Available online at www.sciencedirect.com

ScienceDirect

Global and Planetary Change 60 (2008) 289 – 305

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

On the 'Divergence Problem' in Northern Forests: A review of the tree-ring evidence and possible causes

Rosanne D'Arrigo [a,*], Rob Wilson [a,b], Beate Liepert [a], Paolo Cherubini [a,c]

[a] Lamont-Doherty Earth Observatory, 61 Route 9W, Palisades, New York 10964, USA

[b] University of Edinburgh, Grants Institute, West Mains Road, Edinburgh, EH9 3JW, UK

[c] Forest Ecosystems and Ecological Risks, WSL Swiss Federal Institute for Forest, Snow and Landscape Research Zuercherstrasse 111, CH-8903, Birmensdorf, Switzerland

Received 28 November 2006; received in revised form 23 February 2007; accepted 9 March 2007
Available online 24 March 2007

Abstract

An anomalous reduction in forest growth indices and temperature sensitivity has been detected in tree-ring width and density records from many circumpolar northern latitude sites since around the middle 20th century. This phenomenon, also known as the "divergence problem", is expressed as an offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings. The divergence problem has potentially significant implications for large-scale patterns of forest growth, the development of paleoclimatic reconstructions based on tree-ring records from northern forests, and the global carbon cycle. Herein we review the current literature published on the divergence problem to date, and assess its possible causes and implications. The causes, however, are not well understood and are difficult to test due to the existence of a number of covarying environmental factors that may potentially impact recent tree growth. These possible causes include temperature-induced drought stress, nonlinear thresholds or time-dependent responses to recent warming, delayed snowmelt and related changes in seasonality, and differential growth/climate relationships inferred for maximum, minimum and mean temperatures. Another possible cause of the divergence described briefly herein is 'global dimming', a phenomenon that has appeared, in recent decades, to decrease the amount of solar radiation available for photosynthesis and plant growth on a large scale. It is theorized that the dimming phenomenon should have a relatively greater impact on tree growth at higher northern latitudes, consistent with what has been observed from the tree-ring record. Additional potential causes include "end effects" and other methodological issues that can emerge in standardization and chronology development, and biases in instrumental target data and its modeling. Although limited evidence suggests that the divergence may be anthropogenic in nature and restricted to the recent decades of the 20th century, more research is needed to confirm these observations.
© 2007 Elsevier B.V. All rights reserved.

Keywords: tree rings; dendrochronology; divergence; paleoclimate; reconstructions

1. Introduction

Tree rings are a critically important proxy for reconstructing the high resolution climate of the past millennium and are the dominant data type in most large

* Corresponding author. Tel.: +1 845 365 8617; fax: +1 845 365 8152.
E-mail address: rdd@ldeo.columbia.edu (R. D'Arrigo).

0921-8181/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2007.03.004

scale hemispheric reconstructions [e.g. Mann et al., 1999; Esper et al., 2002; D'Arrigo et al., 2006]. The statistical calibration and verification of tree-ring based reconstructions have made the science of dendrochronology perhaps the most rigorous of those available in this regard. Such records are invaluable for placing recent climatic changes in a long-term context, which can aid considerably in the detection of anthropogenic change.

A number of recent tree-ring studies have addressed the 'divergence problem' in northern forests. It is defined herein as the tendency for tree growth at some previously temperature-limited northern sites to demonstrate a weakening in mean temperature response in recent decades, with the divergence being expressed as a loss in climate sensitivity and/or a divergence in trend (Jacoby and D'Arrigo, 1995; Briffa et al., 1998a,b; Vaganov et al., 1999; Barber et al., 2000; Briffa, 2000; Jacoby et al., 2000; Wilson and Luckman, 2003; Briffa et al., 2004; D'Arrigo et al., 2004a; Wilmking et al., 2004, 2005; Driscoll et al., 2005; Büntgen et al., 2006a). Divergence-related studies have investigated what appears to be a widespread shift in the ecophysiology of tree growth response to climate, at least for many sites within the higher latitudes of the Northern Hemisphere (Briffa et al., 1998a,b). This problem is rather distinct from the forest decline issue identified at many temperate sites beginning in the 1960s, which was determined to be caused by a stress syndrome partly linked to air pollution (e.g., Cook et al., 1987; Wilson and Elling, 2004; E. Cook, TRL-LDEO, pers. comm.).

Herein we provide an overview of key studies published on the divergence problem to date and describe their varying assessments of the nature, spatial extent and possible causes of shifts in tree growth sensitivity identified in tree-ring data over the recent period. Despite the considerable efforts documented thus far to understand the divergence phenomenon, there is still substantial uncertainty regarding its possible causes. This uncertainty is largely due to the fact that there are a variety of potential environmental forcing factors, both climatic and non-climatic, natural and anthropogenic, that have covaried with each other over the twentieth century and which could potentially impact radial growth in the manner that has been observed. Possible explanations for the divergence which have been proposed by various researchers are reviewed herein, along with discussion of some of the complexities involved in evaluating this problem. Significant implications of the divergence problem are also reviewed, including impacts of this phenomenon on the ability to reconstruct large-scale temperatures from tree rings, and to directly place recent anthropogenic changes in a long-term context with prior natural variations. We also introduce the first attempt to purposely develop a "divergence-free" Northern Hemisphere temperature reconstruction up to 2000 (Wilson et al., in review).

The paper is organized as follows: Section 1 provides an introduction to the divergence problem, Section 2 presents an overview of published case studies which describe evidence of divergence on varying spatial scales, Section 3 addresses the implications of the divergence on the generation of large-scale temperature reconstructions using tree rings, Section 4 addresses possible causes of the divergence, and Section 5 provides the discussion and conclusions.

2. Tree-ring studies of decreased temperature sensitivity

2.1. Northwestern North America

Declines in temperature sensitivity (divergence effects) have been described in several local to regional scale studies, the first of which was published only a decade ago in the mid 1990s. A number of these studies focused on tree-ring sites in Alaska and vicinity. For example, Jacoby and D'Arrigo (1995; and see Taubes, 1995), in the first study to note this problem, observed that ring width and maximum latewood density chronologies from elevational and latitudinal treeline white spruce (*Picea glauca*) sites in interior and northern Alaska had a weakened temperature signal in recent decades. They theorized that this weakened response in trees previously limited by temperature might be caused by decreased temperature limitation and related moisture stress due to pronounced recent warming in Alaska (e.g. Arendt et al., 2002). In support of this theory, an increased correlation was found with local precipitation data and the Alaskan tree-ring records over recent decades, while precipitation levels also declined during this interval. Consistent with these observations, a time-dependent relationship between tree growth and precipitation (evaluated using the Kalman filter — Visser and Molenaar, 1990) first became significant after the 1960s.

It is important to note that standard temperature measurements, as obtained from meteorological data are not always sufficient to represent the tree's thermal environment, as trees can integrate the effects of other factors such as soil temperature, soil moisture and insolation (Tranquillini, 1979; Kozlowski et al., 1991; Jacoby and D'Arrigo, 1995). Declines in soil moisture availability may cause drying out of the active (top) soil layers and root zone, seeping off shallow moisture and contributing to more rapid snow melt and runoff, further enhancing tree growth sensitivity to moisture effects (Jacoby and D'Arrigo, 1995).

Fig. 1updates the earlier Jacoby and D'Arrigo (1995) analysis for the whole of Alaska by comparing a large scale composite tree-ring series derived using the Regional Curve Standardization (RCS) method (the mean of CSTA, SEW, NWNA, WRA and CNTA, D'Arrigo et al., 2006 — see Fig. 4B for locations and full names of these sites) with June–July mean temperatures (Fig. 1A, B) and July–August precipitation (Fig. 1C) averaged over the region bounded by the latitude/longitude coordinates 60°–70° N/170°–140° W. These two seasonalized parameters represent the mean optimal response of the Alaskan tree-ring composite series to climate. The relatively high correlations (~0.5–0.6) with June–July temperatures in the early 20th century weaken until there is little coherence with temperature in the recent period (Fig. 1B). Even if the series are transformed to 1st differences where coherence is marginally greater, this weakening in signal is still observed, with the correlations over the 1910–1969 and 1970–2002 periods being 0.62 ($p=0.0000$) and 0.31 ($p=0.08$) respectively, and is therefore not solely related to trend differences between the time series. Concurrent with this decrease in response to temperature, correlations with precipitation are weakly negative in the early 20th century, but rise until they are

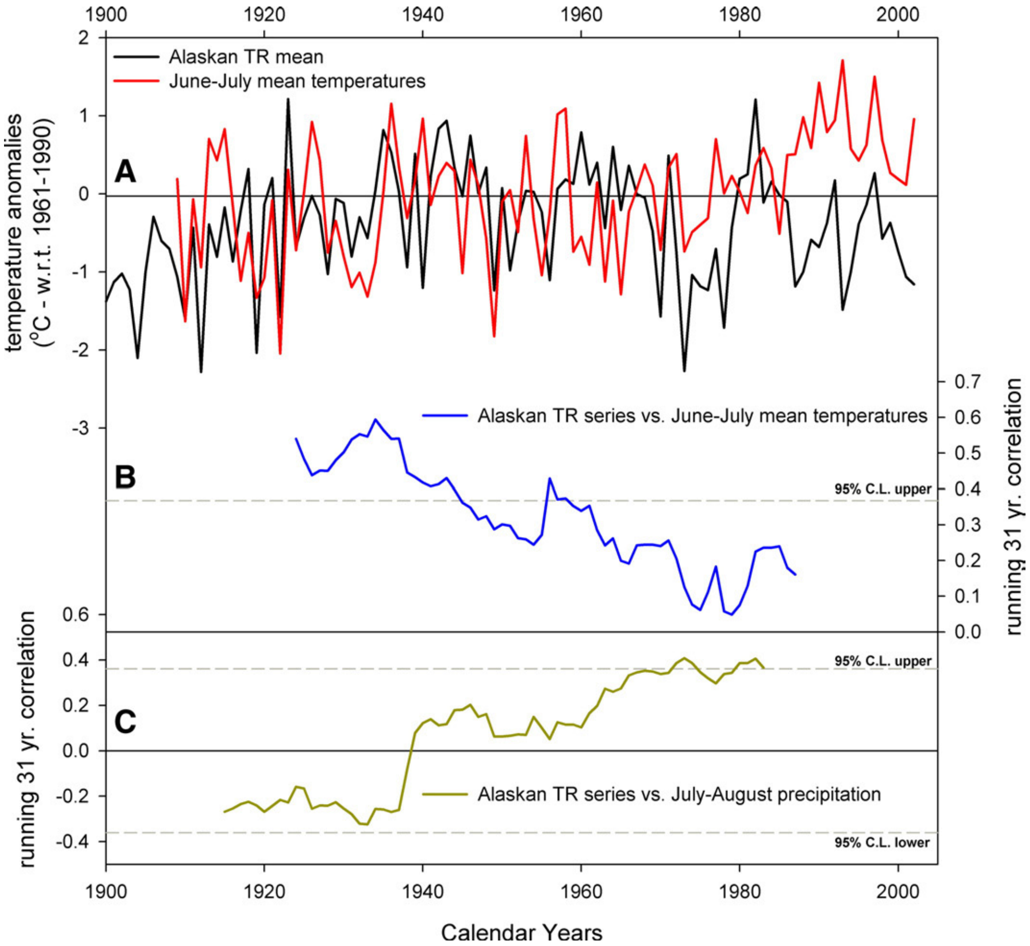

Fig. 1. A. Comparison of Alaskan mean tree-ring composite (mean of CSTA, SEW, NWNA, WRA and CNTA, regional series that had been detrended using the RCS method, D'Arrigo et al., 2006 — see Fig. 4B for locations of these composites) with June–July mean temperatures for Alaska (60°–70° N/170°–140° W, Brohan et al., 2006). The tree-ring composite was scaled (same mean and variance) to the temperature data over the 1909–1950 period; B. Running 31-year correlation between the tree-ring composite and Alaskan mean June–July temperatures; C. As for B, but with July–August precipitation (Hulme, 1992; Hulme et al., 1998) for the same region. The 95% confidence limits (C.L.) have been adjusted to take into account the 1st order autocorrelation in the tree-ring and instrumental series (Dawdy and Matalas, 1964). In this analysis and that of Fig. 2 below the presented seasons are optimal for the TR series utilized for analysis.

significantly positive (~0.3–0.4) in the late 20th century. These large scale results for Alaska are consistent with the earlier findings of Jacoby and D'Arrigo (1995; which were based partly on the same tree-ring data but with a common period ending in 1990 rather than ~2000), as well as with some other Alaskan studies cited below (some with overlapping data; including Davi et al., 2003; D'Arrigo et al., 2005).

In another tree-ring study for Alaska, but utilizing samples taken from sites with differing ecological features, Barber et al. (2000) investigated ring widths (raw measurements and indices), density and isotopic (^{13}C) records from 20 closed canopy, productive upland white spruce stands in the interior boreal forest zone of Alaska. At such sites, trees are typically more complacent and less responsive to temperature than at the alpine and latitudinal treeline sites investigated by Jacoby and D'Arrigo (1995). Despite this difference in site type and overall climate sensitivity, Barber et al. (2000) also concluded that temperature-induced drought stress was the cause of divergence at their sites, with the greatest declines in temperature sensitivity found in the faster-growing trees. They based these conclusions on a comparison of their tree-ring data with a climate index of combined temperature and precipitation. This index revealed unprecedented adverse (warm, dry) conditions in interior Alaska in the late 20th century that was believed to have broad applicability for northern boreal forests of western North America. Note that Barber et al. (2000) included raw measurements of tree growth rates, which likely have more direct implications than standardized tree-ring indices for the global carbon cycle and related modeling of large-scale forest growth variability.

Lloyd and Fastie (2002) found that growth declines were widespread in an analysis of tree-ring records from eight alpine and latitudinal treeline sites in Alaska. After ~1950, warmer temperatures were associated with decreased tree growth in all but the wettest region, the Alaska Range. Negative responses to temperature were found that were widespread across Alaska's boreal forests. Growth declines were more common at the warmer and drier locations, leading these authors to conclude that drought stress may have accompanied the increased warming of these forests in recent decades. D'Arrigo et al. (2004b, 2005) evaluated ring width and density data for the Seward Peninsula, Alaska, a region also studied by Lloyd and Fastie (2002), although overall the trees in the latter data set were considerably younger than in the former. Using correlation and regression analysis, the Seward Peninsula ring width data of D'Arrigo et al. (2005) showed a decline in temperature sensitivity after ~1970. The density data at these same sites (D'Arrigo et al., 2004a) also showed divergence, with a decrease in positive correlation with May–August temperatures beginning around 1950 that became more noticeable after ~1970. This density data set was used to reconstruct Nome, Alaska May–August temperatures (most reliable from ~AD 1630–1970) based on a 1909–1950 calibration period. The reconstruction was truncated after 1970 due to the weakened recent signal (D'Arrigo et al., 2004b).

Davi et al. (2003) detected a decline in temperature sensitivity and tree growth after ~1970 in ring width data from elevational treeline sites in the Wrangell mountain region of southeastern Alaska. This decline coincided with warming in the instrumental temperature data, and was attributed to probable drought stress for at least one of the sites studied. Partly as a result, a formal temperature reconstruction could not be developed from these ring width data. However, maximum latewood density records from these same sites did not appear to show such a decline, and were used successfully to reconstruct warm season (July–September) temperatures for the region back to AD 1593.

Another analysis examined four elevational treeline white spruce ring-width chronologies from sites in the Lake Clark National Park and Preserve on the Alaskan Peninsula, southern Alaska (Driscoll et al., 2005). The climate of this region is strongly influenced by coastal effects related to the Aleutian Low pressure cell and the North Pacific Ocean (Driscoll et al., 2005). Since around the 1940s, annual average temperatures at this location have increased (by ~2 °C) and mean annual precipitation has decreased (by ~5 cm). While two of the tree-ring sites displayed an internally consistent, positive growth response to increasing April–July temperatures after 1950, the other two sites each contained two subpopulations showing varying growth responses. In both cases, one subpopulation diverged from historical temperature data after 1950, while the other showed increased growth consistent with recent warming. Driscoll et al. (2005) attributed the growth declines to late growing season temperature-induced drought stress that, due to microsite differences, may only be operating on some of the trees studied (also see discussion of Wilmking et al., 2004, 2005 below). Driscoll et al. (2005) concluded that, due to the existence of possible drought and other (anthropogenic) stresses in recent years, assumptions about the temporal stability of climate response may need to be re-evaluated for many northern sites.

A divergence between temperature and tree growth was also investigated at an elevational treeline temperature-sensitive white spruce site (Twisted-Tree-Heartrot Hill; TTHH) in the Yukon Territory, not far from some of the Alaskan sites noted above (D'Arrigo et al., 2004a). The trees at this location, when compared with local climate data for Dawson, Yukon Territory, appeared to have reached a temperature threshold due to recent warming. The positive ring-width/temperature relationship weakened such that a pre-1965 linear model systematically overpredicted tree rings at this site from 1965–1999. A nonlinear model showed an inverted U-shaped relationship between this chronology and summer temperatures. This model was used to compute optimal average temperatures of 12.4 °C for July and 10.0 °C for August; these two optima were consistently exceeded since the 1960s. The decreased sensitivity and growth decline observed at TTHH were interpreted to signify that tree growth can be negatively affected when temperatures warm beyond a physiological threshold, even at treeline limits (Kramer and Kozlowski, 1979; Kozlowski et al., 1991; Hoch and Korner, 2003).

Here we take the opportunity to expand upon and clarify the interpretation of D'Arrigo et al. (2004a). D'Arrigo et al. (2004a) utilized a version of the Dawson instrumental temperature record that had been adjusted for inhomogeneities (Global Historical Climate Network (GHCN), V. 2; Peterson and Vose, 1997). These adjusted data were considered to be more appropriate than unadjusted data, in part because they better reflect the warming trend of the 20th century observed at other stations in this general region (David Easterling, NOAA National Climate Data Center, Lucy Vincent, Environment Canada, pers. comms. 2004). However, the corrected Dawson station data from the Historical Canadian Climate Database (HCCN, Vincent and Gullett, 1999) have less pronounced positive trends than the GHCN version used in D'Arrigo et al. (2004a). Fig. 2 illustrates the differences between these climate records which have been corrected from the same unadjusted data. The apparent disparity between these time series suggests a somewhat more cautious interpretation than that stated by D'Arrigo et al. (2004a). If the HCCN version is closer to reality, then the divergence at the TTHH site would still be present but considerably weakened, and the estimates of threshold optima would need to be modified accordingly. However, the overall conclusion would still be the same: i.e. that there is a divergence between tree growth and temperature at this site in the recent period (D'Arrigo et al., 2004a). This analysis helps illustrate an important consideration in evaluating tree growth response to climate and potential divergence: i.e. that in the far north, meteorological stations are typically sparse and short, and often located some distance from, and at different (typically lower) elevations than the tree-ring sites. Differences in elevation are important because they can cause decoupling of climatic conditions at the tree and meteorological sites, making comparisons difficult. There can also be difficulties with homogenization since there are typically few meteorological records available from a given region for comparison.

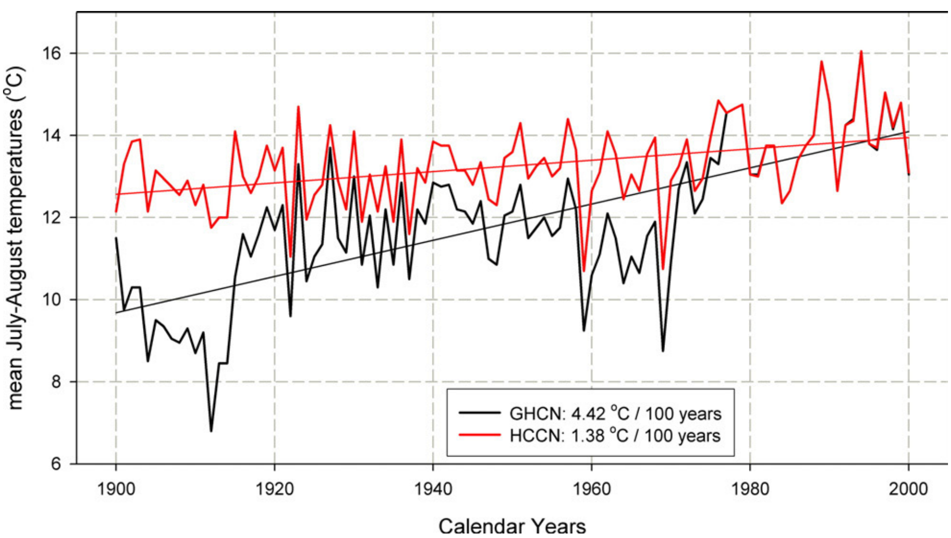

Fig. 2. Time series plots of mean July–August temperatures for the Dawson meteorological station, Yukon Territory. The data were taken from the homogeneity corrected Global Historical Climate Network (GHCN, Peterson and Vose, 1997) and Historical Canadian Climate Network (HCCN, Vincent and Gullett, 1999) data-sets. The lines denote the linear trend of each record over the 1900–2000 period.

Thus, it can be hard to generate reliable local tree-climate models in many northern areas due to the lack of good climatic data near the tree locations.

Wilson and Luckman (2003) detected a decrease in sensitivity of both ring-width and maximum density upper treeline chronologies in the southern Canadian Cordillera. They noted also, however, significant differences in trend between summer mean (Tmean), maximum (Tmax) and minimum (Tmin) temperatures in the region over the last few decades with a greater absolute rate of increase in mean and minimum temperatures. They therefore developed a superior reconstruction of maximum temperatures (versus mean temperatures) which showed no loss of sensitivity or divergence in the recent period. They hypothesized that in general, trees from temperature limited environments (i.e. upper and high latitudinal treelines) may be more strongly influenced by summer daytime temperatures than night-time temperatures. Therefore, in regions where there is a marked difference in trend between nighttime and daytime temperatures, there could be resulting calibration problems if mean temperatures are the focus predictand data set. The consideration of Tmax, Tmean and Tmin, which can themselves covary with both cloud cover/available radiation and precipitation for a particular location, is one example of how multiple varying environmental factors impact tree growth, and how the impacts of such factors can be difficult to tease apart. Youngblut and Luckman (in press), for an area to the south of TTHH (the site studied by D'Arrigo et al., 2004a), have partly tested the hypothesis of Wilson and Luckman (2003) by developing a reconstruction of summer maximum temperatures that shows no loss of temperature sensitivity in the tree-ring width records. They suggested that this difference from the TTHH site discussed above may be explained by a weaker warming trend at their southwest Yukon study sites compared to locations further north.

2.2. Eurasian continent and vicinity

Temperature-sensitive chronologies have been developed from larch (*Larix spp*.) trees on the Taymir Peninsula, Siberia, the northernmost conifers on the globe (Jacoby et al., 2000). These trees exhibited a loss of thermal response of ring widths since ~1970, and tree-ring/climate regression models were weakened if they included data from 1971–1989. Calibration and verification models were thus truncated in 1970 for the Jacoby et al. (2000) analysis. The Taymir trees were, however, found to be reliable recorders of temperature prior to 1970. A reconstruction based on the Taymir tree-ring data indicates significant warming in the middle 20th century, consistent with meteorological records for the region (Jacoby et al., 2000). Another long ring width chronology from the Taymir Peninsula does not, however, describe any divergence from temperatures, based on a recent review of tree-ring data from this region (Naurzbaev et al., 2002). However, these latter authors do state that, since the 1960s, the warming seen in Northern Hemisphere temperatures is absent in their reconstructed Taymir temperature record (although this may simply reflect a difference between local and large-scale temperature trends).

Using a data set of tree-ring width and density chronologies from the Siberian Arctic combined with a mechanistic model of tree growth, Vaganov et al. (1999) identified a link between decreased temperature sensitivity and an increasing trend in winter precipitation since the 1960s. They concluded that this positive trend resulted in delayed melting of snowpack and a delayed growing season, and that these delays could explain the divergence they observed in these trees. This shift may have resulted in slower growth rates and reduced temperature-tree growth correlations. Vaganov et al. (1999) suggested that such changes in winter precipitation should be considered a possible cause for shifts in the timing of spring greening of high latitude forests observed in remote sensing vegetation data (e.g., Myneni et al., 1997) and for the changing role of the Siberian subarctic forests in the global carbon cycle. This study illustrates the point that changes in seasonality and non-linear interactions between tree growth and climate variables must be considered in evaluating recent growth changes.

The recent portion of an 896-year composite Norway spruce (Picea abies) tree-ring width chronology based on 208 living and historic wood samples from three subalpine valleys in the Swiss Alps was shown to have an unstable response to temperature and precipitation (Büntgen et al., 2006a). These findings were based on moving 51-year correlations with long instrumental temperature data dating back to 1760, and precipitation data dating back to 1858. Along with other subalpine spruce chronologies for the region (e.g., Frank and Esper, 2005a,b; Büntgen et al., 2006a), these shifts in response were thought to indicate increased late-summer drought stress, coincident with recent warming trends. While significant similarities were found between this chronology and regional and large-scale temperature reconstructions for the centuries prior to ~1900, the relationship with large-scale temperatures in the 20th century is weakly negative (Büntgen et al., 2006a). By comparison, an increasing response to precipitation was observed over the 1858–2002 common period, particularly during warm intervals. Due to this mixed signal, a dendroclimatic reconstruction could not be developed (Büntgen et al., 2006a). It should be noted that Wilson and Topham (2004) developed a 500-year high elevation spruce summer temperature proxy for the Bavarian Forest/Austrian Alps region which expressed no sensitivity decrease in the recent period, suggesting that the results of Büntgen et al. (2006a) may be regionally specific. In addition to drought stress, Büntgen et al. (2006a) suggested that cloud cover changes, temperature-related threshold effects or trend differences between minimum, maximum and mean temperatures were possible contributing factors. These authors noted that other, non-spruce chronologies for the region tend to show more stable correlations during the 20th century, one indication that there are likely to be species-specific differences in response to divergence-related factors. Büntgen et al. (2006a) did not, however, consider pollution effects, despite Wilson and Elling (2004) showing productivity loss and climate/growth response change related to local SO_2 emissions in low elevation spruce and fir chronologies in the neighboring Bavarian Forest. However, this latter study was not strictly a divergence issue *per se*, as the low elevation tree-ring chronologies were interpreted as precipitation proxies. However, the study did highlight the potential influence of anthropogenic pollution on tree response to climate that needs to be also considered when addressing the 'divergence problem'.

Long-term changes in climate sensitivity were identified for elevational treeline *Larix decidua* (European larch) sites in northern Italy, when these ring width chronologies were compared to long climate records available from 1800–1999 (Carrer and Urbinati, 2006). Correlation and response function analyses were used to assess consistency over time in the climate-growth relationships at these sites. Carrer and Urbinati (2006) found significant, time-dependent shifts in climate sensitivity between the 19th vs. 20th centuries, and suggested that these shifts could represent a deviation from the uniformitarian principle traditionally applied to dendroclimatology. 20th century warming was believed to trigger a shift in temperature sensitivity via a type of threshold mechanism, as described elsewhere (e.g. D'Arrigo et al., 2004a; Wilmking et al., 2004, 2005; and see below). However, the climatic shifts described in Carrer and Urbinati (2006) are not necessarily a general feature of tree growth in the European Alps (e.g., Wilson and Topham, 2004; Frank and Esper, 2005a,b; Büntgen et al., 2006a,b). Other studies that have identified dynamic, time-dependent shifts in tree growth response to climate (although not necessarily declines in overall climate sensitivity per se) include Solberg et al. (2002) and, for North America, Biondi (2000).

A weakened temperature sensitivity in ring-width data from Hinoki cypress (*Chamaecyparis obtusa*) trees in central Japan was observed after ~1962 (Yonenobu and Eckstein, 2006). They were unable to verify their temperature/tree growth model after this time, as no significant correlations were found in the post-1962 period. However, they did develop a reconstruction for early spring (February–April) temperatures based on an earlier (1900–61) period of calibration. Similar to results by Wilson and Elling (2004), Yonenobu and Eckstein (2006) suggested that anthropogenic SO_2 emissions might be the cause of the divergence at this location, and perhaps for other sites in Japan as well. Elsewhere in Asia, Brauning and Mantwill (2004) found a weakened climate signal over recent decades in a density data set for Tibet, one of the few such data sets for this parameter for lower latitudes, and suggested that this weakening in response might have resulted from divergence-related factors.

2.3. Large-scale hemispheric studies

In an analysis of eight selected tree-ring sites across the circumpolar northern latitudes, Wilmking et al. (2005) determined that individual cores from each of these sites could be sorted into groups of positive and negative "responders" with regards to their direction of response to recent temperature trends. They suggested that this disparity might be due to microsite factors (e.g., slope, aspect, depth to permafrost) that cause some trees to be more drought-stressed than others, even those from the same site (see also Driscoll et al., 2005). The negative responders were negatively correlated (or only weakly positively correlated) to recent warming, likely due to moisture stress, whereas the positive responders still reacted as expected to warmer temperatures. Thus, they argued that screening of cores has the advantage of potentially enhancing the common climatic signal of interest at a given site, which is an ultimate goal of dendroclimatology (e.g., Esper et al., 2003a,b). Pisaric et al. (2007) utilized similar methods to explain recent growth trends and intrasite differences in the Mackenzie Delta region of Canada.

In the largest-scale analysis yet conducted to examine the extent of the divergence problem in northern forests, a data set of over 300 tree-ring width and density records from across the circumpolar northern latitudes was examined by Briffa et al. (1998a,b, 2004). Although not strictly from treeline sites, these data were considered to represent cool, moist locations in the northern boreal forests. Divergence became widespread across this region beginning in the second half of the 20th century (Briffa et al., 1998a,b). Although also present in the ring width data, divergence was most clearly evident in the density data. These authors stressed that the apparent large-scale nature of the decline requires a large-scale explanation, and proposed recent changes in levels of ozone and ultraviolet (UV-B) radiation, or solar radiation, as possible causes (Briffa et al., 1998a,b; and see Bradley and Jones, 1992). This topic is addressed more fully below (see Section 4, Causes).

This section presented an overview of key studies regarding the divergence problem that has recently been identified in formerly temperature-sensitive northern tree-ring data for North America and Eurasia ranging in spatial scales from individual sites to the circumpolar Arctic. Despite these various cited efforts, additional physiological and other analyses are needed to improve our understanding of the complex interactions between climate and environmental/biological factors (e.g., genetics, soil moisture availability, atmospheric CO_2 concentrations) that can impact photosynthesis and tree growth on individual tree, site and larger spatial scales. These studies also illustrate that one must consider non-linearities, threshold effects and time-varying aspects of growth response to climate and forcing with regards to the divergence issue (e.g., Jacoby and D'Arrigo, 1995; D'Arrigo et al., 2004a; Wilmking et al., 2004, 2005; Carrer and Urbinati, 2006). Much more work is needed in this regard.

3. Implications for hemispheric-scale proxy temperature

3.1. Reconstructions

The divergence problem has important consequences for the utilization of tree-ring records from temperature-limited boreal sites in hemispheric-scale proxy temperature reconstructions (Jones et al., 1998; Mann et al., 1999; Briffa, 2000; Briffa et al., 2001; Esper et al., 2002; Cook et al., 2004a; Moberg et al., 2005; D'Arrigo et al., 2006; Hegerl et al., 2006). The principal difficulty is that the divergence disallows the direct calibration of tree growth indices with instrumental temperature data over recent decades (the period of greatest warmth over the last 150 years), impeding the use of such data in climatic reconstructions. Consequently, when such data are included, a bias is imparted during the calibration period in the generation of the regression coefficients. Residuals from such regression analyses should thus be assessed for biases related to divergence, as this bias can result in an overestimation of past temperatures and an underestimation of the relative magnitude of recent warming (Briffa et al., 1998a,b).

As a result of the divergence problem, attempts to directly estimate large-scale temperatures for the recent period in dendroclimatic reconstructions have generally not been successful (Briffa et al., 1998a,b; Briffa, 2000; Briffa et al., 2001; Esper et al., 2002; D'Arrigo et al., 2006, see Fig. 3). The inability of many reconstruction models to verify in the recent period has compelled a number of researchers to eliminate recent decades from their calibration modeling, effectively shortening the available periods for direct calibration and verification testing between tree rings and climate (e.g., Briffa et al., 2001; Cook et al., 2004a; Rutherford et al., 2005; D'Arrigo et al., 2006). Another alternative is to use an empirical correction for the divergence effect (e.g., Briffa, 1992; Osborn et al., submitted for publication, Glob. Planet. Change). Compounding the problem is that many of the tree-ring records available for use in such reconstructions have been sampled at different times over the past few decades, so that their common period does not extend through to the present. This results in weaker replication of the recent period, just when stronger replication is most needed to address the divergence issue. Updating of these chronologies, many of which are from remote locations, is ongoing but requires considerable effort and resources. These difficulties serve to impede a robust comparison of recent warming during the anthropogenic period with past natural climate episodes such as the Medieval Warm Period or MWP (Esper et al., 2005).

Any theory seeking to explain the observed divergence of northern forests (see Section 4, Causes, below) will need to account for the absence of decreased climate sensitivity at some northern tree-ring sites. One notable example is a millennial-length tree-ring width record of Siberian pine (*Pinus sibirica*) from Mongolia (Sol Dav), which demonstrates a pronounced positive response to warming in recent decades (Jacoby et al., 1996; D'Arrigo et al., 2001). The trees at Sol Dav, based on ecological considerations and comparisons with instrumental temperatures, do not appear to be sensitive to moisture stress (but see Wilmking et al., 2005, who identified, for Sol Dav, a small subset of cores with a weaker temperature signal and less positive recent trend). A few more recently generated chronologies for Mongolia do show limited evidence of decreased sensitivity (Jacoby et al., in review, Quat. Res.). It should

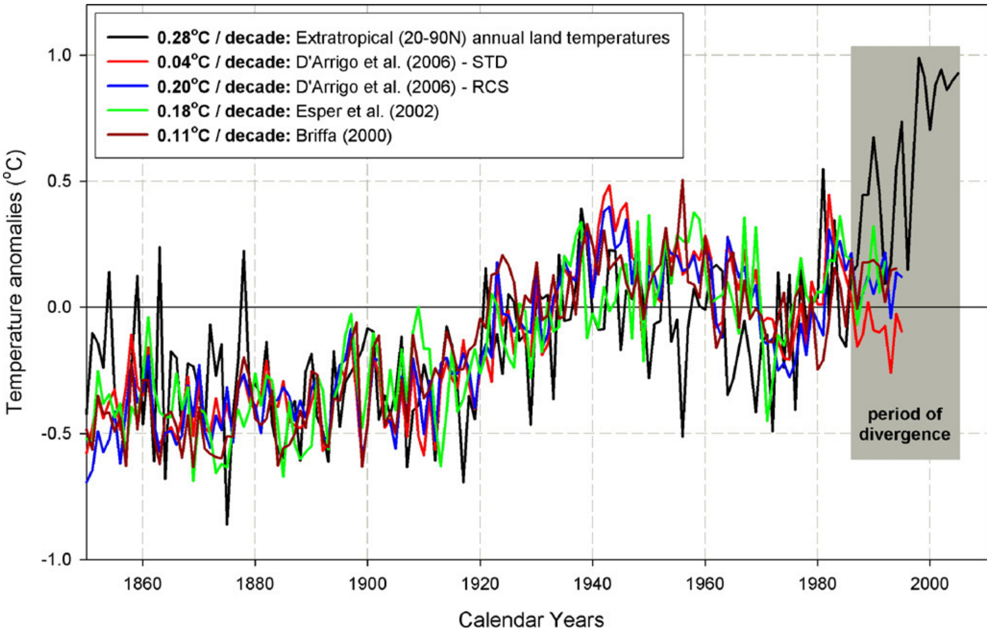

Fig. 3. Plot comparing recent tree-ring based Northern Hemisphere temperature reconstructions (Briffa, 2000; Esper et al., 2002; D'Arrigo et al., 2006) that extend into the 1990s with land based mean annual extra-tropical temperatures (20°–90° N — Brohan et al., 2006). The reconstructions have been scaled to the instrumental data over the common 1856–1992 period and the linear increase per decade calculated over the same period.

also be noted that Mongolia lies south of the zone of greatest divergence indicated by Briffa et al. (1998a,b). Other published examples of temperature-sensitive tree-ring records that do not appear to show evidence of divergence or loss of sensitivity are: Szeicz and MacDonald (1994), Biondi et al. (1999), Kirchhefer (2001), Wilson and Luckman (2002), Cook et al. (2003), Wilson and Topham (2004), Salzer and Kipfmueller (2005), Büntgen et al. (2006a,b, 2007), Frank and Esper (2005b), Wilson et al. (2007), Youngblut and Luckman (in press). There are also additional studies that indicate increases in forest growth productivity and radial growth in some areas of Europe (Rolland et al., 1998; Spiecker, 1999).

Perhaps one of the main problems with many existing millennial length tree-ring based reconstructions of Northern Hemisphere temperatures is that a number of their constituent chronologies show divergence against local temperatures in the recent period and therefore, it is not surprising that some divergence is noted during calibration of Northern Hemisphere temperatures. Fig. 3 presents three mainly ring-width based reconstructions (Briffa, 2000; Esper et al., 2002; D'Arrigo et al., 2006) of extra-tropical NH temperatures after they had been scaled to the instrumental data. Divergence is noted after the mid 1980s in each record, although the degree of underestimation is variable between the series. The series, generated using the RCS detrending method (Briffa, 2000; Esper et al., 2002; D'Arrigo et al., 2006), better track the increasing trend in the instrumental data (1970–1992 — 0.28 °C/decade) at ~0.20 °C/decade, compared to, for example, the more traditionally detrended (STD) version of D'Arrigo et al. (2006) which barely shows any trend over this period. This difference may be related to an end effect bias from the detrending of the raw tree-ring data (Melvin, 2004; and see Causes below).

Wilson et al. (in review) hypothesized that the use of "divergence-free" chronologies (at local/regional scales) may be the only way to develop large-scale, valid temperature reconstructions through the recent period. Fig. 5 presents a new temperature reconstruction for the Northern Hemisphere (hereafter WNH2006) that utilizes 15 (see Fig. 4A for locations) tree-ring based proxy series that express no divergence effects, based on modeling with local gridded data (Wilson et al., in review). WNH2006 extends from 1750–2000, is completely independent from previous Northern Hemisphere temperature reconstructions (i.e. no data overlap), and was developed exclusively to test whether a "divergence-free" Northern Hemisphere temperature reconstruction could be derived if appropriate unbiased (i.e. showing no divergence at the local scale) tree-ring proxies were used. It should be noted, however, that this

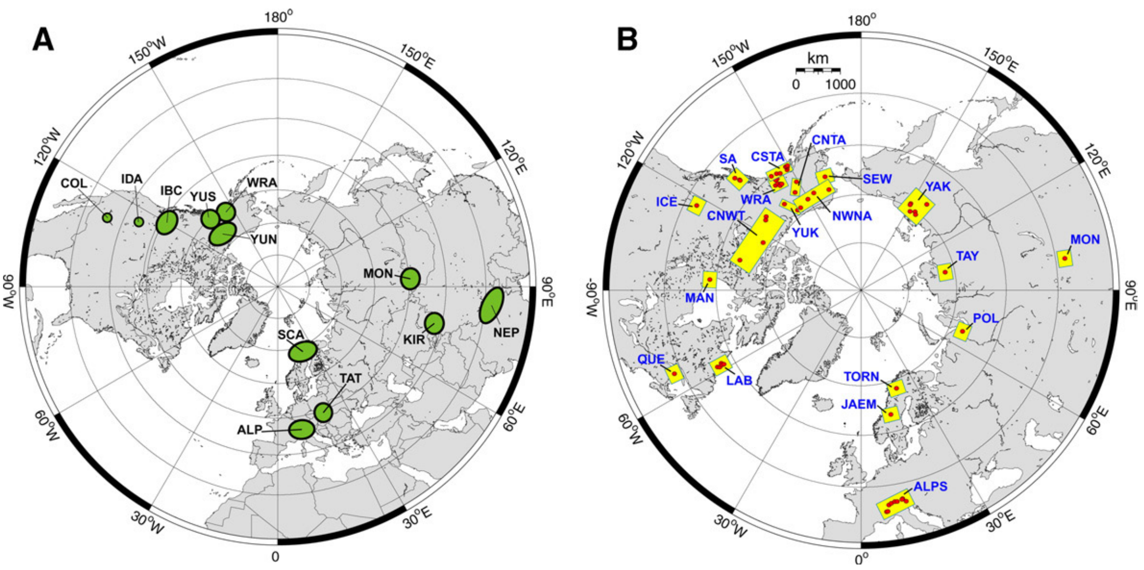

Fig. 4. A: Location of tree-ring reconstructions and composite series used to developed the new independent Northern Hemisphere temperature reconstruction (Wilson et al., in review). COL = Colorado (Salzer and Kipfmueller (2005), IDA = Idaho (Biondi et al. (1999), MBC = British Columbia (Wilson and Luckman (2002), YUS = Yukon (south — Youngblut and Luckman (in press), YUN = Yukon (north — Szeicz and MacDonald (1994), WRA = Wrangells (Davi et al. (2003), NQU = Northern Quebec (Payette (in press); Wilson et al. in prep), ALP = Alpine region (Büntgen et al., 2006a, b), TAT = Tatra Mountains (Büntgen et al., 2007), SCA = Northern Scandinavia (Kirchhefer, 2001; Wilson et al. in prep), WSI = Western Siberia (Wilson et al. in prep), MON = Mongolia (D'Arrigo et al., 2000), KYR = Kirgistan (Wilson et al., in review), TSH = Tien Shan (Esper et al., 2003b), NEP = Nepal (Cook et al., 2003); B. Location map of composite chronologies utilized by D'Arrigo et al. (2006). SEW = Seward, NWNA — NW North Alaska, YUK = Yukon, CNTA = Central Alaska, WRA = Wrangells, CSTA = Coastal Alaska, CNWT = Central Northwest Territories, SA = Southern Alaska, ICE = Icefields, MAN = Manitoba, LAB = Labrador, QUE = Quebec, JAEM = Jaemtland, TORN = Tornetraesk, POL = Polar Urals, TAY = Taymir, YAK = Yakutia, ALPS = Alps and MON = Mongolia. There are no common tree-ring data between both these studies.

"divergence-free" reconstruction includes sites at lower latitudes than the more typically northern treeline locations used in previous reconstructions (Fig. 4). WNH2006 models recent warming reasonably well, a general improvement upon earlier reconstruction attempts (Fig. 3), but despite the warmest decade in the series being 1989–1998, it still underestimates temperature values over the recent period. Between 1970 and 2000, the linear increase in instrumental temperatures is 0.32 °C/decade (Fig. 5), compared with 0.18 °C/decade in WNH2006. Wilson et al. (in review) discuss many possible reasons why it is so difficult to track recent trends in large scale temperatures, even when using tree-ring series that express no divergence at the local/regional scale, and suggest that (1) more data and sites are needed, (2) care must be taken in identifying the optimal target seasonal parameter (i.e. annual vs. summer) and (3) that further work needs to explore the hypothesis (see earlier) that calibration should target maximum daytime temperatures (Wilson and Luckman, 2003). If WNH2006 is calibrated against extra-tropical (20°–90° N) May–August maximum temperatures, no divergence is noted over the recent period (Wilson et al., in review).

Other important issues to consider in evaluating the divergence problem are whether or not this phenomenon is unprecedented over the past millennium, and to what extent it is spatially constrained to northern latitude (boreal) forests. A recent analysis by Cook et al. (2004a) suggests that the divergence is restricted to the recent period and is unique over the past thousand years. It is thus likely to be anthropogenic in origin. Cook et al. (2004a) utilized a fourteen chronology ring width data set used previously to model low-frequency temperature variability for the past millennium (Esper et al., 2002). The data from these fourteen sites were split into northern (eight boreal sites, 55°–70° N), and southern (six temperate sites, 30°–55° N) groups. While the northern group, which broadly corresponds to the region considered most sensitive to divergence by Briffa et al. (1998a,b), shows a significant recent downturn, the southern group does not and is more consistent with recent warming trends. Prior to recent decades, the subgroups track each other reasonably well back in time until around the MWP, when replication and sample size are relatively low and the reconstructed temperatures are less certain. Thus, Cook et al. (2004a) concluded that at no time prior to the 20th century (at least until the MWP) was there a separation between the north and south groups that was at all comparable to that found after around 1950. One caveat, however, is that these analyses were based on a rather small number of tree-ring records. Another is that the southern group included tree-ring data that may contain a purported CO_2 fertilization signal (e.g., LaMarche et al., 1984; Graybill and Idso, 1993). If present, such a signal might impart an exaggerated estimate of the extent of north vs. south growth divergence. However, the existence of a CO_2 fertilization signal remains very uncertain at present. Note also that the Sol Dav, Mongolia record, which shows evidence of pronounced recent warming (see above), was included in the southern group. Furthermore, end effect issues (see elsewhere in this study) can also complicate an exercise such as this one. One final point of note is that greater uncertainty exists in the earlier part of this record, and in other reconstructions, during the MWP, when sample size and replication are typically low (Cook et al., 2004a; D'Arrigo et al., 2006). Previously, Briffa et al. (1998a) conducted a similar analysis of their large-scale tree-ring data set for northern latitudes. As found by Cook et al. (2004a), Briffa et al. (1998a) discovered less divergence in the more southern regions, with declines in common variance with temperature of 5–12% vs. over 30% for some northern regions. Some of these more southern sites may have been less temperature-limited than those at the very limits of survival at treeline. Considerably more such research is needed, however, before we can conclude unequivocally that the recently observed divergence phenomenon is unique over the past thousand years.

4. Possible causes of tree growth divergence

We have discussed a number of factors that can potentially impact climate sensitivity on local to regional scales and cause or simulate divergence effects (e.g., Moisture stress: Jacoby and D'Arrigo, 1995; Barber et al., 2000; Lloyd and Fastie, 2002; Büntgen et al., 2006a; Complex non-linear or threshold responses: Vaganov et al., 1999; D'Arrigo et al., 2004a; Local pollution: Wilson and Elling, 2004; Yonenobu and Eckstein, 2006, Differential response to maximum and minimum temperatures: Wilson and Luckman, 2002, 2003, Youngblut and Luckman (in press); and Detrending end effects: Melvin, 2004; see below). The observation that the divergence phenomenon appears confined to recent decades strongly suggests an anthropogenic cause (Cook et al., 2004a). Its widespread nature may also imply a cause that is hemispheric to global in scale, possibly related to (likely anthropogenic) air pollution effects (Briffa et al., 1998a, b). Focusing on their density data set for circumpolar northern latitudes, Briffa et al. (2004) proposed that falling stratospheric ozone concentration is a possible cause of the divergence, since this observed ozone decline has been linked to an increased incidence of ultraviolet (UV-B) radiation at the ground. They cited limited, experimental evidence (e.g., Tevini, 1994) of a deleterious impact of enhanced UV-B radiation on the photosynthetic process of some higher plants that may result in decreased tree productivity (Briffa et al., 1998a,b, 2004). They performed what they referred to as a preliminary investigation of the potential role of stratospheric ozone in the recent density changes.

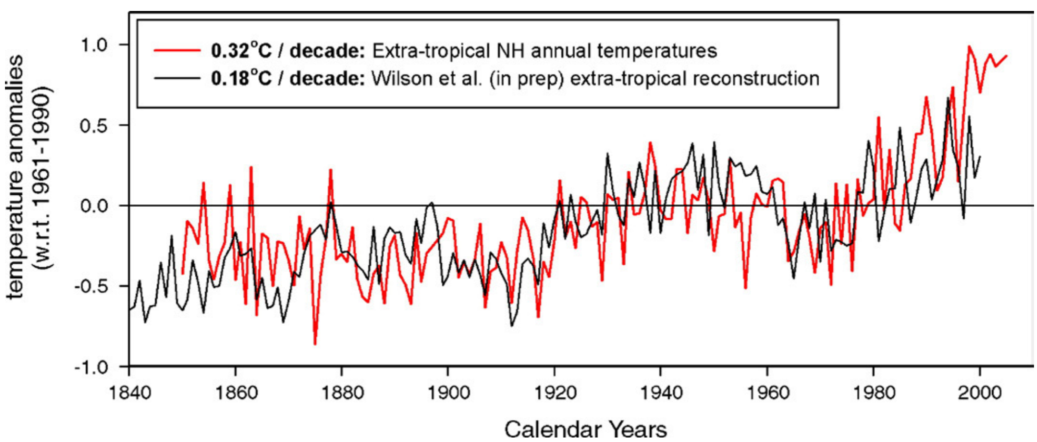

Fig. 5. Time series plot of the new "divergence-free" Northern Hemisphere reconstruction (Wilson et al., in review) with mean annual Northern Hemisphere (20°–90°) land temperatures. As with Fig. 3, the tree-ring reconstruction has been scaled to the instrumental data over the 1850–1992 period. The linear trends have been calculated over the 1970–2000 period.

Satellite ozone data since 1979 demonstrated a decline over the entire land area north of 40°N, but with large interannual variability. Briffa et al. (2004) correlated these ozone data with residuals from regression analyses of the density data with instrumental temperatures, and found marginally significant correlations for some northern regions. However, as they note, these results are far from conclusive and more research is needed if a definitive ozone-tree growth link is to be established.

Another possible cause of the divergence, which may be taking place in concert with the decline in ozone and other anthropogenic related changes mentioned previously, is global dimming (Abakumova et al., 1996; Gilgen et al., 1998; Stanhill and Cohen, 2001; Liepert, 2002). Here we briefly examine the possibility that the divergence problem is at least partly caused by this phenomenon, but note that this topic will be addressed more fully elsewhere. Global dimming is defined as a measured decline in solar radiation reaching the ground, which has been observed since the beginning of routine measurements over approximately the past half century (Stanhill and Cohen, 2001). The identified causes are a combination of cloud changes and air pollution (e.g., Russak, 1990; Liepert, 2002). The combination of more cloud water and more aerosols effectively decreases incoming solar radiation (Cohen et al., 2004; Liepert et al., 2004). It is estimated that the average amount of sunlight reaching the ground has declined by 4–6% over 1961–1990, although the estimated effects can vary from region to region (Stanhill and Cohen, 2001; Liepert, 2002; Che et al., 2005), and there can be considerable disagreement between instrumental measurements at the ground and satellite estimates of surface solar radiation (e.g. Xia et al., 2006). A decline in solar radiation of this magnitude can potentially have a profound impact on climate, the hydrological cycle (Liepert et al., 2004), and ecosystems worldwide (Stanhill and Cohen, 2001).

Dimming affects the full spectrum of solar radiation, including those wavelengths critically important for photosynthesis and plant growth (Tranquillini, 1979; Kozlowski et al., 1991). Although termed global, the changes in solar radiation associated with dimming nevertheless appear to be highly variable in spatial extent, magnitude and even sign. Continuous data sets are not available for many locations, and are missing from many areas of the tropics and Southern Hemisphere. There has been some indication of a recovery since around 1990 (Wild et al., 2005, 2007) due to efforts to reduce air pollution in industrialized countries. This recovery (termed “brightening”) indicates a slowing down or leveling off of air pollution growth rates. Although this recovery is not present at all locations, it indicates that the dimming has not continued to decline globally.

There is some support for the theory that dimming may have its greatest impact on tree growth at northern latitudes, where the greatest decline in tree-growth/temperature sensitivity has been observed. For example, Stanhill and Cohen (2001) analyzed an Arctic data base that showed a highly significant ($p<0.0001$) annual reduction of 3.7% per decade in solar radiation at many Arctic sites in North America, Scandinavia and Eastern Siberia. A related consideration is that Arctic haze, especially in winter and spring, can lead to persistent incursions of polluted air due to the stable climate of high northern latitudes. The attenuation of sunlight by aerosol particles increases with the increasing path of the sunlight at higher zenith angle in the north. Such concentrated pollution can thus lead to significant radiative forcing and impacts on ecosystems in far northern areas (Stanhill and Cohen, 2001).

Additional support of the dimming theory as a cause of the divergence is that northern forests are stressed not only by low temperatures per se, but by a short growing season. In fact, the season of radial growth can be as short as four weeks at some northern sites (e.g., Giddings, 1941), although more recent satellite and other observations suggest greening and possibly an increase in length of the growing season in many northern areas (e.g. Myneni et al., 1997). Thus, such (relatively cloudy) forests may be some of the most light-limited on the globe and hence the most sensitive to impacts of decreasing solar radiation (e.g., Stanhill and Cohen, 2001). By contrast, light is not as typically limiting to plant growth at lower latitudes and many areas of the Southern Hemisphere. In these latter locations, photosynthesis and plant growth are more likely to be limited by factors other than solar radiation, and light levels would need to decline substantially to cause a measurable shift in growth and climate response (Stanhill and Cohen, 2001). In more drought-prone regions where plant productivity is limited by moisture stress, small declines in solar radiation may have little or no impact on growth relative to the moister, cooler forests in the far north, as decreases in solar radiation can actually benefit tree growth via decreased water use and evapotranspiration (Stanhill and Cohen, 2001). Such considerations may help explain why the divergence appears to be concentrated primarily at temperature-limited northern sites, even if such hemispheric to global scale phenomena as dimming or ozone and associated cloud effects turn out to be the primary causes.

There can also be methodologically-induced uncertainties due to the type of standardization and chronology development applied (e.g., composite vs. individual detrending, use of power transformation, etc.) and calibration method and period used. Such so-called "end effect" issues can introduce uncertainties in evaluating tree growth variations over recent decades (Cook and Peters, 1997). It has been suggested that end effects resulting from the detrending process in tree-ring standardization may exaggerate recent growth declines in tree-ring chronologies and reconstructions (e.g., D'Arrigo et al., 2004a), and estimates of the magnitude of divergence, mainly at local scales (see Melvin, 2004 for a detailed discussion of these and related topics; K. Briffa and T. Melvin, Climatic Research Unit, pers. comm., 2006). Trees from different age classes can also vary in their response to environmental factors (Szeicz and MacDonald, 1994). Another complication is that there may be an upward bias in surface thermometer temperature measurements in recent years related to heat island effects (Hoyt, 2006). There can also be biases in identifying optimal target seasons for modeling of tree growth and climate (D. Frank, WSL, pers. comm. 2006). Other uncertainties, as noted earlier, relate to the quality (e.g., raw vs. homogenized and rural vs. urban) and quantity (sparseness) of instrumental station measurements in areas where many of the tree-ring sites affected by divergence are located (mainly at remote high northern latitudes or high elevations).

5. Discussion and conclusions

We have presented an overview of the currently available literature regarding the divergence problem observed in tree rings over recent decades. This phenomenon has been described on a range of spatial scales, and appears to be largely confined to northern forests (e.g., Briffa et al., 1998a; Cook et al., 2004a). However, the relative scarcity of ring width and density records from the lower mid latitudes, tropics and Southern Hemisphere precludes making definitive conclusions about the spatial extent of this phenomenon, and more research is needed to more fully evaluate the extent of the divergence problem worldwide. Some studies show a greater divergence effect in data based on the density parameter (e.g., Briffa et al., 1998a,b), and, in a few smaller scale studies (e.g., for Alaska), there may be a greater effect, or at least a comparable effect, on ring width (e.g., Jacoby and D'Arrigo, 1995; Davi et al., 2003; D'Arrigo et al., 2004b, 2005). Other studies show no divergence at all (e.g., Szeicz and MacDonald, 1994; Jacoby et al., 1996; Biondi et al., 1999; D'Arrigo et al., 2000; 2001; Kirchhefer, 2001; Wilson and Luckman, 2002; Cook et al., 2003; Davi et al., 2003 (for density), Wilson and Topham, 2004; Frank and Esper, 2005b; Salzer and Kipfmueller, 2005; Büntgen et al., 2006a,b, 2007; Wilson et al., 2007; Youngblut and Luckman, in press). Note however that some of these cited studies are not strictly based on data from the far north. Other more southern, drought-stressed sites also do not show evidence of divergence — e.g., Cook et al. (2004b). The density parameter may be particularly sensitive to changes in solar radiation (e.g., dimming), as appears to be the case following volcanic events (e.g., Jones et al., 1995). Alternatively, density variations may reflect non-linear response to cooler conditions at the end of the growing season (Neuwirth et al., 2004). The relative scarcity of density data sets as compared to ring width (but see Briffa et al., 1998a) precludes a more definitive evaluation of the differential response of these two parameters to divergence effects. This is particularly the case for lower latitudes (one exception is Brauning and Mantwill, 2004).

There has been expressed concern that the divergence problem challenges the uniformitarianism assumption in tree rings (e.g., National Research Council, 2006). However, if the divergence is in fact anthropogenic in origin then it will only directly impact reconstructions within the past few decades. Some evidence suggests that this is the case, and that the divergence is limited, and unique to this recent period (Briffa et al., 1998a; Cook et al., 2004a). Nevertheless, there are still significant implications for the development of dendroclimatic reconstructions, as we have noted in this paper. For example, reconstructions based on northern tree-ring data impacted by divergence cannot be used to directly compare past natural warm periods (notably, the MWP) with recent 20th century warming, making it more difficult to state unequivocally that the recent warming is unprecedented. Inclusion of divergence-affected tree-ring variations in the calibration period of such reconstructions could result in overestimation of past reconstructed temperatures, and underestimation of recent warming. As noted, some researchers do not include the recent divergence period in the calibration interval, which effectively decreases the opportunities for independent verification. Individual samples at a given site can be assessed to evaluate within-site differences in climate response (Esper et al., 2003a,b; Wilmking et al., 2004, 2005; Driscoll et al., 2005). Such information can be exploited to enhance the climate signal at a given site, improving any resultant reconstructions of climate (Esper et al., 2003a,b; Wilmking et al., 2004, 2005). It is also important to be aware of additional considerations regarding potential detrending-related end effects, age-related response differences, high vs. low-frequency divergence, and differential climatic response with variable temperature parameters (e.g. maximum, minimum or mean temperatures). Interestingly, the dimming phenomenon may be a cause of the slower increase in maximum vs. minimum temperatures in recent decades (Dai et al., 1999; Wild et al., 2007; Romanou et al., 2007). Tree-ring data coverage is still sparse for many far northern regions, and substantially more data are needed if we are to understand the magnitude and extent of the divergence problem. Development of proxy temperature reconstructions based on tree-ring records from divergence-free sites (Wilson et al., in review), evaluation of time-dependent and nonlinear responses of tree growth to climate (Visser and Molenaar, 1990, E. Cook, TRL-LDEO, pers. comm. 2006), and updating of chronologies through to the present will also greatly improve our ability to model large-scale temperatures over recent decades.

Several possible explanations for the divergence problem have been reviewed herein. There is valid evidence for both local to regional causes (e.g., drought stress, physiological threshold effects) as well as potential hemispheric to global scale environmental causes. These include changing stratospheric ozone levels, which have thus far only been investigated in a preliminary manner and only for density, not ring width data (Briffa et al., 2004). Another potential large-scale factor that merits further investigation is global dimming (Liepert, 2002; Liepert et al., 2004), as we have noted herein, but which needs to be investigated in much more detail. These large-scale factors may be distinct from more localized pollution effects (e.g. Wilson and Elling, 2004; Yonenobu and Eckstein, 2006).

This review did not yield any consistent pattern that could shed light on whether one possible cause of divergence might be more likely than others. We conclude that a combination of reasons may be involved that vary with location, species or other factors, and that clear identification of a sole cause for the divergence is probably unlikely. The studies cited herein also varied with method of analysis (e.g., regression, Kalman filter, modes of standardization) and site ecological conditions (e.g. latitudinal/elevational treeline or productive forest, coastal or interior sites). The issue is thus highly complex, with likely ecophysiological feedbacks coming into play related to differences in environmental conditions between sites, species and regions. For example, there have been recent shifts in patterns of insect infestation (G. Juday, Univ. Alaska Fairbanks, pers. comm. 2006), as well as forest dynamics that can preclude a purely positive response to warmer temperatures in areas of Alaska (Jacoby and D'Arrigo, 1995). In short, we believe the problem is real but that there does not appear to exist a single "divergence" phenomenon with an underlying causal mechanism.

Large-scale greening in some northern regions observed in satellite data since the early 1980s (Myneni et al., 1997; Nemani et al., 2003; Brown et al., 2004) is thought to be due to enhanced warming; however in some areas it could be replaced by decreased growth (browning; Zhang et al., submitted for publication; Bunn and Goetz, 2006) and weakened sensitivity of temperature response related to divergence (D'Arrigo et al., 2004a). If widespread, the divergence could thus slow or reverse carbon uptake by northern forests. Without correcting for the divergence, carbon cycle models may underestimate the future carbon uptake capacity of northern forests, and hence future levels of atmospheric CO_2 (Briffa et al., 1998a,b; Barber et al., 2000). Future analyses will benefit from comparing different tree growth parameters, conducting multi-proxy studies with scientists from a variety of disciplines, and vegetation and carbon cycle modeling (Briffa, 2000; Briffa et al., 2004). Particular effort should be focused on understanding the ecophysiological factors that determine tree growth response to recent divergence-related forcings. Mechanistic tree growth models may aid in this regard (Melvin, 2004 and references cited therein, Anchukaitis et al., 2006; Evans et al., 2006), as they can be used to assess changes in tree growth response to climate over time due to multiple, and nonlinear causes. As existing records are updated and new ones developed, we will improve our ability to make more defined, direct evaluations of the climate of recent decades relative to the past.

Acknowledgements

This research was funded by the National Science Foundation's Earth System History and EROC programs, and NOAA's Climate Change and Data Detection Program. It was also partially funded by the Office of Science (BER), US Dept of Energy, through the Western Regional Center of the National Institute for Global Environmental Change under Cooperative Agreement No. DE-FC03-90ER61010 and DE-FC02-03ER63613. Additional funding for R. Wilson was obtained from the European Union Millennium Project (Grant No. EU-017008-2-Millennium) and for B. Liepert from the National Science Foundation's Atmospheric Dynamics program (Grant No. ATM0224807). We thank Keith Briffa, Ulf Büntgen, David Frank, Gordon Jacoby and one anonymous reviewer for suggestions that improved this manuscript. Lamont-Doherty Earth Observatory Contribution No. 7021.

References

Abakumova, G., Feigelson, E., Russak, V., Stadnik, V., 1996. Evaluation of long-term changes in radiation, cloudiness, and surface temperature on the territory of the former Soviet Union. J. Climate 9, 1319–1327.

Anchukaitis, K., Evans, M., Kaplan, A., Vaganov, E., Hughes, M., Grissino-Mayer, H., Cane, M., 2006. Forward modeling of regional-scale tree-ring patterns in the southeastern United States and the recent influence of summer drought. Geophys. Res. Lett. 33, L04705. doi:10.1029/2005GL025050.

Arendt, A.A., Echelmeyer, K.A., Harrison, W.D., Lingle, C.S., Valentine, V.B., 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. Science 297, 382–386.

Barber, V., Juday, G., Finney, B., 2000. Reduced growth of Alaska white spruce in the twentieth century from temperature-induced drought stress. Nature 405, 668–672.

Biondi, F., 2000. Are climate-tree growth relationships changing in north-central Idaho, USA? Arctic Ant. Alpine Res. 32, 111–116.

Biondi, F., Perkins, D.L., Cayan, D.R., Hughes, M.K., 1999. July temperature during the second millennium reconstructed from Idaho tree rings. Geophys. Res. Lett. 26, 1445–1448.

Bradley, R., Jones, P., 1992. Records of explosive volcanic eruptions over the last 500 years. In: Bradley, R., Jones, P. (Eds.), Climate Since A.D. 1500. Routledge Press, London, UK, pp. 606–622.

Brauning, A., Mantwill, B., 2004. Summer temperature and summer monsoon history on the Tibetan Plateau during the last 400 years recorded by tree rings. Geophys. Res. Lett. 31, L24205. doi:10.1029/2004GL020793.

Briffa, K., 1992. Increasing productivity of "natural growth" conifers in Europe over the last century. In: Bartholin, T., et al. (Ed.), "Tree Rings and Environment": Proceedings of an International Symposium, Ystad, South Sweden, 3–9 Sept. 1990. Lundqua Report, vol. 34. Dept Quat. Geol., Lund University, pp. 64–71.

Briffa, K., 2000. Annual climate variability in the Holocene: interpreting the message from ancient trees. Quat. Sci. Rev. 19, 87–105.

Briffa, K., Schweingruber, F., Jones, P., Osborn, T., 1998a. Reduced sensitivity of recent tree growth to temperature at high northern latitudes. Nature 391, 678–682.

Briffa, K., Schweingruber, F., Jones, P., Osborn, T., Harris, I., Shiyatov, S., Vaganov, A., Grudd, H., 1998b. Trees tell of past climates: but are they speaking less clearly today? Philos. Trans. R. Soc. Lond., B 353, 65–73.

Briffa, K.R., Osborn, T.J., Schweingruber, F.H., Harris, I.C., Jones, P.D., Shiyatov, S.G., Vaganov, E.A., 2001. Low frequency temperature variations from a northern tree-ring density network. J. Geophys. Res. 106, 2929–2941.

Briffa, K., Osborn, T., Schweingruber, F., 2004. Large-scale temperature inferences from tree rings: a review. Glob. Planet. Change 40, 11–26.

Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B., Jones, P.D., 2006. Uncertainty estimates in regional and global observed temperature changes: a new data set from 1850. J. Geophys. Res. 111, D12106. doi:10.1029/2005JD006548.

Brown, M., Pinzon, J., Tucker, C., 2004. New vegetation index data set available to monitor global change. EOS, Trans. AGU 85 (52), 565–569.

Bunn, A. Goetz. S. 2006. Trends in satellite-observed circumpolar photosynthetic activity from 1982 to 2003: the influence of seasonality, cover type, and vegetation density. Earth .Interact 10, Paper no. 12.

Büntgen, U., Frank, D., Schmidhalter, M., Neuwirth, B., Seifert, M., Esper, J., 2006a. Growth/climate response shift in a long subalpine spruce chronology. Trees 20, 99–110.

Büntgen, U., Frank, D.C., Nievergelt, D., Esper, J., 2006b. Summer temperature variations in the European Alps, a.d. 755-2004. J. Climate 19 (21), 5606–5623.

Büntgen, U., Frank, D.C., Kaczka, R.J., Verstege, A., Zwijacz-Kozica, T., Esper, J., 2007. Growth/climate response of a multi-species tree-ring network in the Western Carpathian Tatra Mountains, Poland and Slovakia. Tree Physiology 27, 689–702.

Carrer, M., Urbinati, C., 2006. Long-term change in the sensitivity of tree-ring growth to climate forcing in *Larix decidua*. New Phytol. 170, 861–872.

Che, H.Z., Shi, G.Y., Zhang, X.Y., Arimoto, R., Zhao, J.Q., Xu, L., Wang, B., Chen, Z.H., 2005. Analysis of 40 years of solar radiation data from China, 1961–2000. Geophys. Res. Lett. 32, L06803. doi:10.1029/2004GL022322.

Cohen, S., Liepert, B., Stanhill, G., 2004. Global dimming comes of age. EOS 85, 362–363.

Cook, E., Peters, K., 1997. Calculating unbiased tree-ring indices for the study of climatic and environmental change. Holocene 7, 361–370.

Cook, E., Johnson, A., Blasing, T., 1987. Forest decline: modeling the effect of climate in tree rings. Tree Physiol. 3, 27–40.

Cook, E.R., Krusic, P.J., Jones, P.D., 2003. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. Int. J. Climatol. 23, 707–732.

Cook, E.R., Esper, J., D'Arrigo, R.D., 2004a. Extra-tropical Northern Hemisphere land temperature variability over the past 1000 years. Quat. Sci. Rev. 23, 2063–2074.

Cook, E., Woodhouse, C., Eakin, C., Meko, D., Stahle, D., 2004b. Long-term aridity changes in the Western United States. Science 306 (5698), 1015–1018. doi:10.1126/science.1102586.

Dai, A., Trenberth, K.E., Karl, T.R., 1999. Effects of clouds, soil moisture, precipitation and water vapour on diurnal temperature range. J. Climate 12, 2451–2473.

D'Arrigo, R.D., Jacoby, G., Pederson, N., Frank, D., Buckley, B., Baatarbileg, N., Mijiddorj, R., Dugarjav, C., 2000. Mongolian tree rings, temperature sensitivity and reconstructions of Northern Hemisphere temperature. Holocene 10, 669–672.

D'Arrigo, R., Jacoby, G., Frank, D., Pederson, N., Cook, E., Buckley, B., Mijiddorj, R., Dugarjav, C., 2001. 1738 years of Mongolian temperature variability inferred from a tree-ring record of Siberian pine. Geophys. Res. Lett. 28, 543–546.

D'Arrigo, R., Kaufmann, R., Davi, N., Jacoby, G., Laskowski, C., Myneni, R., Cherubini, P., 2004a. Thresholds for warming-induced growth decline at elevational treeline in the Yukon Territory. Glob. Biogeochem. Cycles 18. doi:10.1029/2004GBO02249.

D'Arrigo, R., Mashig, E., Frank, D., Jacoby, G., Wilson, R., 2004b. Reconstructed warm season temperatures for Nome, Seward Peninsula, Alaska since AD 1389. Geophys. Res. Lett. 31, L09202. doi:10.1029/2004GL019756.

D'Arrigo, R., Mashig, E., Frank, D., Wilson, R., Jacoby, G., 2005. Temperature variability over the past millennium inferred from northwestern Alaska tree rings. Clim. Dyn. 24 (2–3), (Feb.).

D'Arrigo, R., Wilson, R., Jacoby, G., 2006. On the long-term context for late twentieth century warming. J. Geophys. Res. 111, D03103. doi:10.1029/2005JD006352.

Dawdy, D.R., Matalas, N.C., 1964. Statistical and probability analysis of hydrologic data, Part III: analysis of variance, covariance and time-series. In: Chow, V.T. (Ed.), Handbook of Applied Hydrology, A Compendium of Water-Resources Technology. McGraw-Hill, New York, NY, pp. 8.68–8.90.

Davi, N., Jacoby, G., Wiles, G., 2003. Boreal temperature variability inferred from maximum latewood density and tree-ring width data, Wrangell Mountain region, Alaska. Quat. Res. 60, 252–262.

Driscoll, W., Wiles, G., D'Arrigo, R., Wilmking, M., 2005. Divergent tree growth response to recent climatic warming, Lake Clark National Park and Preserve, Alaska. Geophys. Res. Lett. 32, L20703. doi:10.1029/2005GL024258.

Esper, J., Cook, E.R., Schweingruber, F.H., 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295, 2250–2253.

Esper, J., Cook, E., Krusic, P., Peters, K., 2003a. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. Tree-Ring Res. 59, 81–98.

Esper, J., Shiyatov, S.G., Mazepa, V.S., Wilson, R.J.S., Graybill, D.A., Funkhouser, G., 2003b. Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. Clim. Dyn. 21 (8), 699–706.

Esper, J., Wilson, R., Frank, D., Moberg, A., Wanner, H., Luterbacher, J., 2005. Climate: Past ranges and future changes. Quat. Sci. Rev. 24, 2164–2166.

Evans, M., Reichert, B., Kaplan, A., Anchukaitis, K., Vaganov, E., Hughes, M., Cane, M., 2006. A forward modeling approach to paleoclimatic interpretation of tree-ring data. J. Geophys. Res. 111, G03008. doi:10.1029/2006JG000166.

Frank, D., Esper, J., 2005a. Characterization and climate response patterns of a high-elevation, multi-species tree-ring network for the European Alps. Dendrochronologia 22, 107–121.

Frank, D., Esper, J., 2005b. Temperature reconstructions and comparisons with instrumental data from a tree-ring network for the European Alps. Int. J. Climatol. 25, 1437–1454.

Giddings, J., 1941. Dendrochronology in northern Alaska. Univ. Ariz. Bull. 12 (4).

Gilgen, H., Wild, M., Ohmura, A., 1998. Means and trends of short-wave irradiance at the surface estimated from global energy balance archive data. J. Climate 11, 2042–2061.

Graybill, D., Idso, S., 1993. Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree-ring chronologies. Glob. Biogeochem. Cycles 7, 81–95.

Hegerl, G., Crowley, T., Hyde, W., Frame, D., 2006. Climate sensitivity constrained by temperature reconstructions over the past seven centuries. Nature 440. doi:10.1038/Nature 04679 (20 April 2006).

Hoch, G., Korner, C., 2003. The carbon charging of pines at the climatic treeline: a global comparison. Oecologia 135, 10–21.

Hoyt, D., 2006. Urban heat islands and land use changes. http://www.warwickhughes.com/hoyt/uhi.htm. 2006April 13, 2006.

Hulme, M., 1992. A 1951–80 global land precipitation climatology for the evaluation of General Circulation Models. Clim. Dyn. 7, 57–72.

Hulme, M., Osborn, T.J., Johns, T.C., 1998. Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulations. Geophys. Res. Lett. 25, 3379–3382.

Jacoby, G.C., D'Arrigo, R., 1995. Tree-ring width and density evidence of climatic and potential forest change in Alaska. Glob. Biogeochem. Cycles 9, 227–234.

Jacoby, G.C., D'Arrigo, R., Davaajamts, T.S., 1996. Mongolian tree rings and twentieth century warming. Science 273, 771–773.

Jacoby, G., Lovelius, N., Shumilov, O., Raspopov, O., Kurbainov, J., Frank, D., 2000. Long-term temperature trends and tree growth in the Taymir region of northern Siberia. Quat. Res. 53, 312–318.

Jacoby, G., Baatarbileg N., Davi, N., Curtis, A., D'Arrigo, R., in review. A Central Asian millennial temperature record based on tree rings from Mongolia. Quat. Res.

Jones, P., Briffa, K., Schweingruber, F., 1995. Tree-ring evidence of the widespread effects of explosive volcanic eruptions. Geophys. Res. Lett. 22, 1333–1336.

Jones, P., Briffa, K., Barnett, T., Tett, S., 1998. High-resolution paleoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. Holocene 8, 455–471.

Kirchhefer, A.J., 2001. Reconstruction of summer temperatures from tree-rings of Scots pine (*Pinus sylvestris* L.) in coastal northern Norway. Holocene 11, 41–52.

Kozlowski, T., Karmer, P., Pallardy, S., 1991. The Physiological Ecology of Woody Plants. Academic Press, California.

Kramer, P., Kozlowski, T., 1979. The Physiology of Woody Plants. Academic Press, California.

LaMarche Jr., V.C., Graybill, D., Fritts, H., Rose, M., 1984. Increasing atmospheric carbon dioxide: tree-ring evidence for growth enhancement in natural vegetation. Science 225, 1019–1021.

Liepert, B., 2002. Observed reductions in solar surface radiation in the United States and worldwide from 1961 to 1990. Geophys. Res. Lett. 29, 1421. doi:10.1029/2002GL014910.

Liepert, B., Feichter, J., Lohmann, U., Roeckner, E., 2004. Can aerosols spin down the hydrological cycle in a moister and warmer world? Geophys. Res. Lett. 31, L06207. doi:10.1029/2003GL019060.

Lloyd, A., Fastie, C., 2002. Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. Clim. Change 58, 481–509.

Mann, M.E., Bradley, R., Hughes, M., 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties and limitations. Geophys. Res. Lett. 26, 759–762.

Melvin, T., 2004. Historical growth rates and changing climatic sensitivity of boreal conifers. Ph.D. thesis, Climatic Research Unit, East Anglia, UK.

Moberg, A., Sonechkin, D., Homgren, K., Datsenko, N., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low-and high-resolution proxy data. Nature 433, 613–617. doi:10.1038/nature03265.

Myneni, R., Keeling, C., Tucker, C., Asrar, G., Nemani, R., 1997. Increased plant growth in the northern latitudes from 1981 to 1991. Nature 386, 698–702.

National Research Council, 2006. Report on Surface Temperature Reconstructions for the Last 2,000 Years. June 22, 2006. http://nationalacademies.org.

Naurzbaev, M., Vaganov, E., Siderova, O., Schweingruber, F., 2002. Summer temperatures in eastern Taimyr inferred from a 2427-year late-Holocene tree-ring chronology and earlier floating series. Holocene 12, 727–736.

Nemani, R., Keeling, C., Hashimoto, H., Jolly, W., Piper, S., Tucker, C., Myneni, R., Running, S., 2003. Climate-driven increases in global net primary production from 1982. Science 300, 1560–1563.

Neuwirth, B., Esper, J., Schweingruber, F., Winiger, M., 2004. Site ecological differences to the climatic forcing of spruce pointer years from the Lotschental, Switzerland. Dendrochronologia 21, 69–78.

Osborn, T., Briffa, K., Schweingruber, F., Jones, P., Annually resolved patterns of summer temperature over the Northern Hemisphere since AD 1400 from a tree-ring density network. Glob. Planet. Change. Submitted for publication.

Payette, S. Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. Ecology in press.

Peterson, T.C., Vose, R.S., 1997. An overview of the Global Historical Climatology Network temperature data base. Bull. Am. Meteorol. Soc. 78, 2837–2849.

Pisaric, M., Carey, S., Kokelj, S., Youngblut, D., 2007. Anomalous 20th century tree growth, Mackenzie Delta, Northwest Territories, Canada. Geophys. Res. Lett. 34, L05714. doi:10.1029/2006GL029139.

Rolland, C., Petitcolas, V., Michalet, R., 1998. Changes in radial tree growth for *Picea abies, Larix decidua, Pinus cembra* and *Pinus uncinata* near the alpine timberline since 1750. Trees 13, 40–53.

Romanou, N., Liepert, B., Schmidt, G., Rossow, W., Zhang, J., Ruedy, R., 2007. Simulated and observed changes in surface solar irradiance in the 20th century. Geophys. Res. Lett. 34, L05713. doi:10.1029/2006GL028356.

Russak, V., 1990. Trends of solar radiation, cloudiness, and atmospheric transparency during recent decades in Estonia. Tellus 42b, 206–210.

Rutherford, S., Mann, M., Osborn, T., Bradley, R., Briffa, K., Hughes, M., Jones, P., 2005. Proxy-based Northern Hemisphere surface temperature reconstructions: sensitivity to method, predictor network, target season, and target domain. J. Climate 18, 2308–2329.

Salzer, M., Kipfmueller, K., 2005. Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado plateau, U.S.A. Clim Change 70, 465–487. doi:10.1007/s10584-005-5922-3.

Solberg, B., Hofgaard, A., Hytteborn, H., 2002. Shifts in radial growth responses of coastal *Picea abies* induced by climatic change during the 20th century, central Norway. Ecoscience 9, 79–88.

Spiecker, H., 1999. Overview of recent growth trends in European forests. Water Air Soil Pollut. 116, 33–46.

Stanhill, G., Cohen, S., 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. For. Meteorol. 107, 255–278.

Szeicz, J., MacDonald, G., 1994. Age-dependent tree-ring growth responses of subarctic white spruce to climate. Can. J. For. Res. 24, 120–132.

Taubes, G., 1995. Is a warmer climate wilting the forests of the north? Science 267, 1595.

Tevini, M., 1994. Physiological change in plants related to UV-B radiation: an overview. In: Biggs, R.H., Joyner, M. (Eds.), Stratospheric Ozone Depletion/UV-B Radiation in the Biosphere. NATO ASI Series, vol. 118. Springer-Verlag, Berlin, pp. 38–56.

Tranquillini, W., 1979. Physiological Ecology of the Alpine Timberline. Springer-Verlag, New York.

Vaganov, E., Hughes, M., Kirdyanov, A., Schweingruber, F., Silkin, P., 1999. Influence of snowfall and melt timing on tree growth in Subarctic Eurasia. Nature 400, 149–151.

Vincent, L.A., Gullett, D.W., 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. Int. J. Climatol. 19, 1375–1388.

Visser, H., Molenaar, J., 1990. Detecting time-dependent climatic responses in tree rings using the Kalman filter. In: Cook, E., Kairiukstis, L. (Eds.), Methods of Dendrochronology. Kluwer Academic Press, Dordrecht, pp. 270–277.

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C., Dutton, E., Forgan, B., Kallis, A., Russak, V., Tsvetkov, A., 2005. From dimming to brightening: decadal changes in solar radiation at Earth's surface. Science 208, 847–850.

Wild, M., Ohmura, A., Makowski, K., 2007. Impact of global dimming and brightening on global warming. Geophys. Res. Lett. 34, L04702. doi:10.1029/2006GL028031.

Wilmking, M., Juday, G., Barber, V., Zald, H., 2004. Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. Glob. Change Biol. 10, 1724–1736. doi:10.1111/j.1365-2486.2004.00826.

Wilmking, M., D'Arrigo, R., Jacoby, G., Juday, G., 2005. Divergent growth responses in circumpolar boreal forests. Geophys. Res. Lett 32, L15715. doi:10.1029/2005GLO23331.

Wilson, R., Luckman, B., 2002. Tree-ring reconstruction of maximum and minimum temperatures and the diurnal temperature range in British Columbia, Canada. Dendrochronologia 20, 1–12.

Wilson, R.J.S., Luckman, B.H., 2003. Dendroclimatic reconstruction of maximum summer temperatures from upper tree-line sites in interior British Columbia. The Holocene 13, 853–863.

Wilson, R., Elling, W., 2004. Temporal instability in tree-growth/climate response in the Lower Bavarian Forest region: implications for dendroclimatic reconstruction. Trees 18, 19–28.

Wilson, R.J.S., Topham, J., 2004. Violins and Climate. Theor. Appl. Climatol. 77, 9–24.

Wilson, R., Wiles, G., D'Arrigo, R., Zweck, C., 2007. Cycles and shifts: 1300-years of multi-decadal temperature variability in the Gulf of Alaska. Clim. Dyn. 28, 425–440. doi:10.1007/s00382-006-0194-9.

Wilson, R., D'Arrigo, R., Buckley, B., Büntgen, U., Esper, J., Frank, D., Luckman, B., Payette, S., Vose, R., Youngblut, D., in review. A matter of divergence-tracking recent warming at hemispheric scales using tree-ring data. J. Geophys. Res.

Xia, X., Wang, P., Chen, H., Liang, F., 2006. Analysis of downwelling surface solar radiation in China from National Centers for Environmental Prediction reanalysis, satellite estimates, and surface observations. J. Geophys. Res. 111, D09103. doi:10.1029/2005JD006405.

Yonenobu, H., Eckstein, D., 2006. Reconstruction of early spring temperature for central Japan from the tree-ring widths of Hinoki cypress and its verification by other proxy records. Geophys. Res. Lett. 33, L10701. doi:10.1029/2006GL026170.

Youngblut, D., Luckman, B. Maximum June–July temperatures in the southwest Yukon over the last 300 years reconstructed from tree rings. Dendrochronologia. In press.

Zhang, K., Kimball, J., Hogg, E., Zhao, M., Oechel, O., Cassano, J., Running, S. Satellite remote sensing detection of a recent decline in northern high latitude terrestrial vegetation productivity with regional warming and drying. Global Change Biol. Submitted for publication.