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Tree-ring reconstruction of maximum and minimum temperatures and the diurnal temperature range in British Columbia, Canada

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Summary

This paper demonstrates the possibility of reconstructing May-August maximum (T_{max}) and minimum (T_{min}) temperatures plus the diurnal temperature range (DTR) using ring-width (RW) and maximum density (MXD) series from treeline sites across Interior British Columbia. Multiple linear regression of three orthogonal principal components (derived from 12 ring-width and 7 maximum density chronologies) were used to reconstruct each climate parameter separately over the 1820–1991 interval. Calibration explains 64 % (T_{max}), 39 % (T_{min}) and 40 % (DTR) of the variance in the instrumental climate record (1895–1991). The T_{max} reconstruction shows cool 19th century conditions with the warmest period in the 1940s. This trend agrees well with other summer temperature reconstructions in the southern Canadian Cordillera. The coolest reconstructed T_{min} values are in the 1880s and increase steadily to the 1990s. Regional climate data show that the DTR has decreased in the late 20th century due to differences in the rate of change in T_{max} and T_{min}. These exploratory reconstructions suggest that recent trends in DTR are not unique in Interior British Columbia in context of the last 180 years. Our results also indicate that: (1) T_{mean}, T_{max} and T_{min} may not vary consistently; (2) tree growth at these temperature-limited sites may be more closely related to T_{max} than T_{mean} or T_{min}; (3) recently reported changes in the relationships between mean temperatures and tree-ring variables may in part reflect the changing relative influence of maximum and minimum temperatures on mean temperature values. It may therefore be prudent, where possible, to reconstruct all three parameters to evaluate past temperature variability.

Keywords: Dendroclimatology, British Columbia, ring-width, maximum density, maximum temperatures, minimum temperatures, diurnal temperature range, changing tree-ring/climate relationships

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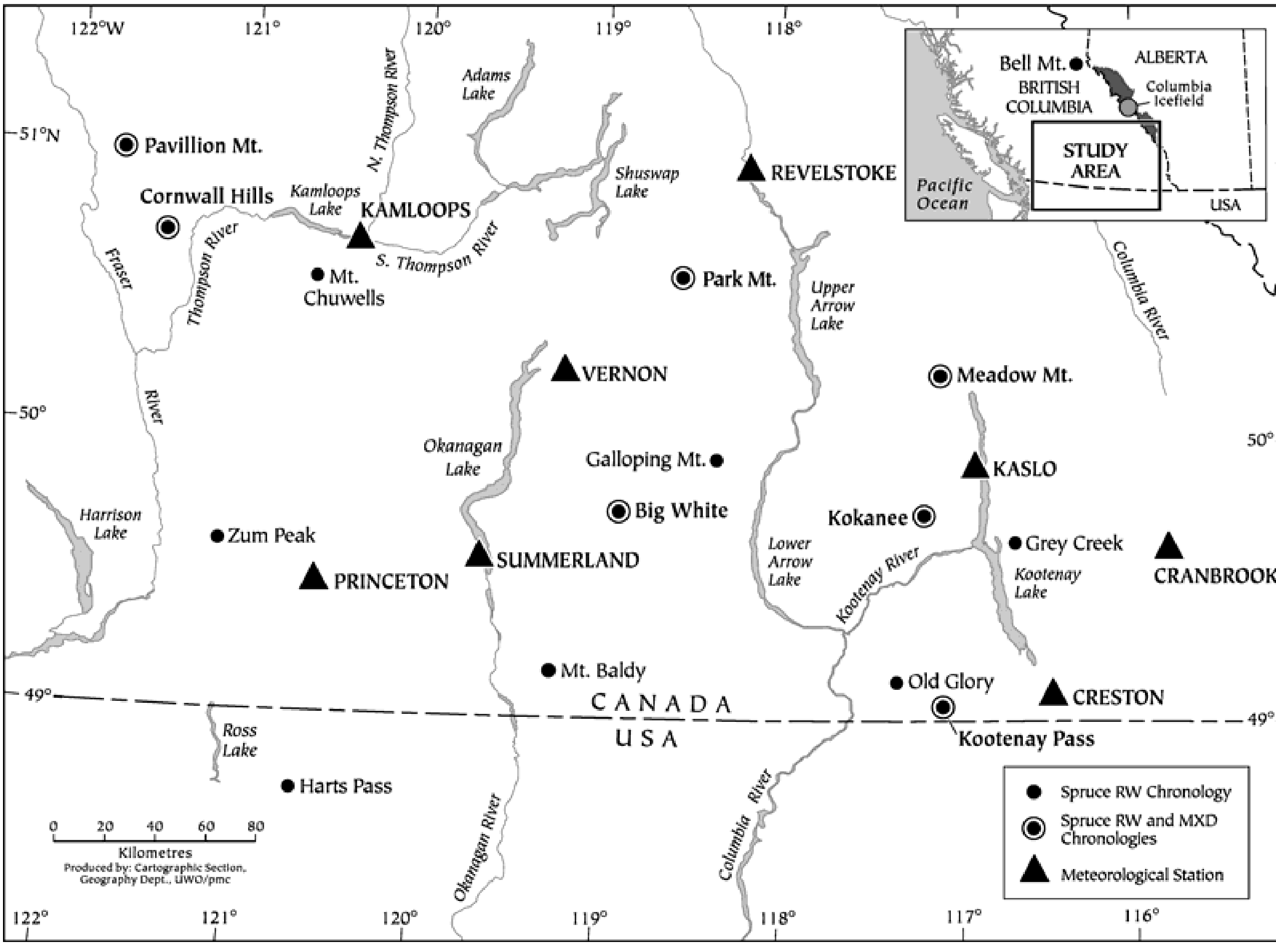

Figure 1. Location map showing tree-ring sites and meteorological stations. The Galloping Mountain, Grey Pass and Bell Mountain chronology sites are shown for location only. They were not used in the reconstructions developed in this paper.

Introduction

Traditionally, dendroclimatic studies reconstruct mean temperatures (T_{mean}), probably because this is the most universally available summary climate statistic and is assumed to be a sufficient and representative measure of temperature[1]. Recent studies of twentieth century instrumental climate records at global (Karl et al. 1993; Easterling et al. 1997) and regional scales (Skinner, Gullett 1993; Vincent et al. 1999), plus high elevation sites (Diaz, Bradley 1997), have shown that minimum temperatures (T_{min}) have been rising significantly faster than mean or maximum temperatures (T_{max}) and that the daily temperature range (DTR) has been decreasing. Concurrently, several dendroclimatic studies from regions in the Northern Hemisphere demonstrate a reduction in tree sensitivity and/or change in the response of tree growth to climate over the last 4–5 decades, (Jacoby, D'Arrigo 1995; Briffa et al. 1998a, b; Vaganov et al. 1999; Barber et al. 2000; Lloyd, Fastie 2002). Similar changes in the relationships between ring-width (RW), maximum latewood density (MXD) and May-August T_{mean} were observed during investigations of tree-ring growth/climate relationships in interior British Columbia (BC), Canada (Fig. 1; Wilson 1999). Reconstructions developed using these data significantly under-predicted observed mean temperatures in the last few decades. Examination of the BC regio-

[1] T_{mean} is ultimately derived by averaging maximum (T_{max}) and minimum (T_{min}) values for each 24 hour period.

nal instrumental temperature record used in that study also revealed significant differences in the pattern of decadal variation of T_{mean}, T_{max} and T_{min} during this recent period (Fig. 2) and prompted further investigation of tree-growth climate relationships.

Wilson and Luckman (*in press*) developed a May-August T_{max} reconstruction that was statistically superior to the May-August T_{mean} reconstruction. Wilson (1999) also noted that about 10 % of the ring-width chronologies from Interior BC show statistically significant relationships with T_{min}. The present paper demonstrates the possibility of developing dendroclimatic reconstructions of both T_{max} and T_{min} for Interior BC where observed changes in these parameters generally mirror the Northern Hemispheric trends (Karl et al. 1993; Skinner, Gullet 1993; Easterling et al. 1997; Dai et al. 1999; Vincent et al. 1999). It also uses these reconstructions to assess the uniqueness of recent changes in T_{max}, T_{min} and DTR in a longer term context for this region. These results should alert the dendroclimatic community to the influence that changing relation-

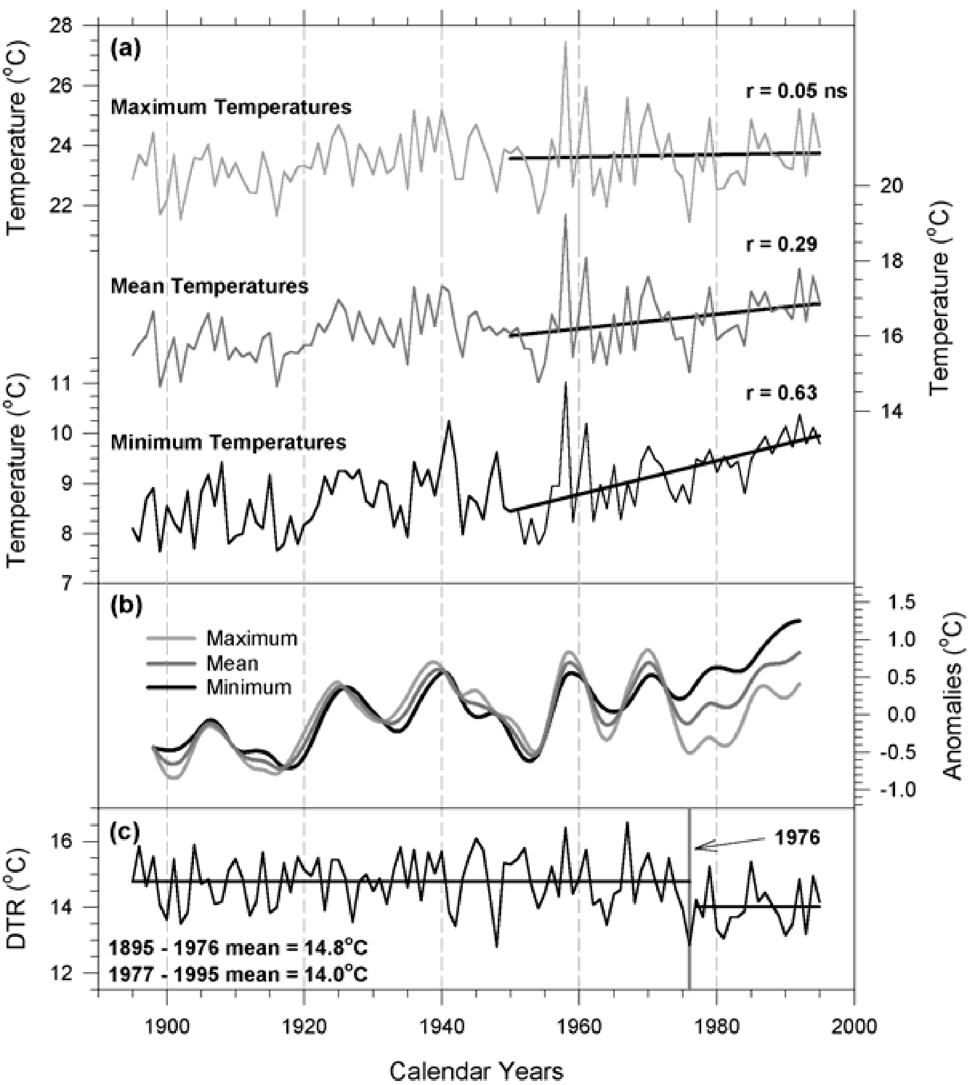

Figure 2. (**a**) Plots of maximum, mean and minimum May-August temperatures for the BC regional series developed in this paper. The post 1950 linear trends are presented to merely emphasise differences between maximum and minimum temperatures over this period (ns = not significant at 95 % level). (**b**) Plots of smoothed (10 year spline) maximum, mean and minimum May-August temperature anomalies (reference period = 1901–1980). (**c**) May-August diurnal temperature range.

ships within instrumental temperature records may have on conventional reconstructions based solely on mean temperature data, thereby encouraging investigations that explore the reconstruction of a wider range of temperature variables.

Tree-ring and climate data

In 1998 a network of 20 upper tree-line Engelmann spruce (*Picea engelmannii* Parry) sites was sampled across the southern interior of British Columbia to provide data for reconstruction of a regional summer temperature record (Wilson 1999). MXD chronologies were developed for the seven sites with the longest tree-ring records. An additional RW chronology was developed for Harts Pass in Washington State from five spruce chronologies with an end date of 1991 (Peterson, Peterson, 1994). Wilson and Luckman (*in press*) developed two reconstructions of May-August T_{max} from independent subsets of these chronologies. Their Interior British Columbia (IBC) reconstruction (1600–1997) utilised the two longest MXD and three longest RW chronologies, while a shorter regional reconstruction (1847–1997) was developed from 5 MXD and 12 RW chronologies. The present paper utilises a different subsampling of this network consisting of the 12 RW and 7 MXD chronologies that have a sample depth of at least five trees back to 1750 (Fig. 1; Tab. 1). The reconstructions presented in this paper are therefore different from, but not entirely independent of, those presented in Wilson and Luckman (*in press*).

Table 1. List of the ring-width (RW) and maximum density (MXD) chronologies used in this paper. The EPS value for the least replicated period in the chronologies (1750–1780) is shown.

Site name	Site Code	EPS 1750–1780
Ring-width chronologies		
Meadow Mt.	MEADRW	0,70
Kokanee	KOKRW	0,75
Old Glory	GLORW	0,63
Kootenay	KOOTRW	0,93
Park Mt.	PRKRW	0,97
Big White	BIGRW	0,93
Mt. Baldy	BALDRW	0,82
Pavilion Mt.	PAVRW	0,94
Cornwall Hills	CORNRW	0,94
Mt. Chuwells	CHUWRW	0,82
Zum Peak	ZUMRW	0,90
Harts Pass	HPRW	0,98
Maximum density chronologies		
Meadow Mt.	MEADMXD	0,94
Kokanee	KOKMXD	0,83
Kootenay	KOOTMXD	0,97
Park Mt.	PRKMXD	0,96
Big White	BIGMXD	0,93
Pavilion Mt.	PAVMXD	0,94
Cornwall Hills	CORNMXD	0,93

Monthly T_{max}, T_{mean} and T_{min} data were obtained from the Historical Canadian Climate Database (Vincent, Gullet 1999) for eight stations in Interior British Columbia (Fig. 1). These records have been assessed and corrected for homogeneity problems (Vincent 1998) and share a common period from 1912–1995 with four records extending back to 1895. Regionally representative series of T_{max}, T_{mean} and T_{min} were developed from these records using techniques outlined in Jones and Hulme (1996). Monthly values for each station were standardised as z-scores relative to the 1912–1995 common period and averaged to calculate monthly z-scores for the regional average series. These monthly z-scores were converted to "absolute" temperature values using the average of the means (grand mean) and standard deviations (grand standard deviation) of each of the original monthly series. A regional DTR series was calculated for each month by taking the difference between the T_{max} and T_{min} regional series (Fig. 2). Using the station monthly series, the Expressed Population Statistic (EPS; Wigley et al. 1984; Briffa, Jones 1990) shows that a valid robust signal can be obtained from four meteorological records. Therefore, the dendroclimatic calibrations utilised the full 1895–1995 regional temperature data-set.

Methods

The samples for RW and MXD measurement were prepared using standard procedures (Stokes, Smiley 1968; Jacoby et al. 1988; Wilson 1999). The RW series were detrended by taking ratios between ring width and fitted negative exponential functions or regression lines of negative or zero slope. The series were averaged to form site standard chronologies.

The MXD series were detrended using residuals from negative or zero slope regression functions. The signal strength of the site chronologies was assessed using the EPS statistic (Wigley et al. 1984; Briffa, Jones 1990; Wilson 1999). Principal component analysis (PCA), employing a varimax rotation, was used to reduce the 12 RW and 7 MXD chronologies to orthogonal principal components (PCs) with an eigenvalue > 1.0, over the 1750–1991 interval. The inclusion of the Hart's Pass RW chronology restricted the last year of the PCA to 1991.

Using simple correlation analysis, the PCs were compared to regional monthly temperature data (T_{max}, T_{mean} and T_{min}) using a 17-month period from May of the previous year to September of the growth year. This 'climate window' allows the assessment of the influence of pervious and present year's climate on current year's growth.

Climate reconstructions of T_{max}, T_{min} and DTR were developed using multiple linear regression. Each of the identified PC scores was lagged at t – 1, t, and t + 1 to ensure that the effects of previous years' climate upon growth were included in the modelling. A stringent stepwise procedure was employed (F-to-enter = 0.01; F-to-remove = 0.05) to minimise multicollinearity in the models. Multicollinearity was assessed in the final models using the Variance Inflation Factor (Fox 1997) and the determinant of the correlation matrix of the predictor variables (McCuen 1985). Full model calibration was made over the period 1895–1991. Split period calibration/verification (1895–1943 and 1944–1991) was undertaken to assess the temporal stability of the identified models. The verification statistics used were Pearson's correlation coefficient (r), the reduction of error statistic (RE), the coefficient of efficiency (CE), the product means test, and the sign test (Fritts 1976; Cook et al. 1994). Verification was undertaken using both the original series and their 1st differences.

Results and discussion

Tree-ring chronologies and growth/climate relationships

The RW and MXD chronologies used in the present study are listed in Tab. 1 together with the EPS value for the early, least replicated 30-year period (1750–1780) of each chronology. Over this short initial period, five RW chronologies and one MXD chronology have an EPS value less than 0.85 which is generally cited as an acceptable threshold for dendroclimatic reconstruction (Briffa, Jones 1990). Nevertheless, all of these values are above 0.60 and this slightly weaker signal probably does not constitute a serious problem. However, the final reconstructions are only presented back to 1820 to ensure that no potentially anomalous trends are introduced into the analyses due to low replication.

Three PCs were extracted from the 19 chronologies with an eigenvalue > 1.0. The loadings of each chronology on each eigenvector are presented in Tab. 2 and PC scores are plotted in Fig. 3. PC1 reflects the signal in the MXD chronologies, while PC2 and PC3 express different RW variance modes in the network. These eigenvector scores compare well with similar eigenvectors identified in PCAs of

Table 2. Principal component analysis (1750–1991) results for the RW and MXD chronologies. The site codes are listed in Tab. 1.

Site	PC1	PC2	PC3
BIGMXD	0,95	0,03	0,06
PRKMXD	0,94	0,05	0,08
KOOTMXD	0,93	0,08	0,08
CORNMXD	0,92	0,09	–0,06
MEADMXD	0,92	0,15	–0,02
PAVMXD	0,90	0,04	0,08
KOKMXD	0,86	–0,06	0,22
PRKRW	0,04	0,87	0,16
CORNRW	–0,02	0,86	–0,08
HPRW	0,12	0,86	0,13
BIGRW	–0,02	0,83	0,28
MEADRW	0,08	0,78	0,16
ZUMRW	0,20	0,72	0,21
KOOTRW	0,13	0,69	0,50
PAVRW	–0,01	0,59	0,51
BALDRW	–0,08	0,55	0,40
CHUWRW	0,07	0,48	0,37
GLORW	0,16	0,26	0,86
KOKRW	0,10	0,29	0,86
Eigenvalue	7,50	5,28	1,39
% Variance	39,50	27,78	7,31
Cumulative var.	39,50	67,27	74,58

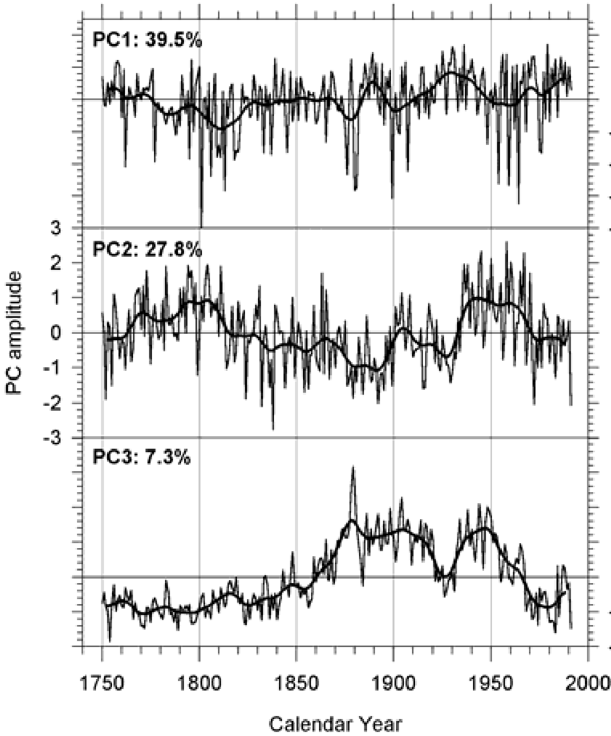

Figure 3. Time series plots of the PC scores with an eigenvalue > 1.0. The common variance explained by each component is shown in the top left hand corner of each plot. PCA was undertaken from 1750–1991. The heavy line is a 20 year cubic smoothing spline.

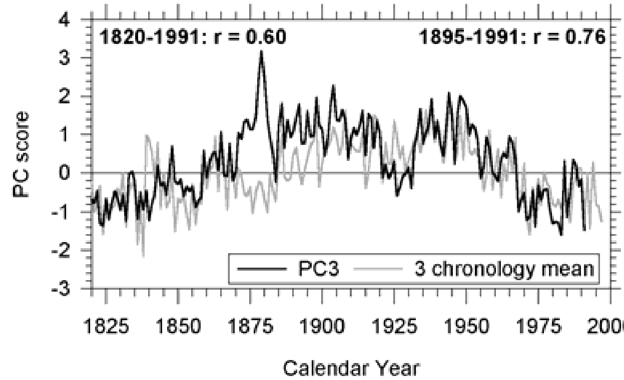

Figure 4. Comparison plot between PC3 and the three chronology z-score mean series.

the full 21 chronology BC network (Wilson 1999) and a 14 chronology network of Engelmann spruce from the Canadian Rockies (St. George, Luckman 2001).

PC3 is principally derived from a linear weighted combination of two RW chronologies (Old Glory and Kokanee) with some contribution from Kootenay and Pavilion Mt (Tab. 2). As the two principal chronologies are relatively close to each other (Fig. 1) this could simply be a local signal. However, two other chronologies from the BC network (Grey Creek and Galloping Mountain) and a chronology from the Rocky Mountain spruce network (St. George, Luckman 2001; Bell Mountain: see inset map, Fig. 1) also show the PC3 pattern. These chronologies are not included in the present reconstruction because they are either outside the area represented by climate data used in this analysis (Bell Mountain) or were too short (Grey Creek) or poorly replicated prior to 1800 (Galloping Mt.). PC3 correlates reasonably (r = 0.76) with a normalised series of the mean of these three chronologies over the 1895–1991 period (Fig. 4) which suggests that the variance mode expressed by PC3 is not simply a local phenomenon.

The significant (95 %) correlations between each PC and regional monthly series of T_{max}, T_{mean} and T_{min} are presented in Fig. 5. PC1 correlates positively with March to August temperatures (not July) and inversely with previous August and October. PC2 correlates positively with June/July temperatures and inversely with previous August. In general, the correlations of PC1 and PC2 are stronger with T_{max} and T_{mean} and are weaker or non-significant with T_{min}. Although there is no significant difference between the monthly correlations of PC1 and PC2 with T_{max} and T_{mean}, Wilson and Luckman (*in press*), using stringent calibration and verification statistics, demonstrated that the most robust reconstruction of summer temperatures was made using T_{max}.

PC3 correlates negatively with February-August T_{min} (not April) of the current year and negatively with previous year's June-September T_{min}. This component also correlates inversely with June-August T_{mean} of the previous year and February/March T_{max} and T_{mean} of the present year. In every case the correlations with T_{min} are higher than with T_{max} and T_{mean}. However, if both PC3 and the climate data are pre-whitened, no significant correlations exist between these data. Therefore, the negative correlations of PC3 presented in Fig. 5 are primarily controlled by the lower frequency trends in these data.

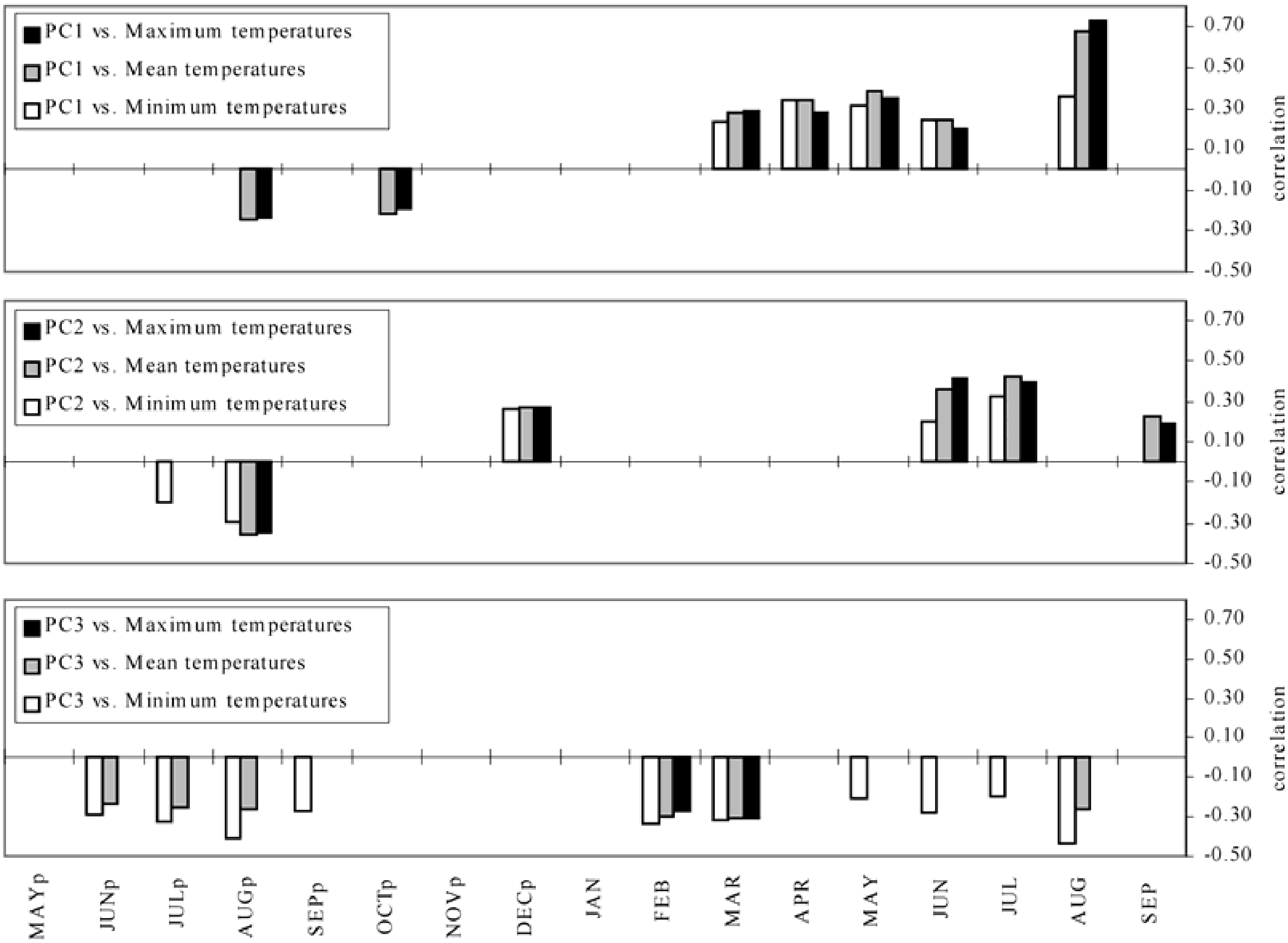

Figure 5. Significant correlations between each of the PC scores and monthly temperatures for the 1895–1991 period. Analyses were carried out for T_{max}, T_{mean} and T_{min} for all months from prior May to current September. Only correlations significant at the 95 % confidence limit are shown.

The growth climate relationships observed for PC1 and PC2 are described in Wilson and Luckman (*in press*) but the observations related to PC3 need further discussion. Essentially, the negative correlations between PC3 and T_{min} suggest that increasing night-time temperatures (T_{min}) are negatively correlated with growth. A detailed investigation of the difference in response of these chronologies is beyond the scope of this study (see Sveinbjörnsson (2000) for a recent review of temperature/tree growth relationships at treeline). However we suggest two possible mechanisms that might explain the observed growth/climate correlations:

1) Changing balance between respiration and photosynthesis: Alward et al. (1999) hypothesised that elevated night-time T_{min} would cause an increase in nocturnal respiration rates in grassland vegetation without a compensatory increase in daytime photosynthesis. A similar process in trees would lead to a reduction in carbon allocation to rings in each year as night-time T_{min} increases. Such a process would result in both an overall decrease in productively (e. g. a decreasing trend in the 20^{th} century for PC3, Fig. 3) and negative correlations between growth and T_{min} (Fig. 5).

2) Differential effects of increased cloud cover on daytime and night-time temperatures: Through the 20^{th} century and especially in the last few decades, cloud cover has significantly increased in the southern Canadian Cordillera (Henderson-Sellers 1989;

Dai et al. 1999). Increased cloud cover may lead to a decrease in DTR because daytime T_{max} is reduced due to greater reflection of incoming radiation from the upper surface of clouds and night time T_{min} increases because of enhanced downward radiation from clouds (Dai et al. 1999). Assuming daytime temperatures have a stronger influence on tree-growth, lower T_{max} would result in reduced photosynthesis and a decrease in tree growth. Tree-growth and night-time T_{min} are both therefore related to changes in cloud cover resulting in an inverse correlation between these two variables.

As both of these hypothesised mechanisms are universal, neither explains why some upper tree-line sites respond differently to similar climatic variations. The instrumental temperature record across Interior BC is homogenous (Wilson 1999; Wilson and Luckman *in press*) and it seems unlikely that local temperatures could result in the regional scale differences observed in the RW data. The precipitation signal is more difficult to assess as it is both spatially more heterogeneous and complex precipitation/elevation relationships remain unsampled by records from valley-floor meteorological stations. Correlations between the RW chronologies and monthly precipitation parameters are weak (Wilson 1999) and therefore unlikely to be major controls of ring-width variability. The differences in signal and trend between PC2 and PC3 (Fig. 3) must therefore be related to ecological conditions at these sites that affect the trees' abilities to respond to large-scale climate conditions. Unfortunately, there is no obvious consistent ecological factor that differentiates between the sites that load on PC2 and PC3. Therefore, although the cause of these differences in response cannot be identified with any confidence, the data indicate that the variance mode of PC3 is regional in extent and not a local specific signal.

Dendroclimatic calibration and verification

Calibration trials over the 1895–1991 period show that the optimal seasonalised parameters for temperature reconstruction are May-August T_{max}, T_{min} and DTR. This is the same monthly window reconstructed by Wilson and Luckman (*in press*). The models for May-August T_{max}, T_{min} and DTR explain 64 %, 39 % and 40 % of the climate variance respectively with no multicollinearity problems and/or significant autocorrelation in their residual series (Tab. 3).

The split period calibration/verification results are presented in Tab. 4. The models perform very well when the verification tests are made on the original series. However, if 1st difference series are used, the T_{min} model performs poorly over the 1895–1943 period with both RE and CE producing values close to zero and the sign-test failing at the 95 % confidence level. Cook et al. (1994) suggest that using the sign test with 1st differenced data provides a very strong measure of the high frequency agreement between series. This poor result might be anticipated as correlation analyses using pre-whitened PC3 and climate data also showed no significant correlations. This suggests that the statistical strength in the T_{min} model is in the low frequency signal and reflects an inverse relationship between growth and T_{min}.

Temperature Reconstructions

Although the T_{max} reconstruction is undoubtedly the best model of the three (Fig. 6), the other models also faithfully replicate the low frequency trends of the actual measured data. The T_{min} reconstruction is the weakest of the three models and does not capture the range in variability as well as the other two models and there is also a slight divergence between the modelled and actual data over the last few years.

The T_{max} reconstruction shows cool conditions through the 19th century with the warmest period in the 1940s. These trends agree well with the IBC reconstruction (1600–1997; Wilson, Luckman, *in press*), although this new reconstruction explains substantially more climatic variance (64 % compared to 53 %). This is probably due to the inclusion of an additional, lagged, MXD predictor ($PC1_{t-1}$) in this new, shorter, reconstruction. The $\sqrt{IF}$ value for this variable does not exceed the 2.0 critical threshold suggested by Fox (1997) (Tab. 3) indicating that this increase in explained variance is not an artefact of multicollinearity (i. e. artificial predictability (Cook et al. 1994)).

The coolest period in the T_{min} reconstruction is around the 1880s with the reconstructed minimum temperatures increasing steadily to the present. The reconstructed series indicate that T_{min} in the early 19th century was comparable to T_{min} over the last few decades. Reconstructed DTR values are low both for the early 19th century and later 29th century. These results suggest that the recent differences in trend between T_{max} and T_{min} are not unique to the late 20th century and may therefore be related to natural processes in the climate system rather than an anthropogenic forcing.

Table 3. Dendroclimatic Model summaries and collinearity diagnostics. r = correlation coefficient; $_{a}r^2$ = square of the multiple correlation coefficient following adjustment for loss of degrees of freedom; SE = Standard error of the estimate; DW = Durbin and Watson statistic for residual autocorrelation. There is no significant autocorrelation in each model at the 99 % confidence limit. The square root of the Variance inflation factor (VIF) for each independent variable is shown. All $\sqrt{IF}$ values are well below the 2.0 critical limit suggested by Fox (1997). A value > 2.0 indicates a potential collinear problem. MD = Determinant calculated from correlation matrix of predictor variables. McCuen (1985) states that a value of 1.0 denotes orthogonality between the predictor variable. A value > 0.5 implies no significant multicollinearity and a value < 0.2 indicates serious collinear problems.

Model	r	ar^2	SE	DW	VIF1	VIF2	VIF3	MD
T_{max}	0,80	0,64	0,60	1,82	PC1 (1.00)	PC2 (1.20)	PC1t-1 (1.07)	0,974
T_{min}	0,64	0,39	0,53	1,55	$PC3_{t-1}$ (1.07)	PC2 (1.05)	PC1 (1.02)	0,996
DTR	0,65	0,40	0,65	1,68	PC1 (1.02)	$PC3_{t-1}$ (1.07)	PC2 (1.05)	0,996

MD = Determinant calculated from correaltion matrix of predictor variables.

Table 4. Calibration and verification statistics for the T_{max} and T_{min} and DTR reconstructions. Full regression equations are also shown. Values in grey box are not significant at the 95 % confidence limit.

Maximum Temperatures

Calibration					Standard Verification						1st Difference Verification					
Period	r	r^2	aR^2	SE	Period	r	RE	CE	PM	ST	Period	r	RE	CE	PM	ST
1895–1943	0,80	0,65	0,62	0,52	1944–1991	0,79	0,60	0,58	3,50	38/10	1944–1991	0,82	0,67	0,67	3,90	38/9
1944–1991	0,82	0,67	0,65	0,66	1895–1943	0,78	0,56	0,52	3,75	35/13	1895–1943	0,78	0,60	0,60	3,90	37/10
1895–1991	0,80	0,65	0,64	0,60	$T_{max} = 0.625\ PC1 + 0.486\ PC2 + 0.171\ PC1_{t-1} + 23.245$											

Minimum Temperatures

Calibration					Standard Verification						1st Difference Verification					
Period	r	r^2	aR^2	SE	Period	r	RE	CE	PM	ST	Period	r	RE	CE	PM	ST
1895–1943	0,49	0,24	0,18	0,55	1944–1991	0,60	0,43	0,14	3,38	39/9	1944–1991	0,68	0,46	0,46	3,00	34/13
1944–1991	0,64	0,41	0,37	0,54	1895–1943	0,47	0,47	0,14	4,13	37/11	1895–1943	0,32	0,01	0,002	1,81	26/21
1895-1991	0,64	0,41	0,39	0,53	$T_{min} = 0.231\ PC2 + 0.205\ PC1 - 0.349\ PC3_{t-1} + 8.926$											

Diurnal Temperature Range

Calibration					Standard Verification						1st Difference Verification					
Period	r	r^2	aR^2	SE	Period	r	RE	CE	PM	ST	Period	r	RE	CE	PM	ST
1895–1943	0,56	0,31	0,26	0,62	1944–1991	0,67	0,43	0,40	3,64	38/10	1944–1991	0,71	0,50	0,50	4,54	36/11
1944–1991	0,71	0,51	0,47	0,68	1895–1943	0,53	0,30	0,23	3,77	21/17	1895–1943	0,62	0,39	0,39	3,59	36/11
1895–1991	0,65	0,42	0,40	0,65	$T_{DTR} = 0.396\ PC1 + 0.278\ PC3_{t-1} + 0.212\ PC2 + 14.406$											

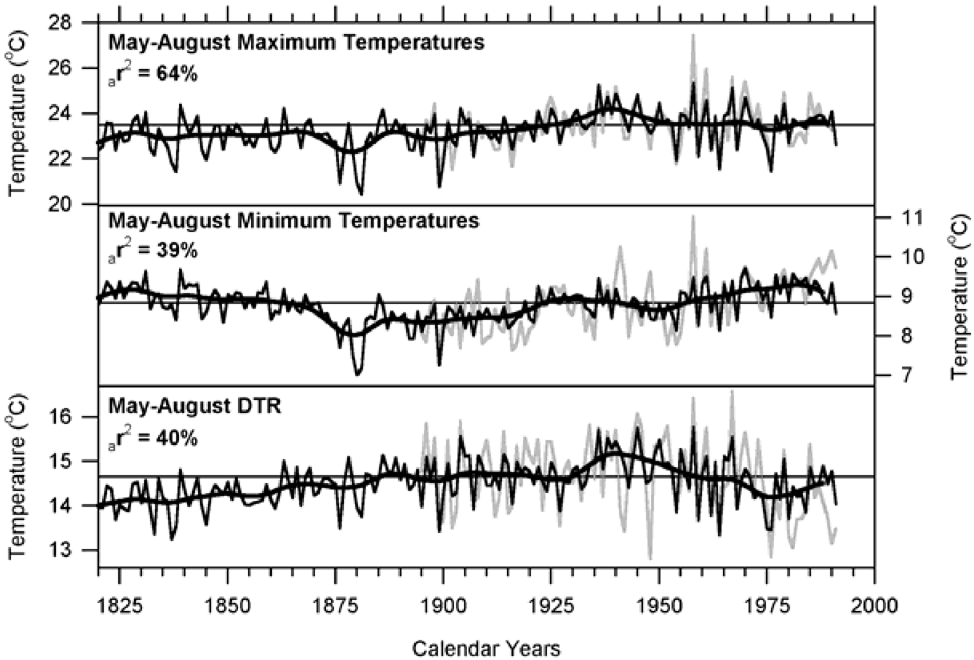

Figure 6. Time series plots of the T_{max} and T_{min} and DTR reconstructions (1820–1991) compared with actual measured temperature data (grey). The low pass filter is a 20-year cubic smoothing spline of the reconstruction.

In many regions of the Northern Hemisphere, DTR has been observed to decrease in recent decades due to an increase in night-time T_{min} values that exceeds the increase in day-time T_{max}. Empirical evidence suggests that increasing cloud cover appears to be the main cause of rising night-time T_{min} in many of these regions (Karl et al. 1993; Przybylsk 1997; Dai et al. 1999) though the cause of the increase in cloud cover remains unknown (Przybylak 2000). Wilson and Luckman (*in press*) noted that trends in T_{max} and T_{min} (Fig. 2 a) broadly paralleled those observed for Northern Hemisphere temperatures and that there was a decrease in DTR over the last few decades in interior BC with a shift around 1976 (Figs. 2 b and 2 c). A similar shift in DTR values has also been noted by Nemani et al. (2001) in California. The hydrological cycle in these areas has become more vigorous since 1976 due to a deepening of the Aleutian Low, resulting in more low pressure systems bringing warm, moist westerly winds across western North America (Trenberth, Hurrell 1994). Although these large scale processes dominate the Northern Pacific climate in the winter and spring months, they might also produce increased cloud cover in interior BC explaining the apparent 1976 shift in May-August DTR. However, a more detailed investigation of regional changes in temperature and cloud cover is needed before definitive conclusions can be drawn about the possible causes of these changes.

Conclusion

This paper has demonstrated that statistically robust dendroclimatic reconstructions of maximum and minimum temperatures plus the mean daily temperature range can be developed for Interior British Columbia. Regional studies of instrumental climate data have shown that the DTR has changed in the 20^{th} century as a result of differing trends in T_{max} and T_{min} (Skinner, Gullet 1993; Easterling et al. 1997; Dai et al. 1999). Reconstructions of these climate variables would allow these 20^{th} century changes to be evaluated over an extended interval. The preliminary reconstructions presented here suggest that, in Interior British Columbia, trends in T_{max} and T_{min} may also have varied over the last 180 years and that recent trends in DTR are not unique.

These results have potentially profound implications for the reconstruction of proxy temperature records from tree rings. They suggest that T_{mean}, T_{max} and T_{min} may not vary consistently and therefore it may be necessary to reconstruct all three parameters (if possible) to evaluate past temperature variability. It also appears that tree growth at these temperature-limited sites may be more closely related to T_{max} rather than T_{mean} or T_{min} and that the significant temperature control may vary over time. Recent observed changes in tree-ring/mean temperature relationships may, in part, reflect the fact that recent increases in mean temperatures are primarily caused by rising minimum temperatures whereas maximum temperatures are stable or decreasing.

This work raises some questions that cannot be answered from this study alone and require more extensive investigation. Are mean temperatures the best measure of the temperature control on tree growth at temperature limited sites? Are the observed changes in T_{max} and T_{min} restricted to the late 20^{th} century or have they occurred in the past? Do changes in T_{max} and T_{min} compromise the balance between night-time respiration and daytime photosynthesis in trees? Briffa (2000) states that the empirically derived regression equations used for climate reconstruction might be compromised if the balance between photosynthesis and respiration changes as a result of differential changes in night and daytime heating patterns. This would seem to be one explanation for the results we present for these sites in British Columbia.

These questions require continued investigation. We therefore suggest that it would be prudent if future dendroclimatic studies investigate the reconstruction of all three temperature parameters (T_{max}, T_{mean} and T_{min}) to evaluate which parameter provides the best reconstruction. This does not mean that reconstructions using T_{mean} should be abandoned. A robust T_{mean} reconstruction explaining 61 % of the instrumental variability can be developed using the data presented in this paper. It should also be emphasised that these results do not exclude the possibility of other causes of divergence between modelled and actual temperatures related to major tree-growth/climate response changes (e. g. the influence of changing precipitation levels (Jacoby, D'Arrigo 1995; Vaganov et al. 1999; Barber et al. 2000; Lloyd, Fastie 2002) and anthropogenic influences (Briffa et al. 1998)). Our results simply add another list of variables that must be evaluated in future dendroclimatic research to determine possible causes of changes in the relationship between tree growth and climate.

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