean June–July temperature record and also passed all verification tests (Table 4). The high RE values for both verifications are particularly encouraging, as this statistic is extremely sensitive to poor estimates and therefore represents a rigorous test of model skill (Fritts, 1976; Fritts et al., 1990).

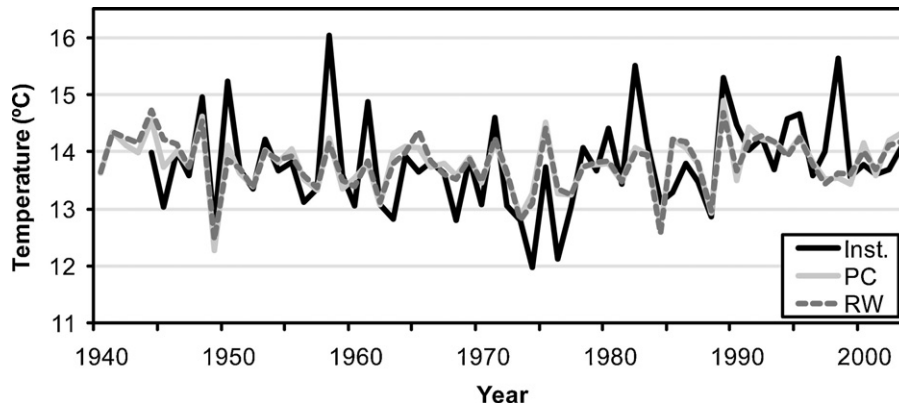


Fig. 2. Comparison of reconstructed and instrumental records of June–July mean temperature.

Although the PC reconstruction explains more of the variance in the instrumental record, both reconstructions faithfully follow annual variability in the instrumental record of mean June–July temperature, aside from under-predicting some of the more extreme years (Fig. 2).

The reconstructions show nearly identical patterns of variability ($r=0.956$, $p=0.000$) throughout most of the record. In both the PC (Fig. 3) and RW (results not shown) reconstructions, the warmest period occurred during the 1940s–1950s, followed by the 1990s. The coldest period in both reconstructions occurred during the late 1970s, with the second coldest period during the 1820s–1830s. Although the two reconstructions are very similar, the PC record is clearly a superior reconstruction based on its consistently, if only marginally, higher level of explained variance and stronger verification statistics. Therefore, only the PC reconstruction was used in further analysis.

The small but consistent improvement in the reconstruction produced using the PCA-based approach compared to the reconstruction created using traditional methods suggests that PCA can in fact enhance the climate signal contained within a chronology by extracting only the variance that is common to all the individual series. The primary drawback to PCA-based chronology development is the fact that the chronology length is limited to the length of the shortest series included in the analysis. The similarity of the two chronologies indicates that the traditional averaging-based method of chronology construction performs reasonably well, at least when combined with double-detrending and prewhitening procedures, and seems to be an adequate substitute for a PCA-based chronology at sites where sample-depth issues make a PCA infeasible.

Comparison with other regional chronologies

The PC reconstruction was compared with several other regional chronologies from British Columbia and the Yukon Territory. The southwestern Yukon (SWY) reconstruction is a record of June–July maximum temperature based on a composite ring-width chronology created from a network of white spruce site chronologies (Youngblut and Luckman, 2008). The southern Canadian Rocky Mountains (SRM) reconstruction is a record of May–August maximum temperature created using ring-width and density chronologies primarily composed of Engelmann spruce (Luckman and Wilson, 2005). The Twisted Tree–Heartrot Hill (TTHH) record is a single-site white spruce ring-width chronology from the northwestern Yukon that shows a positive correlation with June–July mean temperature (Jacoby and Cook, 1981; D’Arrigo et al., 2004). The southern Coast Mountains (SCM) reconstruction is a record of July mean temperature based on subalpine fir ring-width chronologies from southeastern British Columbia (Larocque and Smith, 2005).

Comparison with the dendroclimatic records from western Canada listed above revealed that the northern Canadian Rocky Mountains reconstruction (PC) shares similar patterns of low frequency (decadal or longer time-scales) variability (Fig. 4), although clear regional differences are visible in the timing and magnitude of climatic events on decadal time-scales. Some of these differences may be attributable to the fact that these records were not developed using identical methods, nor with the same species, and some are reconstructions of different climate variables, making them somewhat difficult to directly compare.

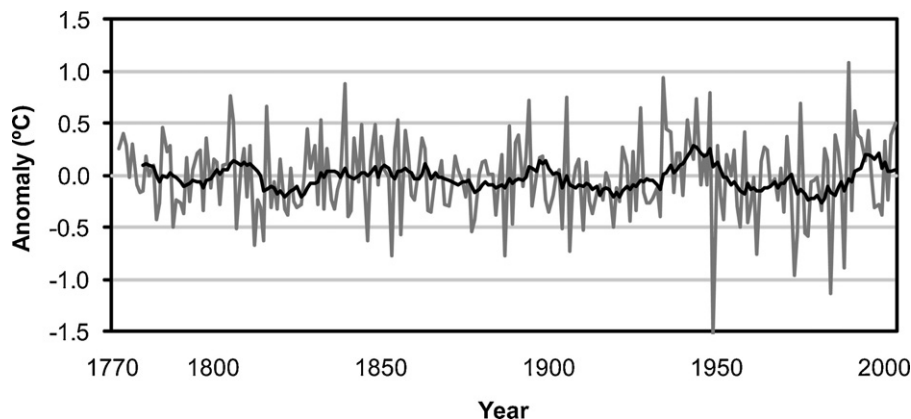


Fig. 3. Reconstructed proxy record of June–July mean temperature. Anomalies calculated with respect to the 1971–2000 mean. Thick line is a 10-year moving average.

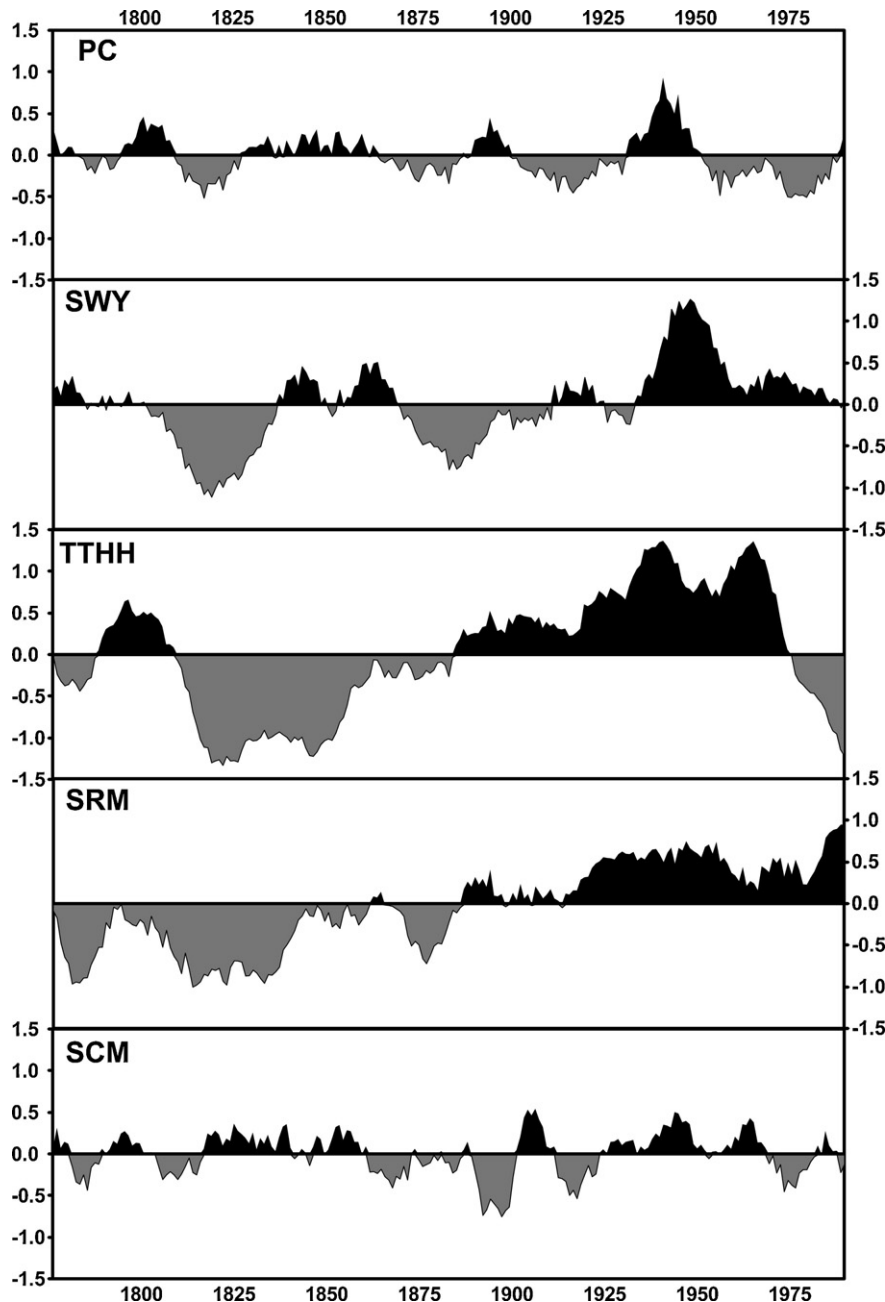


Fig. 4. Standardized regional chronologies from the northern Canadian Rocky Mountains (PC), the southwestern Yukon Territory (SWY), the northwestern Yukon Territory (TTHH), the central Canadian Rocky Mountains (SRM), and the southern Coast Mountains (SCM) presented as 11-year moving averages. Vertical axes are z-scores standardized with respect to the common period (1772–1992).

There is a pattern of greater similarity between the PC reconstruction and other tree-ring records in the north than is apparent with those from further south. Many of the regional records show generally increased growth at the end of the 1700s, and dramatic decreases in growth rates in the 1820s–1830s and 1870s–1880s, with a return to normal growing conditions during the mid-1800s. Peaks in growth are apparent in most of the records near 1900 and during the mid and late 20th century. The PC reconstruction shows greater interannual temperature variability during the late 20th century than during any other period; this pattern is not apparent in any of the other tree-ring records included in this comparison.

Correlation analysis indicates a strong pattern of shared high-frequency variability with the SWY reconstruction (Table 5). A lower, but still statistically significant, correlation is seen with the

TTHH record. The SRM and SCM reconstructions show some similarities to the PC reconstruction at decadal to multi-decadal scales, but much weaker correlations at annual scales. Correlation analyses undertaken for 55-year segments (Table 5) revealed considerable

Table 5

Correlations between the PC reconstruction presented in this paper and other regional reconstructions calculated for their full common period and for 55-year segments. Bold correlations are significant at the 0.05 level.

Time period	SWY	SRM	SCM	TTHH
1772–1991	0.490	0.132	0.120	0.206
1772–1826	0.481	0.251	0.173	0.388
1827–1881	0.427	0.044	0.314	–0.004
1882–1936	0.513	0.258	0.012	0.481
1937–1991	0.585	0.140	0.019	0.213

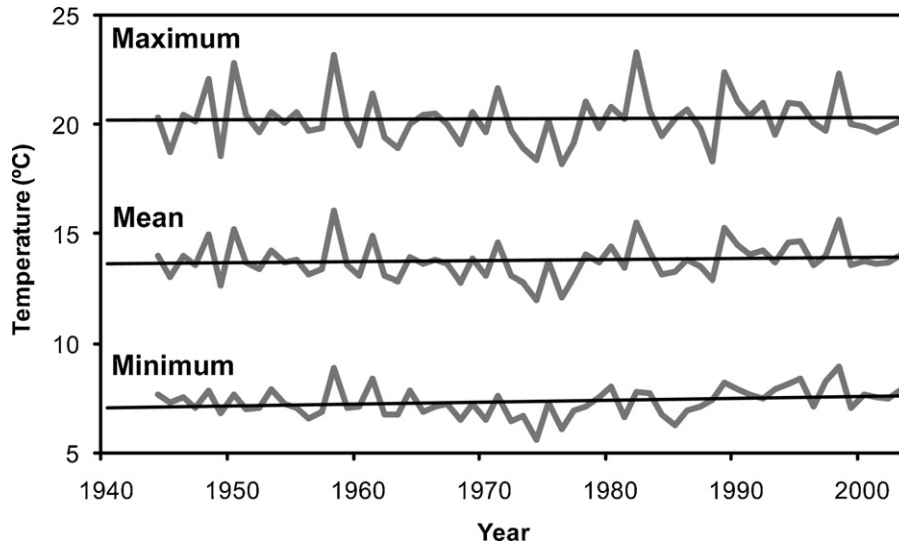


Fig. 5. Trends in the merged instrumental climate record of June–July temperature.

variability in the strength of the relationships between records. The mid-1800s stand out as an anomalous period during which the usually moderate to strong positive correlation between the PC and TTHH records completely vanishes, and the otherwise relatively weak correlation between the PC and SCM reconstructions becomes much stronger. The correlation between the PC record and both the SRM and the SWY records are relatively low during this period. This may represent a period of increased maritime influence on the climate of the northern Canadian Rocky Mountains.

The SWY reconstruction is the only record that is consistently statistically significantly correlated with the PC reconstruction regardless of the period of analysis. In spite of the strong correlation at the annual time scale, comparison of the low-frequency variability in the PC reconstruction and the SWY record reveals an apparent lag in the occurrence of climatic events between these two nearby regions. Decadal-scale periods of cool or warm temperature anomalies almost always begin earlier in the PC reconstruction than in the SWY reconstruction.

Divergence

The most notable difference between the PC and TTHH records occurs during the late 20th century, where the TTHH record indicates consistently and dramatically decreasing growth rates during a period in which this pattern is not apparent in the other ring-width records. The TTHH chronology is no longer statistically significantly correlated with the PC record during the late 20th century. This pattern in the TTHH chronology is an example of the so called “divergence problem” (D’Arrigo et al., 2004) which has been detected in many high-latitude white spruce ring-width chronologies (Barber et al., 2000; Lloyd and Fastie, 2002; Wilmking et al., 2004). The divergence problem manifests as an apparent decrease in the sensitivity of ring-width series to climatic variability or as opposite trends in the ring-width and climate records (D’Arrigo et al., 2008).

Previous studies have detected intra-stand divergence by comparing correlations between ring-width series and climate from before a cut-off date, typically between 1950 and 1965, with correlations after that date (Lloyd and Fastie, 2002; D’Arrigo et al., 2004; Wilmking et al., 2004, 2005). Due to the short instrumental climate record in this region, a comparable analysis could not be conducted. Comparison with longer climate records from more distant stations

was deemed inappropriate due to significant differences in recent warming trends between stations in this region and those further north or south (Zhang et al., 2000). Century-long records of gridded and interpolated data are available for this region (New et al., 2000; Zhang et al., 2000; Wang et al., 2006), but these records suffer from a marked reduction in data quality before approximately 1940 due to a rapid decline in sample depth before that time.

In spite of these limitations, it was still possible to test for divergent growth patterns among individual trees after the mid-20th century. The ring-width series from individual trees were compared to post-1960 instrumental climate data using Pearson’s correlation analysis. No pattern of mixed negative and positive growth responses to temperature variability was apparent among the individual trees. As these divergent intra-stand growth patterns appear to be the reason for reduced climate-growth correlations (Wilmking et al., 2004, 2005), their absence can be viewed as evidence that no divergence-induced reduction in sensitivity has occurred in this chronology. Visual comparison of the individual series for divergent trends over their entire length also revealed no signs of divergence between series. Furthermore, there is no sign of divergence between the PC chronology and the instrumental climate record during the late 20th century (Fig. 2).

The absence of a significant warming trend in local summer temperature records offers a probable explanation for the absence of divergence in this chronology. Divergence has been linked to moisture-stress brought on by increasing temperatures (Barber et al., 2000; Lloyd and Fastie, 2002), differing trends in day and night-time temperatures (Wilson and Luckman, 2003), and non-linear responses to increasing temperatures (D’Arrigo et al., 2004; Wilmking et al., 2004). Based on these hypotheses, divergence should only occur in areas where summer temperature is increasing over time. In the northern Canadian Rocky Mountains spring and winter temperatures show warming trends, but local summer (Fig. 5) and fall temperature records show almost no trend (Zhang et al., 2000). Thus, it makes sense that no divergence is evident in this region.

Conclusion

White spruce trees were sampled for dendroclimatological analysis in the northern Canadian Rocky Mountains. The ring-width chronologies showed a strong positive relationship with mean

temperature during June and July of the current growing season. A 234-year record of summer temperature variability was reconstructed using standard dendroclimatological methods. A second, 232-year reconstruction was created through the use of principal components analysis. Although the two reconstructions indicated very similar patterns of temperature variability over the last 232 years, the principal component based reconstruction was deemed superior due to its consistently greater ability to explain the variance in the instrumental temperature record and stronger performance during verification. This chronology showed no evidence of the recent reduction in sensitivity to climatic variability that is apparent in many other northern spruce chronologies. Comparison of this reconstruction with other dendroclimatological reconstructions from western Canada revealed a coherent pattern of low-frequency variability, although there was considerable spatial and temporal variability in the levels of agreement between reconstructions at annual time-scales. This reconstruction has filled in one of the remaining major gaps in the spatial coverage of dendroclimatic reconstructions in western North America.

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