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Temperature-growth divergence in white spruce forests of Old Crow Flats, Yukon Territory, and adjacent regions of northwestern North America

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Abstract

We present a new 23-site network of white spruce ring-width chronologies near boreal treeline in Old Crow Flats, Yukon Territory, Canada. Most chronologies span the last 300 years and some reach the mid-16th century. The chronologies exhibit coherent growth patterns before the 1930s. However, since the 1930s, they diverge in trend and exhibit one of two contrasting, but well-replicated patterns we call Group 1 and Group 2. Over the instrumental period (1930–2007) Group 1 sites were inversely correlated with previous-year July temperatures while Group 2 sites were positively correlated with growth-year June temperatures. At the broader northwestern North America (NWNA) scale, we find that the Group 1 and Group 2 patterns are common to a number of white spruce chronologies, which we call NWNA 1 and NWNA 2 chronologies. The NWNA 1 and NWNA 2 chronologies also share a single coherent growth pattern prior to their divergence (ca. 1950s). Comparison of the NWNA 1/NWNA 2 chronologies against gridded 20th-century temperatures for NWNA and reconstructed northern hemisphere summer temperatures (AD 1300–2000) indicates that all sites responded positively to temperature prior to the mid-20th century (at least back to AD 1300), but that some changed to a negative response (NWNA 1) while others maintained a positive response (NWNA 2). The spatial extent of divergence implies a large-scale forcing. As the divergence appears to be restricted to the 20th century, we suggest that the temperature response shift represents a moisture stress caused by an anomalously warm, dry 20th-century climate in NWNA, as indicated by paleoclimatic records. However, because some sites do not diverge and are located within a few kilometres of divergent sites, we speculate that site-level factors have been important in determining the susceptibility of sites to the large-scale drivers of divergence.

Keywords: boreal treeline, dendroclimatology, divergence, Old Crow Flats, ring-width, white spruce, Yukon Territory

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Introduction

In high-latitude regions, dendroclimatic studies often report a positive relation between summer temperatures and tree-ring width (e.g., Briffa *et al.*, 1990; Szeicz & MacDonald, 1995; Gostev *et al.*, 1996; D'Arrigo *et al.*, 2006; Frank *et al.*, 2007; Wilson *et al.*, 2007; Youngblut & Luckman, 2008). This observed relation is intuitive for trees living at the cold northern margins of the boreal forest where tree growth is largely thought to be temperature-dependent; however, this is not always the case. In northwestern North America (NWNA), in particular, many white spruce (*Picea glauca* [Moench] Voss) stands are inversely correlated with previous-year summer temperature (e.g., Barber *et al.*, 2000; Lloyd & Fastie, 2002; Wilmking *et al.*, 2004; Pisaric *et al.*, 2007; McGuire *et al.*, 2010). At some of these sites, inverse relations may have persisted over the entire 20th century (Lloyd & Bunn, 2007), but at others they appear to be a recent phenomenon (Jacoby & D'Arrigo, 1995; D'Arrigo *et al.*, 2004). Similar temperature response shifts are also found at high-latitude Eurasian sites (Briffa *et al.*, 1998; Jacoby *et al.*, 2000). Collectively, these instances of transient temperature-growth responses are referred to as the 'Divergence Problem' (DP) (D'Arrigo *et al.*, 2008).

In a paleoclimatology context, DP complicates the use of affected tree-ring chronologies as temperature proxies since reconstructions depend on time-stable proxy-climate relations. However, because high-latitude tree-ring networks are an important data source for centennial- to millennial-length temperature reconstructions (Jansen *et al.*, 2007), it is important to improve understandings of DP and the extent to which past climate-growth relations can be considered time-stable.

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The DP is often observed as a low-frequency departure between summer temperature and ring-width/density occurring after the mid- to late-20th century (D'Arrigo *et al*., 2008), coinciding with the warmest period the Arctic has experienced in the last two millennia (Kaufman *et al*., 2009). Although the cause(s) of DP are largely unknown, many have suggested that the relatively warm late-20th century may be driving this nonlinear behaviour by temperature-induced drought stress (Jacoby & D'Arrigo, 1995; Barber *et al*., 2000; Lloyd & Bunn, 2007; McGuire *et al*., 2010) or optimal biological temperature thresholds being surpassed (D'Arrigo *et al*., 2004; Wilmking *et al*., 2004). Other possible explanations for DP include late-20th-century changes in snow cover (Vaganov *et al*., 1999), UV-B radiation (Briffa *et al*., 2004) and global dimming (D'Arrigo *et al*., 2008). However, current understandings of DP are based on a small number of study sites, limiting our ability to draw conclusions about its causes and the likelihood that past temperature-growth relations were also impacted.

Here we present a new network of site-averaged ring-width chronologies from 23 white spruce sites in Old Crow Flats, Yukon Territory, Canada, to satisfy three objectives: (1) expand the high-latitude tree-ring network into a region where this research has been absent; (2) examine the response of this network to temperature; and (3) determine if trees in this region were impacted by DP. Furthermore, we draw comparisons between these results and a larger-scale network of white spruce sites across NWNA. Old Crow Flats hosts the northernmost extent of boreal treeline in Yukon Territory and is adjacent to interior Alaska, central Yukon and the Mackenzie Delta, areas where divergence has been identified (D'Arrigo *et al*., 2004; Wilmking *et al*., 2004; Pisaric *et al*., 2007). Our site chronology network is unique in NWNA due to its very high site density. This characteristic allows us to better identify regionally significant growth patterns that are more closely linked to regional-scale factors such as climate than any individual site chronology (Hughes, 2011).

Materials and methods

Study region

The Old Crow Flats region (Fig. 1) is a low-lying basin complex bounded by mountain ranges in Alaska and Yukon Territory. The region's surficial geology is primarily defined by a thick glaciolactustrine clay unit deposited by Glacial Lake Old Crow when it occupied the area from ca. 24 000 to 12 000 BP (Hughes, 1972; Morlan, 1980; Thorson & Dixon, 1983; Dyke *et al*., 2002). Much of the region is poorly drained and covered by a vast mosaic of shallow lakes and peatlands (Ovenden &

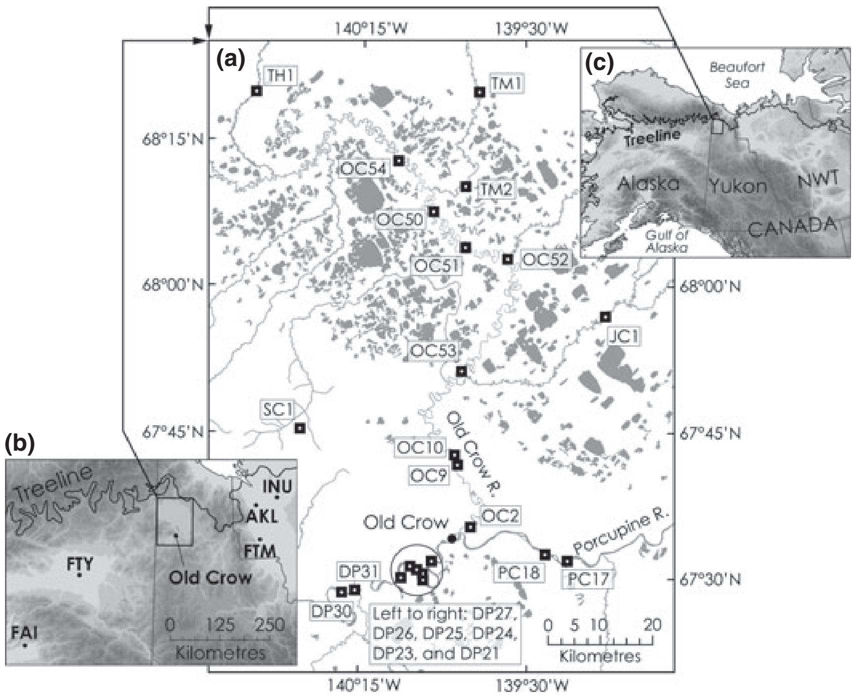

Fig. 1 (a) White spruce sites sampled in Old Crow Flats (site codes indicated, see Table 1). Major lakes and channels are shaded grey. (b) Climate stations at Fairbanks (FAI), Fort Yukon (FTY), Inuvik (INU), Aklavik (AKL) and Fort McPherson (FTM). (c) Large-scale context of Old Crow Flats. Boreal treeline was delineated from the Circumpolar Arctic Vegetation Map dataset (Walker *et al*., 2005).

Brassard, 1989; Labrecque *et al.*, 2009). Meandering channels incise the surficial clay and provide some drainage (Lauriol *et al.*, 2002). Channel floodplains are well drained and covered by thick organic layers underlain by fine-to-coarse fluvial deposits (Hughes & Rampton, 1971). White spruce forests in the region are generally found on floodplains while black spruce (*Picea mariana* [Mill.] BSP) forests tend to occupy poorly drained areas among the lakes.

Old Crow Flats is in the continuous permafrost zone (Heginbottom *et al.*, 1995). Climate is highly seasonal (Fig. 2) with dry, stable Arctic air dominating during winter, and relatively warm, moist air from the North Pacific and Beaufort Sea during summer (Dyke, 2000). Mean annual, winter (December–February) and summer (June–August) temperatures at Old Crow are −9.0 °C, −28.6 °C and 12.6 °C respectively (http://www.climate.weatheroffice.gc.ca). Minimum (maximum) temperatures are below freezing for all months except June–August (May–September) (Fig. 2). Despite its abundance of lakes, annual precipitation at Old Crow Flats is low compared with other northern regions with only parts of the Canadian Arctic Archipelago and northern Greenland receiving less precipitation per annum (Serreze & Barry, 2005). Old Crow receives ca. 265 mm of precipitation annually, ca. 38 mm during winter and ca. 119 mm in summer (Fig. 2).

Tree-ring data

Twenty-three white spruce stands were sampled in 2007 and 2008 (Fig. 1a); all sites are within 150 km of latitudinal treeline. General sampling locations were preselected so that sites would be distributed across the region. In the field, mature sites were preferentially sampled to maximize the length of resultant tree-ring chronologies. Mature sites were identified based on tree morphology and abundance of deadwood. All sites shared a similar open canopy structure such that light could easily penetrate to ground level and a comparable assemblage of shrubs, mosses, grasses and lichens. All sites except TM2 and SC1 are situated on channel floodplains. TM2 is situated on a hill known locally as Timber Hill and faces south-west; SC1 is a relatively high-elevation site (ca. 647 m a.s.l. compared to ca. 267 m a.s.l. on average for the other sites; Table 1) in the Old Crow Range and faces north-east. The remaining sites have no particular aspect.

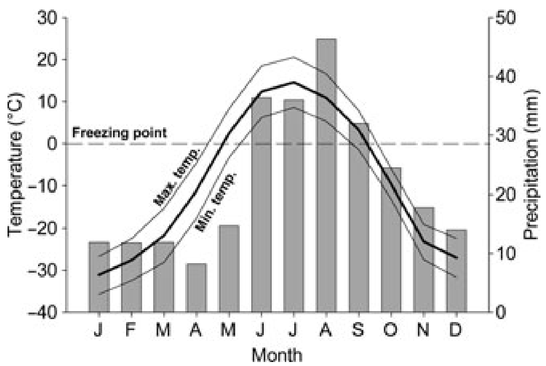

Fig. 2 Monthly normals (1971–2000) for minimum, mean, and maximum temperatures (lines) and total precipitation (bars) at Old Crow (http://www.climate.weatheroffice.ec.gc.ca).

On average, 33 trees were sampled per site, most of which (ca. 80%) were living. Standard dendrochronology techniques were used to collect and prepare tree-ring samples for ring-width measurement (Speer, 2010). Rings were visually cross-dated and measured using a Velmex tree-ring measuring system (precise to 0.001 mm). Two radii per tree were measured in all but a few cases. Cross-dating accuracy was verified with the computer program COFECHA (Holmes, 1983). Age-related trends were removed from raw data using conservative negative exponential or negative/zero slope linear curve fits (Fritts *et al.*, 1969). A 'signal-free' beta version of the computer program ARSTAN (courtesy of Ed Cook, Lamont-Doherty Earth Observatory Tree-Ring Lab, personal communication) was used to calculate standard tree-ring indices according to the 'signal-free standardization' approach described by Melvin & Briffa (2008); mean site chronologies were calculated using the robust bi-weight mean (Cook, 1985). Signal-free standardization was used instead of traditional standardization because it is ideally suited to avoid 'trend-distortion,' an effect that concentrates towards the modern ends of tree-ring series and results in a distorted climate signal in mean tree-ring chronologies (Melvin & Briffa, 2008). For some of our sites, trend distortion would be a valid concern if signal-free methods were not used (Figs S1 and S2).

Temperature-growth analysis

The Old Crow climate record is relatively short (1951–2007) and incomplete. To support a longer comparison with our tree-ring data, we developed a regional composite temperature record from nearby stations including Fairbanks and Fort Yukon in interior Alaska, and Inuvik, Aklavik and Fort McPherson in the Mackenzie Delta region of Northwest Territories (Fig. 1b). These records compare well with the Old Crow record in terms of trend and interannual variability and can be used to estimate regional temperatures. Alaskan data were provided by the Alaska Climate Research Center (M. Shulski, personal communication, 2008) and Canadian data were obtained from Environment Canada (http://www.climate.weatheroffice.ec.gc.ca). These records were averaged by region for interior Alaska and the Mackenzie Delta (following normalization) and the regional means were then combined to create a monthly minimum, mean and maximum temperature record for the larger region centred on Old Crow Flats. The regional composite spans 1930–2007 (pre-1930 data were not used due to limited spatial coverage) and is well correlated with minimum, mean and maximum temperatures at Old Crow ($r = 0.88$, 0.91, and 0.88, respectively, for the average month; $P \leq 0.001$).

Growth-year and previous-year May–August temperatures (1930–2007) were compared with each of the 23 site chronologies to determine their dominant response to temperature. Pearson's Product-Moment Correlation Coefficients (r-values) were used to quantify these relations. Sites that shared a common temperature response were averaged into mean regional chronologies to enhance the common signal and then examined for signs of DP as observed in neighbouring regions.

Table 1 White spruce sites sampled in Old Crow Flats and corresponding tree-ring chronology information

Site code	Lat. (°N)	Long. (°W)	Elev. (m)	No. series/ trees	First year ≥ 1 series	First year ≥ 4 series	Last year	Mean series length (years)
DP21	67.53	139.93	251	67/35	1657	1727	2007	199.7
DP23	67.50	139.96	249	46/24	1711	1716	2007	216.1
DP24	67.51	139.96	249	42/22	1735	1746	2006	208.7
DP25	67.52	139.99	251	43/22	1759	1778	2006	163.7
DP26	67.52	140.02	243	36/20	1728	1739	2006	200.5
DP27	67.50	140.06	243	57/29	1608	1738	2007	150.0
DP30	67.48	140.33	244	71/36	1552	1555	2007	247.2
DP31	67.48	140.26	245	80/41	1617	1620	2007	240.6
JC1	67.95	139.14	286	73/37	1744	1808	2007	157.0
OC2	67.59	139.75	258	67/35	1691	1742	2007	149.7
$OC9_a$	67.70	139.81	267	54/27	1618	1620	1846	183.8
$OC9_b$	67.70	139.81	267	50/26	1874	1881	2007	109.2
OC10	67.72	139.82	259	61/32	1719	1727	2006	111.7
OC50	68.13	139.93	282	45/25	1668	1768	2007	184.8
OC51	68.07	139.78	272	84/43	1680	1714	2007	186.6
OC52	68.05	139.59	269	59/31	1749	1753	2007	158.9
OC53	67.86	139.79	265	82/44	1648	1649	2007	189.3
OC54	68.22	140.09	292	42/21	1615	1627	2007	140.3
PC17	67.55	139.41	251	94/49	1803	1811	2006	159.2
PC18	67.53	139.32	251	60/33	1686	1711	2006	203.4
SC1	67.76	140.52	647	56/29	1537	1553	2007	214.4
TH1	68.33	140.75	339	97/50	1650	1661	2007	225.4
TM1	68.34	139.72	315	94/48	1631	1648	2007	223.6
TM2	68.17	139.78	305	77/41	1522	1547	2007	217.4

$OC9_a$ and $OC9_b$ belong to the same site, but do not overlap because of a stand replacing fire that occurred just prior to circa AD 1850; $OC9_a$ represents a population of trees that died before or during the fire and $OC9_b$ represents the post-burn population.

Results

Temperature-growth relations in Old Crow Flats

Correlations between our 23 mean site chronologies and the regional temperature record reveal two primary and distinctly opposite responses to summer temperature (Table 2). In general, all sites are best correlated with June/July temperatures, but roughly half correlate negatively and the other half positively with June/July temperatures (Table 2). The negatively correlated sites exhibit their strongest correlations with maximum July temperatures of the previous year, while the positively correlated sites exhibit their strongest correlations with minimum June temperatures of the growth year. Sites with the negative/positive temperature response are hereafter referred to as 'Group 1'/ 'Group 2' sites (Table 2). Only one site, DP21, had a 'mixed' temperature relation, albeit weak, and could not be differentiated as either Group 1 or Group 2 (Table 2). As our primary focus is regionally significant growth responses to temperature, we focus on the Group 1 and Group 2 chronologies that are of greater regional importance.

Group 1/Group 2 regional growth patterns

The distinction between Group 1 and Group 2 sites is clear in terms of correlation with summer temperature (Table 2). In terms of growth index, there are many notable differences and similarities between Groups 1 and 2 (Fig. 3a and b) which we emphasize by comparing the mean Group 1 and Group 2 chronologies (Fig. 3c; mean Group 1/Group 2 chronologies calculated for all years defined by two or more site chronologies). The mean Group 1 and Group 2 chronologies are highly coherent over the period 1620–1800, as demonstrated by a strong running correlation coefficient (Fig. 3c; see Fig. S3a for a magnified comparison).

Both groups began the 19th century at their lowest index values on record and maintained similar growth levels until ca. 1850 before following an upward trend into the 20th century (Fig. 3c). However, Group 1 began its upward trend slightly before Group 2 (as early as ca. 1825/1875 for Group 1/Group 2) causing a systematic offset between them until the mid-20th century (Fig. 3c; see Fig. S3b for a magnified comparison). The significance of these differences was tested using a running 2-sample *t*-test (see Note S1). Significant

Table 2 Correlations between the 23 Old Crow Flats site chronologies and previous-year June/July maximum temperatures (left) and growth-year June/July minimum temperatures (right) (see Table S1 for May–August correlations); only correlations significant at $P \leq 0.05$ (two-tailed) are presented; sites are classed as Group 1/Group 2 if negatively/positively correlated with June/July temperatures

	Previous year (t−1) max. temperatures		Growth year (t) min. temperatures	
	June	July	June	July
Mixed				
DP21	–	−0.29	0.31	–
Group 1				
DP27	−0.45	−0.58	−0.28	−0.41
DP30	−0.28	−0.43	–	–
OC9	−0.50	−0.54	−0.42	−0.41
OC10	−0.24	−0.48	–	–
OC50	−0.42	−0.40	–	–
OC52	−0.41	−0.57	–	−0.25
OC53	−0.25	−0.48	–	–
OC54	−0.41	−0.58	−0.31	−0.35
PC18	−0.35	−0.54	–	−0.23
TM1	–	−0.41	–	–
TM2	−0.41	−0.62	–	–
Group 2				
DP23	–	–	0.41	–
DP24	0.35	–	0.54	0.43
DP25	0.35	0.24	0.54	0.48
DP26	0.33	–	0.52	0.38
DP31	–	–	0.48	0.27
JC1	–	–	0.39	–
OC2	–	–	0.44	0.26
OC51	0.24	–	0.57	0.45
PC17	0.38	0.25	0.54	0.41
SC1	0.34	–	0.53	0.43
TH1	0.24	–	0.58	0.42
Regional means				
Group 1	−0.42	−0.61	–	−0.24
Group 2	0.28	–	0.57	0.40

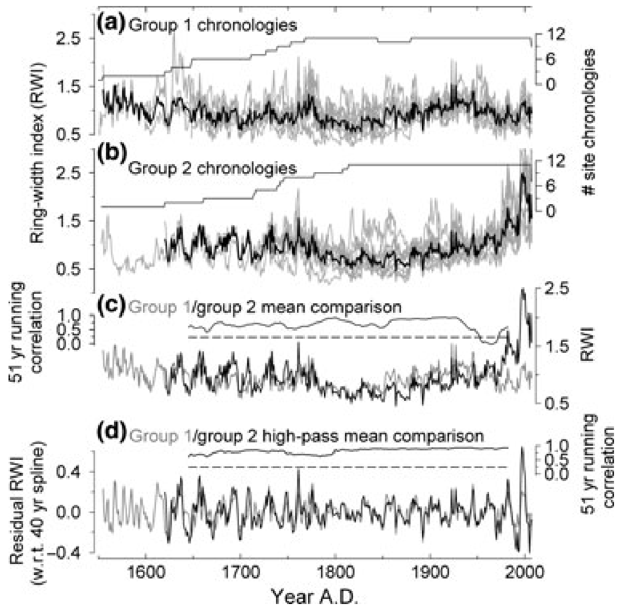

Fig. 3 (a, b) Group 1/Group 2 site chronologies (grey lines); all site chronologies are defined by ≥4 series (≥2 trees). The mean Group 1/Group 2 chronologies (black lines) were calculated using a robust bi-weight mean for all years defined by two or more site chronologies. Sample depth curves are indicated above each plot. (c) A comparison of the mean Group 1 (1555–2007) and Group 2 (1620–2007) chronologies. The running 51-year correlation (above plot) indicates coherence between the chronologies (dashed line is $P \leq 0.05$ level). (d) High-pass filtered (40-year cubic smoothing spline with a 50% frequency cut-off; Cook & Peters, 1981) comparison of the mean Group 1 and Group 2 chronologies; the high-pass series were smoothed with a 3-year cubic smoothing spline for ease of comparison.

($P \leq 0.05$) differences between the Group 1 and Group 2 chronologies are found during 63% of years from 1866 to 1948. However, despite these growth index differences, their respective linear trends were indistinguishable over the period 1866–1948 (+0.043/+0.042 index values per decade for Group 1/Group 2) leading to a strong, stable running correlation (Fig. 3c; mean $r = 0.82$).

Important differences emerge after the 1930s. Group 1 reaches its highest growth values on record in the 1930s (Fig. S3; 1926–1935 mean index = 1.2) and then declines towards low values in the 1980s. Conversely, Group 2 maintains a positive trend throughout the 20th century and reaches record high growth values at present (Fig. S3; 1998–2007 mean index = 2.0). Effectively, this opposing behaviour equates to a 'growth trend divergence' that is evident in the running correlation which drops below the $P \leq 0.05$ significance level in 1953, reaching its lowest point ($r = -0.02$) in 1966 (Fig. 3c). Group 1 growth trends become positive after the 1980s contributing to a small rise in correlation with Group 2. By 1972, correlations become significant again, but remain low relative to pre-1930 correlations (Fig. 3c).

While the Group 1 and Group 2 chronologies are very different in the 'low-frequency' domain since the 1930s, the two groups are coherent at higher-frequencies over all periods. To demonstrate this, we compared high-pass filtered mean Group 1 and Group 2 chronologies (40-year cubic smoothing spline; see Cook & Peters, 1981) and found that both groups exhibited the same high-frequency growth variations over the last 400 years, even after the post-1930s growth trend divergence described above (Fig. 3d).

Group 1/Group 2 vs. temperature

As with their constituent site chronologies, the mean Group 1 and Group 2 chronologies are most strongly correlated with previous-year July maximum and growth-year June minimum temperatures respectively (Table 2). A visual comparison of the mean group chronologies vs. their most closely associated temperature index shows no apparent signs of temperature-growth divergence during recent decades of the 20th century (Fig. 4), as observed in other parts of NWNA. From the 1930s to 1980s, Group 1 growth declined as July maximum temperatures increased, but rebounded from the 1980s to present as July temperatures cooled slightly (Fig. 4). Contrary to July maximum temperatures, June minimum temperatures have increased steadily since the 1930s, a trend that is matched by the Group 2 growth response (Fig. 4).

Larger-scale significance of Group 1/Group 2

To determine if the contrasting Group 1 and Group 2 growth patterns are simply a local phenomenon or reflective of larger-scale growth patterns, a number of long white spruce ring-width chronologies from adjacent parts of NWNA (Fig. 5) were obtained from the International Tree Ring Databank (ITRDB; http://www.ncdc.noaa.gov/paleo/treering.html) and other sources (Table 3), and compared with the mean Group 1 and Group 2 chronologies. Only chronologies spanning 1700–1975 were considered to assess long-term coherence. Moreover, a number of spatial criteria were considered to determine which sites were used. To avoid sites with a strong maritime climate (e.g., Gulf of Alaska coastline; see L'Heureux *et al*., 2004; Serreze & Barry, 2005), only sites above 65°N were used. The

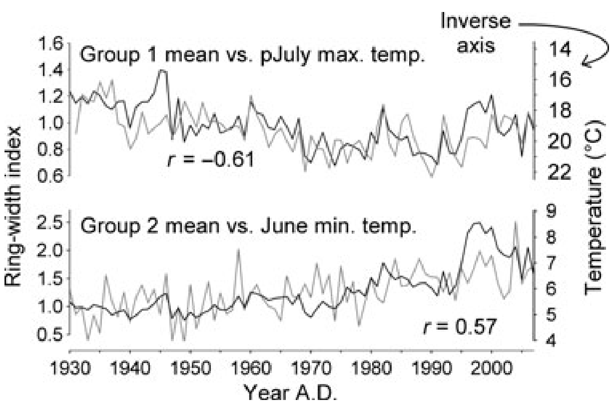

Fig. 4 Comparisons between mean Group 1/Group 2 (black lines) and previous-year July maximum/growth-year June minimum temperatures (grey lines); correlations are significant at $P \leq 0.001$.

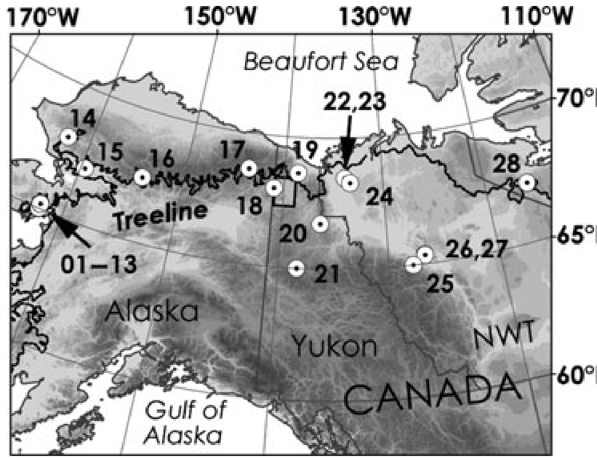

Fig. 5 Locations of all northwestern North America (NWNA) site chronologies compared with the mean Group 1/Group 2 chronologies (site numbers indicated, see Table 3).

longitudinal range of sites extends eastward from the west coast of Alaska to 115°W. This spatial range coincides with sites near boreal treeline where tree growth is expected to be temperature-limited. The ITRDB has 26 chronologies matching our spatiotemporal criteria (Fig. 5; Table 3). Furthermore, we use two 'sub-population' chronologies developed from hundreds of white spruce trees at several sites in the Mackenzie Delta (Pisaric *et al*., 2007; Fig. 5; Table 3). All 28 'NWNA chronologies' were processed using signal-free standardization as outlined in the Methods section.

The NWNA chronologies were considered comparable to Group 1 and Group 2 if they met the following criteria: (1) correlates positively and significantly ($P \leq 0.01$) with both Group 1 and Group 2 from 1850 to 1930; and (2) correlates positively and significantly with only one of Group 1 or Group 2 from 1930 to present. Based on these criteria, 14 NWNA chronologies are not similar to Group 1 or Group 2 (Table 3; sites 02–03, 05–13, 15, 18, and 25), 11 of which (sites 02–03, and 05–13) are clustered in a small area (ca. 8 km radius) on the Seward Peninsula, Alaska. Of the remaining 14 NWNA chronologies, seven are similar to Group 1: sites 14, 17, 19–21 and 23–24 (Table 4); hereafter, we refer to these chronologies, including the mean Group 1 chronology, as 'NWNA 1 chronologies' (Fig. 6a). The other seven NWNA chronologies are similar to Group 2: sites 01, 04, 16, 22 and 26–28 (Table 4). These chronologies, plus the mean Group 2 chronology, are now referred to as 'NWNA 2 chronologies' (Fig. 6b).

A comparison of the mean NWNA 1 and NWNA 2 chronologies reveals the same general observation seen with the Old Crow Flats tree-ring data. NWNA 1 and NWNA 2 had a coherent growth pattern from AD 1550 until the mid-20th century, after which the mean

Table 3 List of 300+ year white spruce ring-width chronologies from upper northwestern North America (NWNA) (65–70°N, 115–170°W) that we compared with the mean Group 1 (G1)/Group 2 (G2) chronologies from Old Crow Flats. Correlations with G1/G2 were calculated for all years of overlapping data for the periods 1850–1930 and 1930–2003; only positive correlations significant at $P \leq 0.01$ (one-tailed) are provided. Site no. corresponds to the map of NWNA sites (Fig. 5). Mean chronologies for each NWNA site were calculated from raw ring-width data using signal-free standardization as outlined in the Methods section. All ring-width files were downloaded from ITRDB (accessed September 2009) unless stated otherwise

			Correlation with G1/G2			
			1850–1930		1930–2003	
Site no.	Site name, ITRDB code	Temporal coverage	G1	G2	G1	G2
01	Almond Butter Lower, AK057	1607–2002	0.26	0.32	–	0.58
02	Almond Butter Upper, AK058	1406–2002	–	–	–	–
03	Alpine View, AK059	1542–2002	–	–	–	–
04	Burnt Over, AK060	1621–2002	0.27	0.29	–	0.46
05	Bye Rosanne, AK061	1575–2002	–	–	0.47	–
06	Death Valley, AK062	1358–2002	–	–	–	–
07	Echo Slope, AK063	1590–2002	–	–	–	–
08	Frost Valley, AK064	1611–2002	–	–	0.31	–
09	Gordon’s Cat, AK065	1400–2002	–	–	–	–
10	Hey Bear, AK066	1533–2002	–	–	–	–
11	Hey Bear Upper, AK067	1383–2002	–	–	–	–
12	Mt. Mole, AK068	1550–2002	–	–	–	–
13	Windy Ridge, AK070	1556–2002	–	–	–	–
14	Four-Twelve with Revisit, AK031*	1515–1990	0.55	0.51	0.63	–
15	Kobuk/Noatak, AK046†	978–1992	–	–	0.36	0.29
16	Arrigetch, AK032*	1585–1990	0.41	0.39	–	0.50
17	Sheenjek River and Flats, AK033	1296–1979	0.41	0.37	0.51	–
18	Firth River, AK047‡	1676–2002	0.71	0.71	–	–
19	Spruce Creek, CANA029	1570–1977	0.34	0.26	0.48	–
20	Richardson Mountain, CANA121§	1547–1992	0.64	0.65	0.59	–
21	Twisted Tree Heartrot Hill, CANA157*	1459–1999	0.65	0.66	0.69	–
22	MDEC Positive Responders¶	1516–2003	0.77	0.82	–	0.86
23	MDEC Negative Responders¶	1501–2003	0.72	0.73	0.82	–
24	Campbell Dolomite Upland, CANA138**	1060–1992	0.56	0.45	0.67	–
25	Mackenzie Mountains, CANA156	1509–1984	–	–	0.69	–
26	Franklin Mountains, CANA154	1621–1984	0.39	0.34	–	0.45
27	Discovery Ridge, CANA117§	1429–1991	0.35	0.26	–	0.63
28	Coppermine River, CANA153*	1046–2003	0.53	0.59	–	0.29

Data contributors by site no.: Church and Fritts (19); D’Arrigo, Mashig, Frank, Wilson, and Jacoby (01–13); Jacoby, D’Arrigo, and Buckley (14, 16–17, 21, 25–26, and 28); King and Graumlich (15); Pisaric (22–23); Szeicz and MacDonald (27); Szeicz, MacDonald, and Lundberg (20 and 24); Wilmking (18).

*Updated versions of sites 14, 16, 21 and 28 (not yet available on ITRDB) were provided by R. D’Arrigo (personal communication).

†Kobuk/Noatak is a regional (ca. 24 000 km^2 area) composite developed from hundreds of trees in the Kobuk and Noatak River basins.

‡Cross-dating verification using COFECHA indicated that two of the Firth River series (BRFR49 and 88) should be adjusted −1 year. The possibility that these series were misaligned was confirmed by M. Wilmking (personal communication, September 2010). Adjusting these series increased their correlation with the BRFR49/88 master chronologies from 0.03/0.11 to 0.40/0.41.

§As per Szeicz & MacDonald (1995), we used only 200+/100+ year series for Discovery Ridge/Richardson Mountain.

¶Mackenzie Delta East Channel (MDEC) represents several sites in the Mackenzie Delta whose individual series were pooled into ‘positive- or negative-responder’ chronologies (Pisaric *et al*., 2007). The positive and negative-responder chronologies used here are modified versions of the originals used by Pisaric *et al*. (2007); see Note S2 for more details.

**A subset (11 trees) of samples collected by Szeicz, MacDonald and Lundberg from Campbell Dolomite Upland was developed into a separate ‘Campbell Dolomite Upland B’ chronology by F. Schweingruber and is available on the ITRDB. Here we only use the Szeicz, MacDonald and Lundberg version because of its much larger sample depth.

Table 4 Northwestern North America (NWNA) chronologies that meet the following two similarity criteria: (1) correlates positively and significantly ($P \leq 0.01$) with both Group 1 and Group 2 from 1850 to 1930; and (2) correlates positively and significantly with only one of Group 1 or Group 2 from 1930 to present. Chronologies that meet these criteria and are most closely associated Group 1/Group 2 during 1930–2003 are classed as NWNA 1/NWNA 2 chronologies

NWNA 1 chronologies
Campbell Dolomite Upland
Four-Twelve with Revisit
MDEC Negative Responders
Richardson Mountain
Sheenjek River and Flats
Spruce Creek
Twisted Tree Heartrot Hill
NWNA 2 chronologies
Almond Butter Lower
Arrigetch
Burnt Over
Coppermine River
Discovery Ridge
Franklin Mountains
MDEC Positive Responders

chronologies diverge from one another (Fig. 6c). This is reflected in the strong running correlation from 1550 to 1930 and the subsequent decline to nonsignificant values by 1957 (Fig. 6c). Unlike with Group 1 and Group 2, NWNA 1 and NWNA 2 have little offset from 1866 to 1948 (Fig. 6c); only 10% of the years over this period are significantly different based on a running 2-sample *t*-test (Note S1). A second important difference between the Old Crow Flats and the NWNA chronologies is that the timing of mid-20th-century divergence differs slightly. NWNA 1 sites do not peak until ca. 1950s, which is roughly 2 decades later than the Group 1 sites in Old Crow Flats. Lastly, as we found in Old Crow Flats, high-frequency growth patterns at the NWNA-scale were coherent over all periods (Fig. 6d) suggesting that growth trend divergence is exclusively a low-frequency phenomenon.

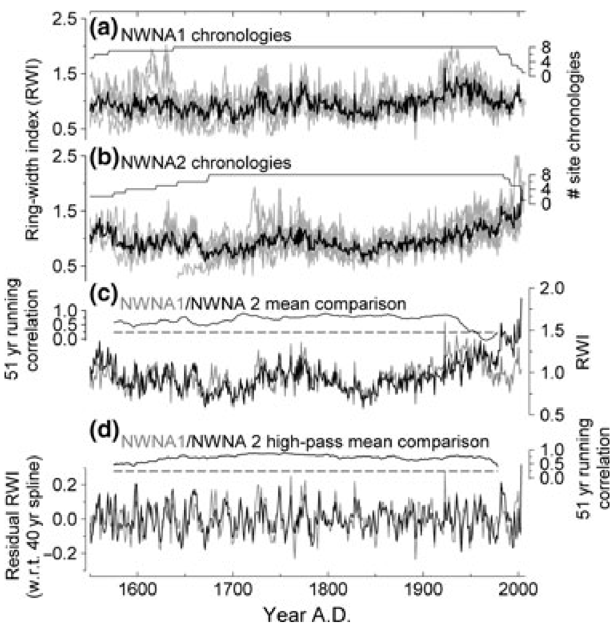

Fig. 6 Same as Fig. 3, but for NWNA 1/NWNA 2 chronologies (Table 4; including the mean Group 1/Group 2 chronologies).

NWNA 1/NWNA 2 vs. temperature

Given their similarity to Group 1/Group 2, it seems plausible that NWNA 1/NWNA 2 may also represent negative/positive responses to 20th-century summer temperature. Indeed, this idea is supported by independent climate-growth analyses for several of the NWNA 1/NWNA 2 site chronologies (Szeicz & MacDonald, 1994, 1996; D'Arrigo *et al*., 2004; Pisaric *et al*., 2007; Visser *et al*., 2010). At broader scales, this is supported by correlations between the mean NWNA 1/NWNA 2 chronologies and a composite of gridded mean monthly temperatures for the greater NWNA region derived from the CRUTEM3v dataset (Brohan *et al*., 2006; see Note S3 for details on the composite).

Overall, NWNA 1 sites were most strongly and negatively correlated with previous-year July temperatures over the last century (1900–2003), as with Group 1 in Old Crow Flats (Table 5). However, NWNA 1's temperature-growth relation was not stable over the 20th cen-

Table 5 Correlations between the mean NWNA 1/NWNA 2 chronologies and regional mean monthly CRUTEM3v temperatures (Brohan *et al*., 2006; see Note S3); correlations for May–August of the prior and current growth years are provided for three periods: 1900–2003, 1900–1950 and 1951–2003; all correlations are significant at $P \leq 0.05$ (two-tailed); underlined coefficients are significant at $P \leq 0.01$

	NWNA1			NWNA2		
	1900–2003	1900–1950	1951–2003	1900–2003	1900–1950	1951–2003
Year t−1						
May	–	–	–	0.34	–	–
June	–	–	–	0.41	–	0.40
July	−0.36	–	−0.40	0.29	–	–
August	–	–	–	0.21	–	–
Year t						
May	−0.20	–	−0.30	0.20	–	–
June	–	0.53	–	0.54	0.47	0.46
July	–	0.39	–	0.54	0.41	0.36
August	–	0.20	–	0.21	–	–

tury as demonstrated by a split-period analysis (Table 5). NWNA 1 sites shared a significant positive relation with growth-year June/July average temperatures in the early-20th century (1900–1950) and a significant inverse relation with prior-year July temperatures in the late-20th century (1951–2003) (Table 5). This transition from a positive to negative temperature response is effectively illustrated with a plot of NWNA 1 vs. June/July temperatures (Fig. 7). However, because of the gradual, low-frequency nature of the change and of the temperature-growth relation itself, it is difficult to pinpoint the timing of temperature-growth divergence with any precision. Based on a visual inspection of the data, the early-1960s appear to be a reasonable approximation (Fig. 7). Conversely, NWNA 2 sites responded positively to growth-year June/July temperatures during both the early- and late-20th century (Table 5; Fig. 7).

Long-term temperature-growth relations in NWNA

As both NWNA 1 and NWNA 2 had a positive temperature response before the mid-20th century, it seems likely that the NWNA 1 growth pattern represents an anomalous temperature response. Although, this idea lacks long-term verification from NWNA instrumental data which are largely restricted to the 20th century. Alternatively, a simple comparison against the mean of 6 northern hemisphere (NH) temperature reconstructions since AD 1300 provides independent verification (Fig. 8a and b). NWNA 1 and NWNA 2 track NH temperatures well before the mid-20th century (Fig. 8b) suggesting that their predivergence growth was a positive function of temperature. We do note that some site chronologies that constitute the mean NWNA chronologies were also used in some of the NH reconstructions; however, the contribution of the shared chronologies to the overall variance of the NH reconstructions is negligible. In other words, virtually all of the coherence between NWNA 1/NWNA 2 and NH temperatures is from independent data. Finally, as was the case with NWNA 1 vs. NWNA temperatures (Fig. 7), NWNA 1 failed to track NH temperatures since the mid-20th century (Fig. 8).

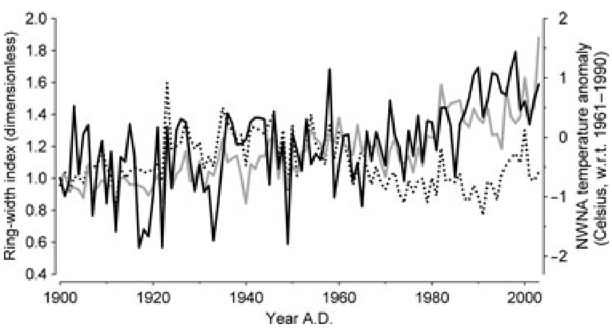

Fig. 7 Comparison between the mean NWNA 1/NWNA 2 (dotted/grey line) chronologies and a regional composite of June/July temperatures for NWNA (solid black line; see Note S3).

Discussion

Implications and timing of growth trend divergence

Here we have provided evidence of widespread growth trend divergence in NWNA. Our Group 1 and Group 2 chronologies showed similar growth patterns prior to the 1930s, but one of two contrasting patterns since then. This growth trend divergence (negative/positive trends) is the main distinction between Group 1 and Group 2 since the 1930s. At larger scales, this growth trend divergence was replicated using 14 white spruce chronologies across NWNA, although the timing of divergence was the 1950s. The coherence of these chronologies before divergence implies that they were responding to a similar regional climatic factor; however, their contrasting behaviour since implies that one of the groups diverged from its former response to climate.

As a result of the instrumental data limitations in Old Crow Flats, we could not directly assess the implied climate-growth response change for Group 1/Group 2 sites. However, the NWNA-scale analysis did reveal

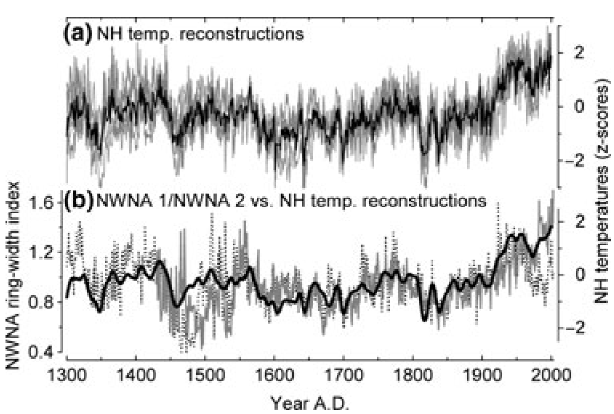

Fig. 8 (a) Northern hemisphere (NH) temperature reconstructions by Jones *et al.* (1998), Briffa (2000), Esper *et al.* (2002), D'Arrigo *et al.* (2006), Wahl & Ammann (2007) and Wilson *et al.* (2007) (grey lines); mean reconstruction (black line). The reconstructions were expressed as *z*-scores relative to the common period of overlap (1750–1980). (b) Comparison of the mean NH temperature reconstruction (thick black line; smoothed with 15-year cubic smoothing spline, Cook & Peters, 1981) against the mean NWNA 1/NWNA 2 chronologies (dotted/grey line). The mean NWNA chronologies are defined by a minimum of two site chronologies.

that NWNA 1 sites transitioned from a positive to negative temperature response in the mid-20th century, while NWNA 2 sites maintained a stable positive temperature response throughout the 20th century. A comparison against reconstructed NH temperatures confirmed that all sites, including NWNA 1 sites, shared a positive temperature response prior to 20th-century divergence.

As reported elsewhere (Jacoby & D'Arrigo, 1995; Briffa *et al*., 1998; Cook *et al*., 2004; D'Arrigo *et al*., 2004, 2008), our NWNA-scale results largely support the idea that temperature-growth divergence is a mid-20th-century phenomenon. However, there does appear to be some variability in timing. For example, in Old Crow Flats Group 1/Group 2 sites began to trend in opposite directions as early as the 1930s. Briffa *et al*. (1998) and Pisaric *et al*. (2007) also found that some regions may have diverged in the 1930s.

On a more cautious note, there is some indication that Group 1 sites began to separate from Group 2 sites in terms of temperature sensitivity during the 19th century given their offset index values thereafter. At the NWNA-scale, this offset was less apparent, but it was evident. Similarly, sub-population (i.e., intra-site dynamics) studies in Alaska have also found evidence of growth pattern divergence during the 19th century (Wilmking *et al*., 2004). However, in Old Crow Flats, we remain cautious of labelling this offset a true temperature-growth divergence given that Group 1 and Group 2 have virtually identical linear trends over their period of offset. This parallel behaviour suggests Group 1 and Group 2 responded to climate in the same manner over this period, but that they had slight differences in terms of climatic sensitivity. Furthermore, we cannot discount the possibility that it is a detrending artefact due to the difficulty in separating age-related trend from two very different externally forced 20th-century growth patterns, one peaking in the 1930s and another with a strong late-century increase. Regardless of its nature, the offset does not imply a major change in temperature-growth response. By contrast, 20th-century growth trend divergence implies a temperature-growth response reversal for some sites.

Long-term stability of temperature-growth relations

The DP has been the subject of on-going research for nearly 2 decades (D'Arrigo *et al*., 2008). From a paleoclimatology perspective, it is important to better understand the spatiotemporal extent of the phenomenon, its causes, and the likelihood that it has impacted past growth. In turn, such insight would help determine the extent to which affected chronologies can be used to provide robust estimates of past temperature. Current understandings of DP remain tenuous due to the limited number of datasets affected by divergence and the collinearity of potential contributing environmental factors (D'Arrigo *et al*., 2008). However, a growing body of evidence suggests that DP may be caused by the anomalously warm temperatures of the 20th century (Jacoby & D'Arrigo, 1995; Barber *et al*., 2000; D'Arrigo *et al*., 2004; Wilmking *et al*., 2004; Pisaric *et al*., 2007) which likely have been unmatched in the last 2000 years (Kaufman *et al*., 2009).

The idea that DP is unique to the 20th century does have some empirical support. Based on their comparison of divergent northern site chronologies with a number of other temperature-sensitive hemispheric chronologies, Cook *et al*. (2004) concluded that 20th-century DP is unique in the context of the last 1100 years. Similarly, our comparison of the NWNA chronologies to reconstructed NH temperatures suggests that 20th-century divergence is unique in the context of the last 700 years, at least. In fact, the coherence between the NWNA 1/NWNA 2 chronologies and NH temperatures prior to divergence is remarkable considering the spatial-scale differences (i.e., NWNA vs. NH) and the well documented regional-heterogeneity of NH temperatures over past centuries (D'Arrigo *et al*., 2006; Mann *et al*., 2009). One notable exception occurs during the late 1400s when the NWNA chronologies indicate a cool period. This period corresponds with the well known Spörer minimum (Stuiver, 1961; Bard *et al*., 2000), one of the longest and most pronounced solar minima of the past millennium.

Large-scale drivers of divergence

Our results support the notion that DP in NWNA is unique to the 20th century suggesting that DP was caused by a large-scale environmental or climatic change that is also unique to the 20th century. Several large-scale factors have been proposed including: temperature-induced drought stress (Jacoby & D'Arrigo, 1995; Barber *et al*., 2000; Lloyd & Fastie, 2002; Wilmking & Juday, 2005; McGuire *et al*., 2010), biological temperature thresholds (D'Arrigo *et al*., 2004; Wilmking *et al*., 2004), snow cover changes (Vaganov *et al*., 1999), UV-B changes (Briffa *et al*., 2004) and global dimming (D'Arrigo *et al*., 2008). Depending on the region, DP may have been caused by one, all, or a combination of these factors. However, negative temperature-growth relations in NWNA have been linked to regional moisture gradients (Wilmking & Juday, 2005; Lloyd & Bunn, 2007) implying that the divergence may be caused by moisture stress. NWNA is already limited in terms of its annual precipitation budget, and the strong 20thcentury warming in this region (ACIA, 2005) has likely placed an even greater moisture limitation on these forests.

We also introduce another large-scale factor that may have contributed to DP in NWNA, but has been absent in discussions of DP: Pacific derived moisture. Directional warming was one of the most prominent climate system changes following the mid-19th century in high-latitude regions (Overpeck *et al.*, 1997; Kaufman *et al.*, 2009). However, in NWNA, this warming was accompanied by important moisture changes towards interior NWNA (Anderson *et al.*, 2007, 2011) due to a major atmospheric circulation reorganisation linked to the strength of the Aleutian Low (Fisher *et al.*, 2004; Anderson *et al.*, 2005). This transition led to a relatively dry 20th century in many parts of interior NWNA compared with the last 1200 years (Fisher *et al.*, 2004; Anderson *et al.*, 2011). This reorganization appears to have been widespread as it coincides with several other large climate system changes in the Pacific basin (e.g., Thompson *et al.*, 1986; Mann *et al.*, 2000; Hendy *et al.*, 2002). Although we cannot say which large-scale factor ultimately caused some sites to diverge, several moisture related factors may be involved including temperature-induced drought stress and reduced Pacific-derived moisture since the mid-19th century.

The role of small-scale factors

Because DP is found across such a large portion of NWNA, it is clear that DP was caused by a large-scale forcing. However, not all sites were affected, some of which are found within a few kilometres of sites that were affected (e.g., DP30 vs. DP31, or DP23–26 vs. DP27; Fig. S4). Therefore, it is also clear that site-specific factors determine how each site has been impacted by putative large-scale forcing that caused DP. Ecological factors may be particularly important. For example, Wilmking & Juday (2005) reported that sites with lower tree densities tended to have a greater proportion of trees that responded positively to temperature, presumably related to soil moisture competition.

Organic layer thickness may also be important. At a white spruce stand in the Mackenzie Delta, King (2009) found that trees with a positive temperature-growth response were linked to thicker surficial organic layers that maintain cooler active layers and limit direct evaporative moisture loss from the soil. Negative temperature responses were linked to a thinner organic layer and warmer active layer. A larger-scale study of black spruce in western Quebec, Canada, by Drobyshev *et al.* (2010) also supports the notion that surficial organic layer thickness may lead to contrasting climate-growth responses (see also Nilsson & Wardle, 2005; Turetsky *et al.*, 2010 on the importance of the organic layer in boreal ecosystem functioning). The contribution of such site-level (or intra-site) factors to DP has not been examined in detail, but presents an exciting research opportunity to better understand the spatial complexity of tree growth responses in high-latitude boreal ecosystems.

Concluding remarks

The DP has been an ongoing issue for dendroclimatologists working in high-latitude regions for the past 16 years. Because of the limited number of datasets affected by DP, progress in characterizing and advancing current understandings of it has been slow. In this study, we made a sizeable contribution to the high-latitude tree-ring network, adding 23 new white spruce chronologies from Old Crow Flats, northern Yukon. Furthermore, we drew comparisons between these sites and 14 other long white spruce chronologies from across NWNA and shed new light on potential causes of DP. Our results suggest that white spruce temperature-growth divergence in NWNA largely began in the 1950s and as early as the 1930s in Old Crow Flats. A long-term comparison of NWNA chronologies against reconstructed NH temperatures provides good independent verification of the idea that these chronologies responded positively to temperature since AD 1300 and that temperature-growth divergence in NWNA is probably restricted to the 20th century.

The large spatial extent of sites that were impacted by DP suggests that a large-scale forcing was the cause. As DP occurs during the warmest period of the last 2000 years (Kaufman *et al.*, 2009), it is likely that temperature-induced drought stress is involved. A strengthened Aleutian Low since the mid-19th century (Fisher *et al.*, 2004; Anderson *et al.*, 2005), which led to anomalously dry 20th-century conditions in interior NWNA (Anderson *et al.*, 2011), may also be a contributing factor. However, considering the proximity of divergent and nondivergent sites in our network, we speculate that site-specific factors (e.g., organic layer thickness; King, 2009; Drobyshev *et al.*, 2010) have an overarching role in determining the susceptibility of individual sites to DP.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Standardized ring-width indices (grey lines) and mean site chronologies (black lines) for each site in Old Crow Flats based on signal-free standardization (Melvin & Briffa, 2008) using conservative 'negative exponential' or 'negative-to-zero slope linear' curve fits (Fritts *et al*., 1969). Sample depth (red lines) indicates the number of series defining the mean chronology. The mean chronologies were calculated with a robust bi-weight mean (Cook, 1985); more details on each chronology are provided in Table 1.
Figure S2. A comparison of each mean site chronology produced using 'signal-free' (black lines) and non-signal-free (red lines) methods. Inter-series differences can be considered the result of 'trend distortion' (Melvin & Briffa, 2008). Due to differences in non-age-related growth (i.e., forced by climate, disturbance, etc.) between sites, trend distortion effects are more pronounced in some chronologies (e.g., JC1, OC9, OC54, SC1, and TH1) than in others (e.g., DP26, OC50, OC52, TM1, and TM2).
Figure S3. Magnified comparison of the mean Group 1 and Group 2 chronologies during (a) 1600–1800 and (b) 1800–2000. Smoothed chronologies were calculated using a 15-year cubic smoothing spline with a 50% frequency cut-off (Cook & Peters, 1981).
Figure S4. Old Crow Flats sites: Group 1 (negative temperature response), Group 2 (positive temperature response), and Mixed (mixed negative/positive temperature response).
Table S1. Correlations between the 23 Old Crow Flats 'signal-free' site chronologies and minimum/maximum temperatures from May to August of the growth year (t) and previous growth year (t−1); only correlations significant at $P \leq 0.05$ (two-tailed) are presented.
Note S1. A running 2-sample *t*-test was used to test the null hypothesis that the Group 1 and 2 site chronologies are derived from the same normal distribution with equal means and variance ($P \leq 0.05$). The null hypothesis was tested for each year that both groups contained four or more site chronologies. The *t*-test result was calculated using the 'ttest2' function (Statistics Toolbox) in MATLAB 7.4.
Note S2. The Mackenzie Delta East Channel (MDEC) negative-responder (neg) and positive-responder (pos) used here are modified versions of the 'negative- and positive-responder' chronologies by Pisaric *et al.* (2007). The main difference is that the modified MDEC neg and MDEC pos chronologies do not contain Campbell Dolomite Upland (CDU) series (Szeicz & MacDonald, 1996). CDU series were excluded from MDEC neg and MDEC pos to ensure our Group 1/Group 2 correlations with CDU, MDEC neg, and MDEC pos would be independent of each other.
Note S3. The mean NWNA 1/NWNA 2 chronologies were compared with a regional average of CRUTEM3v gridded temperatures (Brohan *et al*., 2006). The regional average includes 22 (5° × 5°) grid cells bounded by 60–70°N and 170–115°W; only two grid cells (65–70°N/160–155°W and 65–70°N/150–145°W) did not contain any data. Temperature data before 1900 were not used as spatial coverage is limited. The number of grid cells with data for the year 1900 is 5; the number of grid cells increases steadily to more than 10 by the early-1920s, more than 15 by the early-1940s and a high of 20 by 1959.

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