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Summer temperatures in the Canadian Rockies during the last millennium: a revised record

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Abstract We present a significant update to a millennial summer temperature reconstruction (1073–1983) that was originally published in 1997. Utilising new tree-ring data (predominantly *Piceaengelmannii*), the reconstruction is not only better replicated, but has been extended (950–1994) and is now more regionally representative. Calibration and verification statistics were improved, with the new model explaining 53% of May–August maximum temperature variation compared to the original (39% of April–August mean temperatures). The maximum latewood density data, which are weighted more strongly in the regression model than ringwidth, were processed using regional curve standardisation to capture potential centennial to millennial scale variability. The reconstruction shows warm intervals, comparable to twentieth century values, for the first half of the eleventh century, the late 1300s and early 1400s. The bulk of the record, however, is below the 1901–1980 normals, with prolonged cool periods from 1200 to 1350 and from 1450 to the late 19th century. The most extreme cool period is observed to be in the 1690s. These reconstructed cool periods compare well with known regional records of glacier advances between 1150 and the 1300s, possibly in the early 1500s, early 1700s and 1800s. Evidence is also presented of the influence of solar activity and volcanic events on summer temperature in the Canadian Rockies over the last 1,000 years. Although this reconstruction is regional in scope, it compares well at multi-decadal to centennial scales with Northern Hemisphere temperature proxies and at millennial scales with reconstructions that were also processed to capture longer timescale variability. This coherence suggests that this series is globally important for the assessment of natural temperature variability over the last 1,000 years.

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1 Introduction

Although there are many dendroclimatic reconstructions of temperatures that span the last 300–500 years, there are relatively few that extend back prior to AD 1000. It is therefore critical to obtain data from the early part of the last millennium to assess regional and global records of a possible Medieval warm period (Lamb 1965; Hughes and Diaz 1994) and evidence of an early Medieval cooler (glacial) interval in some alpine areas (Luckman 2004). Luckman et al. 1997 published a mean summer (April–August) temperature reconstruction based on ringwidth (RW) and maximum latewood density data (MXD) from tree-ring sites in the Columbia Icefield area of the Canadian Rockies. This reconstruction was the longest then available for boreal North America (1073–1983). Although developed essentially from a single site, this record was considered to be regionally representative owing to its correspondence with available proxy climate records (Luckman et al. 1997, 2000) and has, subsequently, been verified by comparison with an independently developed regional summer temperature record from several treeline sites in interior British Columbia (Wilson and Luckman 2003). The original Icefield data and chronology have been utilised in several compilations of millennial records for Northern Hemisphere temperatures (Briffa 2000; Esper et al. 2002; Mann et al. 1999). In this paper we present a revised reconstruction (869–1994) that extends and increases replication of the earlier Icefield record, uses additional sites from the Rockies and employs different standardisation techniques to capture more low frequency information. We also provide signal strength and related confidence information not reported in the previous reconstruction.

2 Materials, methods and results

2.1 Tree-ring data

The original IcefieldRW chronology (Luckman 1993) was developed from living trees and snag material from a former higher treeline on the lower slopes of Mount Wilcox (Luckman and Kavanagh 2000; Kavanagh 2000) and other areas immediately adjacent to the Little Ice Age (LIA) limits of the Athabasca Glacier. The original Icefield reconstruction (hereinafter L1997) utilised selected RW and MXD data from the snag material from the Wilcox slope and data from the Sunwapta Pass site (Fig. 1), about 4 km upvalley, collected in 1984 (Schweingruber 1988). In a subsequent study, Wilson and Luckman (2003) developed a very similar reconstruction back to AD 1600 from RW and MXD chronologies from treeline sites some 100–300 km to the southwest in interior British Columbia (IBC, Fig. 1). This study demonstrated a much stronger common signal in the density record, indicating that a lower sample depth was required to meet appropriate signal strength criteria than for RW chronologies. Given the strong regional signal in the MXD data and its importance in these two earlier reconstructions, we decided to extend the Athabasca reconstruction and incorporate a more regional data-set.

Regional RW and MXD chronologies were developed for the Central Canadian Rockies that included the original Icefield's data, new chronologies from sites close to the Columbia Icefield plus older material recovered from glacier forefields that extended the record back

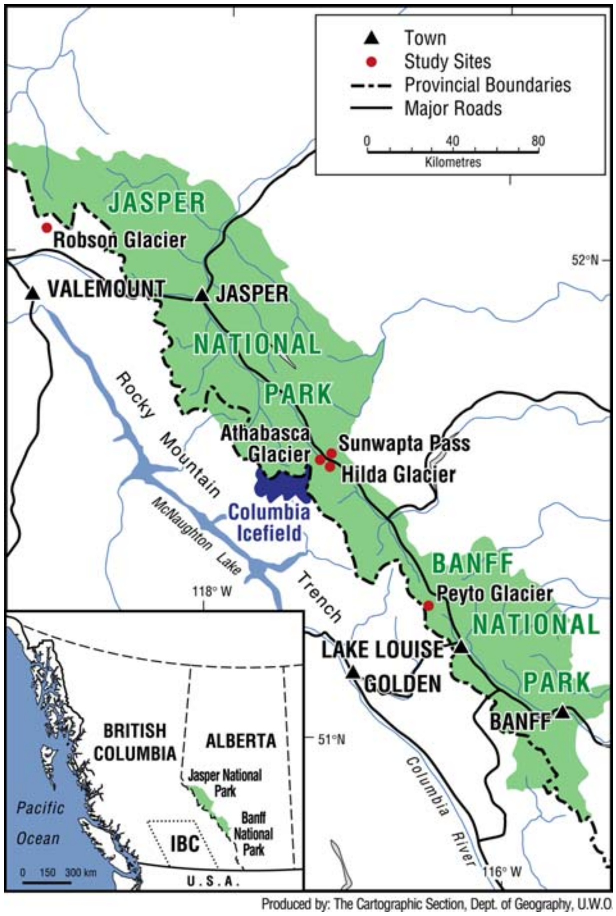


Fig. 1 Location of study sites. Interior British Columbia (IBC) denotes the approximate area sampled for the Wilson and Luckman (2003) reconstruction (see text)

Table 1 Tree-ring data sources

Site name	Latitude (degree)	Longitude (degree)	Elevation (m)	Species	Start	End	*n*	Parameter
Original chronology								
Sunwapta	52.13	117.10	2,050	PCEN	1634	1983	28	MXD and RW[c]
Icefields snags	52.13	117.14	2,100	PCEN[a]	1083	1898	38	MXD and RW[d]
Additional data for this study								
Athabasca Glacier	52.13	117.14	2,000	PCEN	1665	1994	28	MXD
Icefields snags	52.13	117.14	2,100	PCEN[a]	1083	1898	124	RW
Hilda site	52.09	117.12	2,200	PCEN	1428	2000	43	RW
Peyto Lake	51.43	116.30	2,050	PCEN	1634	1983	26	MXD and RW[c]
Peyto Lake	51.43	116.30	2,050	PCEN	1680	1995	20	RW
Peyto Glacier	51.42	116.32	1,850	PCEN	899	1312	6	MXD
Peyto Glacier	51.42	116.32	1,850	PCEN	760	1325	15	RW
Robson Glacier	53.09	119.07	1,690	PCEN[b]	869	1280	28	MXD
Robson Glacier	53.09	119.07	1,690	PCEN	867	1345	48	RW

PCEN Picea engelmannii
[a]Includes some *Abies lasiocarpa* (see Luckman et al. 1997)
[b]Species mainly PCEN
Published sources: [c]Schweingruber (1988),
[d]Luckman et al. (1997), [e]T. Kavanagh, personal communication, 2002. *n* no of measured radii

All maximum latewood density (MXD) and associated ring width (RW) data were processed by WSL at Birmensdorf by E Schär or T. Forster. Other RW measurements were made at UWO using a TRIM or Velmex system to 0.01 mm or 0.001 mm prior to AD 1000 (Table 1). The densitometric chronology at Athabasca Glacier was updated with new *Piceaengelmannii* data sampled in 1996 at the foot of the Wilcox slope, downslope of the previously sampled snags. We also added RW data from a spruce chronology site on a north facing slope about 4 km southeast of Sunwapta Pass, near Hilda Glacier (Fig. 1; Kavanagh 2000; Luckman and Kavanagh 2000). In order to incorporate a broader regional signal into this reconstruction we included RW and MXD chronologies from sites near Peyto Lake, sampled in 1984 (Schweingruber 1988), and RW data recovered from an adjacent site sampled 12 years later by the University of Western Ontario (UWO). These two living-tree sites sit on a bench overlooking Peyto Glacier at treeline in Bow Pass, approximately 70 km south of the Athabasca Glacier. To extend the earlier chronologies, we developed densitometric series from trees overridden by Peyto (Luckman 1996) and Robson Glaciers (Luckman 1995) from the twelth to fourteenth centuries. These sites are 160 km northwest (Robson) and 75 km southeast (Peyto) of the Columbia Icefield (Fig. 1) and were initially cross-dated from the Athabasca and Bennington chronologies (Luckman 1993, 1995). The cross-dating was subsequently and independently confirmed with MXD data. All living tree chronologies were developed from *P. engelmannii* but some of the snag material may include *Abieslasiocarpa* (Luckman et al. 1997).

2.2 Climate data

The L1997 reconstruction was calibrated against a regional temperature record developed by Luckman and Seed (1995), primarily using data from Jasper, Valemount, Banff and Golden records from 1880 to 1984. Recently, the Meteorological Service of Canada has developed a gridded 50×50 km data-set using homogenised data that extends back to 1895 (Zhang et al. 2000; Milewska and Hogg 2001). For this study, calibration was based on the mean of the four grid squares in this data-set immediately adjacent to the Columbia Icefield area (approximately 51°45′–52°45′N by 116°23′–117°52′W). The correlation between the gridded series and Luckman and Seed's series over their common interval (1895–1984) is 0.94 for May–August mean temperatures. Data for minimum, mean and maximum temperatures were extracted from the gridded series. Previous work (Wilson and Luckman 2002, 2003) suggested that, as the relationship between these temperature variables has changed in recent decades, maximum temperatures (T_{max}) might provide a more stable calibration than the more conventionally used mean temperatures (T_{mean}).

2.3 Chronology development

Luckman et al. (1997) originally detrended the tree-ring data using traditional individual series standardisation methods. For the RW data, age-related trends were removed by subtracting either negative exponential or straight line functions, while the MXD data were detrended using straight-line functions. This approach captures multi-decadal to century-scale information, but may remove potential millennial scale low frequency trends (Cook et al. 1995). In the present study, we aim to address the potential loss in centennial-to-millennial scale variability that may bias, in the frequency domain, the original Luckman et al. (1997) study.

For this new tree-ring data-set, the mean sample length (MSL) for the RW and MXD series are 242 years and 232 years, respectively, and, when calculated as a running time series, never fall below 200 years over the length of both composite chronologies. Cook et al. (1995) state that the lowest frequency of climate information that can be realistically recovered from traditional detrending methods is $3/n$ cycles per year (where n = the MSL). Therefore, using traditional individual series detrending methods for either the RW or MXD data, frequencies at timescales greater than a century will not be captured effectively.

In this study therefore, we explored the utilisation of the regional curve standardisation method (RCS, Mitchell 1967; Briffa et al. 1992, 1996; Cook et al. 1995; Esper et al. 2003) that aims to capture secular scale variability at frequencies greater than the MSL. Significantly more low-frequency information was captured using the MXD data (see Appendix) but no significant gain was observed by using the RCS method on the RW data (analysis not shown). Therefore, a RCS chronology was not developed for the RW data. The signal strength and statistical confidence of the chronologies were assessed using both the expressed population signal (EPS, Wigley et al. 1984) and bootstrapped error bars (Efron 1987). EPS values were calculated for each chronology using a 30-year moving window. This 'moving window' EPS approach provides an absolute measure of signal quality through time (Briffa 1995). The final RCSMXD chronology meets the 0.85 EPS criterion for signal strength acceptance (Wigley et al. 1984) after AD 1000, except for minor short periods (ca. 1090, 1140, 1280–1320 and 1500), and remains above 0.70 back to AD 900 (Fig. 2a).

The ringwidth chronology was developed by detrending the individual RW series using conventional negative exponential functions or a regression line of negative or zero slope (the fitted functions were subtracted after appropriate adaptive power transformation of the raw series (Cook and Peters 1997)). After standardisation, all indexed series were averaged in a single composite RW chronology. This composite chronology has much stronger replication throughout its length (Fig. 2b) than the original Athabasca chronology which only averaged between 25 and 35 series for each year within the 1400–1980 interval. EPS values remain above 0.85 back to approximately AD 950 in this new chronology, which has much narrower bootstrapped error bars than the MXD chronology.

2.4 Calibration and verification

The composite MXD and RW chronologies, lagged at t and $t+1$, were regressed (using a stepwise process) against several combinations of mean, maximum and minimum temperature variables. Optimal results were found for May–August T_{max} using MXD (t) and RW (t and $t+1$) as predictor variables. The calibration and verification results plus plots of actual and predicted values are presented in Fig. 3. There is, statistically, no difference between the calibration results using the RCS generated MXD data (hereinafter RCS2004; Fig. 3a) and a second reconstruction (hereinafter STD2004; Fig. 3c), employing composite chronologies developed using only standard 'traditional' detrending methods (negative exponential and linear fits to the data). Both models explain 53% of the temperature variance and pass all conventional verification tests. The calibration for both RCS2004 and STD2004 is stronger than that for L1997 which explained 39% of April–August T_{mean} and failed verification using the more stringent CE statistic. These improved results are, in part, related to the

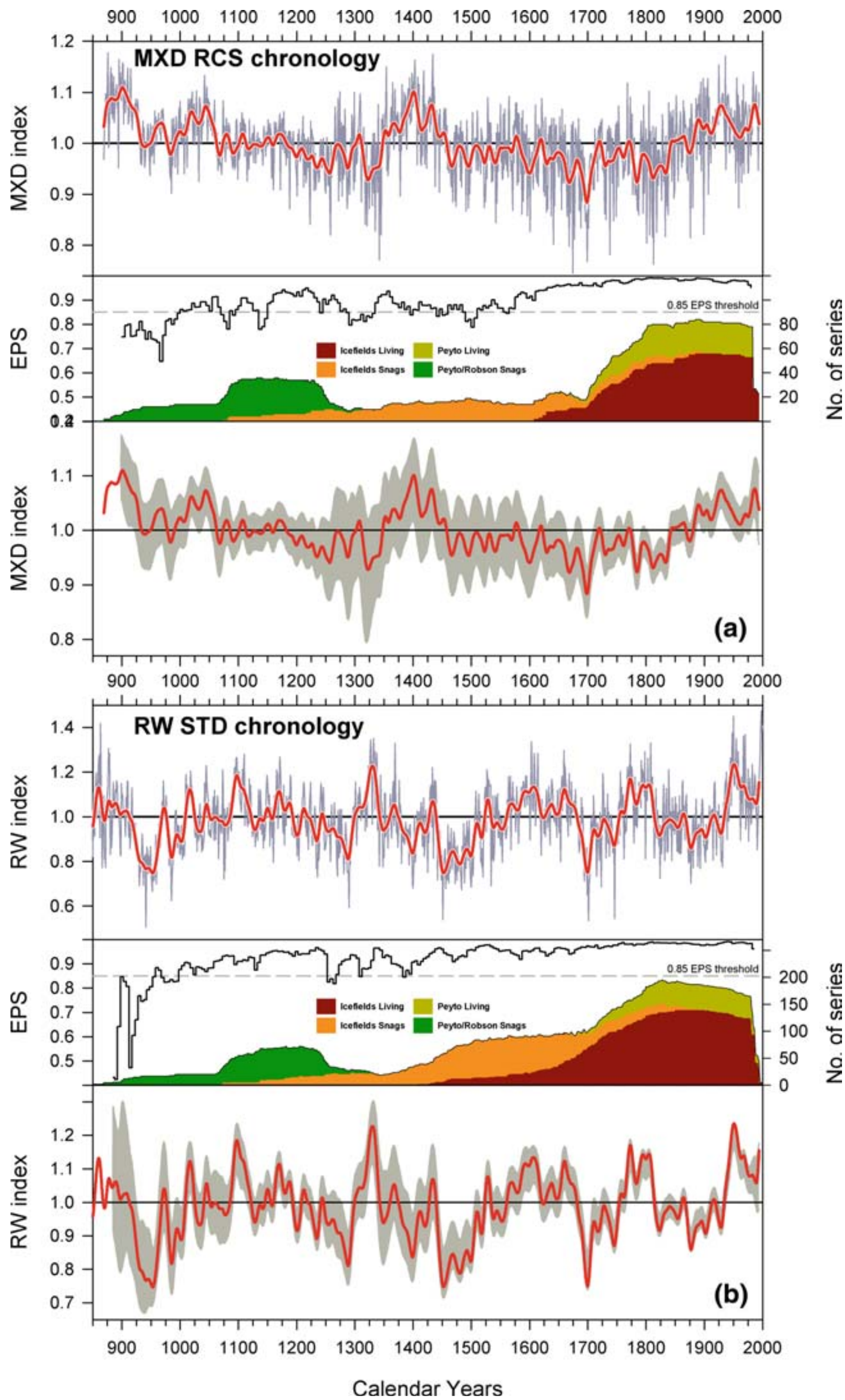
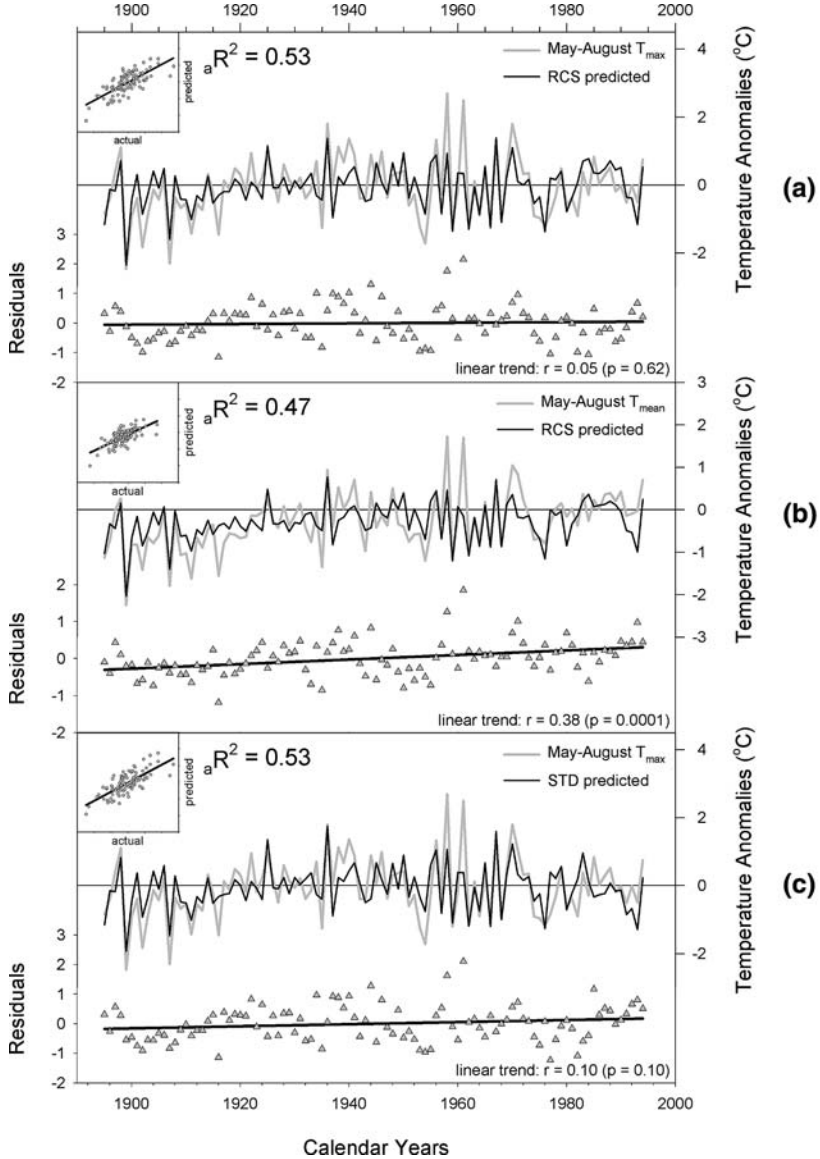


Fig. 2 Time-series plots of the maximum latewood density (MXD) and ringwidth (RW) chronologies. **a** *upper panel* MXD regional curve standardisation (RCS) chronology. The *red smoothed line* is a 20-year cubic smoothing spline; *central panel* expressed population signal (EPS) values (30-year periods lagged by 5 years) and radii replication; *lower panel* 20-year spline with 95% bootstrap error bars (Efron1987).
b As for (**a**) but for the STD RW chronology. To minimise potential index value inflation, the raw RW and MXD series were transformed prior to detrending using an adaptive power transform (Cook and Peters 1997). The Osborn et al. (1997) variance stabilisation method was also utilised for chronology development



RCS2004 (T_{max})

RCS MXD and STD RW: May-August Tmax

CALIBRATION

Period	r	r^2	$_ar^2$	se	dw
1895-1944	0.79	0.63	0.60	0.56	1.76
1945-1994	0.72	0.52	0.49	0.66	1.56
1895-1994	0.74	0.54	0.53	0.62	1.62

$T_{max} = 9.17\ MXD_t + 2.65\ RW_t - 1.15\ RW_{t+1} - 11.18$

VERIFICATION

Period	r	RE	CE	ST
1945-1994	0.67	0.30	0.29	37/12
1895-1944	0.73	0.52	0.51	34/15

RCS2004 (T_{mean})

RCS MXD and STD RW: May-August Tmean

CALIBRATION

Period	r	r^2	$_ar^2$	se	dw
1895-1944	0.76	0.58	0.56	0.43	1.69
1945-1994	0.65	0.42	0.39	0.48	1.69
1895-1994	0.70	0.48	0.47	0.48	1.50#

$T_{mean} = 6.68\ MXD_t + 1.58\ RW_t - 8.89$

VERIFICATION

Period	r	RE	CE	ST
1945-1994	0.60	0.46	0.22	42/7
1895-1944	0.71	0.38	0.12	30/19*

STD2004 (T_{max})

STD MXD and STD RW: May-August Tmax

CALIBRATION

Period	r	r^2	$_ar^2$	se	dw
1895-1944	0.80	0.64	0.61	0.55	1.84
1945-1994	0.73	0.53	0.50	0.65	1.50
1895-1994	0.74	0.54	0.53	0.62	1.60

$T_{max} = 8.71\ MXD_t + 2.58\ RW_t - 1.13\ RW_{t+1} - 10.43$

VERIFICATION

Period	r	RE	CE	ST
1945-1994	0.65	0.31	0.30	37/12
1895-1944	0.70	0.38	0.37	33/16

Fig. 3 Summary calibration and verification statistics for May–August temperatures. **a** Calibration using the RCSMXD and STD RW series against maximum May–August temperatures. Graphs show; bivariate plot of actual and predicted values (*top left*), time-series plot of actual and predicted values and plots of residuals through time (*lower*); *r* correlation coefficient; r^2 explained variance; $_aR^2$ square of the multiple correlation coefficient following adjustment for loss of degrees of freedom; *SE* Standard error of the estimate; *DW* Durbin Watson statistic for residual autocorrelation. *RE* Reduction of error statistic; *CE* coefficient of efficiency statistic. Both RE and CE are measures of shared variance between the actual and modelled series, but are usually lower than the calibration r^2. A positive value for either statistic signifies that the regression model has some skill. CE is the more rigorous statistic. (Cook et al. 1994); *ST*Sign test (Fritts 1976). **b** As (**a**) but using the RCS MXD and STD RW series against mean May–August temperatures. # significant autocorrelation (99% confidence limit) using the Durbin–Watson statistic; *asterisk* failed sign test at the 95% confidence limit. **c** As (**a**) but using the STD MXD and STD RW series against maximum May–August temperatures. Multicollinearity has not inflated the explained variance (Cook et al. 1994) in any of the models as the mean correlation between MXD and RW over the 1895–1994 period is low (−0.03)

fact that calibration was made against T_{max} (see Wilson and Luckman 2003). Regression results of the RCSMXD and STD RW data against May–August T_{mean} are weaker (Fig. 3b). This model explains 47% of the temperature variance, fails verification using the sign test, and the residuals show significant autocorrelation and a significant linear trend ($r=0.38$; $P=0.0001$) through time. These results of trials using T_{mean} or T_{max} are similar to those obtained by Wilson and Luckman (2003) in British Columbia. The improved results of the new models also probably reflect the increased sample depth of the MXD and RW data-sets (Fig. 2) that reduces site-specific effects and ensures that the final reconstruction is more representative of a larger region.

As May–August T_{max} shows no significant long term trends (first-order AC = 0.01) over the calibration period, it is statistically impossible to quantify which reconstruction (RCS 2004 or STD 2004; Fig. 3a, c respectively) most robustly portrays summer temperature variability over the last 1,000 years. However, as it is known that 'traditional' individual series standardisation procedures remove long term trends (i.e. centennial to longer scales) from TR series (Cook et al. 1995), we hypothesise that the RCS2004 reconstruction is a more representative model of past temperature variation. This hypothesis is partially supported by the fact that the RCS2004 reconstruction verifies marginally better than STD2004 and the linear trend of its model residuals is almost zero (Fig. 3a).

3 Discussion

The RCS2004 and STD2004 reconstructions are compared to L1997 and IBC in Fig. 4. The STD2004 and L1997 reconstructions are very similar after ca. AD 1250 (L1997 is poorly replicated prior to AD 1250) at both decadal and longer timescales. Although they use different calibration data, STD2004 is slightly warmer over the common period (the 1250–1980 means are, respectively, 0.24°C and 0.32°C below the 1901–1980 reference period) and the early 1800s are slightly less severe. The IBC reconstruction from Interior British Columbia is very similar to both these reconstructions at decadal and longer timescales; however, the new STD reconstruction shows a greater temperature depression at the end of the seventeenth century.

The RCS2004 reconstruction is, on average, cooler (mean −0.53°C from 1250–1980) and shows more low frequency trend. The 1500s and 1600s are relatively cool and the 1690s are the most extreme reconstructed cold period in the record (Table 2). The cooler interval through the 1200s and 1300s is well developed but the late 1300s and early 1400s approach twentieth century conditions. In fact, 1434 (1.69°C) showed the warmest reconstructed summer, followed by 1967 (1.46°C) and 1936 (1.45°C). The decrease in temperature in the mid-1400s is much stronger than in previous reconstructions. Little is known about conditions during this period but this sharp decrease is shown in ringwidth chronologies of all species in the Canadian Rockies at this time (Luckman 1993, 1997; Colenutt and Luckman 1996;

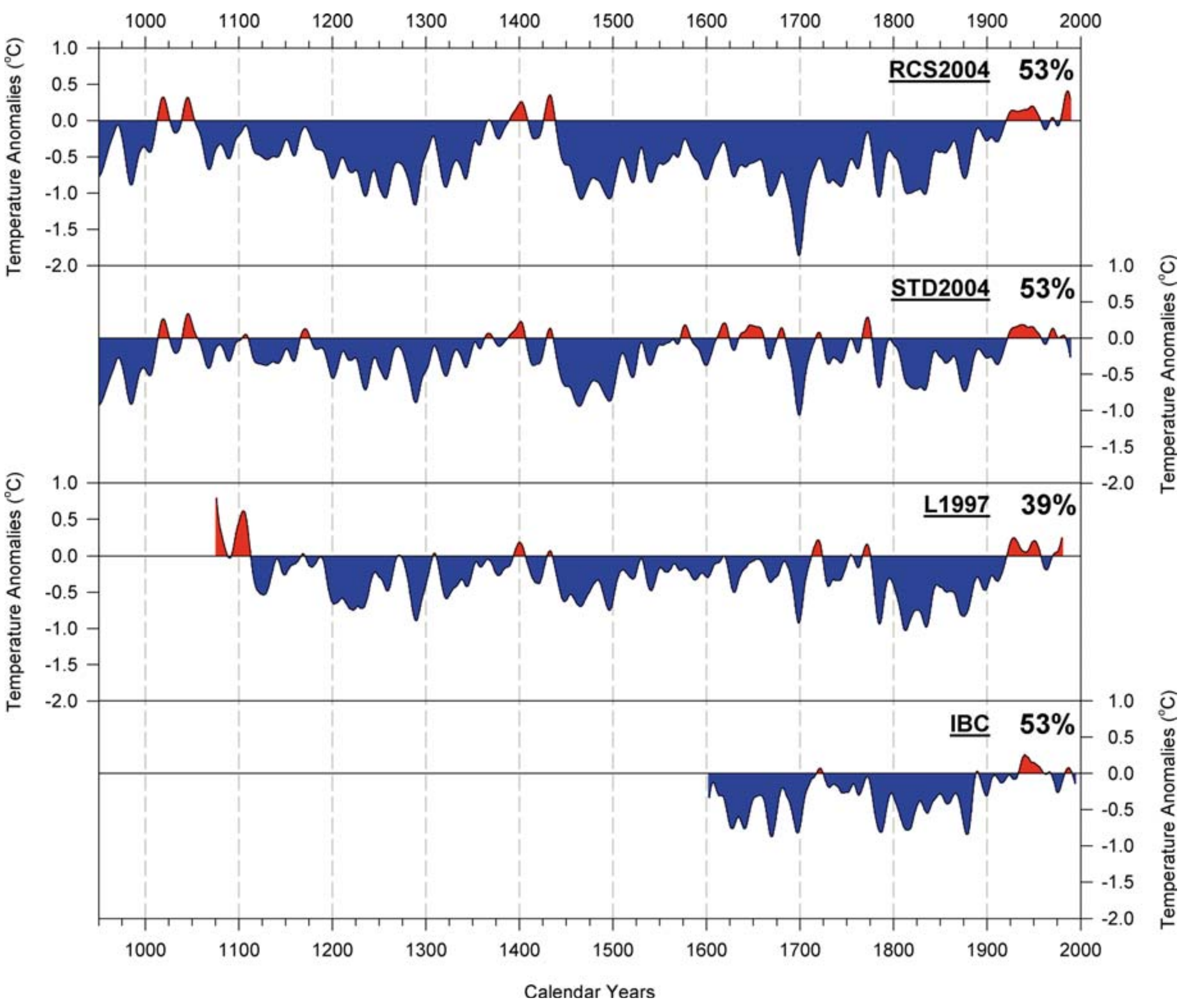


Fig. 4 Comparison of the RCS2004 and STD2004 reconstructions with original Icefield reconstruction (L1997) and IBC. The percentage figures are the adjusted R^2 for each model. Series are smoothed with a 20-year spline. Anomalies to 1901–1980

Table 2 Most extreme non-overlapping 20-year periods in the RCS2004 reconstruction

Cool intervals			Warm intervals		
Start	End	Value	Start	End	Value
1685	1704	−1.52	1970	1989	0.20
1819	1838	−1.06	1391	1410	0.20
1481	1500	−1.01	1939	1958	0.19
1456	1475	−0.98	1009	1028	0.17
1275	1294	−0.97	1033	1052	0.15
1664	1683	−0.94	1418	1437	0.15
1247	1266	−0.93	1917	1936	0.13
1727	1746	−0.92	1360	1379	−0.08
1221	1240	−0.90	1094	1113	−0.12
1799	1818	−0.80	1162	1181	−0.14
1311	1330	−0.80			

Temperatures are anomalies (°C) from the 1900–1980 mean

Colenutt 2000; Youngblut 2003) and in Northern Hemisphere temperature records (Fig. 6, below). The sharp decrease in reconstructed temperatures in the late 1600s is associated with a major dieback of treeline trees at the Athabasca site (Luckman and Kavanagh 2000; Kavanagh 2000) and is more severe than in earlier reconstructions. The inclusion of new data dispels earlier concerns that this temperature decrease was a purely local phenomenon at the Icefield site owing to the advance of the Athabasca Glacier to the base of the sampled slope in the early 1700s. None of the data added to the composite chronologies come from a glacier-proximal site and this period is also reconstructed as cool in the IBC reconstruction. The 1690s are reconstructed as the coldest interval in the last 1,000 years (Fig. 5a) with the 20-year period from 1685–1704 being over 0.4°C cooler than the next coldest 20-year interval (Table 2). It is interesting to note that Briffa et al. (1998) note globally cool years in 1695 and 1698–1699, while 1695 is identified as the sixth highest ranked 'event' since 1500 in a volcanic aerosol index (VAI) for 52°N (Robertson et al. 2001). Davi et al. (2003) associate the light (low density) 1695 ring in the Wrangell Mountains in Alaska with the eruption of Kommaga-Take in Hokkaido, Japan in July 1694. It seems, therefore, probable that this cold period reflects short term volcanic forcing superimposed on a period of low solar activity (the end of the Maunder Minimum, Fig. 5a) when global temperatures were generally cooler (Bard et al. 2000; Robertson et al. 2001; Shindell et al. 2001).

The pre-1300 reconstruction replaces and extends the poorly replicated part of L1997, with some confidence (Fig. 2) to ca. AD950. The poorly replicated, apparently warm, interval in the early 1100s in L1997 is now discounted. RCS2004 indicates cooler conditions through the 1100s (a time of glacier advance in the region, Luckman 2000; Fig. 5). However, the early eleventh century was as warm as the twentieth century and the late tenth century was probably cooler. Development of the new long composite RW chronology also allowed cross-dating of a critical Athabasca snag that was previously undated. Sample A78-S2 was identified as *Larixlyallii* (Y. Bégin, 2004, personal communication) and lived between AD 960 and 1107 (the previous chronology only had one sample between AD 1073 and 1107). This is the only known sample of *Larix* from Jasper National Park, and this is approximately 30 km north of the present range limit of the species, supporting the possibility that conditions were as warm at that time as at present. It is also interesting to note that most of the trees at the Wilcox site that died during the late 1600s began growth in the late 1300s and early 1400s (Luckman 1994) which are reconstructed as relatively warm in RCS2004.

Overall, all three Icefields reconstructions (Fig. 4) are entirely consistent with the known regional glacier history (Luckman 2000). Specifically, the cool periods inferred from the RCS2004 reconstruction coincide very well with periods of glacial advance and moraine formation (Fig. 5b). Although the glacial story becomes less clear further back in time, there is evidence of glacial advance at the Stutfield (Osborn et al. 2001), Robson and Peyto Glaciers during the late twelfth to early fourteenth centuries. This period of glacial activity coincides both with extreme reconstructed 20-year cool intervals (Table 2) and the Wolfe solar minimum. Cool conditions and extreme 20-year cool periods are reconstructed for the mid-to-late 1400s during the Spörer minimum. There is limited evidence of a glacier advance towards the end of this period from minimum lichenometric ages obtained from small moraine fragments in Jasper National Park (Luckman 2000). The reconstructed cold spell in the late 1600s immediately precedes the formation of the outer LIA moraines at about 20% of the glaciers in the Canadian Rockies suggesting that the glaciers responded directly to cool conditions at the end of the seventeenth century. The last major cool period in the RCS2004 reconstruction, at the beginning of the nineteenth century, is again associated with a known period of low solar activity (the Dalton minimum) and immediately precedes the maximum LIA extent of most glaciers in the Rockies ca. 1840–1850 (Luckman 2000) and a series of readvance moraines at many glaciers in the late nineteenth century.

The RCS2004 reconstruction and glacial record shown in Fig. 5 are regionally based records of past climate variability. However, the timing of reconstructed cool periods (Table 2), the periods of glacial advance, and the dated moraines show a remarkable

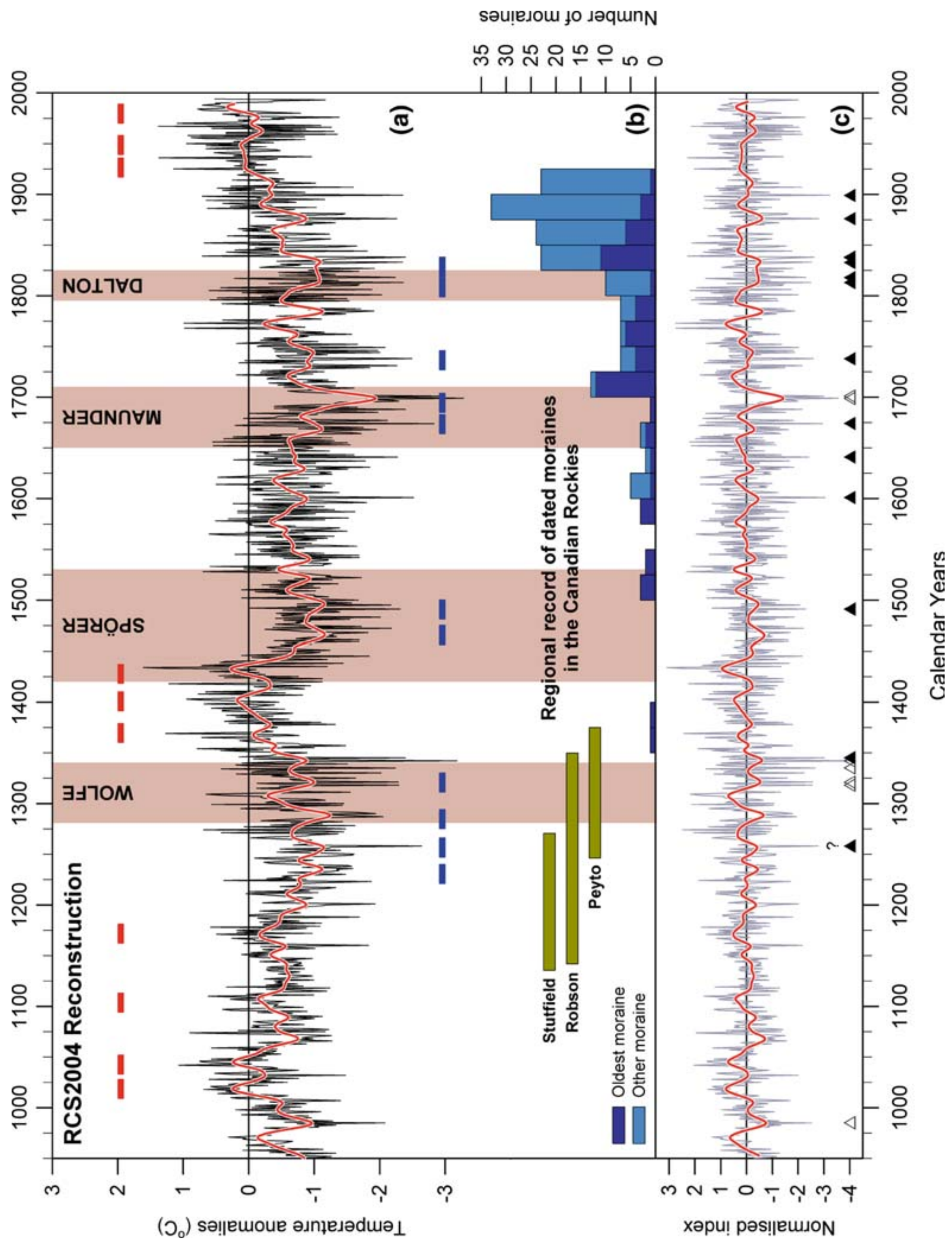


Fig. 5 Comparison of the RCS2004 reconstruction with the regional glacial record in the Canadian Rockies. **a** RCS2004 reconstruction. The *smoothed red line* is a 20-year cubic smoothing spline. *Horizontal bars* denote the ten warmest (*red*) and coolest (*blue*) ranked 20-year non-overlapping periods in the record (Table 3); **b** *Vertical shading*denotes the approximate timing and duration of solar activity minima (Stuiver 1961; Bond et al. 2001). *Horizontal olive green bars* span the outer dates of trees overridden by advances of Stutfield, Robson and Peyto Glaciers. The histogram shows the number of dated moraines, grouped in 25-year periods, based on lichenometric and tree-ring dating in 66 glacier forefields (Luckman 1996; Luckman and Villalba 2001); **c** High pass filtered series (150 year spline) of RCS2004, normalised to the 950–1994 period. The *smoothed red line* is a 20-year cubic smoothing spline. The 20 most extreme negative deviations (Table 4) are highlighted with *triangles*. *Filled triangles* are years that coincide with known volcanic events during the same year or 1 year or 2 years afterwards. *Empty triangles* denote extreme years that do not appear to coincide with known volcanic events

synchroneity with known periods of low solar activity (Stuiver 1961; Bond et al. 2001) and LIA glacial records throughout the Americas (Luckman and Villalba 2001; Wiles et al. 2004). This emphasises the important solar contribution to climate variation over the last millennium (Beer et al. 2000). Volcanic events also cause short term cooling in instrumental and proxy temperature records. Briffa et al. (1998) and Kirchner et al. (1999) state that major volcanic eruptions can reduce global temperatures for 3–4 years after an event.

Figure 5c presents a normalised version of the RCS2004 series after high pass filtering (150-year spline) with the 20 most extreme negative deviations highlighted (triangles). Of these extreme years, 12 occur after 1500 and 10 of these are within 2 years of major volcanic eruptions (Table 3). Prior to 1500 the dating of volcanic events is less precise but the filtered RCS2004 record suggests candidate years for eruption-related effects ca. 985, 1258, 1318, 1321, 1342, 1345 and 1491. The 1258 extreme year is particularly notable, as it is possibly associated with an 'unknown' volcanic event dated around 1257 (Oppenheimer 2003, but dated as 1259 by Crowley's (2000) radiative forcing index; Table 3) that produced the highest atmospheric loading of the last millennium (Crowley 2000; Zielinski 2000) and is seen in ice cores from both hemispheres.

Although the RCS2004 reconstruction is regionally focused, it does show evidence of large-scale external forcing (both solar and volcanic) that suggests that this series is potentially important for studies of large-scale (i.e. global) climate variability. One of the primary objectives in the development of millennial length reconstructions is to add to the meagre database of available millennial records. Figure 6 compares the RCS2004 reconstruction with available composite Northern Hemisphere temperature reconstructions. Overall, the RCS2004 record shows stronger similarities with the BRIFFA2000 and ESPER2002 records until replication becomes a problem prior to ca. 1000. In general, the three records show cool conditions during the thirteenth century to the first half of the fourteenth century, around the late fifteenth century, and from the late sixteenth to late nineteenth centuries. Although all the records show cool conditions around 1700, the relative magnitude (though not timing) of the 1690s crash in the RCS2004 series is unusual. The RCS2004, BRIFFA2000 and ESPER2002 records portray consistent warm conditions in the eleventh and twentieth centuries, implying that temperatures at the beginning of the millennium were at least similar to

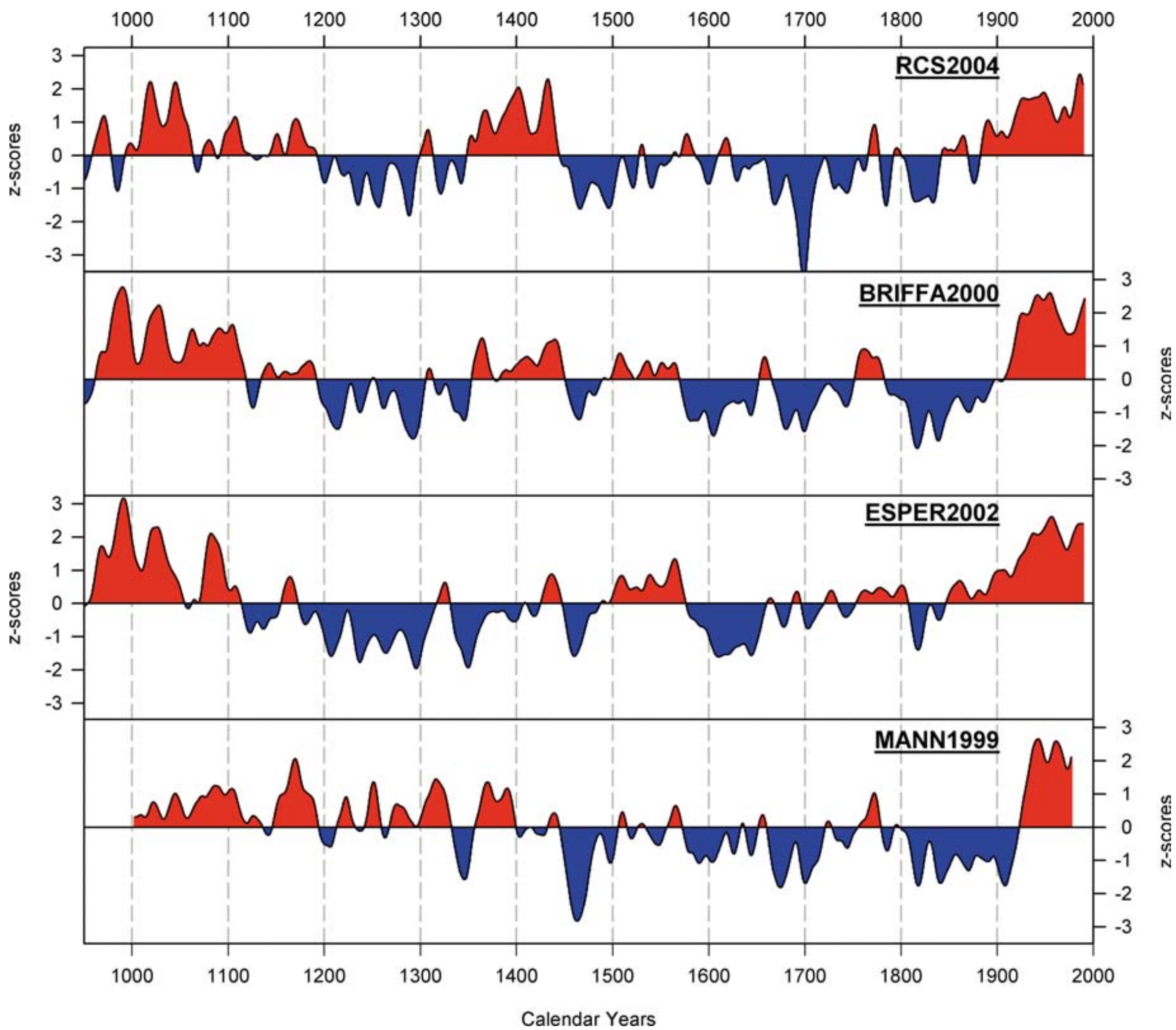


Fig. 6 Comparison between RCS2004, BRIFFA2000, ESPER2002 and MANN1999 temperature reconstructions. Series were smoothed with a 20-year spline and then standardised to the 1000–1980 period. Each global record contains the L1997 data but

Table 3 The 20 coldest reconstructed years in RCS2004 after processing the series with a 150-year high pass filter (Fig. 5c)

Rank	Year	Deviation	Candidate volcanoes	VEI	VAI (52N)	RF
1	1342	−4.23			–	
2	1699	−3.55				
3	1899	−3.22	Mayon, Luzon, Philippines (1897)	4		
4	1601	−3.04	Hyaynaputina, Peru (1600)	6	35 (1601)	6 (1601)
5	1345	−3.01			–	35 (1345)
6	1701	−2.99				
7	1674	−2.95	Gamkonora, Halmahere, Indonesia (1673)	5?	36 (1674)	21 (1674)
8	1876	−2.79	Askja, Northeastern Iceland (1875)	5		
9	1258	−2.77			–	1 (1259?)
10	1335	−2.65			–	
11	1838	−2.62			12 (1836)	
12	1738	−2.58	Fuego, Guatemala (1737)	4?		
13	1321	−2.56			–	
14	1318	−2.55			–	
15	985	−2.52			–	–
16	1833	−2.51	Babuyan Claro, Philippines (1831)	4?	22 (1832), 28 (1831)	48 (1832), 8 (1831)
17	1813	−2.49	Soufriere St. Vincent, West Indies (1812)	4	29 (1811)	
			Awu, Sangihe Islands, Indonesia (1812)	4?		
			Suwanose- Jima, Ryukyu Islands, Japan (1813)	4		
18	1641	−2.41	Llaima, Central Chile (1640)	4	32 (1641), 8 (1640)	4 (1641)
			Komaga-Take, Hokkaido, Japan (1640)	5		
			Kelut, Java, Indonesia (1641)	4?		
			Paker, Mindanao, Philippines (1641)	5?		
19	1818	−2.29	Raung, Java, Indonesia (1817)	4	31 (1817), 4 (1816)	41 (1816)
			Colima, Mexico (1818)	4		
20	1491	−2.29	Katla, Southern Iceland (1490?)	4+	–	

Candidate volcanic eruptions are listed for each year with, where available, the volcanic explosivity index (*VEI*, Newhall and Self 1982), the rank (and related year) of the volcanic aerosol index (*VAI*, for the latitude band 52°N, Robertson et al. 2001) and the rank (and related year) of radiative forcing (*RF* Crowley 2000) associated with volcanic eruptions recorded in ice cores. – = no data for this year

those of the twentieth century. RCS2004 also shows conditions in the early 1400s that are relatively warmer than the other reconstructions though all four reconstructions show similar multi-decadal trends from ca. 1300 to 1500. Conditions in the sixteenth century are most similar between RCS2004 and MANN1999 reconstruction.

Ignoring the obvious coherent multi-decadal variability, the RCS2004, BRIFFA2000 and ESPER2002 series show a centennial–millennial scale trend of warm conditions in the eleventh century, followed by cooler conditions until the twentieth century warming, punctuated by warmer intervals between 1400–1600. The MANN1999 record shows a general linear decrease from 1000 until the beginning of the twentieth century when warming starts. Esper et al. (2004) suggest that this difference in long term trend possibly reflects differences in the processing of the tree-ring data between these reconstructions.

The similarity between RCS2004 and large scale reconstructions of Northern Hemisphere temperatures (Fig. 6) highlights the importance of these data and the region for the assessment of large scale temperature variability. Diaz (1996) noted that western North America was one of the key locations where palaeoclimate research should be targeted because temperature variability within this region could explain a high fraction of Northern Hemispheric temperatures on decadal and longer time scales. Therefore continued work in this area will aim to extend the present data-set further back in time.

4 Conclusions

The revised Icefield reconstruction (RCS2004) remains the longest summer temperature reconstruction from boreal North America and calibrations explain over 50% of the variance of the instrumental temperature record. It is a more regionally based record than the original reconstruction but confirms the general pattern of L1997 in that the 1200s and early 1300s, late 1400s through to the mid-1800s are generally colder (ca. 0.5°C–1°C below 1900–1980 average temperatures). Warm intervals, comparable to twentieth century values, are reconstructed for the first half of the eleventh century, the late 1300s and early 1400s. The 1690s are exceptionally cold (> 0.4°C cooler than other intervals) in RCS2004 (and all component chronologies), probably reflecting a combined response to both volcanic and solar forcing. There is also some evidence of colder conditions in the 900s but this early record needs stronger replication. Compared with large-scale NH temperature reconstructions, the Icefield record is not as cold around the early seventeenth century. As with L1997, the general pattern of reconstructed summer temperatures conforms to the known regional record of glacier advances in the 1150–1300s, possibly the early 1500s, early 1700s and 1800s (Luckman

2000). The RCS reconstruction produces lower average temperatures than more traditional standardisation techniques (−0.53°C:−0.34°C over the 1000–1900 period) and more extended colder intervals. The record from 950–1300 is new and/or better replicated and shows a short warmer interval in the early eleventh century but generally cooler conditions in the later eleventh through fourteenth centuries. The periods of greatest transition and change in the last millennium are cooling in the mid-1400s and late 1600s and the warming trend from the mid-1800s onwards.

The RCS2004 record appears to indicate a reasonable response of local trees to large-scale forcing of climates, with reconstructed cool conditions comparing well with periods of known low solar activity, and also extreme cold reconstructed years coinciding with known volcanic events over the last 500 years. Comparison with Northern Hemisphere reconstructions suggests this record is more similar to the Briffa (2000) and Esper et al. (2002) reconstructions than the Mann et al. (1999) reconstruction, though all these records show periods of strong multi-decadal-centennial common variance (Esper et al. 2004). In fact, the strong similarity of the Icefields reconstruction with these Northern Hemisphere reconstructions of temperature suggest that this data-set is important for the assessment of natural temperature variability over the last 1000 years.

The reconstruction presented in this paper is a significant update to Luckman et al. (1997). Not only have the calibration/verification statistics been markedly improved by the inclusion of new data and utilising different temperature parameters, but more low-frequency information has been captured by using non-traditional detrending methods. The continued recovery of buried wood from several sites in the region may provide the potential to link older 'floating chronologies' to develop a continuous regional chronology extending back several thousand years.

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5 Appendix

5.1 Developing the RCS chronology for the MXD data

Regional curve standardisation (RCS) attempts to capture low-frequency information that is greater than the mean length of the tree-ring series used to build a chronology (Esper et al. 2003). In its most basic form, RCS aligns all available tree-ring series by cambial age to develop a mean series of 'average behaviour' that is typical for the species and region. Deviations of individual series from this regional curve are interpreted as ecological or climatological signals that result in higher or lower growth rates. By averaging the detrended series, the common 'climate' signal is accentuated, while the 'ecological' noise is minimised. However, great care needs to be taken when utilising the RCS method because (1) tree-ring data-sets may represent different populations (i.e. differing growth rates or growth trend types) that cannot be modelled by a single mean regional curve without introducing significant bias into the final chronology (Esper et al. 2003) and (2) an unquantifiable systematic bias may also be introduced into a RCS chronology when the mean biological age of all samples varies over time which results in inflation or depression of index values at either end of the sample time-series (Briffa and Melvin 2004; Melvin 2004).

To address the potential occurrence of differing 'populations' within the MXD data, the MXD series were divided into three groups, to allow better assessment of potential bias from the RCS method (Table 4). These groups are (1) all series from living trees at the Peyto and the Icefield sites; (2) snag data from the Icefield site and (3) snag data from the Peyto and Robson sites. For each sample, pith offset data were estimated (Aruani and J. Esper, 2004, personal communication) to reduce potential bias in generating the cambial age-aligned curves. The pith offsets for the living samples are generally higher than those for the snag material (mainly discs), as many cores did not reach the pith. Separate RCS curves were developed for each group (Fig. 7a). The Peyto–Robson snags were treated as a separate group because their mean MXD values are generally higher than for the other two data-sets. Using a single, regional curve would inflate the final indexed values for the Peyto–Robson data, possibly introducing bias in the earliest part of the reconstruction. The 95% confidence envelopes (Fig. 7b) for each age-aligned curve show that the mean functions are generally robust over their entire length.

The age-aligned curves (Fig. 7a) were smoothed with a cubic spline of 10% their length and used to standardise each maximum density series in their respective groups. This is the same method used by Esper et al. (2003). The final group RCS chronologies are compared in Fig. 7c. The correlation between the living tree and snag series from sites near the Columbia Icefield is reasonable ($r = 0.61$, 1608–1897) but that between Ice-

Table 4 Grouping of tree-ring MXD series for RCS

Group	Replication (series)	Average pith-offset (years)
Living	82	22
Icefields Snags	37	9
Peyto and Robson	34	7

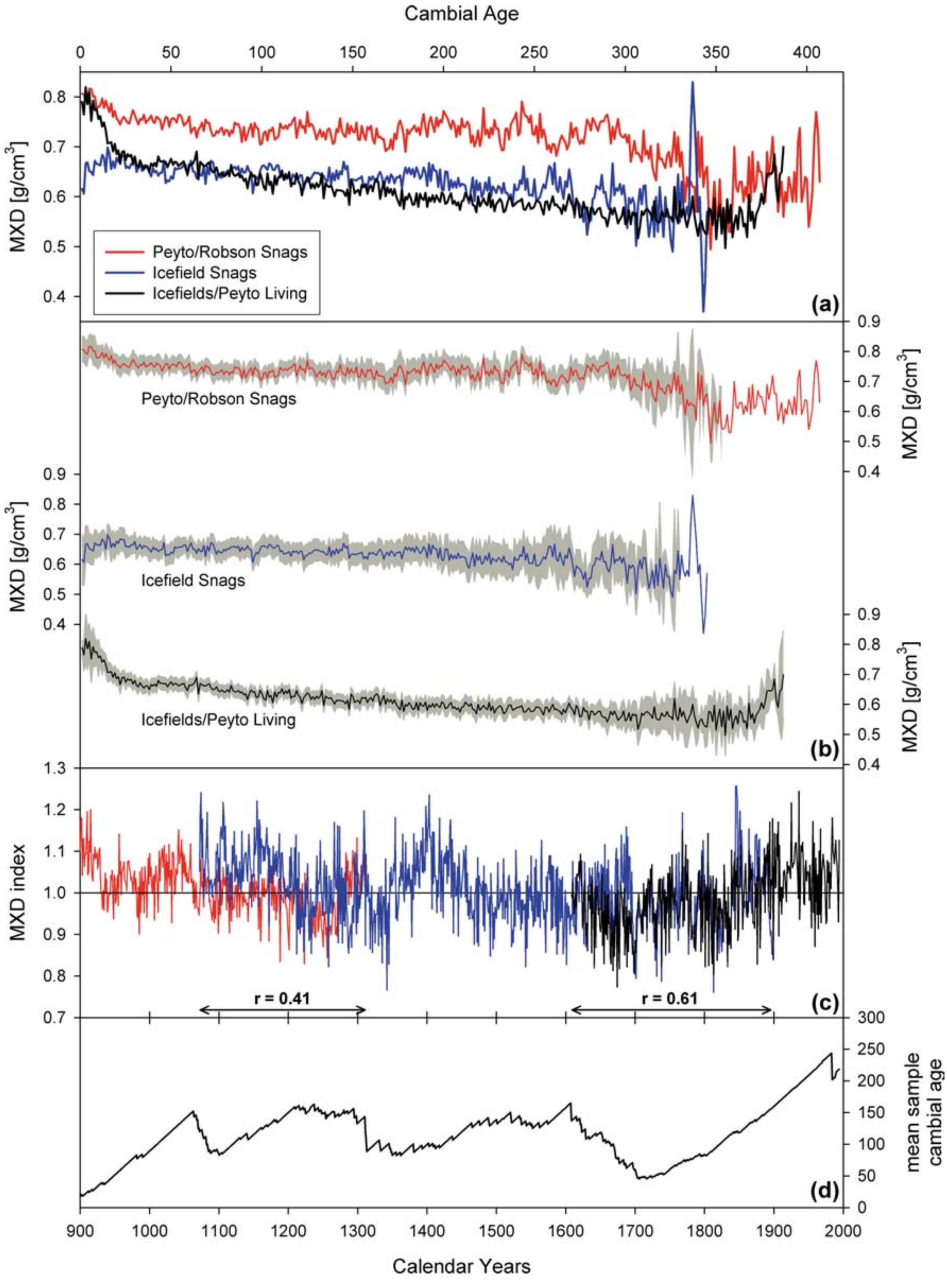

Fig. 7 RCS chronology development. **a** Mean regional cambial age-aligned curves for the three-sub-group data-sets; **b** Mean regional age-aligned curves with two sigma error bars; **c** Comparison of the sub-group RCS chronologies; **d** Mean cambial age of all MXD samples for each year

fields and the Peyto–Robson snags is more noisy ($r = 0.41$, 1072–1312), probably reflecting the low replication of both series in this overlap period (Fig. 3a). The reasonably good fit between the three group chronologies (Fig. 7c) implies that the low frequency trends captured using RCS are real and not an artefact of the detrending procedure. Importantly, the good comparison between the Icefield Snag and Living RCS chronologies around 1700 (Fig. 7c) indicates that the low index values over this period (see also Fig. 3a) portray a relatively robust non-biased signal and are therefore likely not artificially depressed due to underfitting of the age-aligned curves (Briffa and Melvin 2004; Melvin 2004) because of the low mean cambial age of the samples at this time (Fig. 7d).

The final MXDRCS chronology was developed by averaging the individual detrended series from all groups (Fig. 3a). An alternate MXDRCS chronology, generated without pith offset information was very similar to that presented here ($r=0.986$, 869–1994). This observation supports comments and analysis presented by Esper et al. (2003) that the lack of pith-offset information does not pose a serious bias when using RCS so long as sample replication is reasonably high.

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