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Tree growth and inferred temperature variability at the North American Arctic treeline

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ABSTRACT

We present white spruce (*Picea glauca*) tree-ring width and maximum latewood density chronologies for two latitudinal treeline sites in northern interior Canada: along the Coppermine River in the Northwest Territories (NWT); and in the Thelon River Sanctuary, Nunavut. These chronologies provide climate and tree growth information for these two remote locations, filling a sizeable gap in spatial coverage of proxy records used to reconstruct temperature variability for the Northern Hemisphere. They represent some of the longest high-resolution proxies available for northern North America, dating as far back as AD 1046 for Coppermine ring widths. These chronologies correlate significantly with hemispheric-scale annual temperature reconstructions for the past millennium. Density records from both sites show a positive relationship with warm-season temperature data since ~ the mid-20th century, although this link is somewhat weaker in recent decades (since ~1980). Both ring-width chronologies demonstrate even greater loss of temperature sensitivity, and in the Thelon ring-width series a sustained reduction in growth appears linked to increased drought stress in this recent period. Diminishing correlations with temperature are also found when the Thelon ring-width and climate data are prewhitened, indicating that any low frequency uncertainties in the instrumental or tree-ring data (e.g., artifacts from the standardization process) cannot entirely account for this result. Our findings therefore suggest a recent loss of temperature sensitivity at these northern treeline locations that varies with the parameter and site studied. These and other uncertainties in the tree-ring as well as instrumental data will need to be resolved in future efforts to relate northern tree-ring records to temperature variability on a range of spatial scales.

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1. Introduction

Widespread, multiple changes in the Arctic environment are rapidly taking place, largely related to recent warming due to anthropogenic activities (Hinzman et al., 2005, IPY website: http://classic.ipy.org/about/). The response of northern forests to these changes can, in turn, cause significant feedbacks into the Arctic climate system (Serreze et al., 2000; Chapin et al., 2004; IPCC, 2007; Lloyd and Bunn, 2007). Tree-ring records are an important resource for evaluating both the unusual nature of recent anthropogenic changes relative to past natural temperature variability, and also for determining the boreal forest response to these changes. This ground-based, high resolution tree growth information complements recent remote sensing studies that document both greening (Myneni et al., 1997) and browning (Bunn and Goetz, 2006) effects in northern forests.

Limited distribution of tree-ring records in some key northern areas has historically limited the quality of hemispheric-scale temperature reconstructions that attempt to place recent large-scale warming effects in the context of the past thousand years (Jones et al., 1998; Mann et al., 1999; Briffa, 2000; Esper et al., 2002; Moberg et al., 2005; D'Arrigo et al., 2006; Hegerl et al., 2006; National Research Council, 2006). One of the regions of most sparse geographic coverage exists across the latitudinal treeline boreal forests of interior northern Canada, spanning an area from ~70–140°W longitude. Additional tree-ring records from this remote region can help improve the spatial representativity of hemispheric reconstructions, and hence increase our understanding of regional to global temperature variability over the past millennium.

In addition to limited spatial coverage, another important factor that creates uncertainty in interpreting large-scale temperature

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Table 1
Tree-ring chronology information for Coppermine and Thelon sites (see text for details)

Tree-ring site	Parameter	Length	EPS >0.85	Mean RBAR	Median segment length	AR order
Coppermine River	Density	1551–2003	1650	0.38	224	4
Coppermine River	Ring width	1046–2003	1250	0.24	245	4
Thelon River South	Density	1535–2004	1715	0.41	155	3
Thelon River South	Ring width	1309–2004	1400	0.22	288	3

reconstructions based on tree rings is the so-called "divergence problem", defined as the tendency for tree growth indices for a number of northern forest sites to underestimate temperature trends over recent decades (e.g. Jacoby and D'Arrigo, 1995; Briffa et al., 1998a, b; Wilmking et al., 2005, and see D'Arrigo et al., 2008 for a review). The divergence problem has impeded attempts to directly glean quantitative information from paleotemperature reconstructions, and has created doubts regarding the ability of tree rings to reflect past temperature trends consistently over time (National Research Council, 2006). A number of studies have described different aspects of this phenomenon, with some focusing on interior boreal forests (Barber et al., 2000, Alaska), and others on circumpolar boreal sites at "relatively high latitudes or high elevations", but not "strictly at treeline" (Briffa et al., 1998a). It is at actual treeline locations, however, that tree growth may be most limited by temperature and therefore most appropriate for reconstructing temperature variability and investigating possible divergence effects between tree-ring and temperature data.

The divergence problem can be partially circumvented by utilizing tree-ring data for dendroclimatic reconstructions from sites where divergence is either absent or minimal (Wilson et al., 2007; Buntgen et al., in press; Youngblut and Luckman, in press), and can be placed in context with a more detailed understanding of trend uncertainties in both tree-ring data and their instrumental targets (Frank et al., 2007). The tree-ring records described below provide evidence for past temperature variability that can also be used to test for potential divergence at these two latitudinal treeline locations in northern interior Canada (Table 1, Fig. 1).

2. Materials and methods

The tree-ring records described herein are derived from white spruce (*Picea glauca* [Moench] Voss) trees growing along the Coppermine and Thelon Rivers, within the Canadian provinces of the Northwest Territories (NWT) and Nunavut/border of NWT, respectively (Fig. 1). These northern treeline locations, where forest cover is only intermittent, are among the most remote and undisturbed wilderness regions on the globe. Gridded, seasonally-averaged temperature and precipitation data for these areas show generally positive trends over the past half century or so of record (Fig. 2), indicating environmental conditions that would be expected to favorably impact tree growth (Tranquillini, 1979).

Living and subfossil wood samples were first collected by TRL-LDEO scientists from these sites in 1978 (Coppermine River) and 1984 (Thelon River). Sites selected for sampling featured mesic conditions, with no obvious evidence of drought stress or major disturbance due to fires or insect infestation. Although ring-width chronologies produced from these earlier samples were utilized previously in reconstructions of Northern Hemisphere annual temperatures (Jacoby and D'Arrigo, 1989; D'Arrigo et al., 2006), descriptions of these data have not been published in any detail. More recent sampling of living and subfossil wood took place in the summers of 2004 (Coppermine River) and 2005 (Thelon River), allowing us to update these chronologies, improve their sample size and extend them further back in time. The updated ring-width chronologies, each based on combined, cross-dated living and subfossil wood measurements, span from 1046–2003 A.D. for Coppermine (composited from several adjacent sites along the river), and from 1309–2004 A.D. for Thelon South, a site along the Thelon River. The latter location is adjacent to

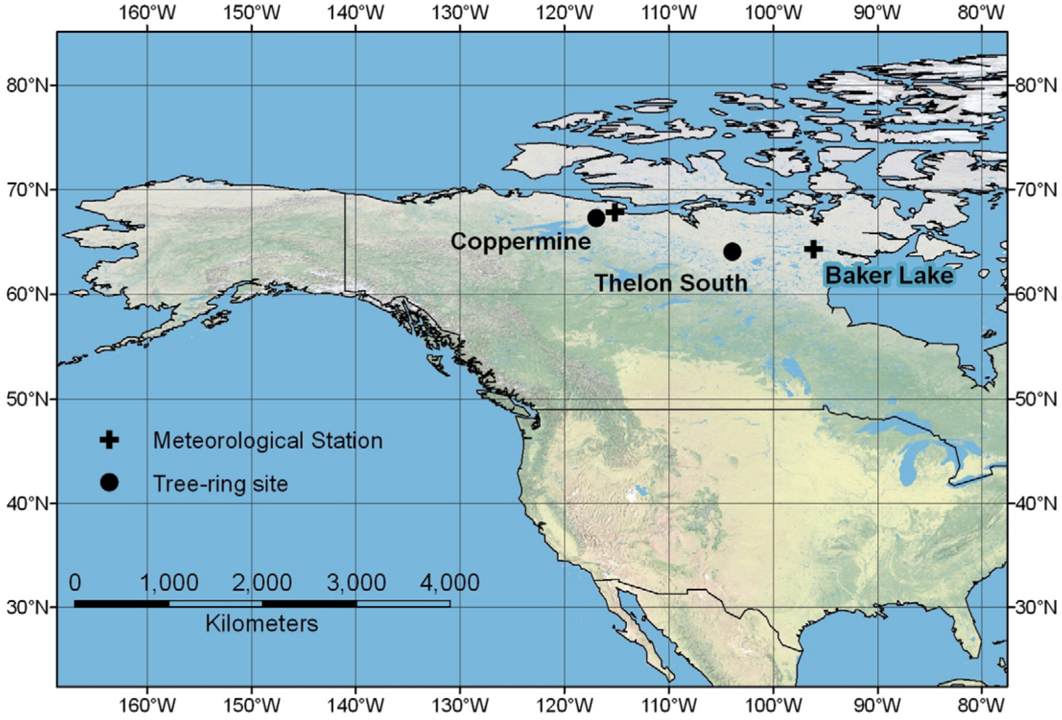

Fig. 1. Map of North America showing Coppermine, Northwest Territories and Thelon South, Nunavut, Canada tree-ring sites (dots), both located along the northern treeline. Also shown are locations of Coppermine and Baker Lake meteorological stations (crosses).

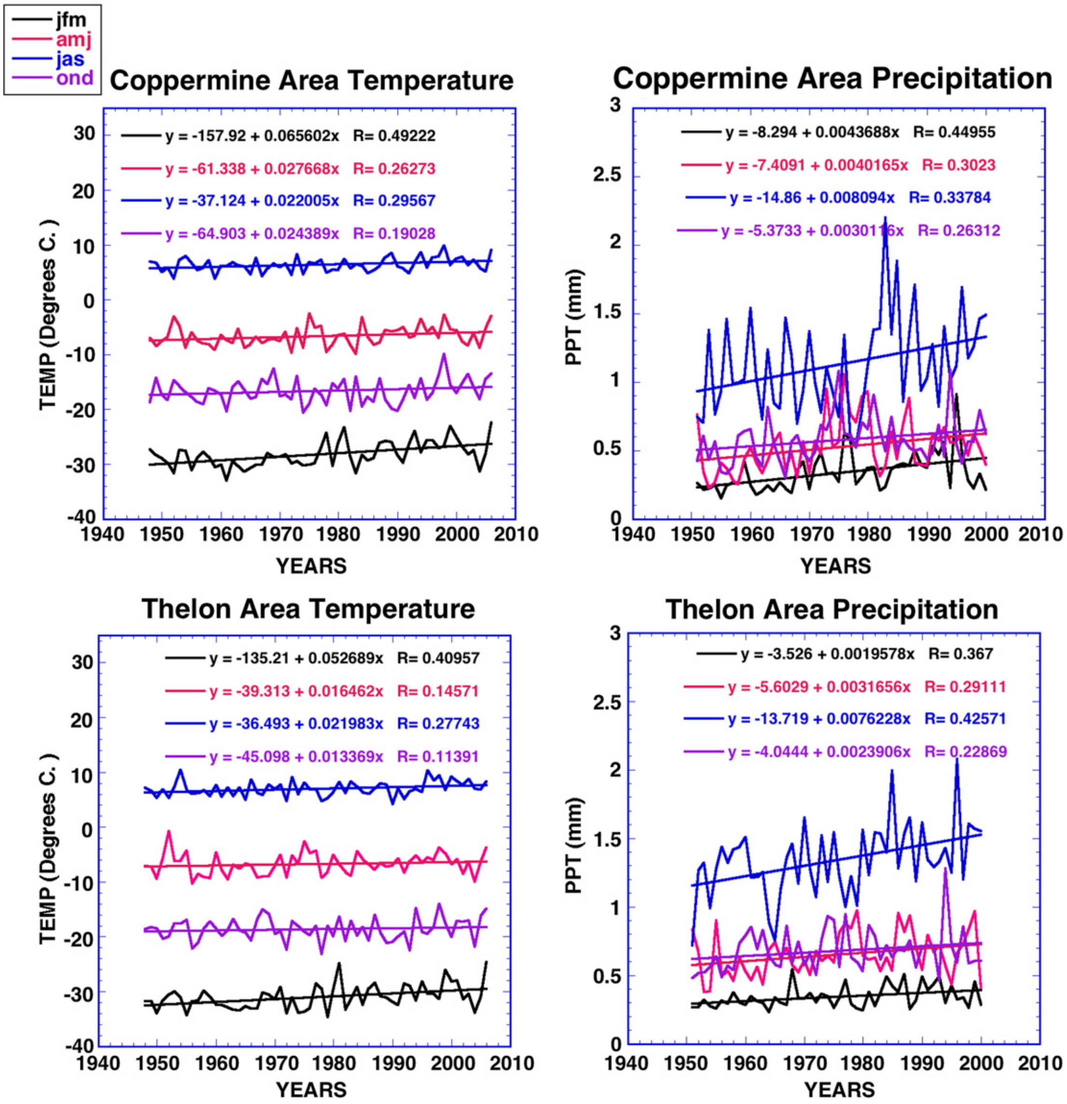

Fig. 2. Trends in temperature (Tmp2M from GHCN/CAMS 2m analysis, Fan and van den Dool, submitted for publication, in °C) and precipitation (GPCC VASCLIM, mm/day, Beck et al., 2005) data by season for gridcells overlapping tree-ring sites. For Coppermine: averaged over 67–69°N, 114–116°W; for Thelon: averaged over 64–66°N, 99–101°W. For both locations, temperature data spans from 1948–2006 and precipitation data from 1951–2000. Linear trend lines and regression equations also indicated.

our previous site for this region (named Hornby Cabin), but had more relict wood available for sampling and soil moisture conditions perhaps even more favorable for growth. The subfossil wood samples for both sites were collected in very close proximity to the living tree locations.

The maximum latewood density parameter (hereafter density) is typically sensitive to extended warm-season temperatures on annual to multidecadal time scales (e.g. Schweingruber, 1988; D'Arrigo et al., 1992). Density chronologies were developed for the updated Coppermine (1551–2003), and Thelon (1535–2004) sites, complementing the ring-width data, which can reflect even lower frequency, summer or annual, temperatures. Attrition is common in processing density data, as typically only a subset of wood samples at a given site are of adequate quality for processing (Schweingruber, 1988; D'Arrigo et al., 1992). These four chronologies (two sites, for ring width and density) allow us to place recent tree growth and inferred temperature trends at these locations into long-term perspective.

Wood samples were cross-dated, measured and processed using standard dendrochronological techniques (Fritts, 1976; Holmes, 1983; Cook and Kairiukstis, 1990). Previous analyses of Coppermine and Thelon ring-width data, in combination with ring width data from 2 other sites in the western NWT (R. Wilson unpublished report, 2005; D'Arrigo et al., 2006) revealed that the Regional Curve Standardization (RCS) method, a potentially useful technique for retaining centennial-scale climatic trends in tree rings (Briffa et al., 1992; Cook et al., 1995; Esper et al., 2002), did not appear to preserve any additional low-frequency information at these sites when compared to more traditional techniques. We thus did not utilize RCS for developing ring width chronologies for the present study, opting for more traditional methods (i.e. individual series detrending). We will, however, continue to explore efforts to capture more low-frequency variability in future studies using RCS and other methods. Due to the above-noted attrition in processing, the density data sets had significantly lower sample size, making RCS less appropriate (Briffa et al., 1992; Esper et al., 2002). The measurements were detrended using negative exponential or straight-line curve fits that are intended to conserve low-frequency variability due to climate (Cook, 1985; Cook and Kairiukstis, 1990). Prior to detrending, the variance of the ring-width series was stabilized using a power-transformation determined for each series based upon relationships between the local mean and standard deviation (Cook and Peters, 1997). This allows detrending by calculating residuals (rather than the more traditionally used ratios) from the expected growth curve in order to reduce potential end-fitting bias resulting from division. We also

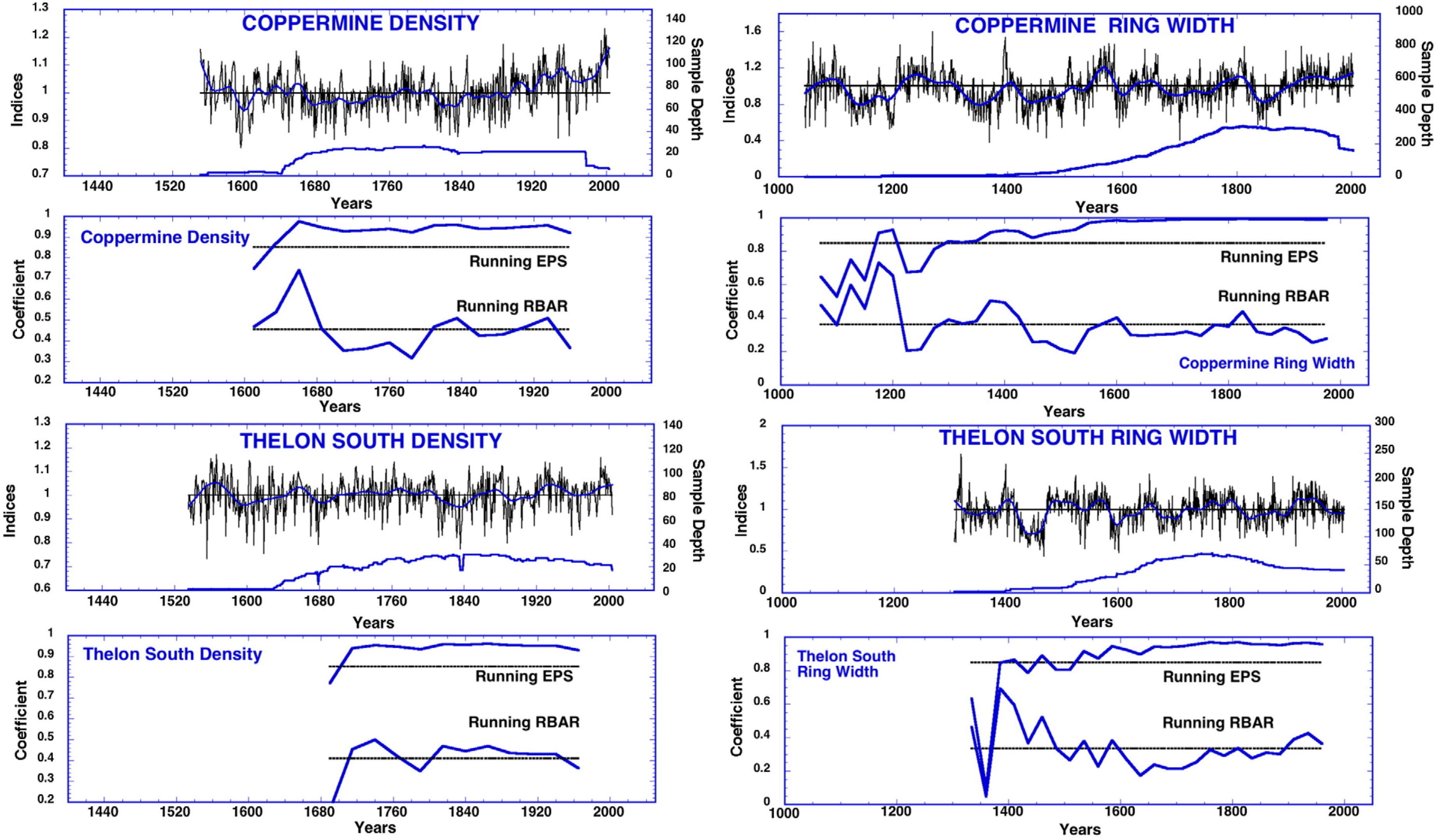

Fig. 3. Coppermine and Thelon density and ring width chronologies. For both density and ring width, first and third panels indicate tree-ring chronologies (black lines) with 5-yr smoothed values (blue lines); sample depth indicated by lower blue lines. Second and fourth panels show running RBAR and EPS results, along with mean RBAR and EPS cutoff (0.85) values.

employed the variance stabilization method of Osborn et al. (1997) to reduce the effects of changing sample size through time. The biweight robust mean was used for calculating each year's mean value function to discount the effects of outliers (Cook, 1985). Sample depth, RBAR (series intercorrelation or agreement within and between trees), median segment length (Cook et al., 1995; an indication of the extent to which very low-frequency information, potentially due to climate, can be resolved in tree-ring data), the Expressed Population Signal (EPS; a measure of chronology signal strength; values exceeding 0.85 generally considered to be reliable; Cook and Kairiukstis, 1990), and the level of persistence or autoregression (AR order) were computed for each of the chronologies. These descriptive statistics, presented in Table 1 and Fig. 3, were used to gauge the reliability and strength of common signal in the chronologies over time.

The four tree-ring chronologies and related statistics are presented in Fig. 3. The Coppermine ring width and density records correlate at $r=0.42$ over their common period (1551–2003); for the Thelon site the ring width-density correlation is similar ($r=0.37$, 1492–2004). The

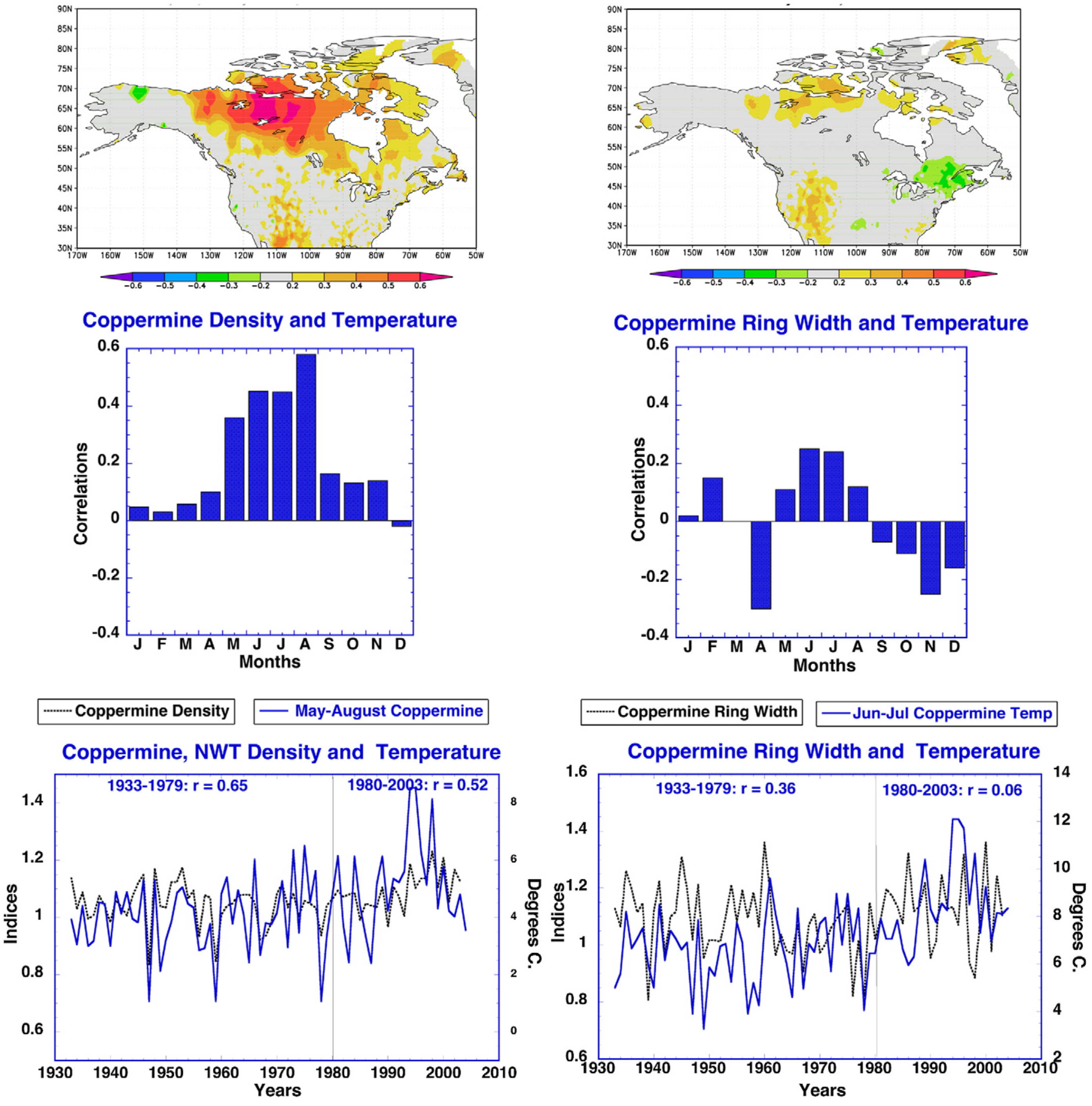

Fig. 4. Coppermine chronologies and temperature data. Top, Spatial correlation plots comparing density (left) and ring width (right) chronologies with monthly GHCN/CAMS gridded temperatures (Fan and van den Dool, submitted for publication) from 1951–2003. Middle, Monthly correlations with Coppermine station temperatures for 1930–2003. Correlations for May through August are statistically significant at the 0.001 level or higher. Bottom, Comparison of Coppermine tree-ring series with Coppermine May–August station temperatures. Vertical black lines divide early and late correlation intervals; note particularly shift after ~1980 from positive to non-significant temperature correlations for the Coppermine ring width record.

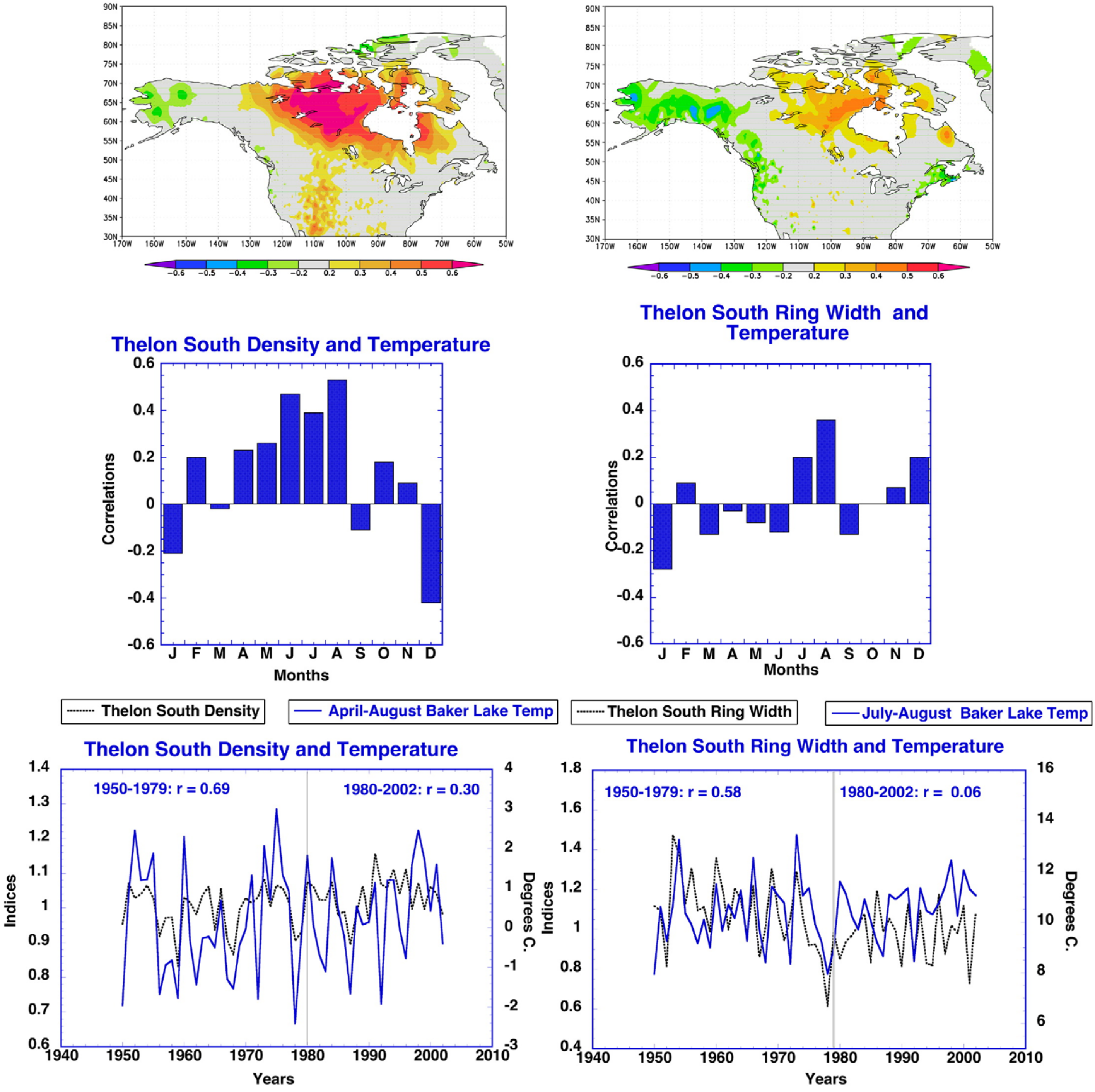

Fig. 5. Thelon South density (left) and ring width (right) chronologies and temperature data. Top, Spatial correlation plots comparing both chronologies with GHCN/CAMS gridded temperatures (Fan and van den Dool, submitted for publication) from 1950–2004. Middle, Monthly correlations with Baker Lake station temperatures for 1950–2002. Correlations for July–August are statistically significant at the 0.01 level for both density and ring width. Bottom, Comparison of Thelon density and ring width chronologies and July–August Baker Lake temperatures. Vertical black lines show shift ~1980 from positive to non-significant temperature correlations for Thelon ring width data.

Thelon ring width-density correlations weaken considerably for the recent period, indicating declining coherency in the 20th century: $r=0.28$ for 1900–2004, and 0.16 for 1950–2004 (see discussion below). This is also the case for Coppermine ($r=0.22$ for 1900–2003, 0.15 for 1950–2003). Between sites, the Coppermine and Thelon density records correlate at $r=0.53$ (1551–2003); and the two ring-width series at $r=0.56$ (1309–2003). These between-site correlations are quite high considering that the chronologies are located more than 1000 km from each other, implying a rather coherent temperature signal over the region. The respective climate stations for these sites (see below) correlate at about $r=0.50$ for their common period (1950–2002) in the summer months.

The tree-growth indices are compared below to monthly temperature data from meteorological stations located at Coppermine, NWT (1930–present) and Baker Lake, Nunavut (1950–present), which are the closest to the respective (Coppermine and Thelon) tree-ring sites (Fig. 1). These data were obtained from the Global Historical Climatology network (GHCN) (http://www.ncdc.noaa.gov/oa/climate/

ghcn-monthly/). We also utilized gridded temperatures from the GHCN/CAMS-2m V2 analysis (Fan and van den Dool, submitted for publication, 1948–2006) and gridded precipitation from the GPCC VASCLIM0-0.5 data set (Beck et al. 2005, 1951–2000) in order to generate spatial correlation maps using the browser-based KNMI Climate Explorer (van Oldenborgh and Burgers, 2005).

3. Climate-tree growth analyses

3.1. Coppermine

The Coppermine density chronology is most strongly correlated with temperatures averaged over the warm-season months (May–August) of the current growth year (Fig. 4). This relationship is illustrated by a spatial correlation map that compares this density record to May–August temperatures over the past ~50 years across northern North America (Fig. 4, top left). A region of significant positive correlation covers northern central Canada, overlapping the Coppermine tree-ring site. A response correlation bar plot (Fig. 4, middle left) reveals a similar relationship (using the longer Coppermine station data for comparison; Fig. 1), with correlations over the May–August season that are statistically significant at the 0.001 level or higher. A plot of the Coppermine density and May–August temperature series (Fig. 4, bottom left) shows a somewhat weaker correlation since around 1980 (r=0.65 for 1933–1979; r=0.52, 1980–2003). In this more recent period, temperature correlations for individual months remain significant in July and August (r=0.61 and 0.45, respectively) but lose significance for May (decreasing from r=0.48 to 0.19) and June (r=0.33, significant in 1933–1979 but not significant for 1980–2003, r=0.34). During the latter period, there is significant underestimation of several positive May–August temperature anomalies during the 1990s.

For the Coppermine ring width record, there is no actual growth decline when this series is correlated and plotted with temperatures for June–July, the months with the strongest apparent relationship between radial growth and climate (Fig. 4, right panels; Fig. 7). However, the ring width-temperature correlations weaken from r=0.36 (1933–1979) to r=0.06 (1980–2003). Tree growth-monthly response correlations in the latter period are no longer significant for June or July (r=0.11, 0.09), nor are they significant and positive for any other month.

3.2. Thelon South

The Thelon density chronology reveals a pattern of positive warm-season temperature correlations (using gridded temperatures as well as station data from Baker Lake; Figs. 1 and 5, left), with significant correlations extending from April to August (Apr–Aug r=0.55, 1950–2002). Correlation with this season's temperatures are strongest for the early period from 1950–1979 (r=0.69), weakening to r=0.30 (not significant) for 1980–2002. However, correlation is higher for a slightly different season in the later period (Jun–Aug, r=0.50).

As for Coppermine, Thelon South ring widths correlate more weakly than density with temperature, and for a shorter summer season (July–Aug; r=0.33, 1950–2002, Fig. 5, right). This tendency for the density parameter to display stronger, more consistent correlations with temperature over a more extended warm season than ring widths for the same site has been reported on previously (e.g. D'Arrigo et al., 1992; Jacoby and D'Arrigo, 1995; Wilson and Luckman, 2003; Frank and Esper, 2005).

As found for Coppermine ring widths, there is an apparent weakening or shift in temperature signal in Thelon ring widths, which also decline in recent decades (Fig. 8 below). After around 1980, the correlation with temperature declines to nearly zero (Jul–Aug r=0.56 for 1950–1979; decreasing to r=0.06 from 1980–2002; temperatures are not significant for any month of the year in this latter period) (Fig. 5, bottom right). A Kalman filter analysis (Fig. 6; Visser and Molenaar, 1988) similarly indicates a weakening of ring width-temperature sensitivity in recent decades, although the signal is only weakly significant in the early period. A similar shift is found when the Thelon ring widths and July–August Baker Lake temperatures are prewhitened (high-pass filtered), indicating that the weakening of temperature correlation is also partly a result of loss of interannual, rather than solely lower-frequency temperature sensitivity (prewhitened correlations are 0.61 for 1950–79 and 0.05 for 1980–2002). As the temperature correlation has weakened, the relationship of Thelon ring widths with precipitation has become positive and significant in the latter interval. This apparent shift in climate response is also evident in spatial correlation maps that compare Thelon ring widths with spring–summer precipitation for early (1950–1979) and late (1980–2002) time periods over the past ~50 years (Fig. 7). Comparison of Coppermine ring widths and precipitation (not shown) reveals a less clear pattern, with correlations with precipitation that are generally weak and negative. Plots of the four tree-ring series for the past 50 years (Fig. 8) show positive recent growth trends (consistent with recent warming) in Coppermine and Thelon density and Coppermine ring width, and the negative trend in Thelon ring widths.

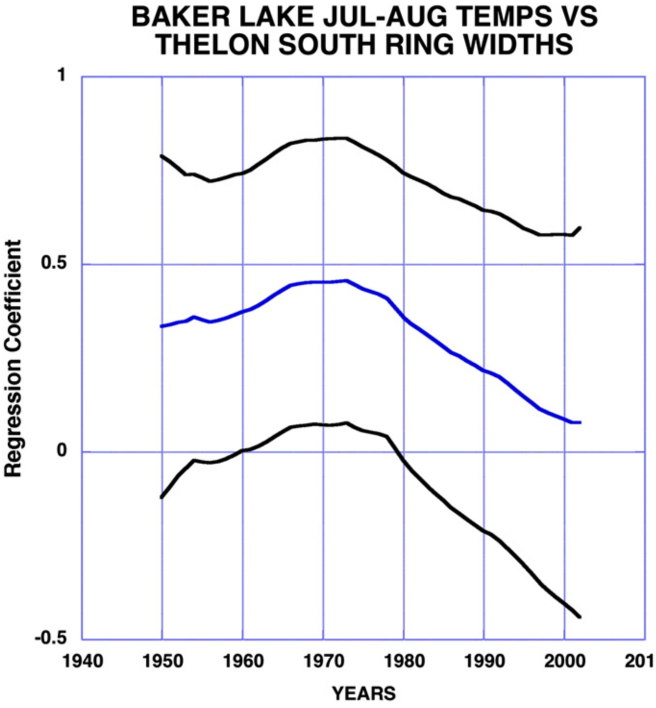

Fig. 6. Kalman filter analysis (Visser and Molenaar, 1988) comparing Baker Lake July–August temperatures and Thelon South ring-width chronology. Correlations are significant for the ~1960–1980 period. Results indicate a loss of temperature sensitivity over recent decades.

4. Linkages to regional to hemispheric-scale temperature variability

The Coppermine and Thelon chronologies generally reveal common low-frequency trends over their length, although there are differences which we ultimately would expect as the sites are located quite far from each other (Figs. 1, 3). Cooler conditions are inferred for the mid-13th century, and warmer conditions in the 1500s. Cooling is inferred around 1700, during the latter part of the Maunder Minimum, which occurred from ~1645–1715 (Rind et al., 2004). There is decreased growth, consistent with cooler conditions, in the early to middle 1800s, the latter part of the period known as the Little Ice Age

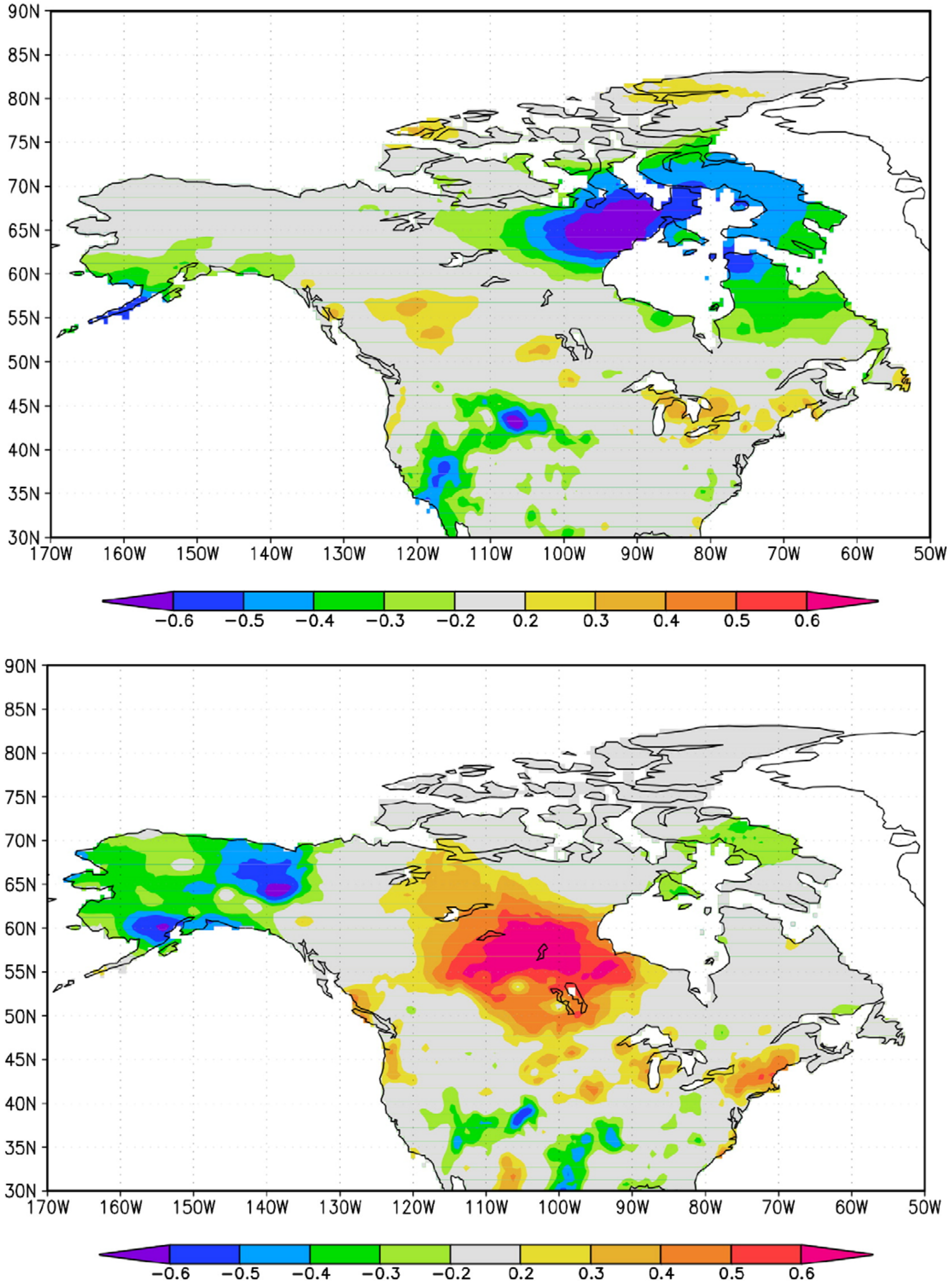

Fig. 7. Spatial correlation fields of Thelon South ring width chronology and Mar–July Vasclim (Beck et al., 2005) precipitation for 1950–1979 (top) and 1980–2002 (bottom), showing shift towards positive correlation with precipitation in recent decades.

(Grove, 1988). This cold period was followed by overall increased growth and inferred warming since around the middle 19th century (Figs. 2, 3). A recent growth increase is most pronounced for Coppermine density, with recent growth decline only evident in Thelon ring widths (Fig. 8). Density values for some years during the past decade or so are unprecedented at Coppermine, which has its highest overall latewood density index value in 1998. This greater increase in density at Coppermine may be related to the greater warming in this area than over the Thelon site in all seasons (Fig. 2). The Coppermine ring-width series is the only one of the four described herein that extends back to the approximate time of the Medieval Warm Period (MWP; 9th–14th centuries (IPCC, 2007, Paleoclimate Chapter). There are some intervals of above-average growth overlapping the MWP (from ~1050–1100 and 1200–1300 AD). However, we caution that this record cannot be considered robust before ~1250, due to relatively low EPS values in this earlier period (Table 1, Fig. 2).

Very low growth indices are observed in both the Coppermine and Thelon ring-width data in the years following the major volcanic eruption of Huaynaputina in Peru in 1600 (Simkin and Siebert, 1994;

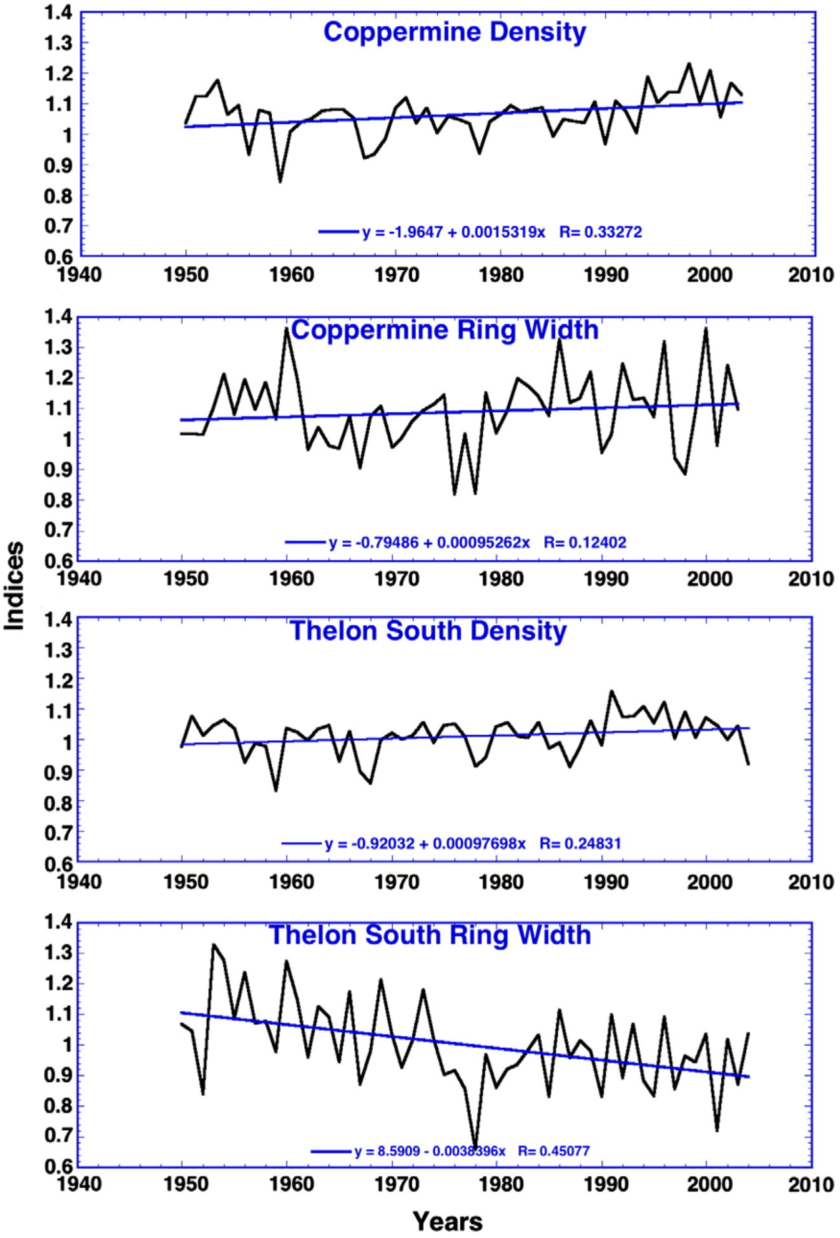

Fig. 8. Tree-ring density and ring-width trends (with linear regression equations and trend lines) for Coppermine and Thelon sites since 1950. Trends are positive except for Thelon ring width series.

density values at both sites are not well replicated for the time of this event). The year 1602 is the one of the lowest in the Thelon ring-width record, with a normalized departure of −2.8. The year 1601 is by far the coldest year on record in a 600-year density-based composite temperature reconstruction for the Northern Hemisphere, for which the greatest negative anomalies were found in density data for westernmost North America (Briffa et al., 1998c). Pronounced negative ring-width anomalies are also observed at both the Coppermine and Thelon sites in 1641–2, following the Komagatake eruption in Japan and other eruptions around this time (Simkin and Siebert, 1994). Some wood samples from the Coppermine site show evidence of unusual frost damage, or breakages in the wood in these years, indicating adverse conditions. By contrast, the tree growth indices are not extremely low following either the Laki, Iceland 1783 eruption (which was followed by dramatic cold in northwestern North America, particularly in Alaska — Jacoby et al., 1999) or the Tambora, Indonesia 1815 eruption (and the subsequent 1816 the "year without a summer", which had a much greater impact further to the east — Harington, 1992).

It has been observed previously that northern tree-ring records can sometimes correlate more strongly with large-scale annual temperature variability than with local station data (Jacoby and D'Arrigo, 1989). The Coppermine and Thelon density chronologies both correlate significantly with the density-based Northern Hemisphere temperature record of Briffa et al. (1998a): Coppermine: $r=0.30$, 1551–1994; Thelon $r=0.25$, 1535–1994 (Fig. 9). Similarly, the respective ring-width chronologies correlate well with a predominantly ring-width based Northern Hemisphere temperature reconstruction (traditional standardized version, D'Arrigo et al., 2006, Fig. 9): For Coppermine ring widths, correlation with this Northern Hemisphere reconstruction is $r=0.42$, 1310–1995; and for Thelon ring widths: $r=0.35$, 1310–1995. Note that previous versions of these ring-width chronologies were included in the D'Arrigo et al. (2006) temperature reconstruction; hence the records are not entirely independent. There

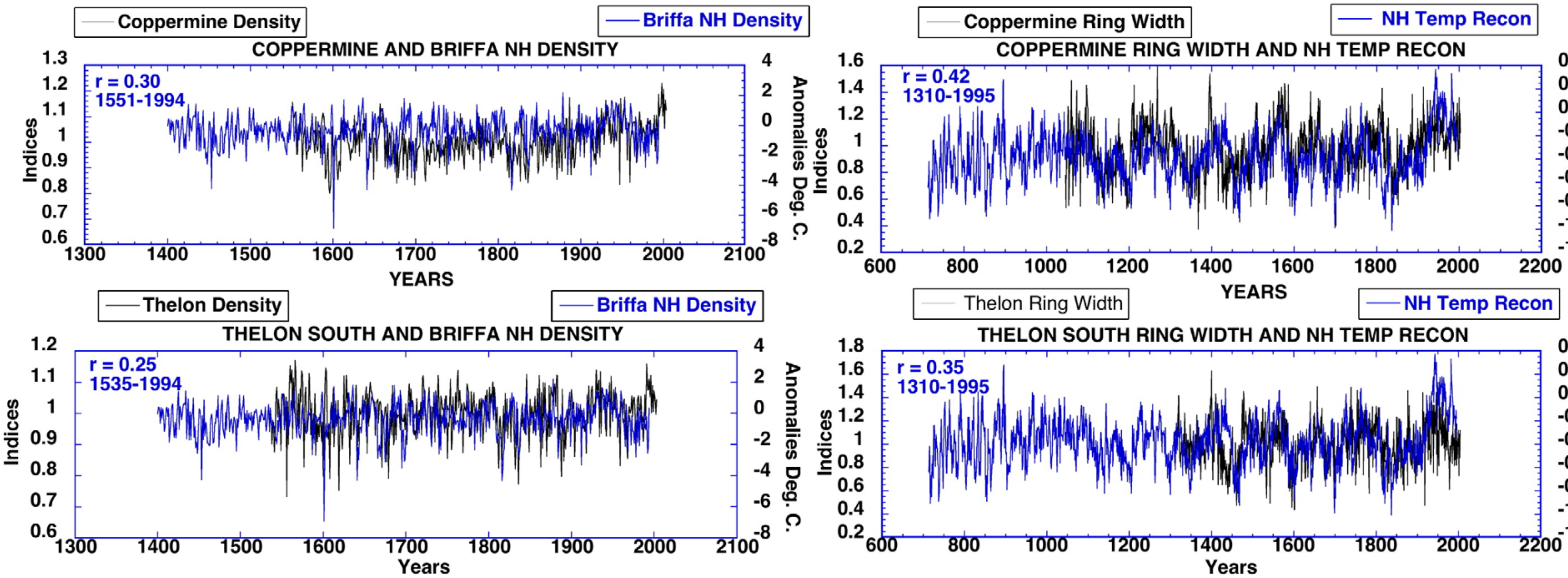

Fig. 9. Comparison of Coppermine and Thelon chronologies with large-scale temperature records for the Northern Hemisphere. Left, comparison of density chronologies with Briffa et al. (1998a) Northern Hemisphere temperature record based on a network of tree-ring density data. Right, comparison of ring width chronologies with Northern Hemisphere temperature reconstruction of D'Arrigo et al. (2006).

is documented divergence of tree growth and temperature trends evident in the Northern Hemisphere density and ring width series of Briffa et al. (1998a,b) and in several Northern Hemisphere reconstructions based on tree rings (e.g. Esper et al. 2002; D'Arrigo et al., 2006).

5. Discussion and conclusions

We have described newly updated, climatically sensitive latewood density and ring-width chronologies for the latitudinal treeline of northern North America. The density and ring width records, for both the Coppermine and Thelon sites, show some loss of temperature sensitivity in recent decades. For the density chronologies, this apparent loss of sensitivity is accompanied by a tendency for early spring temperatures to become less important to growth in recent decades. Both the Coppermine and Thelon ring width records indicate a more pronounced weakening in temperature response than was found for density, with the Thelon ring-width series also indicating an actual decline in growth over this period. We caution however that the overall climate signal for the two ring width series is relatively weak with local temperature station data, and that there are uncertainties inherent in both the instrumental and tree-ring data. The distance between the tree-ring sites and meteorological stations, as well as the shortness of instrumental climate records at remote northern locations, must also be considered.

Our analyses appear to support the hypothesis that drought stress can be an important factor contributing to recent loss of temperature sensitivity at some northern tree-ring sites (e.g. Fig. 7, Jacoby and D'Arrigo, 1995; Barber et al., 2000; D'Arrigo et al., 2008). In a previous paper (D'Arrigo et al., 2004), we identified a temperature threshold to explain decline of tree growth at an elevational treeline site in northwestern Canada. Results showed that this threshold level had been consistently exceeded since the 1960s due to warming, demonstrating that even under treeline conditions trees can be negatively affected when temperatures warm beyond a physiological threshold. Precipitation may have actually increased in some regions of north central Canada in recent decades (Fig. 2), however, although this increase may not be sufficient to counteract increased evapotranspiration due to recent warming (Serreze et al., 2000). The apparent loss of sensitivity in both the high and low frequency domains for the Thelon ring-width record indicates that it cannot be attributed solely to any artifacts of the standardization process (e.g. Melvin, 2004). More research is needed to better understand the physiological nature of climatic response of tree growth in the far north. If warming continues without significant gains in effective precipitation, large-scale greening in recent decades could be replaced by large-scale browning effects that could slow or even reverse carbon uptake by northern forests. Such changes have the potential to greatly impact northern forest ecosystems of North America and Eurasia and their vast stores of carbon (Chapin et al., 2004; Goetz et al., 2005; Lloyd and Bunn, 2007).

The Coppermine and Thelon chronologies help fill a large spatial gap in coverage of tree-ring data utilized in large-scale temperature reconstructions. These chronologies are derived from some of the last remaining wilderness regions on earth, at sites where temperature has been considered to be the dominant factor limiting tree growth, and where site observations indicate generally mesic conditions. The chronologies from these sites display low-frequency temperature-related trends that are broadly similar to those reconstructed for the Northern Hemisphere as a whole, including inferred cooler conditions during the early–middle 19th century and increased growth during recent warming, with variable results for recent decades. Yet, none of these records date back sufficiently to make statements about the magnitude of the MWP in this region relative to 20th century warming. There are indications, as has been found elsewhere (Briffa et al., 1998a,b; Barber et al., 2000; Wilmking et al., 2005; D'Arrigo et al., 2008), that the response of radial tree growth to climate is now changing, perhaps due to the combined effects of large-scale Arctic warming and increased drought stress. Whether or not these changing growth responses are sufficiently widespread to generate significant feedback effects for the climate and carbon cycle of the Arctic is yet to be determined.

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