Extracting a paleotemperature record from *Picea engelmannii* tree-line sites in the central Canadian Rockies

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Abstract: A new network of 21 *Picea engelmannii* Parry ex Engelm. ring-width chronologies was developed from tree-line sites in the Canadian Rockies. These chronologies range in length from 297 to 648 years (mean 423 years) and have mean sensitivities between 0.16 and 0.20 (mean 0.18), first-order autocorrelations between 0.73 and 0.88 (mean 0.83), and subsample signal strengths >0.85 for 246–494 years (mean 324 years). Mean intersite correlations (A.D. 1700–1982) for chronologies with expressed population signals >0.85 are 0.46 and 0.63 for standard and residual chronologies, respectively. Standard ring-width chronologies are, in general, positively correlated with summer temperatures and negatively correlated with spring and previous summer temperatures. A regional June–September temperature reconstruction for the Banff–Jasper region (BJR; A.D. 1715–1982) was developed using multiple regression of three significant principal components from 14 standard ring-width chronologies. The first principal component contains 55% of the total chronology variance. The model reconstructs 38% of summer temperature variance during the calibration period (1888–1982). The BJR is the first regional temperature reconstruction for this area based on ring-width data from a network of sites. The reconstructed temperature patterns are broadly similar to other regional estimates of past temperatures. Above-average summer temperatures occurred in the mid-20th century and the late 1700s – early 1800s. Most of the 19th century was unusually cold, with the coldest conditions in the late 19th century. Detailed differences between BJR and previously developed reconstructions lie well within 2σ confidence limits and may reflect differences in tree species, modelling techniques, spatial coverage, and the seasonal temperature parameter reconstructed.

Résumé : Un nouveau réseau de 21 séries dendrochronologiques de *Picea engelmannii* Parry ex Engelm. a été développé à partir de sites situés à la limite des arbres dans les montagnes Rocheuses canadiennes. Ces chronologies varient en durée de 297 à 648 ans (moyenne 423 ans), ont des sensibilités moyennes de 0,16 à 0,20 (moyenne 0,18), des autocorrélations du premier ordre de 0,73 à 0,88 (moyenne 0,83) et des forces de signal des sous-échantillons >0,85 pour 246 à 494 ans (moyenne 324 ans). Les corrélations moyennes inter-sites (A.D. 1700–1982) pour les chronologies avec un signal de population exprimé >0,85 sont respectivement de 0,46 et 0,63 pour les chronologies standards et résiduelles. Les séries dendrochronologiques standards sont généralement corrélées positivement avec les températures estivales et négativement avec les températures printanières et celles de l'été précédent. Une reconstruction des températures régionales des mois de juin à septembre pour la région de Banff–Jasper (BJR ; A.D. 1715–1982) a été développée à l'aide de la régression multiple de trois composantes principales significatives provenant de 14 séries dendrochronologiques standards. La première composante principale contient 55% de la variation totale de la chronologie. Le modèle reproduit 38% de la variation dans la température estivale au cours de la période de calibration (1888–1982). La BJR constitue la première reconstruction de la température régionale pour cette zone sur la base de données de largeurs de cernes provenant d'un réseau de sites. Les patrons de température obtenus par reconstruction sont généralement similaires à d'autres estimés régionaux de la température dans le passé. Des températures estivales au-dessus de la moyenne sont survenues au milieu du 20e siècle et à la fin des années 1700 et au début des années 1800. Presque tout le 19e siècle a été anormalement froid, particulièrement à la fin du 19e siècle. Les différences entre la BJR et les reconstructions développées antérieurement se situent bien en deçà des limites de confiance correspondant à 2σ et pourraient refléter des différences dans les espèces d'arbres, les techniques de modélisation, la couverture spatiale et le paramètre de la température estivale qui est reconstruit.

[Traduit par la Rédaction]

Introduction

The subalpine forests of the Canadian Rockies contain several long-lived tree species that offer considerable potential for dendroclimatic research. Three tree-line species attain maximum ages of >750 years, namely Engelmann spruce (*Picea engelmannii* Parry ex Engelm., >760 years; Reynolds 1992), alpine larch (*Larix lyallii* Parl., >834 years; M.E.

Received February 11, 2000. Accepted November 22, 2000. Published on the NRC Research Press Web site on March 9, 2001.

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 DOI: 10.1139/cjfr-31-3-457

Colenutt, personal communication 1997) and whitebark pine (*Pinus albicaulis* Engelm., >1050 years; Luckman and Youngblut 1999). In addition, well-preserved tree-line snags and buried sub-fossil material offer the potential to extend these living-tree chronologies by cross dating. In recent years, several chronology networks and long chronologies have been developed for this region and used primarily for cross-dating dead material associated with glacier history (Luckman 1995, 1996).

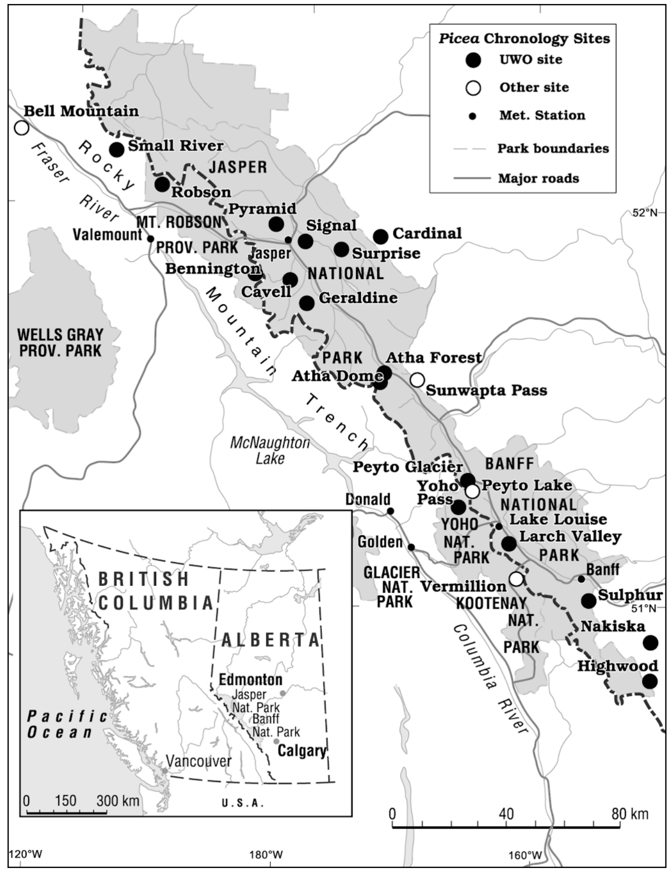
Picea engelmannii is the most widely distributed of these long-lived tree-line species. Previous work with *Picea glauca* (Moench) Voss at the North American Arctic tree line (D'Arrigo and Jacoby 1992) indicates that this species maintains a strong common ring-width signal over several thousand kilometres. This signal is related to variations in past temperatures and has provided a basis for several high-quality dendroclimatic reconstructions of past temperatures over the Northern Hemisphere (Jacoby and D'Arrigo 1989; D'Arrigo and Jacoby 1992). In contrast, exploration of the climate signal in *Picea engelmannii* ring width has been limited and the few climate reconstructions developed from this species are based primarily on densitometric data (Parker and Henoch 1971; Hamilton 1987; Briffa et al. 1992; Luckman et al. 1997). Prior studies of preliminary ring-width data sets from *Picea engelmannii* in the central Canadian Rockies (Luckman and Seed 1995; Luckman 1997) indicate that they contain a strong common signal. The only previous climate reconstruction based solely on *Picea engelmannii* ring width was derived from a single site near the south end of Banff National Park (Wig and Smith 1994). The present paper evaluates the strength and spatial consistency of the ring-width signal in tree-ring chronologies developed from sites within a 500-km long network of *Picea engelmannii* growing at alpine tree line. This common signal is subsequently compared with regional climate records and used to develop a reconstruction of past summer temperatures in the central Canadian Rockies.

Materials and methods

Picea engelmannii ring-width chronology network

Banff and Jasper National Parks fall within the Cordilleran Subalpine Forest region (Krajina 1969), which extends from 49°N to the Yukon Territory. Engelmann spruce is the dominant forest species of this region and is particularly numerous at tree line. Over the past 15 years, the Tree-Ring Laboratory at the University of Western Ontario has developed a tree-ring data base for Banff and Jasper National Parks and adjacent areas. While initial investigations focused on the use of tree rings as dating tools for glacial (Luckman 1988; Watson 1986) and geomorphic activity (Frazer 1985), parallel studies led to the development of long chronologies for individual sites (e.g., Hamilton 1987; Colenutt 1988) and the gradual development of a regional tree-ring network. The current Engelmann spruce network of 21 sites extends approximately 500 km along the Continental Divide (Fig. 1, Table 1). Most sites are located within national or provincial parks and are protected against major anthropogenic disturbances such as logging or mining. Furthermore, no sampled stands contained obvious evidence of insect attacks, disease, or large-scale blowdowns. Sampling was conducted mainly at altitudinal tree line where temperature should be a dominant limiting factor in tree growth, resulting in a strong paleotemperature signal within the ring-width chronologies. A few of the sampled sites are several hundred metres below tree line and (or) located adjacent to the Little Ice Age limits of glaciers (Table 1). At each site, a minimum of 15 trees were cored at breast height, with at least two cores collected 90° apart from each tree.

Fig. 1. Location of the *Picea engelmannii* tree-ring sites and meteorological stations, central Canadian Rockies.



Chronology development

Cores were prepared using standard procedures (Stokes and Smiley 1968) and measured using a tree ring increment measurement system built for the Ontario Ministry of Natural Resources (MacIver et al. 1985). The initial cross dating was confirmed using COFECHA (Grissino-Mayer et al. 1996). Ring width was detrended using conservative negative exponential or linear functions intended to preserve low-frequency variation in the ring-width data. This method was justified by the open grown nature of stands in the tree line – alpine environment as well as the relatively simple growth trends observed in the individual ring-width series. As the maximum wavelength of recoverable information in a detrended tree-ring chronology is equivalent to $3/n$ (where n = mean tree age; Cook et al. 1995), the limit of identifiable fluctuations within this network is likely near century-scale variation (n is approximately equal to 284 years). Expressed population signal (EPS) analysis (Wigley et al. 1984) was used to quantify the signal strength at each site. ARSTAN (Cook 1985) was used to generate "standard" and "residual" chronologies for each of the 17 sites that satisfied the EPS threshold.

Regional climate records

Relatively few long climate records exist for the Canadian Rockies and the available climate data are sparse, topographically and geographically limited, and often of short or seasonal duration (Janz and Storr 1977; Luckman 1990). Luckman and Seed (1995) reviewed the instrumental climate record for this region and concluded that records from Banff, Golden, Lake Louise, Jasper, and

Table 1. *Picea engelmannii* chronology site characteristics.

Site	Code	Latitude (N)	Longitude (W)	Elevation (m)	Aspect	Slope (%)	Elevation below tree line
Bell Mountain[a]	BM	53°20′	120°40′	1530			
Small River	SR	53°10′	119°29′	1900	SE	0–20	Tree line[b]
Robson Glacier	RG	53°09′	119°07′	1690	NW	15–20	200–300[b,c]
Pyramid	PY	52°58′	118°10′	2000	E–SE	Gentle	Tree line
Cardinal Divide	CD	52°53′	117°15′	2050	S	10–20	50–100
Signal Mountain	SM	52°52′	117°58′	2050	E–NE	10–20	Tree line
Surprise Valley	SV	52°48′	117°38′	1800	N	10–20	200–300[d]
Bennington	BE	52°42′	118°21′	1900	S	15–30	100
Cavell Glacier	CG	52°41′	118°03′	1800	N	5–10	300[b]
Geraldine Lakes	GL	52°35′	117°56′	2000	S	20–30	Tree line
AthaDome	AD	52°15′	117°15′	2000	N	Gentle	Tree line[b,e]
AthaForest	AF	52°15′	117°15′	2000	S	10–20	Tree line
Sunwapta Pass[a]	SP	52°12′	117°00′	2050	S	10–20	Tree line
Peyto Glacier	PG	51°42′	116°31′	1850	N	0–10	250–350[b]
Peyto Lake[a]	PL	51°43′	116°30′	2050	S	0–10	Tree line
Yoho Pass	YP	51°29′	116°29′	1950	N–NE	30	Tree line
Larch Valley	LV	51°18′	116°11′	2200	NE	Up to 30	Tree line
Vermillion Pass[a]	VP	51°10′	116°10′	1500			
Sulphur Mountain	SM	52°48′	115°34′	2250	S and N	30	Tree line
Nakiska	NK	50°50′	115°15′	2160	E–NE	20–30	Tree line
Highwood Pass	HP	50°36′	114°59′	2250	NE	Steep	Tree line

Note: Chronologies are ordered from north to south.
[a]Chronologies collected by Dr. Fritz H. Schweingruber of the Swiss Federal Institute of Forest, Snow and Landscape Research.
[b]Valley floor or side site adjacent to Little Ice Age moraines.
[c]Isolated knoll flanked by Little Ice Age limit moraines.
[d]Open grown site on coarse rockslide material.
[e]Between the lateral moraines of the Dome and Athabasca glaciers.

Valemount were the most useful for dendroclimatic reconstruction. Unfortunately, despite their high absolute elevations, all five stations are from valley floor locations situated well below the tree-ring sites. Luckman et al. (1997) developed a composite temperature anomaly series (1961–1990 normals) for this region based on the Banff, Jasper, Golden–Donald, and Valemount records. Sample depth ranges from a single station (Banff) between 1887 and 1891, two stations between 1892–1901 and 1902–1914, to four stations from 1915–1994. Despite masking some local and regional climate variability, this aggregate record is the most appropriate for regional evaluation of temperatures (Luckman 1997). An equivalent composite precipitation series was not generated because of local variability in precipitation patterns (Luckman 1997).

Paleoclimatic reconstruction

Ring-width indices for each standard chronology were correlated against instrumental climate data to identify possible climate signals recorded in the Engelmann spruce ring-width series. Correlation coefficients were generated using 17 months of climate data, from May of the previous year to September of the growth year. The relationships between ring width and climate variables were analysed using both nearest-station and regional climate data sets. Following this exploratory analysis, stepwise multiple linear regression was employed to obtain a statistical expression relating ring-width chronologies and regional temperatures. Selected tree-ring chronologies were transformed into principal components (PCs) to reduce multicollinearity and the number of predictors in the model. Principal components analysis (PCA) emphasizes the variance common to all chronologies and minimizes the unique variance present in any individual tree-ring record (Fritts 1991). Chronologies were transformed into orthogonal principal components using a Varimax rotation, and only those PCs with eigenvalues greater than one were introduced as predictors. Verification of the regression results was carried out using the all-but-one-subsampling method (Gordon 1982; Michaelsen 1988).

Results

Picea engelmannii ring-width chronologies

Chronology characteristics

Summary statistics for the Engelmann spruce standard chronologies are given in Table 2. All chronologies exceed 295 years, with six sites extending into the 16th century and three into the 15th century. Mean ring width ranges from 0.45 to 1.05 mm and is slightly higher than that of alpine larch growing in similar environments (Colenutt and Luckman 1996). The low average mean sensitivity (0.18) of the chronologies in the network is typical for spruce, indicating that the spruce ring widths have relatively low interannual variability. Although high mean sensitivity is considered to be beneficial in chronology development (Fritts 1976), this statistic mainly reflects variance at high frequencies (1 or 2 years), which may or may not be related to climate. Trees with lower mean sensitivities do not necessarily lack a climatic response (LaMarche 1974; G.C. Jacoby, personal communication).

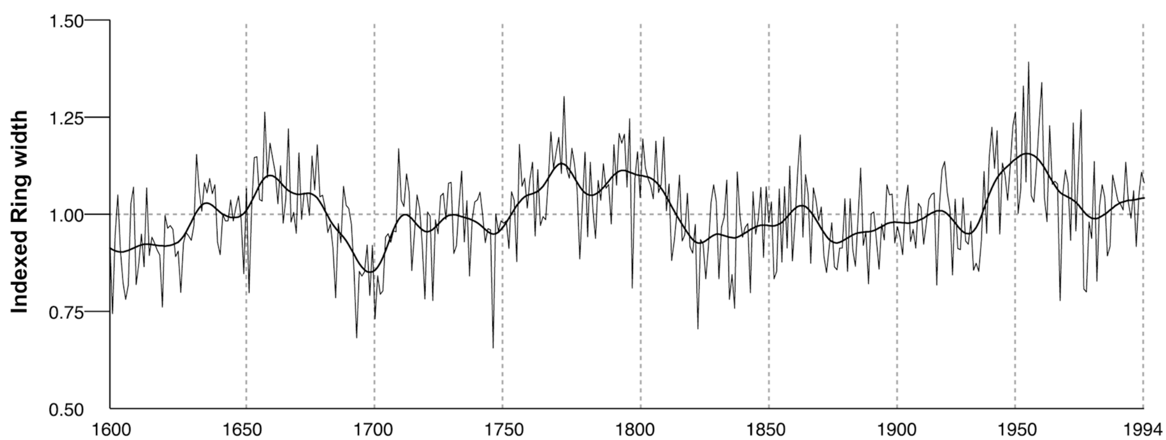
Seventeen spruce sites met Wigley et al.'s (1984) minimum EPS threshold of 0.85, indicating that they contain a strong between-tree ring-width signal. Four sites (Robson Glacier, Bennington, Cavell Glacier, and Peyto Glacier) did not meet the EPS threshold and were removed from subsequent analyses. Three of these sites are lower elevation,

Table 2. Descriptive statistics for the 21 *Picea engelmannii* standard chronologies.

Site	Interval	Total trees	Mean age (years)	Mean ring width (mm)	Mean sensitivity[a]	Autocorrelation[b]	R_{bt}[c]	EPS[d]	SSS > 0.85[e]
Bell Mountain	1649–1983	14	283	0.76	0.17	0.83	0.26	0.87	1679
Small River	1569–1989	12	294	0.72	0.20	0.82	0.28	0.85	1638
Robson Glacier	1567–1982	17	313	0.51	0.16	0.85	0.19	0.81	1628
Pyramid	1625–1990	24	250	0.76	0.20	0.75	0.23	0.90	1675
Cardinal	1528–1990	31	345	0.49	0.20	0.80	0.31	0.94	1591
Signal Mountain	1489–1990	19	283	0.68	0.20	0.79	0.28	0.91	1638
Surprise Valley	1600–1990	18	331	0.72	0.17	0.87	0.20	0.86	1637
Bennington	1563–1991	12	296	0.72	0.17	0.83	0.23	0.83	1654
Cavell Glacier	1639–1990	13	252	0.62	0.16	0.84	0.19	0.78	1686
Geraldine Lakes	1510–1991	18	299	0.56	0.17	0.81	0.21	0.85	1656
AthaDome	1458–1987	27	280	0.45	0.18	0.82	0.25	0.91	1674
AthaForest	1346–1994	53	281	0.54	0.17	0.78	0.23	0.95	1500
Sunwapta Pass	1608–1983	13	292	0.99	0.16	0.87	0.29	0.88	1702
Peyto Glacier	1424–1990	15	293	0.61	0.16	0.88	0.11	0.68	1680
Peyto Lake	1634–1983	13	239	1.05	0.19	0.80	0.40	0.92	1715
Yoho Pass	1526–1990	19	244	0.91	0.18	0.78	0.22	0.86	1741
Larch Valley	1567–1986	10	239	0.88	0.20	0.73	0.35	0.87	1740
Vermillion Pass	1686–1983	12	255	0.77	0.16	0.85	0.41	0.92	1705
Sulphur Mountain	1644–1990	19	232	0.90	0.20	0.82	0.34	0.92	1704
Nakiska	1619–1987	14	321	0.48	0.19	0.83	0.36	0.92	1642
Highwood Pass	1613–1987	17	269	0.79	0.19	0.73	0.26	0.89	1644
Mean	423 years	19	281	0.71	0.18	0.81	0.27	0.87	1663

[a]Mean sensitivity is a measure of year-to-year variations in ring width (Fritts 1976).
[b]Autocorrelation represents the chronology's correlation coefficient at a lag of 1 year.
[c]R_{bt}, the mean between-tree correlation, is the mean interseries correlation calculated between all possible pairs of indexed series drawn from different trees (Briffa and Jones 1990).
[d]EPS is the expressed population signal, which represents the degree to which a particular sampling portrays the hypothetical perfect chronology (Briffa and Jones 1990).
[e]SSS > 0.85 is the earliest date for which the chronology maintains a subsample signal strength of greater than 85% of the original EPS.

Fig. 2. Mean standard ring-width chronology (1600–1994) for the 17 *Picea engelmannii* sites in the central Canadian Rockies. The smoothed line is a 25-year Gaussian filter.



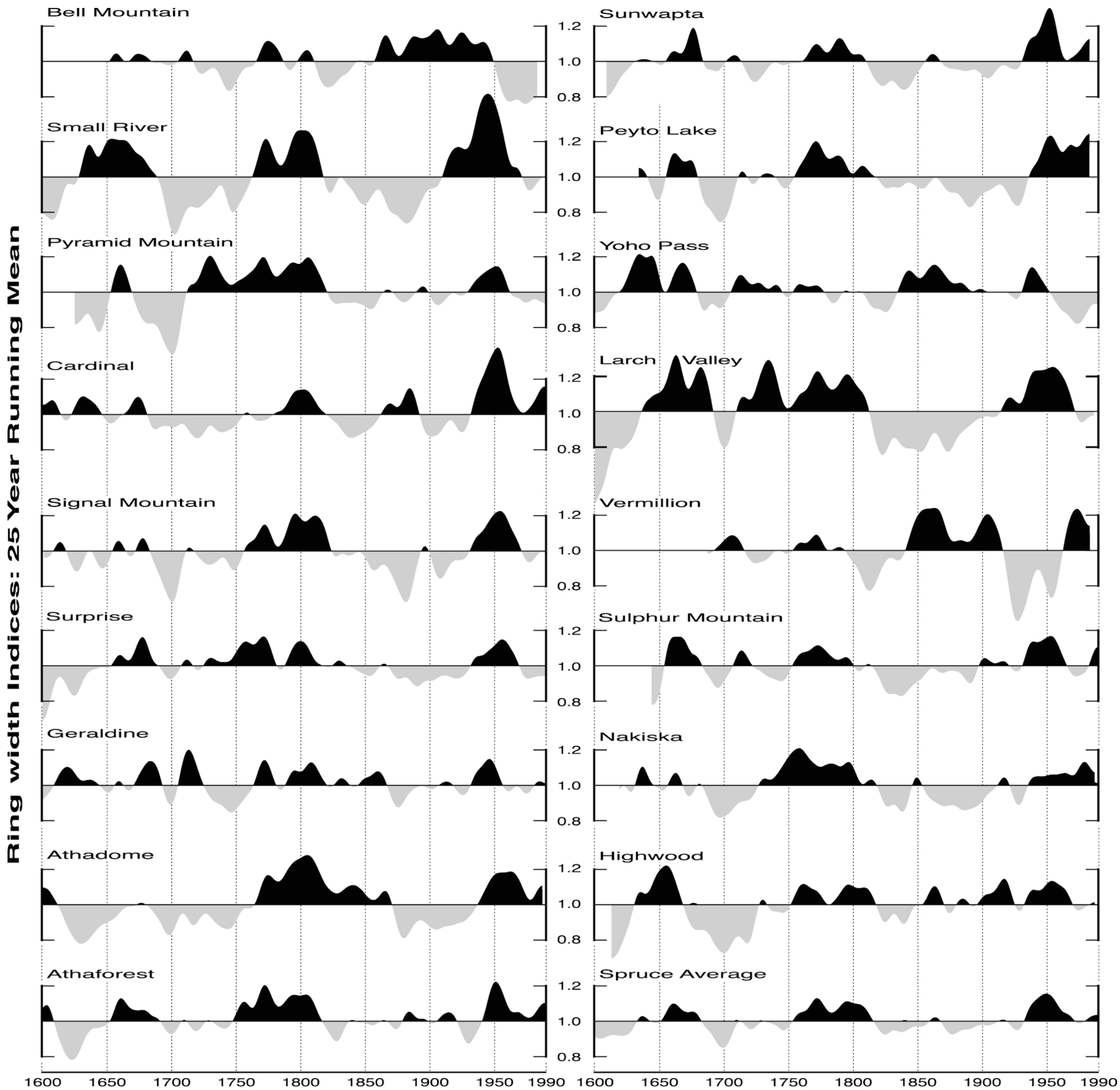
valley-floor stands adjacent to glaciers. Most of the remaining chronologies maintain subsample signal strengths (SSS) >85% well into the 17th century.

Chronology comparison

The mean ring-width record from all 17 standard chronologies contains strong persistence and can be divided into several distinct periods (Fig. 2). Ring widths were below average at the start of the record from 1600 to 1632, with suppressed growth also occurring from 1683 to 1754 and from 1814 to 1932. Above-average growth was observed during 1633–1683, 1755–1815, and 1932–1994. Ring widths for most chronologies were greatest between 1935 and 1970, reaching maximum values ca. 1950. After 1975, ring widths were either close to or slightly above average.

Although most individual series follow the regional trends shown in Fig. 2, each chronology contains some unique variability (Fig. 3). The most obviously different records are from just west of the Continental Divide in Yoho and Vermillion Passes. Both lack the peak in ring width during

Fig. 3. Indexed ring-width chronologies from 17 *Picea engelmannii* sites in the central Canadian Rockies. The chronologies have been smoothed with a 25-year Gaussian filter and are plotted in an approximately north–south sequence. The average chronology is as shown in Fig. 2.



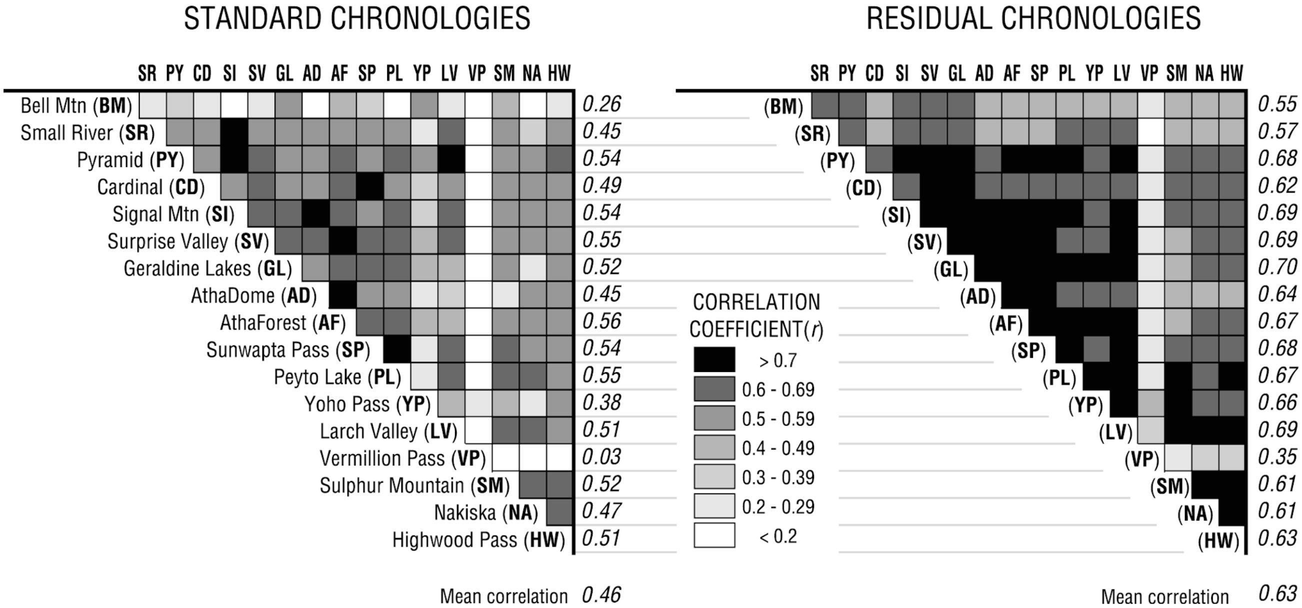
the late 1700s and had generally high levels of growth during the 1800s. Patterns of ring-width variation prior to 1700 (Figs. 2 and 3) should be viewed with caution because of the relatively low number of chronologies and the low SSS values observed during this period. However, several chronologies exhibit a peak in ring width around 1660, and ring widths are generally high from 1650 to 1680. Figure 4 is a correlation matrix for the 17 spruce chronologies with EPS >0.85. The average between-site correlation is 0.46 for standard chronologies and 0.63 for residual chronologies over the 1700–1982 interval. Between-site correlations generally decrease with distance between sites. The residual chronologies (Cook 1985) reflect the stronger common signal in interannual patterns of ring-width variability. Although there are no obvious subgroups within these chronologies, the records for Vermillion Pass, Bell Mountain, and Yoho Pass clearly differ from the majority of the chronologies.

Climate – ring width correlation analysis

Nearest-station analysis

Figures 5*a* and 5*b* illustrate the pattern of significant (p = 0.05) ring width – climate correlations between individual standard chronologies and temperature and precipitation records from the nearest climate station. In general, ring width is positively correlated with summer temperatures and nega-

Fig. 4. Correlation matrices for 17 *Picea engelmannii* chronologies (1700–1982) from the central Canadian Rockies. Residual and standard chronologies are developed using ARSTAN (Cook 1985). Chronologies are ordered in a north–south sequence (Table 1). Luckman (1997) extracted similar correlation patterns from a preliminary version of this data set.



tively correlated with both spring and previous summer temperatures. While summer temperature is significantly correlated with the sites near Banff, this statistical relationship is not present for those ring-width series compared with the Jasper climate record. The more northerly sites surrounding Jasper are most highly and negatively correlated with March and April temperatures. The Vermillion series is unique in that it has no significant correlations with climate records from the nearest station. The results presented in Fig. 5*b* do not show any consistent, statistically significant correlations between monthly precipitation records and tree-ring width across the network. This suggests that these trees have not been sensitive to precipitation variations during the 20th century.

Luckman (1997) discussed some limitations of paleoclimatic reconstructions based on a limited number of climate stations. Although both the climate and spruce data sets contain spatial patterns of variation, the sparse network of climate sites precludes the identification of present-day subregional climate variations. The inconsistent correlations observed in Fig. 5*a* may reflect either varying responses of the trees to the same macroclimatic variables or similar responses of the trees to different microclimates (Fritts 1991). These uncertainties were further explored by examining correlations between the tree-ring series and the regional temperature record.

Regional temperature analysis

All tree-ring records were correlated against the regional temperature record to emphasize variability common to the entire tree-ring network (Fig. 5*c*). The most consistent association is between ring width and summer temperatures. More than two-thirds of the chronologies have significant correlations with June, July, and September temperatures of the growth year, but few are significantly correlated with August temperatures. Bell Mountain, Yoho Pass, and Vermillion Pass are the only chronologies that do not have a significant correlation with either June or July temperatures. Correlations with April and May temperatures are negative but less spatially consistent across the network. Significant correlations with the previous year's temperatures are highly variable.

In contrast with the results from the nearest-station analysis, the Jasper tree-ring sites exhibit a consistent association with regional June and July temperatures. As June and July temperatures for the Jasper and regional data sets are very highly correlated (>0.92), this suggests that the improved correlation between the Jasper tree-ring chronologies and the regional summer temperatures reflect the extension of the analysis period from 1916 to 1888, rather than any subregional differences in tree response.

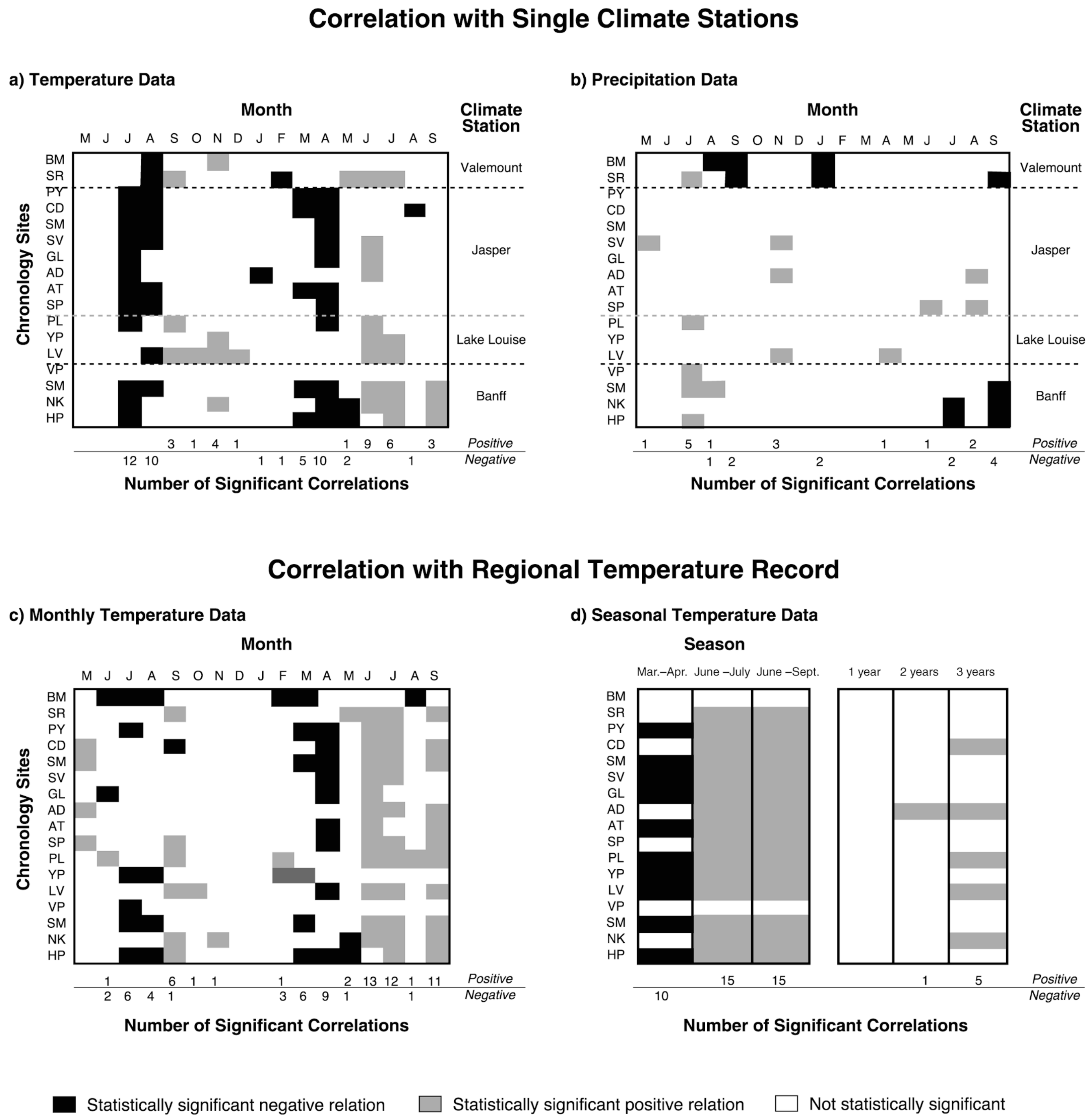
Correlation analysis using various combinations of monthly regional temperatures (Fig. 5*d*) revealed that spruce ring widths were significantly positively correlated with both June–July and June–September temperatures and negatively with March–April temperatures. Linkages were most spatially consistent for the summer combinations, with 15 of 17 ring-width chronologies having significant correlations with June–July ($\bar{r}$ = 0.32, range –0.10 to 0.53) and June–September temperatures ($\bar{r}$ = 0.29, range –0.15 to 0.48). Only 10 of the 17 chronologies show a significant correlation with March–April temperatures ($\bar{r}$ = –0.20). Correlations between ring width and mean annual temperatures (averaged over 1- to 3-year periods) were generally not significant. Five chronologies were significantly correlated with the 3-year average, but generally, correlations were quite weak.

Developing a regional summer temperature reconstruction

Selection of the reconstructed parameter

Correlation analysis suggested three candidates for potential climate reconstruction: spring (March–April), summer (June–September), and high summer (June–July) regional temperatures. Reconstruction of the spring temperature parameter was rejected because of the relatively low correlations and inconsistency across the network. Mean correlation

Fig. 5. Summary of significant correlations ($p = 0.05$) between monthly or seasonal climate data and 17 *Picea engelmannii* standard chronologies. Monthly correlations utilize a 17-month window from May of the previous year to September of the growth year. See Table 1 for definition of the site codes.



coefficient values were very similar for both June–July and June–September temperatures, with the AthaDome site displaying the highest correlation with June–July and June–September temperatures (0.53 and 0.48, respectively). The June–September climate “window” was selected for reconstruction because the longer period should contain more information regarding warm-season temperatures than June–July.

Calibration and verification

Principal components analysis (PCA), employing a Varimax rotation, was used to reduce the 14[3] standard ring-width chronologies to a series of independent predictor variables for the 1715–1982 period. Three principal components had eigenvalues greater than 1 (Table 3, Fig. 6), with the first component accounting for roughly 55% of the total variance of the data set. The amount of variance explained by the first

[3] The chronologies for Geraldine Lakes, Yoho Pass, and Larch Valley were excluded to extend the common period back to 1715.

component of the chronology matrix is comparable with results obtained by other workers in the boreal environment (e.g., 45% in PC1 along Arctic tree line; Jacoby and D'Arrigo 1989). The first component represents ring-width variations for the majority of sites in the network, as all chronologies except Vermillion Pass and Bell Mountain have high loadings on this component. Vermillion Pass and Bell Mountain dominate the second and third principal components, respectively.

The three components with eigenvalues greater than 1 were included as predictors in the multiple regression. The PCs of ring width in year $t + 1$ were also added to the predictor data set to model the effects of previous climate conditions on ring width in the present year. Four variables were significant predictors of June–September temperatures (Table 4): PC1, $PC3_{t+1}$, $PC2_{t+1}$, and $PC1_{t+1}$, with the first three significant at the 0.01 level. The first principal component explains approximately 22% of the total June–September temperature variance and represents the regional response to temperature across the tree-ring network. PC3 largely represents the Bell Mountain chronology, which is on the periphery of network. PC2 lagged 1 year reflects variations in the Vermillion Pass record. These results suggest that, although these chronologies are unusual with respect to regional patterns of tree growth, they contain a summer temperature signal that may be related to elevation (Vermillion Pass) or location (Bell Mountain).

Verification test results using the all-but-one-subsampling method indicate that the temperature – ring width model is highly significant. The correlation coefficient between the observed climate series and the independent estimates (0.56) is only slightly less than that between the observed climate series and the estimates from the full-period regression (0.62); therefore, the regression model appears to be stable regardless of the data set used in the calibration. Positive verification results from the sign test (65 of 95, $p = 0.01$), product means test (3.73), and reduction of error (0.31) also suggest that the regression model is satisfactory.[4]

Table 3. (A) Principal component analysis and (B) eigenvalues of the 14 standard chronology matrix.

(A) Principal components.			
Chronology	PC1	PC2	PC3
Bell Mountain	0.072	0.010	0.936*
Small River	0.615	0.520	0.301
Pyramid	0.764*	0.143	0.313
Cardinal Mountain	0.739*	0.082	0.208
Signal Mountain	0.827*	0.314	0.080
Surprise Valley	0.829*	0.069	0.126
Athadome	0.779*	0.142	–0.081
Athaforest	0.825*	–0.093	0.203
Sunwapta Pass	0.810*	0.054	0.220
Peyto Lake	0.876*	–0.127	0.016
Vermillion Pass	0.075	–0.898*	0.064
Sulphur Mountain	0.700	–0.039	0.429
Nakiska	0.752*	–0.267	0.069
Highwood Pass	0.676	–0.171	0.447

(B) Eigenvalues and the percentages of variance explained.		
Component	Eigenvalue	Percent variance
1	7.655	54.68
2	1.341	9.58
3	1.093	7.81
Cumulative variance		72.08

*More than 50% of the chronology variance is explained by the component.

June–September temperature reconstruction, A.D. 1715–1982

Figure 7 shows the reconstruction of June–September temperature anomalies fitted with a 25-year Gaussian filter to highlight the overall trends. Almost all summers in the reconstructed series are below the 1961–1990 instrumental mean. Temperatures appear to show little trend in the earliest part of the reconstruction, with average values near –0.05°C from 1715 to the 1780s. After 1780, June–September temperatures increase slightly, with a peak ca. 1815. From 1825 onwards, temperatures decline steadily to 1860 and reach their lowest values at the beginning of the 20th century. After 1900, conditions warm rapidly, with the rate of increase being approximately 0.2°C/decade. Reconstructed temperatures reach their peak values during the early 1950s, after which they decrease. Mean June–September temperature for the 1715–1982 period is –0.46°C, which is very close to the instrumental mean (–0.43°C) from 1888–1994.

The coldest period reconstructed is the late 19th century, with the period 1840–1919 containing the eight coldest decades (Table 5). The 10 coldest summers all occur between 1858 and 1907, with seven after 1878 (Table 5). Mean July to September temperature for the 19th century is 0.54°C below the 1961–1990 mean, and the 1850–1899 period averages –0.81°C. No positive temperature anomalies are reconstructed between 1839 and 1933. The warmest June–September reconstructed temperatures occur in the middle of the 20th century (8 of the 10 warmest years between 1948 and 1970). The only decade with reconstructed positive temperatures is the 1950s (0.19°C). The warmest sustained period appears to be the early 18th century and the 1790–1830 period contains four of the eight warmest decades.

Discussion

The variance explained by the reconstruction developed in this study (unadjusted $r^2 = 0.38$) is comparable with results obtained by other ring-width-only reconstructions of summer temperature (e.g., 0.42 in Villalba (1990); 0.37 in Cook et al. (1992); 0.36 in Lara and Villalba (1993)). The regression model also satisfies several rigorous statistical verification tests. However, like any proxy climate record, the reconstructed temperature series for Banff and Jasper contains considerable errors or uncertainties. The standard error of the estimate for the regression model is 0.62°C; therefore,

[4] Statistical significance values cannot be applied for the product means (PM) and reduction-of-error (RE) tests. However, a positive value for the PM test indicates that both the signs and the magnitudes of the estimated and observed June to September temperatures contain a real relationship (Gordon and LeDuc 1981). A positive RE value demonstrates that the model is a better estimator of temperature than the mean of the calibration period.

Fig. 6. The first three principal components from the 14-chronology network (see text and Table 3 for details).

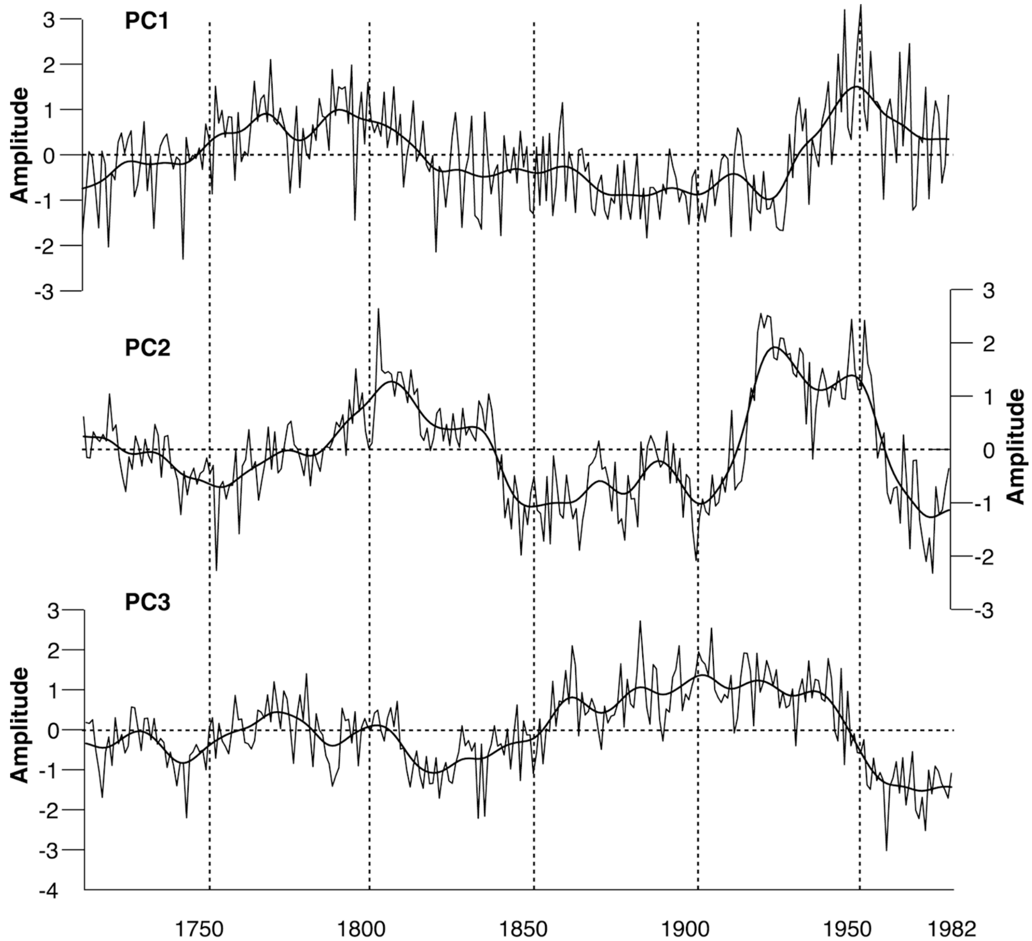


Table 4. (A) Results of multiple regression for June–September temperatures (dependent variable) and (B) the regression coefficients of the spruce chronology (independent variables).

(A) Regression results.						
Calibration period	*n*	*r*	r^2	Adjusted r^{2a}	SE of estimate[b]	SE[c]
1888–1982	95	0.617*	0.381*	0.353	0.63	0.07
(B) Regression coefficients.						
	Beta[d]	SE of Beta	B^e	SE of *B*	$t(90)^f$	p^g
Intercept			–0.46	0.07	–7.01	<0.0001
PC1	0.349	0.111	0.23	0.07	3.13	0.002
$PC3_{t+1}$	–0.373	0.098	–0.23	0.06	–3.79	0.0003
$PC2_{t+1}$	0.266	0.088	0.16	0.05	3.04	0.003
$PC1_{t+1}$	–0.140	0.098	–0.09	0.07	–1.42	0.2

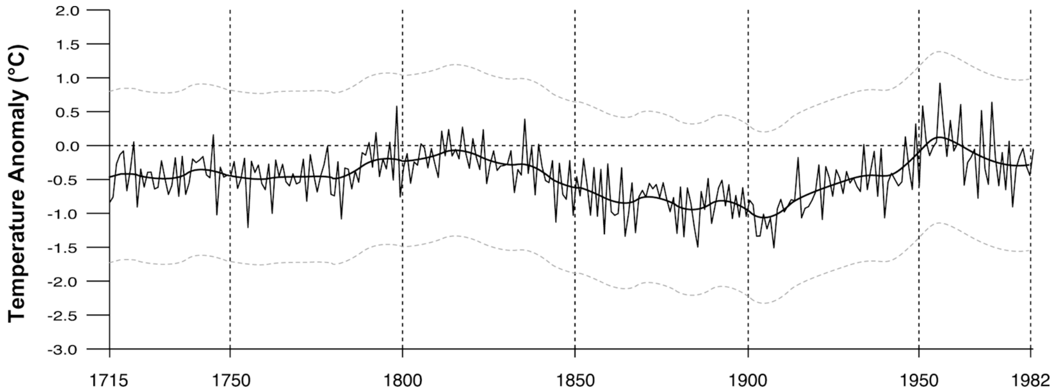
[a]Adjusted r^2 is the r^2 adjusted for loss of degrees of freedom.
[b]Standard error of the estimated June–September temperatures.
[c]Standard error of the intercept.
[d]Beta is the standardized regression coefficient.
[e]*B* is the unstandardized regression coefficient.
[f]$t(n)$ is the *t* value associated with the respective variable's tolerance (adjusted for loss of degrees of freedom).
[g]Statistical significance of the *t* value.

the 95% confidence limits for the temperature estimates are ±1.25°C. As the errors related to the regression model are roughly equivalent to the total range of the temperature estimates (2.4°C), the reconstructed temperature series must be interpreted cautiously. The long-term trends present in the reconstruction, as well as the extreme values, are well within the errors of the regression model.

Comparisons with other paleotemperature records

To determine whether these estimates of past changes in

Fig. 7. Reconstructed June–September temperature anomalies (1961–1990 base) for the Banff–Jasper area from 1715 to 1982. The solid line is a 25-year Gaussian filter. The broken lines show twice the standard error of the estimate for the filtered series.



summer temperature are reasonable, it is necessary to examine other regional estimates of proxy temperatures. Comparisons with other temperature reconstructions based on tree rings from northwestern North America support the broad trends identified in the Banff–Jasper (BJR) reconstruction (Fig. 8). All reconstructions suggest that summer temperatures prior to 1950 were below the 1961–1990 mean and that the 1961–1990 period was as warm or warmer than conditions over the last 300 years. While the tree-ring records show maximum 20th century temperatures during the 1940s–1960s with a slight decrease thereafter, the available instrumental records demonstrate that summer temperatures were relatively constant between 1960 and 1980. Most reconstructions suggest that the 19th century was colder than either the 18th or 20th centuries.

Luckman et al. (1997)'s reconstruction of April to August temperature anomalies (ATHA) used a millennial-length density and ring-width chronology from sites near the Athabasca Glacier. Some of the ring-width data used in this paper and the density data used by Luckman et al. (1997) were obtained from the same trees (although the density data is much more heavily weighted in the ATHA reconstruction). Both series show warmer temperatures in the Banff–Jasper region for most of the late 1700s, cold conditions during the 1800s, and gradual warming in the 20th century.

The Northern Hemisphere reconstruction (NHR; D'Arrigo and Jacoby 1992) is based on ring-width chronologies, primarily from white spruce collected at Arctic tree-line sites. Both the NHR and BJR show a warming during the 20th century, with maximum temperatures in both reconstructions during the 1940s and 1950s. While the two density-based reconstructions presented in Briffa et al. (1992) include data from the Bell Mountain, Vermillion Pass, Peyto Lake, and Sunwapta sites used in this paper, the BCPNW1 and BCPNW2 reconstructions show little long-term variability (above 20–30 years). Although they do reconstruct cooler intervals in the early and late 1800s plus warmer conditions in the mid-20th century, the lack of long term trends in the BCPNW reconstructions reflect the standardization techniques used and, possibly, the greater geographic coverage of this network (it covers an area of ca. 14° latitude by 12° longitude that extends to the Pacific Coast).

Estimates of the timing and degree of cooler conditions in the 19th century vary between reconstructions. The BJR record is unusual in that it shows a more gradual cooling from the 1820s to the 1860s with the coldest summers at the end of the 19th century. The ATHA reconstruction suggests that the 19th century cooling began in the late 1790s and that the lowest temperatures occurred in the 1810–1820 period. The onset of cold conditions in NHR begins ca. 1810–1820, reaches its lowest values during the 1840s and shows a relatively steady rise in temperatures until the late 1940s. The regional glacial record (Luckman 1996, 2000) indicates that the maximum extent of glaciers during the Little Ice Age occurred in the mid-19th century, which is consistent with summer temperature reconstructions showing the coldest conditions during the early 1800s. However, there are also significant (but less-precisely dated) glacier readvances throughout the region in the late 19th century that were only slightly less extensive than the maximum position.

Examination of the regionally averaged spruce ring-width chronology (Fig. 2), PC1 of the 17 tree-ring chronologies (Fig. 6) and many of individual ring-width series (Fig. 3) indicates that tree growth in the area around Banff and Jasper was strongly suppressed throughout the 19th century but the relative severity of conditions during the 19th century varies from site to site. Although BJR differs in detail from other regional reconstructions from northwestern North America, these differences are well within the error terms associated with these reconstructions and may not indicate substantial disagreement between these records.

Difficulties comparing paleoclimatic reconstructions

Figure 8 indicates that regional paleoclimatic temperature reconstructions share a number of long-term trends but differ in detail. The most obvious discrepancies relate to the onset and extremes of the 19th century cold period. While all of the above reconstructions achieved significant verification results, paleoclimatic interpretations are limited by their dissimilarity, which may be attributed to a number of causes.

(1) These differences may be related to real differences in climate between regions. Disparities between the BJR and NHR records may reflect differences in the climate histories of the central Canadian Rockies and the Canadian Arctic.
(2) Although these reconstructions all model temperatures, the seasonal variable reconstructed differs. Disagreements between the reconstructed series may reflect real differences between the trends and patterns for June–

September (BJR), April–August (ATHA), or mean annual temperatures (NHR).

(3) Proxy climate records derived from a single site (e.g., ATHA) may differ from those that integrate signals from several sites spread over a wider geographical area. As site-specific effects can only be detected by comparisons with other nearby proxy records, single-site reconstructions are more likely to include local or nonclimatic effects.

(4) The differences may result from errors in the respective regression models, such as the representation of nonlinear relationships with linear models or changing tree growth – climate relationships at a site over time.

(5) Several studies indicate that ring width and density data from the same trees generate quite different correlation or response function results with the same climate variables (e.g., Schweingruber et al. 1993; D'Arrigo et al. 1992). Thus, even if the two types of data share the dominant control of a single climate variable, the reconstructed proxy series would not be identical, as each also includes unique contributions from other, less important, climate parameters. This "signal pollution" may have a considerable effect on climate reconstruction and effectively determines the errors of the multiple regression model.

No proxy climate record perfectly reflects past variations in climate. Paleoclimatic estimates based on tree-ring data typically account for 30–60% of the variance of the climate parameter modelled. Since these results leave a considerable amount of variance unaccounted for, it follows that the resulting reconstructions are not exact estimates of the climate parameter. In general, the more variance explained by the regression, the better the estimate of previous conditions will be. However, in all cases, the true climate record will fall within a range about the estimated series. The magnitude of this range is controlled by the amount of variance explained and limits the certainty of conclusions concerning long-term change. At present, it is very difficult to attribute differences between these paleoclimatic reconstructions to specific causes.

Conclusion

This paper is the first to examine systematically the climate – ring width relationships for *Picea engelmannii* in the Canadian cordillera and to develop a proxy temperature record based on a regional network of ring-width chronologies from tree-line sites. Most of these records show a coherent, common signal that is related to summer temperature conditions. Multiple regression of principal components derived from these chronologies has been used to reconstruct June–September temperatures between 1715 and 1982, with 38% of the variance in the regional instrumental climate record explained. When evaluating this reconstruction, it is important to remember that the available climate data are limited and come from sites at much lower elevations and a considerable distance from many of the tree-ring sites. Despite these limitations, these results indicate that the temperature signal preserved in these tree line ring-width records is strong enough to reconstruct regional paleotemperatures. They also provide a benchmark to indicate the quality of reconstructions attainable from studies utilizing networks of

Table 5. (A) Decadal reconstructed and observed June–September summer temperatures and (B) annual reconstructed extreme temperatures.

(A) Decadal temperature deviations.

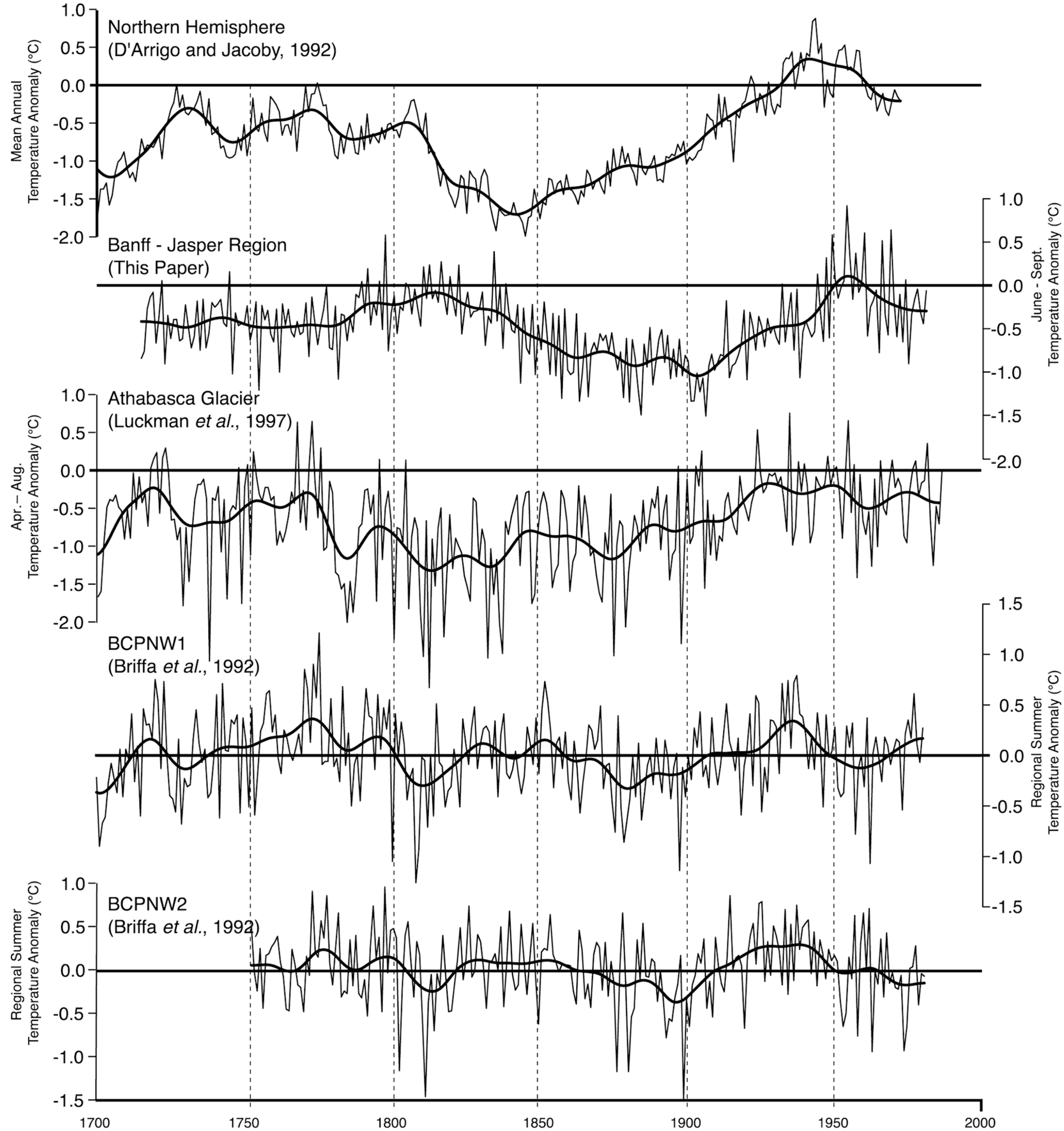
	Deviation (°C)[a]	
	Reconstructed	Observed
1970	–0.23	0.06
1960	–0.16	–0.01
1950	0.19	–0.26
1940	–0.37	–0.10
1930	–0.47	–0.19
1920	–0.54	–0.39
1910	–0.81	–0.97
1900	–1.09	–1.22
1890	–0.80	–1.29
1880	–0.94	
1870	–0.77	
1860	–0.89	
1850	–0.63	
1840	–0.57	
1830	–0.26	
1820	–0.21	
1810	–0.08	
1800	–0.22	
1790	–0.17	
1780	–0.45	
1770	–0.43	
1760	–0.50	
1750	–0.47	
1740	–0.36	
1730	–0.46	
1720	–0.49	

(B) Coldest and warmest summers.

Coldest summers		Warmest summers	
Year	Deviation (°C)[a]	Year	Deviation (°C)[a]
≥2 SD above or below the mean			
1907	–1.51	1955	0.92
1885	–1.50	1970	0.64
1881	–1.35	1961	0.61
1864	–1.34	1950	0.58
1902	–1.34	1798	0.58
1903	–1.33	1967	0.52
1858	–1.30	1835	0.39
1879	–1.29	1958	0.37
1867	–1.29		
1.5–2 SD above or below the mean			
1905	–1.23	1956	0.33
1755	–1.21	1948	0.32
1884	–1.20	1817	0.27
1889	–1.15	1813	0.24
1844	–1.13	1823	0.23
1921	–1.09	1811	0.21
1782	–1.08	1792	0.19
1895	–1.08	1745	0.16

[a]Units are deviations from the 1961–1990 mean temperature.

Fig. 8. Comparison of temperature reconstructions for western Canada. All records are fitted with a 25-year Gaussian filter to illustrate trends. The Northern Hemisphere record is a 5-year mean; other records are annual values. The Northern Hemisphere and Banff–Jasper reconstructions utilize ring-width data exclusively. The other reconstructions are solely or primarily based on densitometry (for details, see text).



spruce ring-width data from tree line. Superior results may be obtained for other mountain areas with better high-elevation climate records or by building tree-ring networks including other parameters (e.g., maximum latewood density).

The Banff–Jasper reconstructed summer temperature record developed in this paper contains similar long-term trends to other northern North American tree-ring reconstructions but differs in details of the timing and extremes of the 19th century cold period. As dendroclimatological reconstructions use different sites, species and tree-ring parameters, each has differences in the climate signal retained in (and therefore reconstructed from) their records. These differences emphasise the need to develop multiple, independent records to verify paleoclimatic reconstructions and highlight some of the difficulties associated with comparing proxy climate records of varying parameters and scales.

Acknowledgements

This research has been primarily funded by the Natural Sciences and Engineering Research Council of Canada with research permits and support from Parks Canada and the B.C. and Alberta Provincial Parks. We thank Ian Besch, Margaret and Ray Colenutt, Catherine Fiske, Gordon Frazer, Jim Hamilton, Rob Heipel, Les Jozsa, David and Heather Luckman, Bill Quinton, James Reynolds, Dale and Ray Smith, and Alex Tarussov for assistance in the field. Several of the above plus Geography 312 (1990–1992), Peter Kelly, Dan McCarthy, Barb Schaus, Jonathon Seaquist, Evan Seed, Valerie Wyatt, and Rob Young provided tree-ring measurements. We are grateful to Fritz Schweingruber (Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf) for providing his tree-ring chronologies; to Susan Muleme, David Mercer, and Trish Chalk of the Cartographic Section, Department of Geography, University of Western Ontario, for the diagrams; and to James Voogt, Dan Smith, Yves Bégin, and Dave LeBlanc for discussion of earlier drafts of the paper.

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