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Tree-ring Reconstruction of Early-growing Season Precipitation from Yellowknife, Northwest Territories, Canada

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Abstract

Twelve jack pine (*Pinus banksiana*) tree-ring chronologies were developed from sites on rock outcrops near Yellowknife, Northwest Territories, Canada. The average chronology length is approximately 180 years spanning the period 1825–2005. The longest extends to 1679, whereas the shortest covers the period 1936–2005. All of the site chronologies are significantly correlated with June, total May–July, June–July, and June–August precipitation, although relations with the single month of June are strongest. June precipitation was reconstructed using a regionally averaged tree-ring chronology. The reconstruction captures 42% of the variance in the instrumental climate record and based on Rbar and EPS statistics is considered robust from 1819 to 2005. Periods of lower June precipitation occurred in 1927–1979, 1880–1893, 1842–1865, 1801–1821, 1776–1796, and 1698–1739. Positive June precipitation anomalies are reconstructed for 1980–1995, 1890–1926, 1822–1841, 1756–1775, and 1687–1697. Throughout the period of reconstruction, there is strong multi-decadal agreement between June precipitation in Yellowknife and other dendrohydrological records from western North America and records of Pacific climate variability. This suggests that large-scale atmospheric patterns influenced by sea surface temperatures (SSTs) in the Pacific basin have controlled continental-scale precipitation patterns at decadal time scales in the Yellowknife region over the past three centuries or more.

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Introduction

Circumpolar regions are expected to experience the most significant impacts of changing climatic conditions during the 21st century (ACIA, 2005). Projections of future hydrologic variability suggest many regions of northern Canada will experience significant increases (+10–40%) in precipitation and runoff by the year 2050 (Milly et al., 2005). Recent studies of river discharge from across the circumpolar north indicate annual flows have increased in response to changes in precipitation, permafrost degradation, or ground water contributions (Peterson et al., 2002; McClelland et al., 2006; Smith et al., 2007; Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009). The records of climate and environmental variability that many of these projections are based upon are sparse and of relatively short duration, and they may capture only a small portion of the spatial and temporal climatic variability possible for a given region (MacDonald, 2007). Paleoenvironmental records, such as those provided by tree-rings, can extend hydroclimatic records to the past several centuries and in some cases millennia (Woodhouse and Overpeck, 1998; Cook et al., 2004). These proxy data may supplement instrumental records providing opportunities to identify climate-forcing mechanisms and improve our understanding of the natural variability inherent in these systems.

Tree-ring–based reconstructions of past climate from northwest Canada have focused on variability in temperature, but statistically robust and annually-resolved records of past hydrologic variability are largely absent. Szeicz and MacDonald (1996) constructed a 930-year moisture-sensitive tree-ring chronology from an upland site near Inuvik, Northwest Territories (NWT), but a statistical reconstruction was not developed because tree growth was sensitive to the combined effects of temperature and precipitation. Stockton and Fritts (1973) and Meko (2002, 2006) reconstructed water levels for Lake Athabasca by studying white spruce (*Picea glauca* (Moench) Voss) trees growing along natural levees in the Peace-Athabasca delta region. Stockton and Fritts (1973) found growth records to be correlated with 10-day mean lake levels for three different sub-periods of the year (21–30 May, 11–20 July, and 21–30 September). Naturally low water levels were noted in the 1860s and the 1940s before closure of the Bennett Dam gates along the upper reaches of the Peace River in 1967 (Stockton and Fritts, 1973). Using a much larger 54-site tree-ring network, Meko (2002, 2006) reconstructed (1) water levels of Lake Athabasca for the period 11–20 July; (2) Peace River annual flow; and (3) Athabasca River annual flow. Meko (2002, 2006) reconstructed low levels for Lake Athabasca during the 1880–1890s, 1940s, and early 1980s. Periods of high lake levels were reconstructed for approximately 1850, 1930s, and 1960s.

Recent investigations from northwest Canada and Alaska suggest that a number of previously identified temperature-sensitive tree-ring chronologies are displaying increased moisture sensitivity under current warming trends (Barber et al., 2000; D'Arrigo et al., 2004; Wilmking, et al., 2004; Pisaric et al., 2007). Reconstructions of precipitation using these series are generally not possible given the climate-growth relationships do not appear to be stationary through time.

Cook et al. (2004) developed reconstructions of the Palmer Drought Severity Index (PDSI) for a large portion of North America, including three grid points (62, 77, and 93) near Yellowknife, NWT. While the network of precipitation sensitive tree-ring chronologies is extremely dense over most of the western

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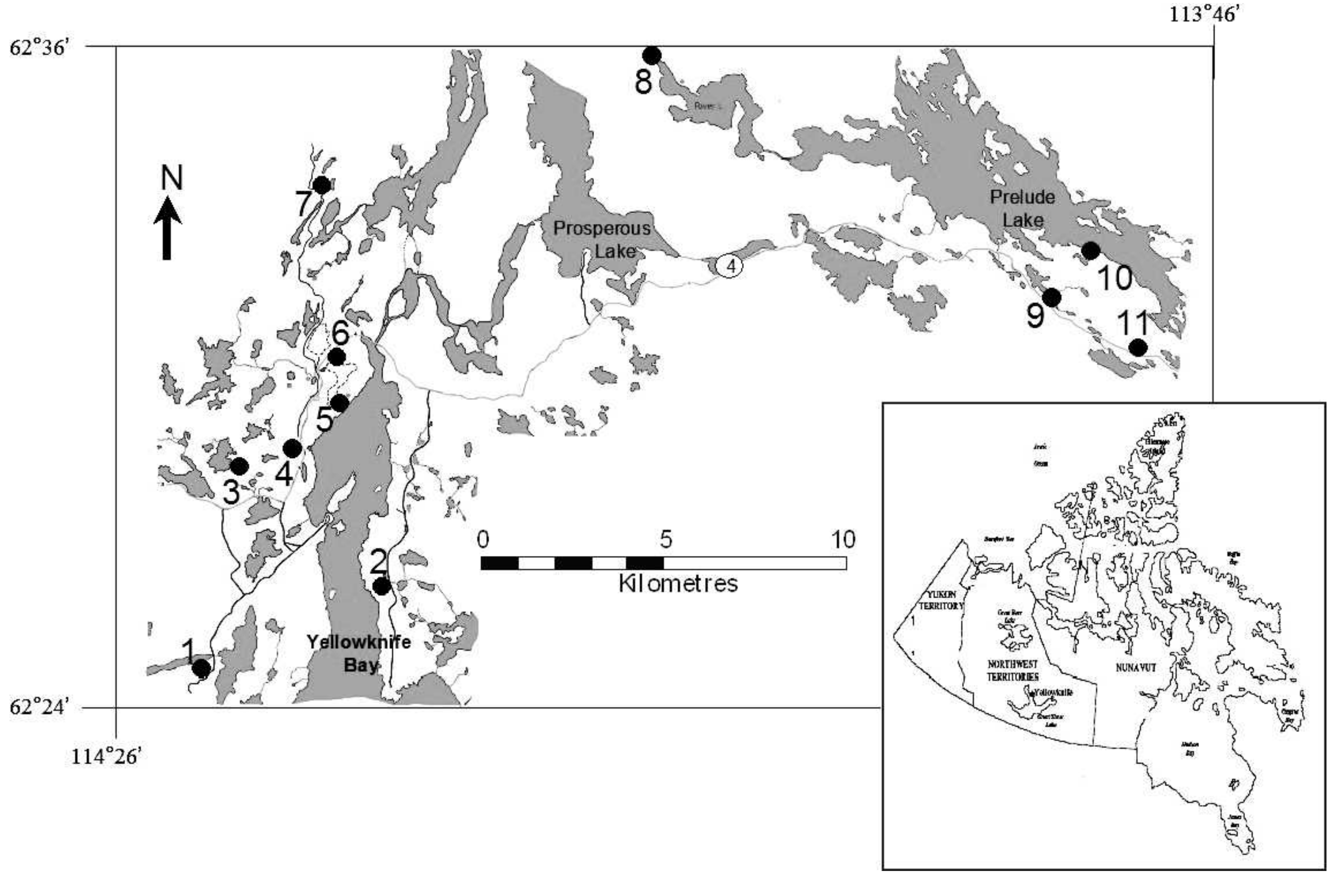

FIGURE 1. Map of the study area. Sites are as follows: (1) KAM, (2) DETT, (3) FOX, (4) APIT, (5) CEN, (6) SET, (7) SHA, (8) RIV, (9) PREE, (10) PRE, (11) ING. Site Fifty Kilometers (FIF) is not shown. It is located approximately 30 km east southeast of (11) along the Ingraham Trail (Highway 4).

United States and southern Canada (Cook et al., 2004), few chronologies exist for the Yellowknife region, reducing the quality of those PDSI reconstructions.

In this study, we demonstrate that long-lived jack pine (*Pinus banksiana* Lamb.) growing on rock outcrops in the North Slave region near Yellowknife, NWT, can provide long and statistically robust dendrohydrological reconstructions of precipitation. The reconstruction of June precipitation, developed from ring width measurements from 12 sites, spans the period from 1680 to 2005, although it is considered statistically robust from 1819 to 2005. This constitutes one of the longest and most statistically robust dendrohydrological reconstructions from northern Canada.

Site Description and Methodology

The sample sites are located within a 50-km radius of Yellowknife, NWT (Fig. 1, Table 1) within the Taiga Shield High Boreal (HB) ecoregion and in particular the Great Slave Upland (HB) ecoregion (Ecosystem Classification Group, 2008). Forests in the region are typical open subarctic woodlands dominated by black spruce (*Picea mariana* (Mill) B.S.P.), white spruce, tamarack (*Larix laricina* (Du Roi) K. Koch), and white birch (*Betula papyrifera* Marsh.). Jack pine is common on upland, rock outcrops where sampling was focused.

The region is underlain by discontinuous permafrost. Precambrian Shield outcrops are abundant in the study area, covered in many areas by a thin and discontinuous veneer of till (Kerr, 2006). All sites are found between 175 and 228 m above sea level (a.s.l.) (Table 1). Ground vegetation at most of the sites is dominated by lichens (*Umbilicaria hyperborean*, *Cladina mitis*, *Cladonia* spp., and *Flavocetraria nivalis*) and moss (*Tomenthypnum nitens*).

Climate of the Yellowknife region is characterized by cool summers and cold winters (Fig. 2). Mean July temperature is 17 °C and mean January temperature is approximately −27 °C (1971–2000) (http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html). Mean annual precipitation is 281 mm (1971–2000) with approximately half of it falling as snow. Snow cover typically begins in October and persists into late April or early May (Wedel et al., 1990). Summer precipitation is variable from year-to-year because much of it results from convective thunderstorm activity (Spence and Woo, 2003). On average, 36% of annual precipitation falls during the summer months, but this may vary as a proportion of total precipitation from as little as 11% to as much as 59% (1943–2005). Similarly, June precipitation accounts for nearly 25% of total summer (June–August) precipitation on average, but has varied from less than 1% to as much as 61% of total summer precipitation during the instrumental period (1943–2005).

CHRONOLOGY DEVELOPMENT

To develop the dendrohydrological reconstruction of precipitation, increment cores were collected during the summer of 2006. At each site, 25–40 trees were cored using a Hagloff increment borer (internal diameter ~4.3 mm). A minimum of two cores were obtained at breast height from opposite sides of the tree.

TABLE 1

Summary statistics for tree-ring chronologies from the Yellowknife region, Northwest Territories, Canada. Numbers in parentheses after site names correspond to locations in Figure 1.

Site Name	Latitude	Longitude	Elevation (m a.s.l.)	Chronology interval	*n**	Series intercorrelation	Mean ring width (mm)	Mean sensitivity	Autocorrelation**
Shadow Lake (7)	62°34′00.5″	114°21′29.4″	209	1868–2005	54	0.633	0.470	0.428	0.504
Settling Pond (6)	62°30′49.3″	114°20′54.2″	189	1861–2005	58	0.673	0.540	0.385	0.498
Central Pond (5)	62°30′12.1″	114°20′31.6″	194	1862–2005	47	0.662	0.560	0.410	0.419
APIT (4)	62°29′14.8″	114°22′20.5″	211	1858–2005	54	0.690	0.380	0.435	0.318
Fox Lake (3)	62°28′43.0″	114°24′43.0″	208	1679–2005	48	0.691	0.390	0.395	0.481
Kam Lake (1)	62°25′04.1″	114°25′12.0″	175	1827–2005	49	0.684	0.390	0.406	0.180
Dettah Road (2)	62°28′23.0″	114°18′06.0″	191	1800–2005	31	0.703	0.560	0.383	0.423
River Lake (8)	62°36′23.4″	114°08′05.6″	195	1828–2005	60	0.664	0.480	0.338	0.258
Prelude Lake (10)	62°33′12.9″	113°51′22.5″	197	1853–2005	47	0.712	0.480	0.363	0.287
Prelude Lake East (9)	62°31′26.5″	113°49′16.0″	199	1936–2005	44	0.691	0.750	0.354	0.316
Ingraham Trail (11)	62°33′03.6″	113°52′07.4″	214	1734–2005	58	0.705	0.580	0.366	0.360
Fifty kilometres	62°29′36.6″	113°26′07.5″	228	1791–2005	48	0.715	0.410	0.335	0.296

* Number of series.

** Autocorrelation of each site chronology (standard chronology) was adjusted using the methods of Meko et al. (2001) so the autocorrelation of the tree-ring records matched that of the instrumental climate data.

Preparation and analysis of the tree cores followed standard dendrochronological methods (Stokes and Smiley, 1968; Fritts, 1976). Cores were visually cross-dated and marker rings were recorded following the list method of Yamaguchi (1991). Cross-dated samples were measured using a Velmex UniSlide traversing table and digital encoder with an accuracy of 0.001 mm. Visual cross-dating was checked using the software program COFECHA (Holmes, 1983). Site chronologies were standardized using conservative detrending methods and the software program ARSTAN (Cook and Holmes, 1986). To measure the strength of the common signal between samples from individual sites, the series intercorrelation was determined by averaging the correlation of each individual series with the site master chronology (Holmes, 1983). The mean sensitivity for each site chronology was also determined as the relative difference in ring width from one year to the next. Mean sensitivity can vary from 0 (no difference) to 2 (repeating pattern of alternating narrow and wide rings) (Fritts, 1976). The agreement between site chronologies was examined using Principal Components Analysis (PCA) during the period of common overlap (1874–2005) for the 11 longest chronologies.

In an effort to maximize the length of the reconstruction and produce a statistically robust regional chronology, master chronologies were developed using two different methodologies.

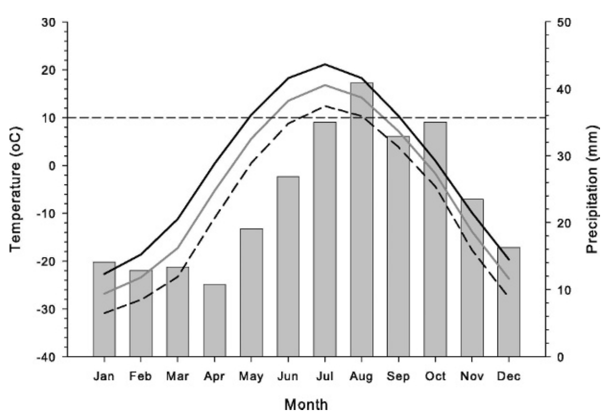

FIGURE 2. Climograph of mean, maximum, and minimum monthly temperature and total monthly precipitation recorded at Yellowknife Airport (1943–2005).

(1) *Yellowknife master 1*: Site chronologies were constructed for each of the 12 sampling sites using the computer program ARSTAN. Following the methods of Meko (2002), a sample-size-weighted mean chronology (SSWMC) was developed. In this method, the resultant master chronology is a weighted mean of all the available chronologies in that year with the weight being proportional to the number of trees in each particular chronology. Complete details regarding the computation of the SSWMC can be found in Meko (2002). (2) *Yellowknife master 2*: Using the site chronologies developed with ARSTAN, PCA (Varimax rotation) was utilized to develop a master chronology; however, the shortest chronology (PREE) was excluded to maximize the length of the PCA-derived master chronology. While this resulted in a much shorter master chronology than method 1 (SSWMC), it afforded the opportunity to compare the two regional series to assess the similarity and robustness of the chronology development procedures by calculating a Pearson correlation between the two master chronologies.

Results

CHRONOLOGY CHARACTERISTICS

Summary statistics for the 12 jack pine chronologies are presented in Table 1. The longest chronology spans the period 1679–2005 (Fox Lake), while the shortest extends from 1936 to 2005 (Prelude Lake East). The average time span covered by all of the chronologies is approximately 1825–2005. Series intercorrelation for all sites is high (Table 1), suggesting a common growth signal within respective sites. Correlations between all 12 chronologies over the common period of overlap (1936–2005) are high (mean $r = 0.715$) (Table 2), indicating that the common signal also persists across the study region. Similarly, PCA of the site chronologies indicates the weights of individual chronologies are relatively evenly distributed across the sampling sites (Table 2). The first PC explains a significant amount of variance in the data set (50.9%). The analyses both support a common regional signal in tree growth that is likely climatically controlled.

Annual growth at the 12 jack pine sites is low as indicated by the small annual growth increment (Table 1). Mean ring width among the sites varies from 0.380 mm at APIT to 0.750 mm at Prelude Lake East (PREE). PREE has the youngest trees which

TABLE 2

Correlations between Jack pine chronologies for the Yellowknife region, Northwest Territories. The common period used in the analysis spans 1936–2005 ($n = 70$). All correlations are significant at $p \leq 0.05$. *Principal Components Analysis (Varimax rotation) of the 11 longest site chronologies for the common period of overlap (1874–2005); values are the coefficients of tree growth for PC1 for each of the site chronologies. The variance explained by PC1 is 50.9%.

	APIT	CEN	DETT	FIF	FOX	ING	KAM	PRE	RIV	SET	SHA	PREE	PCA*
APIT	—	0.865	0.878	0.473	0.900	0.638	0.849	0.635	0.714	0.817	0.832	0.661	0.867
CEN		—	0.770	0.437	0.817	0.582	0.835	0.633	0.716	0.878	0.743	0.620	0.840
DETT			—	0.512	0.899	0.705	0.899	0.665	0.682	0.794	0.823	0.676	0.869
FIF				—	0.473	0.747	0.475	0. 803	0.604	0.546	0.541	0.662	0.347
FOX					—	0.630	0.877	0.593	0. 720	0.781	0.785	0.607	0.803
ING						—	0.672	0.903	0.709	0.678	0.716	0.832	0.281
KAM							—	0.653	0.760	0.835	0.742	0.696	0.797
PRE								—	0.728	0.713	0.701	0.838	0.356
RIV									—	0.770	0.690	0.695	0.713
SET										—	0.814	0.713	0.763
SHA											—	0.645	0.765
PREE												—	—

- 1.00
>0.900
0.710-0.899
0.500-0.709
0.300-0.499

consist of a greater proportion of juvenile growth than the series from most of the other sites. Regardless, PREE still correlates relatively well with nearly all of the other 11 site chronologies (mean $r = 0.695$) (Table 2).

Ring widths exhibit considerable variability from one year to the next as indicated by the mean sensitivity for the sites which varies from 0.335 to 0.435. Based on data housed at the International Tree-ring Databank (ITRDB), mean sensitivities reported here are higher than those for white spruce growing near treeline at comparable latitudes in Yukon Territory and Alaska which are typically around 0.200. Year-to-year variability in ring width is also supported by the first-order autocorrelation for the 12 sites, which ranges from 0.180 to 0.504 for the standard chronologies. These values are also lower than those typical of white spruce populations in northwest North America (typically >0.750) (based on data from the ITRDB). These lower autocorrelation values suggest that year-to-year variability in the Yellowknife jack pine chronologies is greater and the long-term, low frequency variability is lower than reported for northern white spruce populations. While autocorrelation of the jack pine chronologies is low in comparison to other northern tree species, it is still considerably higher than the autocorrelation in the Yellowknife instrumental precipitation record. For example, first-order autocorrelation for June precipitation (1943–2005) is −0.04. Therefore, autocorrelation of the individual site chronologies was adjusted to match that in the instrumental record (*sensu* Meko et al., 2001).

Considering the strong correlations between the 12 site chronologies, the similar responses to climate across the region (see below and Table 3), and the relatively even distribution of site chronologies on PC1, individual series from each of the 12 sites were combined using the SSWMC procedure to construct a single regional jack pine chronology for Yellowknife spanning from 1680 to 2005. The strong correlation between the PCA-derived and sample-size-weighted mean chronologies ($r = 0.757$; $p \leq 0.05$) (Fig. 3a) suggests the SSWMC (Fig. 3b) is a robust and valid record of tree growth for the region, and subsequently was used to develop the dendrohydrological reconstruction of June precipitation described below.

The strength of the common signal in the regional chronology was assessed using the running series of average correlation (Rbar) (Fig. 3c) and the expressed population signal (EPS) statistics (Wigley et al., 1984) (Fig. 3d). The Rbar statistic was truncated at 1819, prior to which it was highly variable. From 1819 onwards the Rbar statistic is generally consistent at ~0.3. The EPS statistic is a measure of how well a composite chronology reflects a hypothetically perfect chronology, with values above 0.85 generally acceptable (Briffa and Jones, 1990). The running EPS statistic is above 0.85 from 1819 onwards. Prior to 1819, EPS falls below 0.85 as sample depth declines to 10 series or less. These statistics indicate that 1819 can be considered an acceptable cutoff for the Yellowknife precipitation reconstruction. However, we present the full reconstruction spanning the period 1680–2005 because (1) the correlation is high between the SSWMC and the PCA-derived chronology during the period of overlap, and (2) it shares compelling similarities with other dendrohydrological reconstructions from Canada and the United States as discussed below.

TREE-RING/CLIMATE RELATIONSHIPS

Precipitation and temperature records from Yellowknife Airport (1943–2005) were used to evaluate the climate signal contained in the 12 site chronologies (Table 3). The adjusted precipitation and homogenized temperature records were utilized since both have been corrected for inhomogeneities and missing data (Mekis and Hogg, 1999; Vincent and Gullett, 1999). Adjusted climate data for Yellowknife Airport are available from the Adjusted Historical Canadian Climate Data (AHCCD) web site (http://www.cccma.ec.gc.ca/hccd/). Pearson correlations were computed between each of the 12 site chronologies and monthly precipitation and temperature records for the 20-month period from the previous May to December of the current growing season. Seasonal (e.g., May–July precipitation) and annualized precipitation (12 month periods; e.g., $_{previous}$July–June, $_{previous}$August–July) indices were also developed and correlations were computed for these indices and the 12 site chronologies and the SSWMC (Table 3a). Ring width and June precipitation consistently showed the strongest correlations. Growing or summer season precipitation indices (total May–July, June–July, and June–August precipitation) were also highly correlated with the individual site chronologies and the regional chronology.

TABLE 3

Pearson correlation coefficients for significant relations between the Yellowknife regional Jack pine chronology (SSWMC) and monthly (a) precipitation totals and (b) mean temperatures recorded at the Yellowknife Airport. Period of correlation analysis with temperature and precipitation is 1943–2005. (c) Palmer Drought Severity Index (PDSI) values for three grid points near Yellowknife. Instrumental PDSI data from Cook et al. (2004); period of correlation analysis between tree-ring chronologies and PDSI data is 1900–1990. Only significant correlations ($p < 0.05$) are shown.

	APIT	CEN	DETT	FIF	FOX	ING	KAM	PRE	RIV	SET	SHA	PREE	SSWMC
(a) Precipitation													
JUN	**0.506**	**0.519**	**0.590**	**0.523**	**0.488**	**0.614**	**0.653**	**0.699**	**0.473**	**0.538**	**0.466**	**0.569**	**0.648**
JUL	0.262	0.252						0.250		0.313	0.302		0.277
AUGUST				−0.258									
ANNUAL						0.278		0.317					
JUN–JUL	0.487	0.486	0.487	0.428	0.445	0.500	0.517	0.574	0.416	0.544	0.495	0.438	0.577
MAY–JUL	0.468	0.457	0.465	0.467	0.425	0.534	0.490	0.592	0.451	0.549	0.506	0.485	0.584
JUN–AUG	0.257		0.277			0.292	0.337	0.313			0.258		0.287
$_{\text{previous}}$JUL–JUN				0.386		0.352		0.393	0.283	0.253			0.263
$_{\text{previous}}$AUG–JUL				0.417		0.385		0.446	0.320	0.350	0.283	0.259	0.343
(b) Temperature													
JAN	0.277	0.321	0.251		0.257						0.321		0.269
AUG	0.296	0.291	0.252		0.263			0.259				0.334	0.255
(c) PDSI													
Grid point 62				0.249		0.296		0.357		0.246			0.231
Grid point 77				0.260		0.301		0.367		0.245			0.236
Grid point 93				0.270		0.306		0.375		0.243			0.241

Previous studies investigating hydrologic controls on tree growth have found that annualized data incorporating precipitation contributions over more than one growing season are often more strongly correlated and explain a higher percentage of variance in tree-ring records (e.g., Case and MacDonald, 1995; Sauchyn and Beaudoin, 1998; Watson and Luckman, 2001; St. George and Nielson, 2002). This was tested using the Yellowknife jack pine chronologies and calculating correlations between tree growth and precipitation over two growing seasons (e.g., $_{\text{previous}}$July–June). While the regional chronology did correlate with various annualized periods, it did not result in stronger relations than that of June precipitation or the growing season precipitation indices (Table 3). Furthermore, when individual sites were analyzed, the relations were not consistent across all sites, unlike the June and the combined June–July index.

Correlations between ring width and monthly temperatures were also calculated over the same 20-month period (Table 3b). The months of January and August were the only months that had significant relationships with tree growth over the period of overlap (1943–2005). Seven of the 12 site chronologies had positive and significant ($p \leq 0.05$) correlations with January temperatures while only 3 of the 12 had significant correlations with August temperatures (Table 3).

Instrumental and reconstructed PDSI data were obtained from North American Drought Atlas website (http://iridl.ldeo.columbia.edu/SOURCES/.LDEO/.TRL/.NADA2004/.pdsi-atlas.html). The PDSI are averaged values for the summer months (June–July–August) and generally fall between +6 and −6. Several of the individual site chronologies are significantly correlated with the instrumental PDSI records for the Yellowknife region (Table 3). The SSWMC is also correlated with PDSI for the three grid points near Yellowknife, but the correlations are weaker than for June precipitation.

CLIMATE RECONSTRUCTION

Based on the correlation analysis presented in Table 3, a reconstruction of June precipitation was developed using the SSWMC. Given the lack of autocorrelation in June precipitation in the Yellowknife region, lagged predictors were not included as potential predictors in the regression analysis. Since instrumental climate data for Yellowknife is only available since 1943, a leave-one-out cross validation procedure was used to evaluate the skill of the model (Gordon, 1982). The regression model using only the SSWMC as a predictor explains approximately 42% (R^2_{adj}) of the variance in the instrumental record during the full calibration period.

MODEL VERIFICATION

The reconstruction model for the full period (1943–2005) took the form:

$$J = -21.1 + 42.9\ (YK), \qquad (1)$$

where J is June precipitation and YK is the Yellowknife regional jack pine tree-ring chronology. To test the stability of the model and the relationship with June precipitation through time, the leave-one-out validation scheme was utilized (Gordon, 1982).

The calibration and verification statistics are provided in Table 4. The full model passed all of the independent verification statistics that were used ($p \leq 0.05$). A positive value for the reduction of error (RE) statistic indicates that the model possesses reconstructive skill and that meaningful climatic information exists within the reconstruction (Fritts, 1976). The Durbin-Watson statistic of 1.94 suggests there is no issue of autocorrelation in the residuals during the calibration period. Since the full model demonstrated significant abilities at predicting June precipitation during the leave-one-out process, we consider the transfer function to be robust and time stable. Subsequently, the model developed above was used to reconstruct June precipitation back to 1680.

Figure 4 shows that there is good correspondence between the reconstructed values and the instrumental June precipitation data throughout the period of overlap ($r = 0.654$). Mean June precipitation is 26.9 mm for the instrumental record and 23.3 mm for the reconstructed data during the period 1971–2000. The

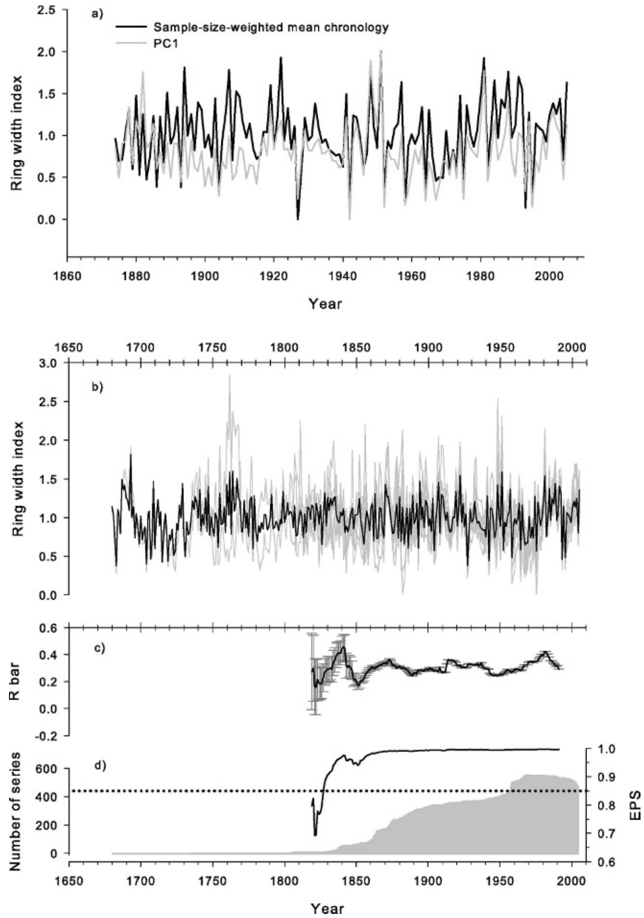

FIGURE 3. (a) Two jack pine master chronologies developed for Yellowknife using the Sample-size-weighted mean chronology (SSWMC) and Principal Components (1874–2005). The correlation between the series during the period of overlap is $r = 0.730$ ($p \leq 0.05$). (b) Jack pine standard chronology for Yellowknife region. Thick black line is the SSWMC chronology based on the 12 site chronologies, while the thin gray lines are the individual site chronologies highlighting the variability between sites. (c) Running Rbar and (d) expressed population signal (EPS) and sample depth. The Rbar and EPS values were computed using a 30-yr moving window advanced 1 year. The gray bars on the Rbar plot are two standard errors. The shaded gray area in (d) is the number of individual tree-ring series in the regional chronology through time.

instrumental and reconstructed June precipitation records also share similar autocorrelation signatures: −0.04 for the instrumental data and −0.15 for the reconstructed values (1943–2005). The reconstruction is particularly effective during the period 1943–1995 where broader trends in the instrumental data are captured quite well. A series of high June precipitation values (1984, 1988, and 1991) are not reconstructed well by the tree rings. Similar difficulties have been noted in other hydrological reconstructions (e.g., Graumlich et al., 2003), probably in response to decreased sensitivity of tree growth to above-average growing conditions. A return to average June precipitation values after 1991 is captured by the tree rings, but they fail to closely track the year-to-year variability with much skill until 2003 (Fig. 4).

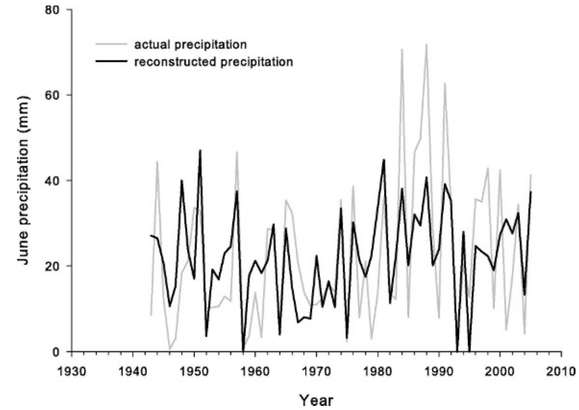

FIGURE 4. A comparison of the tree-ring reconstructed total June precipitation and the instrumental data from Yellowknife Airport during the 1943-2005 calibration period. Correlation between the predicted and actual June precipitation is $r = 0.65$ ($p \leq 0.05$).

The reconstruction of June precipitation (presented as anomalies from the 1680–2005 mean) is presented in Figure 5a. The 326-year June precipitation reconstruction for the Yellowknife region extends the precipitation record by more than 260 years. Mean June precipitation for the full reconstruction (1680–2005) is 21.7 mm. Over the reconstructed period, the most prolonged period of dry anomalies was the mid-20th century. During the 1927 to 1976 period, June precipitation anomalies were consistently negative, in particular, from 1958 to 1976. The driest June during the entire record was found to be 1927 (Table 5). Other notable periods of extended negative June precipitation anomalies include 1879–1893, 1842–1865, 1776–1796, and 1698–1735. Periods of positive June precipitation anomalies include 1976–2005, 1894–1926, 1822–1841, and 1756–1775. These prolonged periods of above/below average precipitation coincide with similar dry/wet episodes in dendrohydrological reconstructions from western Canada, the Prairies, and parts of the United States at multi-decadal time scales (Figs. 5a–5e). It also displays coherence with a record of Pacific climate variability suggesting

TABLE 4

Calibration and verification statistics for Yellowknife June precipitation reconstruction model[a]

Calibration period	Standard error	R[b]	R^2adj[c]	Verification period	r[d]	RE[e]	Sign test (agree/disagree)	Durbin-Watson[f]
1943–2005	6.41	0.427	0.418	1943–2005	0.623	0.39	45/17**	1.94

[a] All reported statistics are significant at $p \leq 0.05$ except ** which is significant at $p \leq 0.01$.
[b] R, multiple correlation coefficient.
[c] R^2adj, multiple correlation coefficient adjusted for degrees of freedom.
[d] r, correlation coefficient between model and observational data.
[e] RE, Reduction of error (values > 0 considered acceptable).
[f] Statistically significant serial autocorrelation is not present in the residuals.
Full Model: June precipitation = −21.1 + 42.9 * Yellowknife regional chronology.

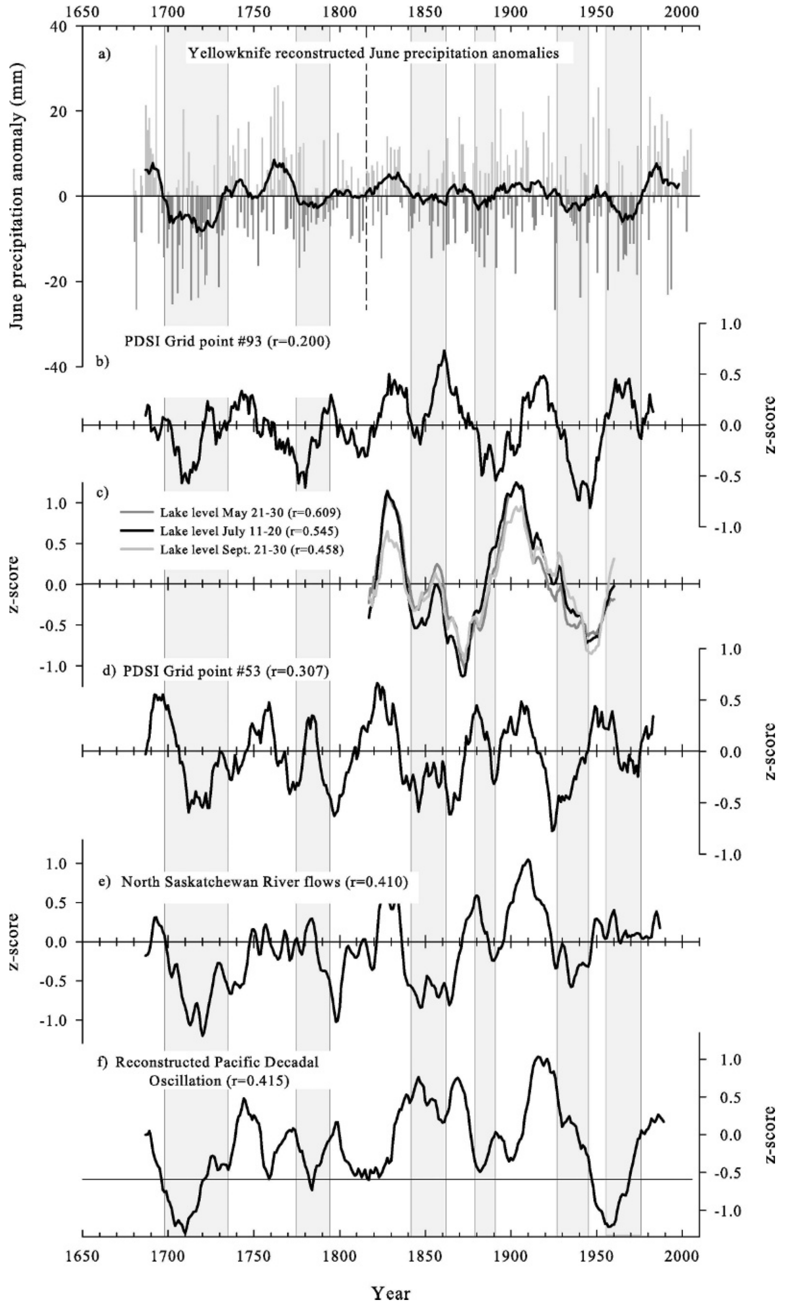

FIGURE 5. Time series plots of dendrohydrological reconstructions and Pacific climate variability for select regions of North America. All series are presented as z-scores (smoothed with a 15-year moving average), except the Yellowknife June precipitation reconstruction which shows anomalies with respect to 1680–2005 mean. The time series are as follows: (a) Yellowknife June precipitation reconstruction (this study). The vertical dashed line separates the portion of the reconstruction that is statistically robust based on EPS and Rbar statistics (1819–2005). Prior to 1819 the reconstruction is less robust. (b) PDSI Grid point 93 (Cook et al., 2004); (c) Lake Athabasca water level for three time periods (Stockton and Fritts, 1973); (d) PDSI Grid point 53 (Cook et al., 2004); (e) North Saskatchewan riverflow (Case and MacDonald, 2003); and (f) Reconstructed Pacific Decadal Oscillation Index (MacDonald and Case, 2005). The gray shaded columns indicate periods of extended negative June precipitation anomalies in the Yellowknife reconstruction. Numbers in brackets indicate the Pearson's correlation coefficient and significance level for the smoothed time series and the Yellowknife precipitation reconstruction. Significance levels were adjusted for decreased degrees of freedom that resulted from smoothing the time series with a 15-year moving average.

some climatic forcing originates in the Pacific basin (Fig. 5f). The instrumental climate record from Yellowknife also shows coherence with Pacific climate variability (Table 6), suggesting that coherence with the proxy record is not simply an artifact of the tree-ring reconstruction. Five-year averages of June precipitation from Yellowknife Airport are highly correlated with similarly averaged values of the Pacific Decadal Oscillation (PDO) Index for numerous months of the year and annually (Table 6). The highest and most consistent relations with the monthly PDO index values are with precipitation during the months of February, May, and June.

Discussion

Jack pine grows farther north than any other pine species in North America and is the most widely distributed pine across Canada (Burns and Honkala, 1990). In north-central Canada, it grows almost to treeline and dominates throughout much of its range on rock outcrops with little or no soil. The accessibility of the Yellowknife sampling sites combined with the fact that individual trees commonly attained ages of >150 years make this species attractive for dendrohydrological investigations in the northern Canadian Shield where instrumental records are sparse and typically span only the last half century or less. The reconstruction developed here extends the June precipitation record for Yellowknife (North Slave Region) by >260 years.

CLIMATE-GROWTH RELATIONS

Correlation analysis between the jack pine site chronologies and climate data from Yellowknife Airport suggests that a significant portion of variability in annual growth is determined by precipitation during the month of June (Table 3). Similar but slightly weaker correlations are noted with total precipitation for the periods May–July, June–July, and June–August, indicating the annual growth increment is influenced by precipitation falling

TABLE 5

Extreme June precipitation values in the reconstructed time series, 1680–2005. (Values in brackets predate 1819 when sample replication is low and should be interpreted with caution.)

Wettest years		Driest years	
Year	Deviation	Year	Deviation
2.0 SD above or below the 1680–2005 mean			
(1693)	3.40	1927	−2.56
(1764)	2.50	(1683)	−2.55
(1762)	2.45	(1704)	−2.44
1951	2.45	(1715)	−2.35
1922	2.26	(1719)	−2.29
1981	2.24	1942	−2.27
(1767)	2.14	1993	−2.22
(1687)	2.05	(1707)	−2.19
		1958	−2.12
		1995	−2.10
		(1731)	−2.05
1.5–2.0 SD above or below the 1680–2005 mean			
1894	1.96	(1723)	−2.00
(1709)	1.96	(1724)	−1.77
1907	1.89	1975	−1.76
1988	1.84	1904	−1.75
(1729)	1.83	1952	−1.73
(1760)	1.79	1964	−1.69
1870	1.79	(1710)	−1.64
1948	1.77	1893	−1.61
(1689)	1.77	(1778)	−1.61
1991	1.69	1886	−1.60
(1747)	1.68	(1754)	−1.56
1984	1.59		
1957	1.53		
(1741)	1.52		
2005	1.51		

throughout the short growing season and not just the single month of June. It is interesting to note that only a few of the individual site chronologies are significantly correlated with annualized precipitation indices across 12-month periods (e.g., $_{\text{previous}}$July–June, $_{\text{previous}}$August–July) (Table 3). These annualized indices often incorporate climatic inputs during two growing seasons while also including the contribution of non-growing season precipitation which can be important for soil moisture recharge and availability during the growing season (Case and MacDonald, 1995). In Yellowknife, the last day with measureable snow on the ground averages 4 May (earliest 22 April; latest 15 May; 1943–2005), while the date at which mean monthly temperatures generally rise above 10 °C is approximately 3 June (http://www.climate.weather office.ec.gc.ca/climate_normals/index_e.html) (1943–2005). Ko Heinrichs et al. (2007) determined the onset of jack pine growth near Lac Duparquet, Quebec, commenced in mid-May when mean temperatures fluctuated widely, but were generally above 10 °C. Fluctuating air temperatures and increasing day length can promote bud burst and signal the onset of cambial reactivation and xylem cell production (Partanen et al., 1998). In Yellowknife, similar temperature conditions generally do not occur until early June, several weeks after the snow has melted and moisture on outcrops has been lost to runoff or evaporation.

The potential decoupling of snowmelt and the onset of the growing season has implications for jack pine phenological processes. Zahner (1968) suggested that a lack of adequate moisture is most important during early wood cell growth. The asynchrony between snowmelt and the onset of the growing season could result in moisture stress early in the growing season, inhibiting photosynthetic activity and protein production and ultimately reduce the resources for early wood formation and overall ring width. The correlation analyses appear to support this idea since no winter season precipitation series were significantly correlated with the site chronologies (Table 3). This is in contrast with the Campbell Dolomite Uplands in northwest NWT (Szeicz and MacDonald, 1996) where snowmelt occurs several weeks later and can provide important moisture supplies for early season tree growth. The strong response to precipitation conditions during the single month of June may be a unique feature of precipitation-sensitive trees from northern sites in contrast to those from more southerly latitudes which are able to respond to a longer growing season.

JUNE PRECIPITATION 1819–2005

From 1819 to 2003 there is good agreement between the Yellowknife precipitation reconstruction and multi-decadal variability in records from other regions of North America and the Pacific basin (Fig. 5). The period of negative precipitation anomalies reconstructed for Yellowknife from ~1840–1865 broadly coincides with dry conditions in other parts of Canada and the United States, including reconstructed PDSI values for the

TABLE 6

Pearson correlation coefficients for significant relations between Yellowknife Airport monthly precipitation totals and monthly Pacific Decadal Oscillation Index values (http://jisao.washington.edu/pdo/ PDO.latest). Both series are 5-year averages and the period of the correlation analysis is 1943–2005. Only significant correlations ($p < 0.05$) are shown. Significance levels were adjusted for decreased degrees of freedom that resulted from smoothing the time series with a 5-year moving average.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$_{\text{PDO}}$JAN	0.318	0.605		0.286	0.335	0.502	0.322			0.364	0.282	
$_{\text{PDO}}$FEB	0.274	0.505		0.303	0.378	0.500				0.373		−0.323
$_{\text{PDO}}$MAR		0.424			0.420	0.562						−0.340
$_{\text{PDO}}$APR		0.417			0.408	0.551		−0.346		0.290		−0.302
$_{\text{PDO}}$MAY		0.420	0.395	0.281	0.504	0.467		−0.344	0.366			
$_{\text{PDO}}$JUN		0.427	0.441	0.338	0.425	0.409		−0.371	0.335			
$_{\text{PDO}}$JUL		0.432			0.468	0.617		−0.332				
$_{\text{PDO}}$AUG		0.420	0.278		0.553	0.602						
$_{\text{PDO}}$SEP		0.368			0.510	0.586						
$_{\text{PDO}}$OCT		0.374			0.644	0.392				0.338		
$_{\text{PDO}}$NOV		0.428			0.627	0.522				0.369		
$_{\text{PDO}}$DEC		0.467			0.516	0.500						−0.282
$_{\text{PDO}}$ANNUAL		0.490		0.273	0.522	0.573		−0.275		0.280		

Yellowknife region (Fig. 5b) (Cook et al., 2004). Lake Athabasca water levels from 1866 to 1868 were found to be the lowest during the reconstructed period (1810–1967) (Stockton and Fritts, 1973) (Fig. 5c), and Case and MacDonald (2003) reconstructed low flows on the North Saskatchewan River from 1841 to 1873 (Fig. 5d). Watson and Luckman (2004) identified the period from 1839 to 1859 as a prolonged interval of dry conditions in the southern Canadian Cordillera which is also apparent in the PDSI reconstruction (Grid Point 53; Fig. 5d) from the same region (Cook et al., 2004). Other reconstructions have identified extreme dry or drought conditions centered on the 1860s in the southern Canadian Cordillera (Watson and Luckman, 2001), and the Great Plains and south-central United States (Blasing et al., 1988; Meko, 1992). Decreased June precipitation during the early 20th century in Yellowknife also corresponds to widespread drought during the Dustbowl years throughout western Canada, the Prairies, and numerous regions of the United States (Fig. 5).

JUNE PRECIPITATION 1679–1819

Although sample depth is low in the early part of the reconstruction, the portion from 1679 to 1819 also contains multi-decadal variability that appears to coincide with similar dry/wet periods in other regions of Canada and the United States (Fig. 5). The multi-decadal variability in the Yellowknife reconstruction also appears to vary in step with sea surface conditions in the Pacific Basin related to the PDO (Fig. 5f). For example, the Yellowknife reconstruction suggests very dry June conditions during the period 1698–1735 when only 11 years with positive anomalies occurred. Similarly dry conditions are noted in the Rocky Mountain Foothills (Case and MacDonald, 1995), the southern Canadian Rockies (Watson and Luckman, 2001; Cook et al., 2004), and on the Canadian Prairies (Case and MacDonald, 2003). This period also coincides with a negative state of the PDO as reconstructed by MacDonald and Case (2005) (Fig. 5f). While interpretations of the record prior to 1819 are statistically tenuous because of low sample replication, it does appear the early portion of the reconstruction may provide valuable climatic information for the region.

CLIMATIC DRIVERS OF PRECIPITATION IN THE YELLOWKNIFE REGION

The Yellowknife June precipitation reconstruction shares many similarities with dendrohydrological reconstructions from other sites across western North America, which may provide insights into drivers of summer precipitation in the Yellowknife region. It has been widely illustrated that interactions between coupled ocean-atmosphere systems can lead to large-scale changes in climate and air mass circulation (e.g., Minobe, 1997; Nigam et al., 1999; Barlow et al., 2001). The large inertia of the oceans can lead to persistence of such anomalies for multi-decadal time periods leading to meso-scale reorganization of climate (Ropelewski and Jones, 1987; Bonsal et al., 1993; Zhang et al., 1997). Within the Pacific basin, sea surface temperatures (SSTs) have been identified as a primary driver of climate throughout western North America across multiple time scales (Namais and Cayan, 1981; Trenberth et al., 1988; Case and MacDonald, 1995; Woodhouse and Overpeck, 1998; Cayan et al., 1999; Graumlich et al., 2003; MacDonald and Case, 2005; Cook et al., 2007; MacDonald, 2007). Similarly, numerous studies have described the importance of North Pacific circulation patterns in the generation of precipitation in the Mackenzie Basin (Smirnov and Moore, 1999; Petrone and Rouse, 2000; Spence and Rausch, 2005). Given (1) the similarity in timing between periods of positive/negative precipitation anomalies in the Yellowknife reconstruction with other dendrohydrological records from North America; (2) the strong correlations between the instrumental precipitation data from Yellowknife Airport and monthly PDO index values; and (3) the coherence between the Yellowknife June precipitation reconstruction and the PDO reconstruction from MacDonald and Case (2005), it appears that conditions in the Pacific basin could be an important driver of decadal scale variability in summer precipitation in the North Slave region. The exact mechanisms that control these relations are still not clear, warranting further investigation.

Conclusions

There is a paucity of robust precipitation reconstructions for Canada north of 60° latitude. This study demonstrates that moisture-sensitive ring width chronologies can be developed from jack pine growing on rock outcrops in the Yellowknife region. Correlation analysis suggests June precipitation has a dominant control on the growth of jack pine in the study area. Regression-based techniques were used to reconstruct June precipitation with the resulting model capturing 42% of the variance in the instrumental precipitation record from the Yellowknife Airport. The reconstruction is statistically robust from ~1819–2005, but extends back to 1680. Although the early part of the record is not statistically robust, it displays patterns of variation with notable similarities to other dendrohydrological reconstructions from southern Canada and the United States. The coherency between dry periods in the Yellowknife reconstruction and extra-regional dendrohydrological reconstructions from other regions of North America suggests early-growing season precipitation may be controlled by large-scale atmospheric circulation patterns, possibly driven by SST patterns in the North Pacific. Additional field investigations could increase sample depth in the early part of the reconstruction and strengthen our conclusions prior to 1819. Further analyses focusing on the spectral characteristics of the reconstruction could also help to isolate the large-scale climate drivers in this region over longer time scales than previously examined.

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References Cited

ACIA, 2005, *Arctic Climate Impact Assessment*. Cambridge: Cambridge University Press, 1042 pp.

Barber, V. A., Juday, G. P., and Finney, B. P., 2000: Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature*, 405: 668–673.

Barlow, M., Nigam, S., and Berbery, E. H., 2001: ENSO, Pacific decadal variability, and U.S. summertime precipitation, drought, and stream flow. *Journal of Climate*, 14: 2105–2128.

Blasing, T. J., Stahle, D. W., and Duvick, D. N., 1988: Tree-ring-based reconstruction of annual precipitation in the south-central United States from 1750 to 1980. *Water Resources Research*, 24: 163–71.

Bonsal, B. R., Chakravarti, A. K., and Lawford, R. G., 1993: Teleconnections between North Pacific SST anomalies and growing season extended dry spells on the Canadian prairies. *International Journal of Climatology*, 13: 865–878.

Briffa, K., and Jones, P. D., 1990: Basic chronology statistics and assessment. *In* Cook, E. R., and Kairiukstis, L. A. (eds.), Methods of Dendrochronology, Dordrecht: Kluwer Academic, 137–152.

Burns, R. M., and Honkala, B. H. (technical coordinators)., 1990: *Silvics of North America: Volume 1. Conifers*. Washington, D.C.: U.S. Department of Agriculture, Forest Service, Agriculture Handbook, 654: 675 pp.

Case, R. A., and MacDonald, G. M., 1995: A dendroclimatic reconstruction of annual precipitation on the western Canadian prairies since A.D. 1505 from *Pinus flexilus* James. *Quaternary Research*, 44: 267–275.

Case, R. A., and MacDonald, G. M., 2003: Tree-ring reconstructions of streamflow for three Canadian prairie rivers. *Journal of the American Water Resources Association*, 39: 703–716.

Cayan, D. R., Redmond, K. T., and Riddle, L. G., 1999: ENSO and hydrologic extremes in the western United States. *Journal of Climate*, 12: 2881–2893.

Cook, E. R., and Holmes, R. L., 1986: *Guide for Computer Program ARSTAN*. Tucson, Arizona: Laboratory of Tree-ring Research, University of Arizona.

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., and Stahle, D. W., 2004: Long-term aridity changes in the western United States. *Science*, 306(5698): 1015–1018.

Cook, E. R., Seager, R., Cane, M. A., and Stahle, D. W., 2007: North American drought: reconstructions, causes, and consequences. *Earth-Science Reviews*, 81: 93–134.

D'Arrigo, R. D., Kaufmann, R. K., Davi, N., Jacoby, G. C., Laskowski, C., Myneni, R. B., and Cherubini, P., 2004: Thresholds for warming-induced growth decline at elevational tree line in the Yukon Territory, Canada. *Global Biogeochemical Cycles*, 18: article GB3021, doi:10.1029/2004GB002249.

Ecosystem Classification Group, 2008, *Ecological regions of the Northwest Territories—Taiga shield*. Yellowknife, NT, Canada: Department of Environment and Natural Resources, Government of the Northwest Territories.

Fritts, H. C., 1976: *Tree-rings and Climate*. New York: Academic Press.

Gordon, G. A., 1982: Verification of dendroclimatic reconstructions. *In* Hughes, M. K., Kelly, P. M., Pilcher, J. R., and LaMarche, V. C. Jr (eds.), *Climate from Tree Rings*. Cambridge: Cambridge University Press, 58–61.

Graumlich, L. J., Pisaric, M. F. J., Waggoner, L. A., Littell, J. S., and King, J. C., 2003: Upper Yellowstone River flow and teleconnections with Pacific Basin climate variability during the past three centuries. *Climatic Change*, 59: 245–262.

Holmes, R. L., 1983: Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, 43: 69–78.

Kerr, D. E., 2006: Surficial geology and exploration geochemistry, Yellowknife area. *In* Anglin, C. D., Falck, H., Wright, D. F., and Ambrose, E. J. (eds.), *Gold in the Yellowknife Greenstone Belt, Northwest Territories, Results of the EXTECH III Multidisciplinary Research Project*. St. John's, N.L, Canada: Geological Association of Canada, 301–324.

Ko Heinrichs, D., Tardif, J. C., and Bergeron, Y., 2007: Xylem production in six tree species growing on an island in the boreal forest region of western Quebec, Canada. *Canadian Journal of Botany*, 85: 518–525.

MacDonald, G. M., 2007: Severe and sustained drought in southern California and the West: present conditions and insights from the past on causes and impacts. *Quaternary International*, 173–174: 87–100.

MacDonald, G. M., and Case, R. A., 2005: Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters*, 32: article L08703, doi:10.1029/2005GL022478.

McClelland, J. W., Déry, S. J., Peterson, B. J., Holmes, R. M., and Wood, E. F., 2006: A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century. *Geophysical Research Letters*, 33: article L06715, doi:10.1029/2006GL025753.

Mekis, E., and Hogg, W. D., 1999: Rehabilitation and analysis of Canadian daily precipitation time series. *Atmosphere-Ocean*, 37: 53–85.

Meko, D. M., 1992: Dendroclimatic evidence from the Great Plains of the United States. *In* Bradley, R. S., and Jones, P. D. (eds.), *Climate since AD 1500*. London: Routledge.

Meko, D. M., 2002: *Tree-ring study of hydrologic variability in the Peace-Athabasca Delta, Canada*. Vancouver, British Columbia: report prepared for Lawson Lundell.

Meko, D. M., 2006: Tree-ring inferences on water-level fluctuations of Lake Athabasca. *Canadian Water Resources Journal*, 31: 229–248.

Meko, D. M., Therrell, M. D., Baisan, C. H., and Hughes, M. K., 2001: Sacramento River flow reconstructed to A.D. 869 from tree rings. *Journal of the American Water Resources Association*, 37: 1029–1039.

Milly, P. C. D., Dunne, K. A., and Vecchia, A. V., 2005: Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438: 347–350, doi:10.1038/nature04312.

Minobe, S., 1997: A 50–70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters*, 24: 683–686.

Namais, J., and Cayan, D. R., 1981: Large-scale air-sea interactions and short-period climatic fluctuations. *Science*, 214: 869–876.

Nigam, S., Barlow, M., and Berbery, E. H., 1999: Analysis links Pacific decadal variability to drought and streamflow in the United States. *EOS*, 80: 621–625.

Partanen, J., Koski, V., and Hänninen, H., 1998: Effects of photoperiod and temperature on the timing of budburst in Norway spruce (*Picea abies*). *Tree Physiology*, 18: 811–816.

Peterson, B. J., Holmes, R. M., McClelland, J. W., Vorosmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., and Rahmstorf, S., 2002: Increasing river discharge to the Arctic Ocean. *Science*, 298: 2171–2173.

Petrone, R. M., and Rouse, W. R., 2000: Synoptic controls on the surface energy and water budgets in sub-arctic regions of Canada. *International Journal of Climatology*, 20: 1149–1165.

Pisaric, M. F. J., Carey, S. K., Kokelj, S. V., and Youngblut, D., 2007: Anomalous 20th century tree growth, Mackenzie Delta, Northwest Territories, Canada. *Geophysical Research Letters*, 34: article L05714, doi:10.1029/2006GL029139.

Ropelewski, C. F., and Jones, P. D., 1987: An extension of the Tahiti-Darwin Southern Oscillation Index. *Monthly Weather Review*, 115: 2161–2165.

Sauchyn, D. J., and Beaudoin, A. B., 1998: Recent environmental change in the southwestern Canadian Plains. *The Canadian Geographer*, 42: 337–53.

Smirnov, V. V., and Moore, G. W. K., 1999: Spatial and temporal structure of atmospheric water vapour transport in the Mackenzie River basin. *Journal of Climate*, 12: 681–696.

Smith, L. C., Pavelsky, T. M., MacDonald, G. M., Shiklomanov, A. I., and Lammers, R. B., 2007: Rising minimum daily flows in northern Eurasian rivers: a growing influence of groundwater in the high-latitude hydrologic cycle.

Journal of Geophysical Research, 112: article G04S47, doi: 10.1029/2006JG000327.
Spence, C., and Rausch, J., 2005: Autumn synoptic conditions and rainfall in the subarctic Canadian Shield of the Northwest Territories, Canada. *International Journal of Climatology*, 25: 1493–1506.
Spence, C., and Woo, M.-K., 2003: Hydrology of subarctic Canadian Shield: soil-filled valleys. *Journal of Hydrology*, 279: 151–166.
St. George, S., and Nielson, E., 2002: Hydroclimatic change in southern Manitoba since A.D. 1409 inferred from tree-rings. *Quaternary Research*, 58: 103–111.
St. Jacques, J.-M., and Sauchyn, D. J., 2009: Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. *Geophysical Research Letters*, 36: article L01401, doi:10.1029/2008GL035822.
Stockton, C. W., and Fritts, H. C., 1973: Long-term reconstruction of water level changes for Lake Athabasca by analysis of tree-rings. *Water Resources Bulletin*, 9: 1006–1027.
Stokes, M. A., and Smiley, T. L., 1968: *An Introduction to Tree-Ring Dating*. Chicago: University of Chicago Press.
Szeicz, J. M., and MacDonald, G. M., 1996: A 930-year ring-width chronology from moisture-sensitive white spruce (*Picea glauca* Moench) in northwestern Canada. *The Holocene*, 6: 345–351.
Trenberth, K. E., Branstator, G. W., and Arkin, P. A., 1988: Origins of the 1988 North American drought. *Science*, 242: 1640–1645.
Vincent, L. A., and Gullett, D. W., 1999: Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology*, 19: 1375–1388.
Walvoord, M. A., and Striegl, R. G., 2007: Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: potential impacts on lateral export of carbon and nitrogen. *Geophysical Research Letters*, 34: article L12402, doi:10.1029/2007GL030216.
Watson, E., and Luckman, B. H., 2001: Dendroclimatic reconstruction of precipitation for sites in the southern Canadian Rockies. *The Holocene*, 11: 203–213.
Watson, E., and Luckman, B. H., 2004: Tree-ring based reconstructions of precipitation for the southern Canadian Cordillera. *Climatic Change*, 65: 209–241.
Wedel, J. H., Smart, A., and Squires, P., 1990: *An Overview Study of the Yellowknife River Basin, NWT*. Yellowknife, NWT, Canada: Inland Waters Directorate, Environment Canada.
Wigley, T. M. L., Jones, P. D., and Briffa, K. R., 1984: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology*, 23: 201–213.
Wilmking, M., Juday, G. P., Barber, V. A., and Zald, H. S. J., 2004: Recent climate warming forces contrasting growth responses of white spruce at tree line in Alaska through temperature thresholds. *Global Change Biology*, 10: 1724–1736.
Woodhouse, C. A., and Overpeck, J. T., 1998: 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society*, 79: 2693–2714.
Yamaguchi, D. K., 1991: A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research*, 21: 414–416.
Zahner, R., 1968: Water deficits and growth of trees. *In* Kozlowski, T. T. (ed.), *Water Deficits and Plant Growth, Volume 2*. New York: Academic Press, 191–254.
Zhang, Y., Wallace, J. M., and Battisti, D. S., 1997: ENSO-like interdecadal variability: 1900–93. *Journal of Climate*, 10: 1004–1020.

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