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1 A ring-width-based reconstruction of June-July minimum temperatures since AD 1245 from
2 white spruce stands in the Mackenzie Delta region, northwestern Canada

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15 temperature reconstruction

Abstract

We present a reconstruction of June-July minimum temperatures since AD 1245 for the Mackenzie Delta region based on a 29-site network of white spruce (*Picea glauca*) ring-width series. Most, but not all trees experienced a divergent temperature-growth response, similar to the divergence that has affected other white spruce trees across Yukon and Alaska. However, divergence in the study region began as early as AD 1900 and we have documented our methods to avoid including divergent signals in the reconstruction. Calibration/verification testing based on local temperature data, and multi-century coherence with nearby and large-scale temperature proxy records, confirm our reconstruction is robust. The reconstruction shows cool conditions in the late 13th, early 18th and early 19th centuries, corresponding with solar minima and increased volcanism. These cool periods are interrupted by warm periods consistent with early to mid-20th-century warmth. The late 20th century is the warmest interval, and the last decade is estimated to be 1.4°C warmer than any decade before the mid-20th century. The reconstructed climate history corroborates other proxy-based inferences and supports the notion that high-latitude regions such as the Mackenzie Delta have experienced rapid warming in recent decades that is exceptional in the last eight centuries.

Introduction

The circumpolar north has experienced rapid climate warming in recent decades (ACIA, 2005), which has stimulated a broad range of ecosystem-level changes (Tape et al., 2006; Bunn et al., 2007; Turetsky et al., 2011; Lantz et al., 2012). However, Arctic climate is characterised by a sparse network of instrumental records that are mostly shorter than 100 years in duration (Lawrimore et al., 2011). This instrumental network is inadequate for evaluating regional-scale

1 variability and providing the long-term context for recent climate changes. Climate proxies can
2 improve on existing knowledge of climate in northern regions, and tree-rings are ideal since they
3 are annually resolved and comparable to instrumental records (Hughes, 2011). Of interest to our
4 study is the development of millennial-length ring-width chronologies for climate reconstruction.
5 Such long chronologies are not found in all regions, either because the living trees are short-lived
6 or the environmental conditions are not suitable for deadwood preservation. Long chronologies
7 are more typical in northern Eurasia, but are virtually absent in northern North America (Jansen
8 et al., 2007). Here we focus on the Mackenzie Delta region, which hosts Canada's northernmost
9 treeline extent and has potential for multi-centennial- to millennial-length, climatically sensitive
10 tree-ring chronologies (Szeicz and MacDonald, 1996; Bégin et al., 2000; Pisaric et al., 2007).

11 A network of temperature-sensitive white spruce (*Picea glauca*) ring-width series, from
12 10 existing and 19 new sites (Fig. 1), is used to develop a regional chronology and reconstruct
13 June-July minimum temperatures since AD 1245. Most trees in this network shared a divergent
14 temperature-growth response during the 20th century (Pisaric et al., 2007) that is consistent with
15 the 'divergence problem' reviewed by D'Arrigo et al. (2008). The divergence we observe in the
16 Mackenzie Delta began as early as ca. AD 1900, which is earlier than in most other regions, and
17 we document our methods to avoid including divergent signals in our regional chronology.

18 Our regional chronology improves upon several previously developed chronologies from
19 the region as it represents one of the densest tree-ring networks ever compiled in northwestern
20 North America (NNA), allowing us to isolate regional growth patterns linked to climate and
21 attenuate site- and tree-specific noise (Hughes, 2011). The reconstruction quality is demonstrated
22 by standard calibration and verification tests (Cook and Kairiukstis, 1990) over the instrumental
23 period, and multi-century coherence with temperature proxy records from neighbouring regions,

and from large-scale Arctic and hemispheric networks. Our reconstruction provides a long-term context for evaluating the significance of recent warming in the Mackenzie Delta region.

Background

Three notable ring-width studies on white spruce have been published from the Mackenzie Delta region: Szeicz and MacDonald (1996), Bégin et al. (2000), and Pisaric et al. (2007). Szeicz and MacDonald (1996) and Bégin et al. (2000) developed two of the longest chronologies back to AD 1060 and 1172, respectively. The Bégin et al. (2000) chronology was developed from living trees and deadwood snags (i.e., resting on the surface) from an isolated stand in the Eskimo Lakes district, north of treeline (site 1 – Fig. 1). As is typical of trees from cold, high-latitude regions, their chronology was positively correlated with summer temperatures and was used to reconstruct temperatures. Conversely, Szeicz and MacDonald (1996) sampled trees from rocky outcrops on Campbell Dolomite Upland (CDU; site 3 – Fig. 1) and found their chronology was moisture-sensitive due to its inverse correlation with prior-summer temperatures and positive correlation with annual precipitation. More recently, the CDU chronology has been interpreted as a proxy for summer temperature (Esper et al., 2002; Frank et al., 2007; Porter and Pisaric, 2011). Comparisons against other temperature proxies suggest the CDU chronology had responded positively to temperature before the 20th century, but shifted to a negative temperature response in the 20th century (Porter and Pisaric, 2011). Similarly, temperature-growth divergence is found in other white spruce stands across NWN (Jacoby and D'Arrigo, 1995; D'Arrigo et al., 2004; Wilmking et al., 2004; Pisaric et al., 2007; Porter and Pisaric, 2011).

Pisaric et al. (2007) were the first to examine the climatic response of individual trees at sites in the Mackenzie Delta plain (sites 6-13, Fig. 1). They too found that temperature-growth

1 divergence was widespread, but a subset of trees from several sites maintained a stable, positive
2 temperature response over the full 20th century. The point of divergence is evident by comparing
3 separate chronologies developed from the means of divergent and divergence-free trees (referred
4 to as ‘negative and positive responders’ by Pisaric et al., 2007; *sensu* Wilmking et al., 2004). The
5 divergent population began exhibiting contrasting low frequency growth patterns as early as ca.
6 AD 1900. Prior to the point of divergence, divergent and divergence-free trees shared a common
7 growth pattern that was a positive function of temperature based on comparisons with long proxy
8 records (Porter and Pisaric, 2011).

9 While many trees across NRNA were susceptible to temperature-growth divergence,
10 others were not (Bégin et al., 2000; Wilmking et al., 2004; Pisaric et al., 2007; Porter and Pisaric,
11 2011). The spatiotemporal coverage of tree-ring and climate records in NRNA are limitations to
12 understanding the cause(s) of divergence and likelihood it occurred in the past (D’Arrigo et al.,
13 2008), which has implications for tree-ring-based climate reconstructions (Jansen et al., 2007).
14 However, mounting evidence suggests that temperature-growth divergence is unique to the 20th
15 century and was caused by a large-scale climatic forcing (Cook et al., 2004; Porter and Pisaric,
16 2011). Warming-induced drought stress is often blamed (Jacoby and D’Arrigo, 1995; Lloyd and
17 Fastie, 2002; McGuire et al., 2010), and proxy records do support the idea that the 20th century
18 has been anomalously warm (D’Arrigo et al., 2006) and dry (Anderson et al., 2007, 2011). The
19 exceedance of temperature thresholds resulting in physiological stress has also been proposed
20 (D’Arrigo et al., 2004; Wilmking et al., 2004). However, not all trees in affected regions exhibit
21 a divergent response (Wilmking et al., 2004; Pisaric et al., 2007; Porter and Pisaric, 2011), which
22 implies that local-scale factors determine why some trees are susceptible and others not (Porter
23 and Pisaric, 2011). For example, stand density and surficial organic layer thickness are important

soil hydroclimate moderating factors (Wilmking et al., 2004; King, 2009; Drobyshev et al., 2010; Yarie and Van Cleve, 2010) and could influence a tree's susceptibility to divergence if related to moisture stress.

Regardless, if temperature-growth divergence is unique to the 20th century and has not affected all trees, it should be possible to develop robust temperature reconstructions in regions affected by divergence if careful selection procedures are used to exclude divergent signals from the reconstruction (Wilson et al., 2007). Here, we re-examine the aforementioned tree-ring data from the Mackenzie Delta region and develop a divergence-free regional chronology, which we use to reconstruct summer temperatures over most of the last millennium.

Methods

Study area

The Mackenzie Delta is an alluvial feature of Holocene age comprised of sediments from the Mackenzie and Peel Rivers (Mackay, 1963). White spruce trees dominate the delta plain and grow in well-drained alluvium underlain by permafrost (Nguyen et al., 2009). Most delta plain sites studied here (sites 6-29, Fig. 1) are open-canopy, white spruce/lichen-crowberry stands, as described by Pearce et al. (1988), which have abundant mature trees, deadwood, and lichen cover (e.g., *Cladonia rangiferina*; *Caldina mitis*; Supplementary Fig. 1). The development of ice-rich permafrost has elevated these surfaces above the regular spring flooding level (Kokelj and Burn, 2005a), and has helped to prevent rot and preserve deadwood. The general absence of wildfires in the delta also helps to preserve centuries-old trees and deadwood, making these site types well suited for dendroclimatic research.

Five upland sites examined here (sites 1-5, Fig. 1), adjacent to the Mackenzie Delta, are broadly consistent with the delta plain sites in terms of canopy and understory structure, but they differ in terms of surficial geology. Three of these sites (CDU, CDU1, and CDU2) are found on the Campbell Dolomite Upland (Supplementary Fig. 2), a dolomite, quartzite, and shale outcrop of Precambrian to Lower Devonian age (Norris, 1981). The area was overridden by Laurentide ice between 14 and 21 ¹⁴C ka BP (Dyke et al., 2002). Forested sites have only a shallow mineral soil layer, presumably from weathered parent material or glacial till. The two other upland sites (ESK and NL1) are isolated tundra stands on hummocky moraine deposits (Rampton, 1988).

Seasonal temperatures and precipitation are greatest in summer. Mean temperature normals (AD 1971-2000) at Inuvik for the winter (DJF), spring (MAM), summer (JJA), and fall (SON) seasons are -26.7, -11.9, 12.2, and -8.5°C, respectively; the same seasonal normals for total precipitation are 41.1, 38.5, 95.2, and 73.8 mm (<http://climate.weatheroffice.gc.ca>).

Tree-ring data

Nineteen white spruce stands (Table 1) were sampled in 2007 and 2008 using standard dendrochronology methods (Speer, 2010). General sampling areas were preselected so that sites would be well distributed across the region. Mature sites with abundant snags were targeted to maximize the length of tree-ring chronologies. On average, 45 trees were sampled per site, most of which (ca. $\geq 80\%$) were living. A single bark-to-bark core (i.e., representing two radii) passing through or near the pith was collected from living trees; ‘cookies’ were cut from snags. Samples were sanded to a smooth finish so the rings could be visually cross-dated and measured using a Velmex measuring system (± 0.001 mm). Two radii per tree were measured in nearly all cases. Cross-dating accuracy was verified using the program COFECHA (Holmes, 1983).

1 These 19 sites are supplemented by 10 previously sampled sites (Table 1): 8 eastern delta
2 sites – Pisaric et al. (2007); the Eskimo Lakes ‘ESK’ site – Bégin et al. (2000); and the Campbell
3 Dolomite Upland ‘CDU’ site – Szeicz and MacDonald (1996). Details about the ring-width data
4 from these sites are provided in Supplementary Note 1.

5 Age-related trends were removed from ring-width series using standard data-adaptive
6 negative-exponential or linear negative-to-zero slope curves (Fritts et al., 1969) following the
7 ‘signal-free’ approach by Melvin and Briffa (2008). The signal-free approach improves upon
8 traditional tree-ring standardisation as it helps to avoid distortion caused by climate signals in
9 growth series. Ideally, an expected growth curve fitted to raw ring-width measurements should
10 reflect only the age-related trend (i.e., independent of climate). However, when data-adaptive
11 curves are used, they are unavoidably distorted (referred to as ‘trend distortion’) by the climate
12 signal. Removing these curves from raw data will, therefore, remove some of the original climate
13 signal. Because data-adaptive curves, determined by least squares, are most influenced by series
14 ends, trend distortion is also most severe at the ends of series. In the case of mean chronologies
15 where the modern ends of many standardised indices end on the same year (e.g., living trees) and
16 are averaged together, a large trend distortion may occur and cause a poor fit between the climate
17 series and mean chronology (Melvin and Briffa, 2008). Signal-free standardisation avoids trend
18 distortion by estimating and removing the common climate signal from each series, based on the
19 iterative procedure outlined by Melvin and Briffa (2008), resulting in ‘signal-free measurements’
20 that can be used to better characterise age-related trends. However, it is important to note that
21 data-adaptive signal-free standardisation is subject to the same low-frequency limitations or
22 ‘segment length curse’ (Cook et al., 1995) as more traditional methods, with potential loss of
23 low-frequency signals at wavelengths greater than the mean series length.

1 A signal-free-enabled version of the program ARSTAN (provided by E. Cook, Lamont-
2 Doherty Earth Observatory) was used to calculate the standardised ring-width indices. Indices
3 belonging to the same tree were averaged into mean ‘tree indices’ (Supplementary Fig. 3). Site
4 and regional chronologies were calculated using the robust bi-weight mean (Cook, 1985).

6 *Climate data*

7 Regional composites of monthly minimum, mean and maximum temperatures and total
8 precipitation were developed from several nearby climate station records (Supplementary Fig. 4;
9 see Supplementary Note 2 for details on the regional composites) to allow the longest possible
10 comparisons between local climate and our tree-ring data. The temperature composites span AD
11 1892-2007 and are continuous only from AD 1910-2007 for most months (Supplementary Figs.
12 5-7). The total precipitation composites span AD 1926-2007, continuously (Supplementary Fig.
13 8). Temperature variability is coherent across the region, but total precipitation is more spatially
14 heterogeneous (Burn and Kokelj, 2009). These points are well confirmed by strong inter-station
15 correlations for the selected temperature records for all months (Supplementary Figs. 5-7), and
16 weak inter-station correlations for total precipitation for most months (Supplementary Fig. 8). As
17 such, the total precipitation composites may be less representative of the region compared to the
18 temperature composites. Therefore, correlations between the tree-ring and total precipitation data
19 should be interpreted with caution.

21 **Results and Discussion**

22 *Regional growth patterns and divergence*

Tree-ring series from the network span the period AD 1060-2007 (Table 1). More than 70% of the sites yielded samples that extend into the 16th century, more than 40% extend into the 15th century, and just over 20% extend into the 14th century or earlier. The oldest samples are from the upland sites ESK, CDU, CDU1, and CDU2, which extend into the 11th or 12th centuries. All sites share a large amount of common variability suggesting a regional growth-limiting factor such as climate. This is demonstrated by a comparison of each site chronology against a regional mean defined by the remaining trees from the network (Fig. 2). Each site is well correlated with its corresponding regional mean. The most strongly correlated sites (e.g., DW, BB, MP, M, FT, KC2 and SC1) are delta plain sites. Nevertheless, most upland sites (e.g., ESK, NL1, CDU and CDU2) are also well correlated regionally.

All tree indices were averaged into a mean chronology (Fig. 3a; hereafter the Mackenzie Delta Regional Chronology or MDRC) to isolate the regional growth pattern and assess its climate response. The MDRC was calculated for the period AD 1245-2007 only, defined by an Expressed Population Signal (EPS; Wigley et al., 1984) above 0.7 (i.e., 70% signal, 30% noise), except during the five years AD 1399 and 1405-1408 when EPS is 0.66-0.69. A 51-year window was used to calculate the EPS. The EPS statistic is commonly used in dendroclimatology studies as a measure of the common tree growth pattern in the mean chronology. An EPS of 0.85 is often adopted as a threshold below which the chronology may be less reliable (Wigley et al., 1984), but it is a subjective threshold. The more liberal EPS value of 0.7 is used to facilitate a longer interpretation of the MDRC (n.b., the point in time when EPS exceeds 0.85 is also noted in Fig. 3a), and we show towards the end of this paper that early portions of the chronology defined by EPS values between 0.7-0.85 contain valuable climatic information that corresponds with other paleoclimate reconstructions. EPS drops well below 0.5 prior to AD 1245 due to the low number

of samples (≤ 15 trees). The MDRC was not weighted by site, but a site-weighted MDRC is virtually identical to the un-weighted MDRC (AD 1245-2007, $r = 0.97$, $p \leq 0.001$).

The strong regional growth coherence indicates a regional forcing such as climate, but does not necessarily imply that the average tree's response to any specific forcing has been time-stable. The MDRC emulates the divergent growth pattern reported by Pisaric et al. (2007) in the Mackenzie Delta. Pisaric et al. (2007) showed that most, though not all, trees in the delta were susceptible to temperature-growth divergence, and that this divergence began earlier than in most other regions of NWNA. Pisaric et al. (2007) demonstrated that the mean growth patterns of the divergent and divergence-free populations were indistinguishable prior to ca. AD 1900 and very different since then. Comparisons against reconstructed hemispheric-scale temperatures confirm that divergent and divergence-free trees shared a positive temperature response prior to AD 1900 (Porter and Pisaric, 2011). Since AD 1900, divergent and divergence-free trees show contrasting low frequency growth patterns, divergence-free trees with a positive temperature response over the 20th century, and divergent trees with a transient temperature response (Pisaric et al., 2007).

We reiterate this last point with a comparison of the MDRC against a well-verified ring-width-based June-July temperature reconstruction (AD 1638-1988) by Szeicz and MacDonald (1995) from a network of five high-elevation white spruce sites in the middle-Mackenzie Valley, and parts of central and northern Yukon (all within 500 km of the Mackenzie Delta; Fig. 1). This comparison (Fig. 3b) shows that the average Mackenzie Delta tree was coupled to reconstructed June-July temperatures from AD 1638-1900 ($r = 0.61$, $p \leq 0.01$). However, there is a clear loss of temperature sensitivity, at least at lower-frequencies, since AD 1900 (AD 1900-1988, $r = 0.00$, n.s.; Fig. 3b). This temperature-growth divergence begins roughly a half century before it occurs in most other parts of NWNA (D'Arrigo et al., 2008; Porter and Pisaric, 2011). This same result

1 is observed when the MDRC is compared with Northern Hemisphere reconstructed temperatures
2 (AD 1600-1900, $r = 0.30$, $p \leq 0.01$; AD 1900-2000, $r = 0.09$, n.s.; Fig. 3c), in spite of the large
3 spatial-scale differences.

4 A unique feature of divergence in the Mackenzie Delta is that it occurs in two phases.
5 The first phase spans ca. AD 1900-1950 when tree growth overestimates summer temperatures,
6 and the second phase follows when tree growth underestimates temperatures (Figs. 3b). The first
7 phase is uncommon in NRNA, but the second phase is common (Porter and Pisaric, 2011). The
8 observation that many sites in NRNA responded negatively to late 20th-century temperatures, a
9 period of exceptional warmth in recent millennia (Kaufman et al., 2009), has led some to suggest
10 that this response may be linked to warming-induced drought stress (McGuire et al., 2010; Porter
11 and Pisaric, 2011) or a physiological stress due to temperature threshold exceedance (D'Arrigo et
12 al., 2004; Wilmking et al., 2004). However, the first phase of divergence in the Mackenzie Delta,
13 a period of accelerated growth, is clearly a response to favourable not stressful conditions.

14 The strong coherence between our tree-ring network and the Szeicz and MacDonald
15 (1995) network prior to AD 1900 reflects the fact that both are based on white spruce and both
16 experienced similar temperature histories, given their proximity. However, the lack of coherence
17 during the early 20th century suggests that climate-environment feedbacks may influence growth
18 differently across this range of environments. Elevation is a notable difference. The Szeicz and
19 MacDonald (1995) trees are from high-elevation mountain sites while most of our trees are from
20 low-lying delta plain sites. A simple comparison between a mean chronology representing our
21 five upland sites and the Szeicz and MacDonald (1995) reconstruction reveals that the early 20th-
22 century growth surge is unique to delta plain trees (Fig. 3d), implying that conditions unique to
23 the delta plain are responsible for the anomalous early 20th-century growth surge.

One potential factor contributing to the growth surge in the Mackenzie Delta is a release of water and nutrients from near-surface permafrost due to active layer thickening. Trees in the Mackenzie Delta grow on fine-grained alluvial soils underlain by an aggrading permafrost table that traps ice-lenses (Kokelj and Burn, 2005a) and dissolved cations (Ca^{2+} and Mg^{2+} ; Kokelj and Burn, 2005b) in near-surface permafrost. Little Ice Age conditions are probably associated with colder permafrost (Kokelj et al., 2007) and a thinner active layer. Warming following the Little Ice Age may have caused the active layer thickness to increase, with air temperatures reaching a local maximum in the 1940s (Burn and Kokelj, 2009), potentially releasing water and nutrients that had accumulated over previous centuries in a relatively short period of time, and resulting in augmented growth. Following this warming, mean annual air temperatures cooled into the 1970s, and later increased to record high levels by the late 20th century (Burn and Kokelj, 2009). While trees at alluvial sites experience water and nutrient additions following flooding, and increases in active layer thickness and rooting depth, upland trees at Campbell Dolomite Upland, which grow in thin soils on bedrock, would not benefit from an increase in active layer thickness, which may explain why they did not experience the early 20th-century growth surge.

If the early 20th-century growth surge is linked to an increase in active layer thickness, then a more pronounced growth trend might have been expected in the late 20th century when air temperatures were higher and further active layer thickening occurred (Burn and Kokelj, 2009). However, the late 20th century is a period of subdued growth for many white spruce stands across NWNA, including the Mackenzie Delta, and the large-scale factors responsible for the depressed growth (e.g., warming-related stress; Barber et al., 2000; D'Arrigo et al., 2004; Lloyd and Bunn, 2007; McGuire et al., 2010) may have countered some of the benefit of an increased active layer thickness in the late 20th century.

Climate-growth correlations

Since the first point of divergence (ca. AD 1900), the MDRC expressed a strong positive growth trend to record high index values in the AD 1930s, then a negative trend to low values in the AD 1980s, and then a positive trend to higher values at the time of sampling (Fig. 3a). This low-frequency pattern is inconsistent with local instrumental climate data. A correlation analysis between the MDRC and instrumental temperatures (AD 1892-2007) and total precipitation (AD 1926-2007) finds no significant correlations except a weak inverse correlation with December precipitation (Table 2). This result is not surprising given the evidence for a transient response to climate since AD 1900, discussed above. Time-dependent correlations between unfiltered tree-ring and climate series have been used to detect transient responses (e.g., D'Arrigo et al., 2004). However, these raw moving correlation analyses are unable to assess the frequency-dependence of the transient response. It is difficult to draw conclusions on lower-frequency climate-growth correlations (e.g., by low-pass filtering the climate and tree-ring series) when only short climate series (e.g., < 100 years) are available, as the effective degrees of freedom are severely reduced with autocorrelation (Wigley et al., 1987). However, high-frequency correlations are not prone to this effect.

A correlation analysis based on first-differenced data (i.e., high-frequency only) shows that the average tree had a significant, positive correlation with June and July temperatures over the 20th century (see '1st diff.', Table 2). First-difference correlations are strongest for minimum and mean temperatures, and slightly weaker for maximum temperatures. A comparison of first-differenced June-July mean temperatures and ring-width for AD 1911-2007 (Fig. 3e) shows that the relation was stable over the 20th century (n.b., first-differenced June-July temperatures were

not available before AD 1911). This point is supported by similar inter-series correlations for the first (AD 1911-1959, $r = 0.57$, $p \leq 0.01$) and second (AD 1960-2007, $r = 0.47$, $p \leq 0.01$) halves of the comparison period. The overall correlation is $r = 0.53$ ($p \leq 0.01$), a level of agreement that is typical for some Alaskan white spruce (Andreu-Hayles et al., 2011). Results from a sign-test also indicate a strong coupling between the two variables (65+/31-, $p \leq 0.01$).

The results presented thus far suggest that divergence in the Mackenzie Delta is mostly restricted to the low-frequency domain and post-AD 1900. However, as was demonstrated by Pisaric et al. (2007), and as we will show next, not all trees from a given site were affected by divergence, and this provides an opportunity to develop a divergence-free regional chronology that can be used to reconstruct past temperatures.

Divergence-free regional chronology

Large-scale (e.g., hemispheric) climate-proxy reconstructions are often developed from extensive networks of site chronologies that are well correlated and have a time-stable relation with the target climate variable (Briffa et al., 2002; D'Arrigo et al., 2006). In some high-latitude regions, ring-width-based temperature reconstructions have been most successful when tree-ring records were screened for divergence (Wilson et al., 2007). Here, we apply the same principles on our tree-ring network to develop a divergence-free regional chronology. However, rather than excluding divergent series altogether, we exclude only the divergent portions of these series (i.e., post-AD 1900) as the pre-divergence portions are not in question based on prior analyses and our discussion above.

Divergent and divergence-free records can be separated based on their correlation with summer temperature, but as Esper and Frank (2009) suggest, this approach is circular and would

surely lead to a mean chronology that is tuned to the temperature index used in the correlation analysis. Alternatively, growth-trend (positive vs. negative) could be used as a sorting criterion. At the NWN scale, Porter and Pisaric (2011) found that most divergent and divergence-free records have consistent growth trends, with respect to sign, over all periods except ca. AD 1950-1980. During the AD 1950-1980 period, divergent records have a negative growth trend while divergence-free trees have a positive trend. However, in areas such as Old Crow Flats (Porter and Pisaric, 2011) and the Mackenzie Delta (Pisaric et al., 2007) the period of contrasting growth trends begins slightly earlier, ca. AD 1930-1980.

We examined all 1286 tree indices from the 29 sites and sorted them based on growth trend from AD 1930-1980. Trees with a negative trend were sorted as 'Group 1', and trees with a positive trend were sorted as 'Group 2'. The Group 1 and Group 2 trees were then averaged into regional chronologies (Figs. 4a and 4b). The regional chronologies are only given for years with an EPS above 0.7 ($\text{EPS} \geq 0.85$ is also noted in Fig. 4), as was done for the MDRC. Ring-width series from deadwood that did not cover the AD 1930-1980 period were left unsorted and were averaged into a 'Snag' regional chronology (Fig. 4c).

Of the sorted trees, most are Group 1 (Table 3). Three sites did not contain any Group 2 trees (FT, AK1, and AK2). Of the 26 sites that had both responses, the majority of trees (82% for the average site) were Group 1. The dominance of Group 1 trees was observed at all sites except ESK and CDU1. Group 2 trees represent 20-30% of the population at some sites including NL1, CDU2, TM, MS, HL, AC1, NC2, KC1, and WC1. Regionally, there is no statistical difference in mean series length between Group 1 and Group 2 trees (261 vs. 263 years; $1\sigma = 76$ vs. 79 years), suggesting that the contrasting growth responses are not a function of age. Rather, they are more likely due to differences in local factors (King, 2009; Porter and Pisaric, 2011).

1 A comparison of the regionally averaged Group 1, Group 2 and Snag chronologies shows
2 that all trees, regardless of grouping, shared a common growth pattern from AD 1644 until 1900
3 (Fig. 4d). The mean inter-series correlation between the three chronologies during this period is
4 0.87 ($p \leq 0.001$). After AD 1900, Group 1 trees had a sharp upward trend to ca. AD 1930, then a
5 decline to ca. AD 1980. As would be expected, the Snag chronology closely follows the Group 1
6 chronology post-AD 1900 as it is an unsorted chronology and is defined mostly by Group 1 trees
7 which dominate regionally. Conversely, Group 2 trees had a positive trend since AD 1900.

8 To demonstrate that the contrasting growth patterns post-1900 are not an artefact of the
9 detrending method, the raw series belonging to each group were re-standardised and compared
10 using three other methods: traditional negative-exponential/negative-to-zero-slope linear (Fig.
11 5a); horizontal line equal to series mean (Fig. 5b); and regional curve standardisation (Fig. 5c).
12 Regional curve standardisation (Briffa et al., 1990) was applied on a site-by-site basis, as growth
13 rate varies between sites and, therefore, a single regional curve is not appropriate for all trees in
14 the region (Briffa and Melvin, 2011). Each method demonstrates the same post-1900 differences
15 between Group 1 and Group 2 trees, suggesting these contrasting patterns are not artefacts of the
16 curve fitting method chosen. The comparison of the ‘horizontal line’ chronologies is particularly
17 informative, as it reflects raw growth variability (i.e., climate- and age-driven trends), unaltered
18 by curve fitting. Another notable point is that there seems to be little if any loss of long-timescale
19 variance from use of data-adaptive curve standardisation, based on the similarity of chronologies
20 produced by regional curve and negative-exponential standardisation methods. Regional curve
21 standardisation is generally considered superior in ability to retain long-timescale variance.

22 A running standard deviation of all ring-width indices (Fig. 4e) was calculated as further
23 evidence that all trees, regardless of grouping, had similar growth patterns before AD 1900, but

1 increasingly variable growth patterns since. The regional standard deviation was relatively stable
2 during AD 1245-1900, with smoothed (41-year cubic smoothing spline, 50% frequency cut-off;
3 Cook and Peters, 1981) values ranging from 0.30-0.47 (mean = 0.37). Subsequently, the regional
4 standard deviation increases sharply to a local maximum of ca. 0.66 in the AD 1930s, a period
5 when the Group 1 and Group 2 trees show considerable differences. During the mid-20th century,
6 the regional standard deviation returns to pre-AD 1900 levels, since Group 1 and Group 2 indices
7 are similar in value as they cross each other trending in opposite directions. Finally, the regional
8 standard deviation increases sharply to end the record above 1.0, indicating that ring-width
9 indices across the region are most variable during the late 20th century. Again, these differences
10 are evident between the Group 1 and Group 2 regional chronologies (Fig. 4d).

12 *Calibration and verification*

13 Based on the premise that temperature-growth divergence is restricted to the 20th century
14 (Cook et al., 2004; Porter and Pisaric, 2011), we calculated a Divergence-Free Regional
15 Chronology (DFRC) from the robust bi-weight mean of all ring-width indices before AD 1900
16 and only Group 2 indices since AD 1900, thereby excluding divergent signals. As was the case
17 for the other chronologies presented thus far, the DFRC is defined by an EPS above 0.7.

18 The DFRC was correlated with the regional climate data to determine its optimal climate
19 response (Table 2). The strongest and most significant correlations were observed for June and
20 July minimum and mean temperatures, as noted earlier for the ‘all trees’ first-differenced data
21 (n.b., Group 2 trees that define the modern portion of the DFRC have the same high-frequency
22 growth pattern as ‘all trees’ – Supplementary Fig. 9). The finding that June and July minimum

1 and mean temperatures are well correlated with tree growth at both high- and low-frequencies
2 provides some confidence that these relations are not spurious.

3 June-July (and June-August) is a common season of influence for temperature-sensitive
4 chronologies from high-latitude and -elevational sites in North America and Eurasia (Szeicz and
5 MacDonald, 1995; Gostev et al., 1996; Büntgen et al., 2005; Wilson et al., 2007; Youngblut and
6 Luckman, 2008; D'Arrigo et al., 2009; Esper et al., 2010; Porter and Pisaric, 2011; Flower and
7 Smith, 2012). However, few studies have explored correlations with minimum (night time) and
8 maximum (day time) temperatures. Rather, most studies focus on mean temperature only. Here,
9 we find notable differences between minimum, mean, and maximum temperature correlations.
10 The June correlation is similar between minimum ($r = 0.56$, $p \leq 0.01$) and mean ($r = 0.51$, $p \leq$
11 0.01) temperatures, but the July correlation is much stronger for minimum ($r = 0.43$, $p \leq 0.01$)
12 versus mean ($r = 0.23$, $p \leq 0.01$) temperatures. Wilson and Luckman (2003; also Luckman and
13 Wilson, 2005; Youngblut and Luckman, 2008) showed that maximum temperatures are more
14 closely correlated with tree growth in some environments. Wilson and Luckman (2003) suggest
15 this may be due to the fact that most photosynthesis occurs during the day time and, presumably,
16 day time temperatures are more likely to influence photosynthesis. However, we find the DFRC
17 is more closely associated with June-July minimum temperatures ($r = 0.60$, $p \leq 0.01$) compared
18 mean or maximum temperatures ($r = 0.46$ and 0.31 , respectively, $p \leq 0.01$). This sensitivity may
19 reflect the fact that early June minimum temperatures in the region can approach the freezing
20 point and, therefore, can also significantly limit biological activity and growth.

21 Based on our correlation analysis, June-July minimum temperature is the optimal climate
22 index for the DFRC. Standard split-period calibration-verification testing (Cook and Kairiukstis,
23 1990) was used to evaluate the robustness of the DFRC-temperature relation. Two 53-year

1 calibration periods were defined: AD 1893-1954 (Split 1) and 1955-2007 (Split 2). The Split 1
2 calibration period spans 62 calendar years, but contains only 53 years of June-July temperature
3 measurements due to discontinuities in the regional temperature record (Supplementary Fig. 5).
4 Also, 3 of the 53 years (AD 1893, 1900, and 1908) in Split 1 contain measurements for June but
5 not July, and 2 of the 53 years (AD 1895 and 1896) contain measurements for July but not June.
6 In order to calculate June-July averages for these years, the missing June or July values were
7 estimated from the average of the 4 closest years of data.

8 For each calibration period, the DFRC and the June-July minimum temperature records
9 were compared and the following statistics were calculated to evaluate the relation: Pearson's
10 Product Moment Correlation Coefficient (r), coefficient of determination (r^2), adjusted r^2 ,
11 standard error of the estimate (SE), Durbin-Watson (DW), and sign-test. Calibration models
12 were verified over the years that were excluded from the calibration periods. The following
13 statistics were calculated for each verification period to evaluate the stability of the calibration
14 relations: Pearson's r , Reduction of Error (RE), and Coefficient of Efficiency (CE).

15 Modelled temperatures explain 18% and 23% (adjusted r^2) of observed temperatures for
16 Splits 1 and 2, and 35% for the full period model (Table 4). Values in this range are typical of
17 high-latitude ring-width networks which express temperature signals best at lower frequencies
18 (Cook et al., 2004; D'Arrigo et al., 2006). As expected, the explained variance of the full period
19 model increases with smoothing (e.g., adjusted $r^2 = 0.66$ for the period AD 1910-2007 if a 9-year
20 cubic smoothing spline is used). For Splits 1 and 2, and the full period model, the DW statistic is
21 always close to a value of 2.0 indicating low residual autocorrelation, and the SE has a narrow
22 range from 0.81-0.88 suggesting the magnitude of unexplained variance is stationary. The Split 1
23 and full period calibration models pass a sign-test at the 95% confidence level, but Split 2 does

not. Despite the weaker Split 2 sign-test result, the overall result is encouraging given the lower-frequency nature of temperature signals in high-latitude tree growth and implies that some inter-annual temperature variability is preserved in the rings. This last point is also confirmed by the comparison of first-differenced ring-width and temperature data (Fig. 3e).

The verification statistics indicate that the calibrations are robust and time-stable (Table 4). The most informative statistics are the RE and CE which are always above zero, except the CE of Split 1. By definition, any model with an RE or CE above zero demonstrates some skill and is predictively superior to a model defined by the mean climatologies of the calibration (RE) and verification (CE) periods. Based on the RE results alone, the calibration models are skilful.

Temperature reconstruction, AD 1245-2007

The DFRC passes most of the standard calibration-verification tests, suggesting it can be used as a proxy for June-July minimum temperatures. The full-period model (Table 4) was used to reconstruct June-July minimum temperatures since AD 1245 (Fig. 6). The 2σ confidence interval for the reconstruction is 1.72°C ($2 \times \text{SE}$), which does not account for changes in sample depth or model parameter uncertainties. As such, 1.72°C probably underestimates the true 2σ confidence interval.

From AD 1910-2007, both reconstructed and observed June-July minimum temperatures had warming trends of $0.2^{\circ}\text{C}/\text{decade}$ or a total change of 1.96°C (Fig. 6a). Comparatively, mean June-July temperatures for this region increased by only 1.46°C , which is still more than double the global trend of ca. 0.70°C for the same period (Brohan et al., 2006). The Mackenzie Delta and other regions of NWNA have experienced some of the most rapid warming trends in recent

decades (ACIA, 2005), which is partly explained by sea ice losses in the Beaufort and Chukchi Seas (Serreze et al., 2009).

Over longer time-scales, the reconstruction indicates that the most recent decade (AD 2000-2009) was the warmest on record since AD 1245, and ca. 1.4°C warmer than any other decade prior to the mid-20th century (Table 5). Six of the top ten warmest decades are from the 20th and 21st centuries. The other four warmest decades are the 1520s, 1530s, 1540s, and 1770s. Consistent with the IPCC's Fourth Assessment Report, we also find that the most recent 50-year period was the warmest 50-year period in the last 500 years (Jansen et al., 2007), and since AD 1245.

Four of the ten coldest decades in our reconstruction span AD 1810-1849 (Table 5), which corresponds with a period of increased volcanism (Gao et al., 2008) and the Dalton solar minimum (Bard et al., 2000). Four of the other six coldest decades span the period AD 1260-1299, again coinciding with increased volcanism (Gao et al., 2008) and the onset of the Wolfe solar minimum, but not its peak (Bard et al., 2000). The other two coldest decades are the 1340s and 1700s, which overlap with the Wolfe and Maunder solar minima, respectively (Bard et al., 2000). It is notable that these cool periods are recorded by other temperature-sensitive tree-ring chronologies in NWA (Luckman and Wilson, 2005; D'Arrigo et al., 2006; Porter and Pisarcic, 2011; Anchukaitis et al., 2012), which suggests volcanism and solar output have been important drivers of summer temperature variability before the 20th century. However, recent high-latitude warming is mostly amenable to anthropogenic forcing (IPCC, 2007) and Arctic amplification (Serreze et al., 2009).

Long-term, regional-scale validation

1 Our reconstruction is validated by comparison with several independent temperature
2 proxy records from elsewhere in NNA (Fig. 1). The Szeicz and MacDonald (1995) June-July
3 temperature reconstruction (AD 1638-1988) is well correlated ($r = 0.68$, $p \leq 0.001$) with our
4 reconstruction and shares the same low-frequency trends (Fig. 6b). This coherence is mutually
5 corroborative and demonstrates that both tree-ring networks responded to the same regional
6 climate.

7 A tree-ring $\delta^{18}\text{O}$ -based reconstruction of April-July minimum temperatures (AD 1780-
8 2003) by Porter et al. (2013; see also Porter et al., 2009) for the Mackenzie Delta also correlates
9 well ($r = 0.49$, $p \leq 0.001$) with our June-July temperature reconstruction (Fig. 6c), in spite of the
10 seasonal differences in temperature signal. This result is especially meaningful because the two
11 temperature signals originate from different processes. The $\delta^{18}\text{O}$ -temperature signal derives from
12 temperature-dependent labelling of precipitation isotopes and use of this water during synthesis
13 of cellulose precursors leading to tree-ring formation, whereas the ring-width-temperature signal
14 likely results from several biological processes and phenological constraints that are influenced
15 by temperature. Both records show cool conditions in the early 1800s and a progressive warming
16 trend into the 20th century.

17 The OCF-Group 2 chronology (AD 1620-2007), from a network of 11 divergence-free
18 white spruce ring-width chronologies from Old Crow Flats, northern Yukon (Fig. 1; Porter and
19 Pisaric, 2011), correlates strongly ($r = 0.83$, $p \leq 0.001$) with our reconstruction (Fig. 6d). This
20 strong correlation is due to the early summer temperature sensitivity of both tree-ring networks,
21 and the fact that air temperatures between the regions are strongly coupled (Porter and Pisaric,
22 2011). The coherence of the two records over the last four centuries indicates that both regions
23 shared similar temperature histories.

1 Finally, the Coppermine River ring-width chronology (AD 1046-2003) by D'Arrigo et al.
2 (2009) from a stand of white spruce in Nunavut, Canada (Fig. 1) is also well correlated ($r = 0.44$,
3 $p \leq 0.001$) with our reconstruction (Fig. 6e). The temperature-dependence of this chronology is
4 affirmed by several studies (D'Arrigo et al., 2009; Visser et al., 2010; Porter and Pisaric, 2011).
5 Since AD 1245, the Coppermine chronology has tracked low-frequency trends expressed in our
6 reconstruction, with inter-series coherence being especially strong since AD 1600 ($r = 0.57$, $p \leq$
7 0.01). Reduced coherence before AD 1600 may reflect several factors including lower sample
8 depth, regional temperature differences, or differences in regional-representativeness (e.g., the
9 DFRC represents 29 sites, while the Coppermine chronology represents a single site).

11 *Long-term, hemispheric- and circum-Arctic-scale validation*

12 Our reconstruction is also well matched by larger-scale temperature reconstructions. A
13 composite of six hemispheric-scale reconstructions (see Supplementary Note 4), largely tree-
14 ring-based and representative of the Northern Hemisphere, was compared to our reconstruction
15 (Fig. 6f). The hemispheric reconstructions were produced mainly from tree-ring data detrended
16 by the regional curve standardisation method (Briffa et al., 1990) which is optimized for low-
17 frequency trends, in comparison to the DFRC reconstruction which was produced from tree-ring
18 data detrended by data-adaptive signal-free standardisation (Melvin and Briffa, 2008). Despite
19 differences in data processing and, especially, spatial-scale, the two records are well correlated (r
20 $= 0.54$, $p \leq 0.001$) over the last 8 centuries suggesting they are responding to the same climatic
21 variable, i.e., warm-season temperatures. One notable difference occurs in the mid-20th century
22 when the hemispheric-scale composite indicates pronounced warming, while our reconstruction
23 does not. This mid-20th-century warmth (centered around ca. AD 1950) is common feature of

Northern Hemisphere instrumental temperature records (Brohan et al., 2006), but it is much less pronounced in the Mackenzie Delta region (Fig. 6a). Rather, the Mackenzie Delta experienced subdued summer warming in the mid-20th century followed by recently accelerated warming.

Lastly, our reconstruction agrees with a multi-proxy temperature reconstruction based on a network of Arctic sites (Fig. 6g) by Kaufman et al. (2009). The circum-Arctic reconstruction is based on Kaufman et al.'s (2009) ice- and lake-core records only (see Supplementary Note 5). The temporal resolution of the circum-Arctic reconstruction is coarse (10-year) compared to our annual reconstruction, but both records share similar low-frequency trends. Following AD 1245, both records transition from warm to cool conditions by the late 13th century, and then a warming trend to the ca. AD 1500s; although the circum-Arctic record indicates brief cooling at ca. AD 1525 (n.b., this brief cooling is also evident in the 6-study hemispheric comparison – see Fig. 6f). Subsequently, both records exhibit a long-term cooling trend to the early 19th century, followed by strong warming to present. This qualitative agreement suggests the broader circum-Arctic and Mackenzie Delta regions shared similar temperature histories with exceptionally warmth during recent decades.

Concluding remarks

Divergence is a widespread phenomenon in NWNA, including the Mackenzie Delta. Testing of the common growth signal in the study region and standard deviations indicated that divergence did not occur at these sites prior to the 20th century. Furthermore, divergence has not affected all trees, which provides an opportunity to build chronologies that represent a time-stable response to climate if divergent signals are excluded from the regional chronology, as we have demonstrated here. Local-scale factors that moderate growing conditions, such as organic

layer thickness, stand density, and near-surface ground ice, may be particularly important to why some trees diverge and should be evaluated in future studies. Because the factor(s) responsible for divergence remain uncertain, it is important to assess the long-term stability of reconstructed temperatures based on comparisons with independent proxy reconstructions. Such comparisons provide assurances that earlier periods of divergence have not severely biased the reconstruction. Building on previous studies from this region, we provide a greatly expanded network of white spruce sites and a regional perspective on summer temperatures in the Mackenzie Delta region over the last eight centuries that confirms recent decades have been exceptionally warm.

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1 circum-Arctic temperature reconstruction. Correlations represent the period of overlap between
2 the Mackenzie Delta reconstruction and the comparison series; all correlations are significant at
3 $p \leq 0.001$. Refer to Supplementary Note 5 for details on each comparison series, some of which
4 are modified from their original published form. Note that the time axes differ between some
5 plots.

Table 1. White spruce sites in the Mackenzie Delta region; ‘Site no.’ indicates the site’s location on Fig. 1.

Site no.	Site code	Lat. (°N)	Long. (°W)	No. trees	First year	Last year	Mean series length (yrs)
1	^a ESK	69.13	132.22	25	1172	1990	266
2	*NL1	68.59	133.68	49	1653	2006	202
3	^b CDU	68.28	133.34	64	1060	1992	261
4	*CDU1	68.27	133.41	39	1158	2007	205
5	*CDU2	68.16	133.76	49	1118	2007	239
6	^c TM	68.40	133.80	35	1529	2003	225
7	^c DW	68.43	133.81	39	1483	2003	306
8	^c BB	68.45	133.85	75	1501	2006	258
9	^c MP	68.46	133.87	59	1545	2003	232
10	^c M	68.47	133.85	29	1398	2003	234
11	^c FT	68.52	133.86	44	1332	2003	244
12	^c MS	68.51	134.00	42	1611	2003	262
13	^c HL	68.58	134.10	27	1563	2003	340
14	*AC1	68.68	134.52	52	1579	2006	277
15	*AM1	68.61	134.38	39	1435	2007	254
16	*NC2	68.41	134.26	40	1687	2007	232
17	*KC2	68.27	134.16	42	1596	2007	259
18	*KC1	68.12	134.16	52	1445	2007	225
19	*ES1	68.14	134.77	51	1607	2007	272
20	*AK1	68.26	134.74	46	1631	2006	230
21	*AK2	68.28	134.79	13	1716	2006	235
22	*SC1	68.36	134.66	54	1603	2007	240
23	*NC1	68.43	134.58	46	1580	2007	229
24	*PC1	68.54	134.64	59	1499	2007	256
25	*JA2	68.52	135.07	45	1453	2007	241
26	*JA1	68.37	134.97	42	1587	2007	255
27	*PE1	68.15	135.16	37	1615	2007	257
28	*WC2	68.32	135.20	51	1474	2007	232
29	*WC1	68.45	135.52	41	1591	2006	260

Further information on each site: ^aBégin et al. (2000); ^bSzeicz and MacDonald (1996); ^cPisaric et al. (2007); *this study.

Table 2. Correlations between monthly climate variables and tree-ring width indices: MDRC (Fig. 3a); ‘1st diff.’ (mean of all 1st differenced tree indices; Fig. 3e); and ‘DFRC’ (Divergence Free Regional Chronology; Fig. 4f). Only correlations significant at $p \leq 0.05$ (two-tailed) are shown; correlations significant at $p \leq 0.01$ (two-tailed) are in bold font.

		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Total	MDRC				-0.24								
Precip.	1 st diff.						-0.24		0.30				
	DFRC	0.22											
Min.	MDRC												
Temp.	1 st diff.					-0.20					0.48	0.35	
	DFRC	0.30			0.32	0.24	0.29	0.22	0.25		0.56	0.43	0.23
Mean	MDRC												
Temp.	1 st diff.					-0.20					0.49	0.35	
	DFRC				0.22		0.23				0.51	0.23	
Max.	MDRC												
Temp.	1 st diff.										0.43	0.33	
	DFRC										0.41		

Table 3. The frequency, percentage, and mean and median ages (years) of Group 1 and Group 2 trees at each site.

Site	Group 1				Group 2			
	freq. trees	% of trees	Mean age	Median age	freq. trees	% of trees	Mean age	Median age
ESK	2	15.4	329	329	11	84.6	274	263
NL1	31	81.6	207	227	7	18.4	214	238
CDU	24	85.7	272	238	4	14.3	290	265
CDU1	13	46.4	184	189	15	53.6	209	192
CDU2	24	80.0	231	225	6	20.0	278	267
TM	28	80.0	225	222	7	20.0	223	222
DW	23	95.8	333	359	1	4.2	406	406
BB	48	87.3	288	281	7	12.7	213	214
MP	19	95.0	276	255	1	5.0	340	340
M	15	93.8	263	241	1	6.3	183	183
FT	18	100.0	261	270	0	0.0	n/a	n/a
MS	30	78.9	254	242	8	21.1	282	259
HL	18	66.7	336	358	9	33.3	348	367
AC1	30	81.1	307	327	7	18.9	308	288
AM1	27	96.4	266	253	1	3.6	258	258
NC2	17	68.0	254	258	8	32.0	259	258
KC2	23	85.2	282	258	4	14.8	247	254
KC1	24	66.7	234	224	12	33.3	242	254
ES1	39	92.9	273	298	3	7.1	328	332
AK1	37	100.0	249	245	0	0.0	n/a	n/a
AK2	12	100.0	241	235	0	0.0	n/a	n/a
SC1	38	90.5	251	242	4	9.5	222	214
NC1	24	92.3	261	250	2	7.7	284	284
PC1	48	98.0	258	245	1	2.0	211	211
JA2	30	85.7	243	251	5	14.3	258	255
JA1	23	92.0	276	266	2	8.0	289	289
PE1	23	95.8	289	303	1	4.2	233	233
WC2	37	94.9	233	234	2	5.1	318	318
WC1	24	77.4	259	266	7	22.6	304	297
Average site*	25.8	81.7	263.2	261.6	5.2	18.3	269.9	267.6

*Based on sites that have both response types (i.e., all sites except FT, AK1, and AK2).

Table 4. Split-period calibration and verification, and full-period (AD 1893-2007) calibration statistics for linear regression models of June-July minimum temperatures as a function of the DFRC.

	Split 1	Split 2	Full period
Calibration			
Period	1893-1954	1955-2007	1893-2007
N	53	53	106
Slope	3.27	1.69	2.07
Intercept	2.17	4.06	3.46
r	0.44	0.49	0.60
r ²	0.20	0.24	0.36
Adjusted r ²	0.18	0.23	0.35
SE	0.81	0.88	0.86
DW	1.78	1.84	1.86
Sign (+/-)	34/18*	32/21	65/40*
Verification			
Period	1955-2007	1893-1954	n/a
N	53	53	n/a
r	0.49	0.44	n/a
RE	0.39	0.57	n/a
CE	-0.15	0.08	n/a

N.B., Temperature data for June (1895 and 1896) and July (1893, 1900, and 1908) were not available. To allow the calculation of June-July averages for these years, the missing data points were estimated by the mean of the four closest years of data. The calibration/verification period 1893-1954 (62 years) contains only 53 years of valid data points, and 9 years of missing data. All correlations are significant at $p \leq 0.001$ (one-tailed); sign-test result significant at * $p \leq 0.05$.

Table 5. Ranking of the ten warmest and ten coolest reconstructed decade-averaged minimum temperatures since AD 1245.

Warm Decades	°C	Cool decades	°C
2000-2009	*7.4	1810-1819	4.9
1990-1999	6.9	1280-1289	4.9
1980-1989	6.4	1820-1829	5.0
1970-1979	6.2	1270-1279	5.0
1960-1969	6.0	1830-1839	5.0
1520-1529	6.0	1290-1299	5.0
1540-1549	6.0	1840-1849	5.0
1950-1959	6.0	1260-1269	5.1
1770-1779	5.9	1700-1709	5.1
1530-1539	5.9	1340-1349	5.1

*Based on AD 2000-2007 reconstructed and AD 2008-2009 observed temperatures.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Supplementary Notes and Figures

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Supplementary Note 1.

Raw data for the eastern delta sites were provided by M. Pisaric. The ESK data were provided by C. Bégin (Geological Survey of Canada). The CDU data (independent from ‘CDU1’ and ‘CDU2’) were obtained from two sources: the original Szeicz and MacDonald (1996) dataset was obtained from the International Tree-Ring Databank (file CANA138); an additional 11 trees sampled by Szeicz and MacDonald, but not published until Esper et al. (2002; see also Frank et al., 2007), were also included. These additional CDU series were provided by D. Frank (Swiss Federal Research Institute, WSL).

The program COFECHA (Holmes, 1983) was used to validate the cross-dating quality of the above mentioned data. Nine of the 49 ESK series contained continuous sections (decades to centuries) of ‘B-type’ errors at the ends of the series indicating that they were potentially misaligned with respect to the master series. The remaining portions of these series were not in question as they were strongly correlated with the master series. As the physical samples were not at our disposal, we could not re-measure the problem sections and assess the cause of these errors (e.g., reaction growth, locally absent rings, etc.). To ensure these potential errors would not bias the mean ESK chronology, the problem sections were excluded from further analysis.

Supplementary Note 2.

For the regional temperature composites (Supplementary Figs. 5-7), monthly temperature records for Tuktoyaktuk, Inuvik, Aklavik, Fort McPherson, Norman Wells, and Fort Good Hope were downloaded from Environment Canada (<http://climate.weatheroffice.gc.ca/>). The Fort McPherson record consists of data from the original ‘Fort McPherson’ station (AD 1892-1977) and the newer ‘Fort McPherson A’ station (AD 1981-2007) ca. 3 km from the original station (É.

1 Mekis, Environment Canada, pers. comm.); only the AD 1892-1977 data are used due to a high
2 number of estimated, missing, or incomplete data points in the new station record. Furthermore,
3 there is no overlap between the new and old stations, making it impossible to identify and adjust
4 for systematic biases due to geographical position. The Fort Good Hope record is a composite of
5 data from the original 'Fort Good Hope 2' station (AD 1897-1966; temperature data available
6 since AD 1908) and the 'Fort Good Hope A' station (AD 1944-2007) ca. 1 km from the original
7 station. The mean and variance of the Fort Good Hope 2 record were adjusted to the Fort Good
8 Hope A record to account for systematic differences due to location, and combined into a mean
9 record. The Mackenzie Delta regional temperature composites (Supplementary Figs. 5-7) were
10 developed by first adjusting the mean and variance of each station record to that of the Inuvik
11 record, and then averaging all records to create regional monthly composites.

12 The regional precipitation composites (Supplementary Fig. 8) were developed from
13 Inuvik, Aklavik, and Fort McPherson data only. The reason only these stations were used is
14 because precipitation is highly variable over short distances in the study region (Burn and
15 Kokelj, 2009), and including stations that are more distant from the site network would diminish
16 the representativeness of the regional composites with respect to our sample trees. Inuvik,
17 Aklavik, and Fort McPherson are the most proximal stations to and are likely most representative
18 of the site network. Precipitation data for Inuvik (1957-2007) and Fort McPherson (1932-2007)
19 were downloaded from the Adjusted and Homogenised Canadian Climate Database
20 (<http://ec.gc.ca/dccha-ahccd>), which are adjusted for gauge changes and trace snow and rainfall
21 events (Mekis and Vincent, 2011). Trace events (< 0.2 mm rain, < 0.2 cm snow) cannot be
22 accurately measured, and are assigned a value of zero and flagged in raw climate records. In
23 Arctic regions, trace events can account for a major proportion of the total monthly precipitation

budget, and trace-adjusted data are an attempt to better reflect actual precipitation amounts. Only raw monthly data were available for Aklavik (AD 1926-2007; <http://climate.weatheroffice.gc.ca/>). However, over the 81 year period of station operation, 432 monthly observations were reported and just 10 of the observations were flagged as trace events. These 10 trace events were excluded from the Aklavik record to make it more comparable to the Inuvik and Fort McPherson records. The Aklavik record was as well correlated with the adjusted Inuvik record as the 2 adjusted records were with each other ($r = 0.43$ and 0.36 , respectively, for the average month; $p \leq 0.05$) suggesting that all 3 records exhibit a similar level of intra-regional coherence. The Mackenzie Delta regional precipitation composites (Supplementary Fig. 8) were developed by first adjusting the mean and variance of the Aklavik and Fort McPherson records to that of the Inuvik record, and averaging the three records to create regional monthly composites.

Supplementary Note 3.

The Szeicz and MacDonald (1995) June-July temperature reconstruction (AD 1638-1988) was obtained from NOAA's Paleoclimatology Program archive (<http://www.ncdc.noaa.gov/paleo/recons.html>) and converted to anomalies with respect to its mean value over the period AD 1638-1988.

Supplementary Note 4.

The 6-study hemispheric-scale composite temperature reconstruction consists of the following reconstructions: Jones et al. (1998); Briffa (2000); Esper et al. (2002); D'Arrigo et al. (2006); Wahl and Ammann (2007); Wilson et al. (2007). The reconstructions were obtained from

NOAA's Paleoclimatology Program archive (<http://www.ncdc.noaa.gov/paleo/recons.html>). The reconstructions are largely tree-ring based, and overall the composite reconstruction is weighted towards samples from the Northern Hemisphere. Z-scores were calculated for each reconstruction based on their common period of overlap (AD 1750-1980) and averaged into the composite index using a robust bi-weight mean. We note that the Szeicz and MacDonald (1996) 'CDU' chronology used in our regional chronology was used by Esper et al. (2002); however, the overall contribution of CDU to the Esper et al.(2002) reconstruction is small, and negligible to the hemispheric-scale composite. As such, our regional chronology and the hemispheric-composite can be considered almost entirely independent of each another.

Supplementary Note 5.

Details on comparison series illustrated in Fig. 5:

- (a) See Supplementary Note 2;
- (b) Ring-width-based June-July mean temperature reconstruction by Szeicz and MacDonald (1995) (see Supplementary Note 3);
- (c) Tree-ring $\delta^{18}\text{O}$ -based April-July minimum temperature reconstruction by Porter et al. (2013; see also Porter et al., 2009). The reconstruction is expressed as anomalies from the long-term mean (AD 1780-2003). The reconstruction was developed from a composite $\delta^{18}\text{O}$ record from 6 white spruce trees from 'TM' site (site 6, Fig. 1), Mackenzie Delta;
- (d) Unaltered OCF-Group 2 ring-width chronology by Porter and Pisaric (2011); regional mean of 11 site-chronologies in Old Crow Flats, northern Yukon Territory, Canada;
- (e) A signal-free version of the Coppermine River ring-width chronology by D'Arrigo et al. (2009), West Nunavut, Canada. The signal-free chronology was calculated by Porter and Pisaric (2011);

(f) 6-study composite hemispheric-scale temperature reconstruction (see Supplementary Note 4);
(g) Circum-Arctic, multi-proxy temperature reconstruction by Kaufman et al. (2009). The original Kaufman et al. (2009) reconstruction uses 23 proxy records, 4 that are tree-ring-based. We used the 19 non-tree-ring series only to calculate the circum-Arctic reconstruction shown in Fig. 5g. The full Kaufman et al. (2009) dataset was obtained from the NOAA Paleoclimatology Program archive (<http://www.ncdc.noaa.gov/paleo/recons.html>). Z-scores for the 19 series were calculated based on their common period of overlap (AD 995-1795) and averaged into a composite index using the robust bi-weight mean (Cook, 1985).

Supplementary Figure 1. An overhead view of a ‘white spruce/crowberry-lichen’ forest site (Pearce et al., 1988) which is representative of most of the delta plain sites sampled in this study. These sites are easy to spot from overhead due to their sparse canopies and abundance of reflective lichen.

Supplementary Figure 2. A representative view of ‘CDU2’. This site is characterised by an open-canopy, thick understory of mosses and lichens, and an irregular, rocky terrain. These site characteristics are also shared by ‘CDU’ and ‘CDU1’ (see also Fig. 2 of Szeicz and MacDonald, 1996).

Supplementary Figure 3. Tree-averaged ring-width indices (light grey) and mean site chronologies (dark grey) for all 29 sites; the number of trees defining each year of the mean site chronologies is indicated (black).

Supplementary Figure 4. Climate stations included in the regional temperature and precipitation composites. Periods of station operation are indicated (n.b., data are not available for all years of operation). ‘Fort McPherson*’ represents two non-overlapping station records: ‘Fort McPherson’ (1892-1977) and ‘Fort McPherson A’ (1981-2007). ‘Fort Good Hope*’ is a merged record representing ‘Fort Good Hope 2’ (1897-1966) and ‘Fort Good Hope A’ (1944-2007).

Supplementary Figure 5. Comparison of monthly minimum temperatures from Tuktoyaktuk, Inuvik, Aklavik, Fort McPherson, Norman Wells, and Fort Good Hope (grey lines); regional means (black lines). ‘rbar’ is the mean inter-series correlation (all are significant at $p \leq 0.001$). ‘trend’ is the slope of the regional mean from AD 1910–2007, a period defined by two or more stations in most cases. See Supplementary Note 2 for more details.

Supplementary Figure 6. Same as Supplementary Fig. 5 but for monthly mean temperatures.

Supplementary Figure 7. Same as Supplementary Fig. 5 but for monthly maximum temperatures.

Supplementary Figure 8. Comparison of total monthly precipitation from Inuvik, Aklavik, and Fort McPherson (grey lines); regional means (black line). ‘rbar’ is the mean inter-series correlation ($*p \leq 0.05$). ‘trend’ is the slope of the regional mean from AD 1932-2007, a period defined by two or more stations in most cases. See Supplementary Note 2 for more details.

Supplementary Figure 9. A comparison of average first-differenced ring-width indices from Group 2 trees and all other trees from the Mackenzie Delta regional site network.

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