Global Change Biology (2009), doi: 10.1111/j.1365-2486.2009.01913.x

Trends and uncertainties in Siberian indicators of 20th century warming

JAN ESPER*†, DAVID FRANK*, ULF BÜNTGEN*, ANNE VERSTEGE*, RASHIT M. HANTEMIROV‡ and ALEXANDER V. KIRDYANOV§

**Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland, †Oeschger Centre for Climate Change Research, Erlachstrasse 9a, 3012 Bern, Switzerland, ‡Laboratory of Dendrochronology, Institute of Plant and Animal Ecology, Ural Branch of Russian Academy of Sciences, 8 Marta Street, 222, Ekaterinburg 620144, Russia, §V. N. Sukachev Institute of Forest SB RAS, 660036 Krasnoyarsk, Akademgorodok, Russia*

Abstract

Estimates of past climate and future forest biomass dynamics are constrained by uncertainties in the relationships between growth and climatic variability and uncertainties in the instrumental data themselves. Of particular interest in this regard is the boreal-forest zone, where radial growth has historically been closely connected with temperature variability, but various lines of evidence have indicated a decoupling since about the 1960s. We here address this growth-vs.-temperature divergence by analyzing tree-ring width and density data from across Siberia, and comparing 20th century proxy trends with those derived from instrumental stations. We test the influence of approaches considered in the recent literature on the divergence phenomenon (DP), including effects of tree-ring standardization and calibration period, and explore instrumental uncertainties by employing both adjusted and nonadjusted temperature data to assess growth-climate agreement. Results indicate that common methodological and data usage decisions alter 20th century growth and temperature trends in a way that can easily explain the post-1960 DP. We show that (i) Siberian station temperature adjustments were up to 1.3 °C for decadal means before 1940, (ii) tree-ring detrending effects in the order of 0.6–0.8 °C, and (iii) calibration uncertainties up to about 0.4 °C over the past 110 years. Despite these large uncertainties, instrumental and tree growth estimates for the entire 20th century warming interval match each other, to a degree previously not recognized, when care is taken to preserve long-term trends in the tree-ring data. We further show that careful examination of early temperature data and calibration of proxy timeseries over the full period of overlap with instrumental data are both necessary to properly estimate 20th century long-term changes and to avoid erroneous detection of post-1960 divergence.

Keywords: boreal forest, climate data, proxy data, Siberia, tree-rings, wood density

Received 28 January 2009 and accepted 30 January 2009

Introduction

Recent work has described a disassociation of tree growth from temperatures in high latitude environments (overview in D'Arrigo *et al*., 2008). This disassociation is meanwhile widely recognized as the 'divergence phenomenon' (DP) and effectively describes systematic differences in the trends of summer temperature and radial tree growth. Specifically, greater increases in temperature than in growth are reported since about the 1960s. DP was reported to be strongest in Siberia (Briffa *et al*., 1998), but is also indicated in other high latitude regions of the Northern Hemisphere (Jacoby & D'Arrigo, 1995; Briffa *et al*., 1998; Barber *et al*., 2000; Jacoby *et al*., 2000; Lloyd & Fastie, 2002; Driscoll *et al*., 2005; Wilmking *et al*., 2005; Lloyd & Bunn, 2007; Wilson *et al*., 2007; D'Arrigo *et al*., 2008). If DP would remain as a widespread feature of boreal tree growth, this would limit the skill of tree-ring based climate reconstructions to properly estimate temperature variations during preinstrumental warm periods (Esper *et al*., 2005b), such as the Medieval Warm Period (Lamb, 1965). Shifting growth/climate relationships would also complicate future carbon budgets (Malhi *et al*., 2002; IPCC, 2007), as 21st century tree growth, and thus

Correspondence: Jan Esper, Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland, tel. + 41 44 739 2510, fax + 41 44 739 2515, e-mail: esper@wsl.ch

carbon uptake, will be slower than expected based upon 20th century tree-ring/temperature associations.

While these globally relevant trends and feedbacks are prone to uncertainties (Houghton, 2003), the regional instrumental climate data, that are used to both calibrate tree growth trends and testify to the past warming, also contain error. This is, for example, illustrated by the substantial uncertainty bands accompanying the timeseries averaging land temperatures north of 65°N (IPCC, 2007, p. 249). In the entire Siberian area east of the Ural Mountains and north of 60°N, data from only 13 instrumental climate stations are available in 1910. Further, data from six of these stations are not reported after 1990 coinciding with major political changes in the former USSR. Station records also contain a number of missing values, and their low frequency variations are frequently biased by nonclimatic trends, which may or may not be adjusted before integration in larger scale data compilations (Landsberg, 1981; Karl *et al*., 1988; Parker, 1994; Peterson *et al*., 1998; Hansen *et al*., 1999; Böhm *et al*., 2001; Arnfield, 2003; Böhm *et al*., 2009). As a consequence, uncertainties in regional climate data not only obscure the estimation of 20th century temperature trends – and prediction of these – but also complicate the calibration of tree-ring proxy data (Frank *et al*., 2007a).

In this paper, we address these uncertainties in both proxy and instrumental data using a network of 78 tree-ring sites and 13 temperature stations (with data before 1910) from across Siberia. The tree-ring data represent a large collection of boreal-forest sites visited in 1991, i.e. 1990 is the last complete ring (Schweingruber, 1993, 2002; Schweingruber & Briffa, 1996b), as well as some newly developed data (Hantemirov & Shiyatov, 2002; Knorre *et al*., 2006). This update allows an investigation of growth over the important last decade of the 20th century. The old and new tree-ring collections are used to test the relevance of a number of methodological choices as applied in the recent literature on radial growth dynamics, including the effect of (i) tree-ring detrending on the preservation of long-term chronology trend, and (ii) early (pre-1941) vs. late (post-1940) proxy calibration on the emergence of DP. We link these tests on chronology trend and DP size with estimates of instrumental data uncertainty derived from (iii) the difference between raw and adjusted temperatures from the 13 long-term climate stations in Siberia. For all these approaches (i–iii) we calculate residual timeseries (in °C) to allow for a comparison of the various uncertainties back to 1880.

Tree-ring and temperature data, and the approaches used to analyze these data are presented in the 'Materials and methods' . Results are organized as follows: we first present the 1990 tree-ring network and detail the effects of detrending and calibration techniques on trend preservation and DP. We then present the results obtained from the proxy update to 2000, and finally compare proxy, instrumental, and calibration residual timeseries. Results are discussed with focus on their relevance to the ongoing debate on DP and accuracy of temperature trends across Siberia.

Materials and methods

Proxy data

Tree-ring data from high latitude environments north of 60°N and east of 60°E were aggregated (Fig. 1). These include 3075 samples from 60 larch, 12 spruce, and six pine sites in Siberia (Table 1, see supporting information: Tree-ring data). Seventy of these 78 datasets contained not only tree-ring width (TRW) but also maximum latewood density (MXD) measurements (Schweingruber, 1993; Schweingruber & Briffa, 1995, 1996a; Hantemirov & Shiyatov, 2002; Kirdyanov *et al*., 2007), thus allowing for a comparison of trends in wood density and radial increment.

Correlation based cluster analysis (Friedrichs *et al*., 2008) revealed eight spatially coherent clusters that roughly reflected Siberian orography (Fig. 1): trees in clusters C1–C3 were all located in an area west of 100°E, clusters C4–C6 were located east of 100°E but also included some far northern sites east of 150°E, and cluster C7 was centered south of the Cherskiy Mountains between about 150 and 160°E. Correlations between TRW and MXD mean cluster chronologies – integrating all site chronologies within a cluster – were 0.74 in WSIB (between C1, C2, and C3) and 0.67 in ESIB (between C4, C5, and C6). Because of this coherence of growth variations, and the location and coherence of instrumental stations, we aggregated the data into western Siberia (WSIB: C1–C3), eastern Siberia (ESIB: C4–C6), and northeastern Siberia (NESIB: C7).

Average age of the sampled trees increased from west to east from 190 years in WSIB to 309 in NESIB, and mean correlations between all 78 TRW and 70 MXD site chronologies were 0.17 and 0.20 over the 1951–1980 period, respectively. The tree-ring data reached maximum replication of 2614 series in 1963, but strongly declined from 2456 series in 1990 to 1520 series in 1991 (Fig. 2), the year of the second Swiss/Russian sampling campaign. Overall sample replication changed gradually back in time (1731 series in 1801) with similar tendencies in WSIB and ESIB and a slower decline in the less-well replicated NESIB area. The fraction of data from which only TRW measurements were available was again quite small (max. 304 series in 1982) and characterized by a similar decline in the 1990s from 301

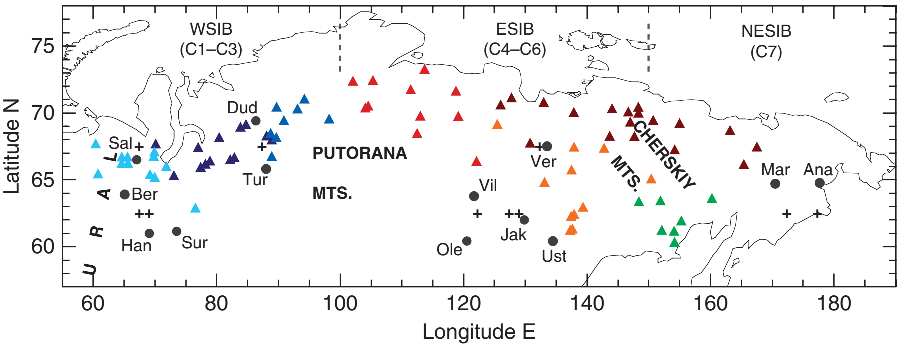

Fig. 1 Siberian tree-ring and station temperature data. The map shows the 78 tree sites (triangles), and 13 climatic stations (circles) with data back to 1910 in the sector north of 60°N and 60–180°E. Crosses indicate locations from which grid point temperature data (Brohan *et al.*, 2006) are available. Tree-ring sites, differentiated using cluster analysis, from west to east: C1 in light blue, C2 dark blue, C3 blue, C4 red, C5 dark red, C6 orange, C7 green.

Table 1 Siberian tree-ring and long-term station temperature data

Region	WSIB	ESIB	NESIB	SIBERIA
Cluster	1–3	4–6	7	1–7
No. tree sites	32	39	7	78
No. tree cores	1438	1341	296	3075
Mean tree age (years)	190	247	309	232
Intercluster correlation	0.74	0.67	–	0.45
Stations	1–6	7–11	12–13	1–13
JJA mean temperature (°C)	13.0	15.2	10.2	13.4
Annual temperature range (°C)	40.4	57.7	37.0	46.6
Interstation correlation	0.59	0.61	0.80	0.23

Cluster numbers correspond to triangles as indicated in Fig. 1; meteorological stations are listed in Table S3. Mean tree age is the average length of measurement series within one or several clusters. Intercluster and inter-station correlations indicate the coherence between RCS-detrended mean cluster chronologies and mean JJA station temperatures over the 1951–1980 period, respectively. Annual temperature range is the average difference between the warmest and coldest months over the 1951–1980 period.

series in 1994 to 128 series in 1995 (not shown). Due to recent field activities, we were able to keep the 1990s sample replication reasonably steady in WSIB (386 series in 2000), which allowed for an extra analysis of growth trends over the most recent decade of the 20th century in this region. Replication declined below 150 series in 2001, defining the maximum period over which reliable conclusions could be drawn.

Instrumental data

Siberia is characterized by relatively small changes in temperature means but steep gradients in annual temperature ranges (Table 1) with maximum continentality displayed towards the center of the study region. Only 13 climate stations in the Global Historical Climatology Network (GHCN; Peterson & Vose, 1997; Peterson *et al.*, 1998) database that started recording temperatures before 1910 are present in this region (see supporting information: Climate data). Data from these stations showed correlation patterns similar to those derived from the tree-ring data, resulting in clusters of six stations in WSIB, five in ESIB, and two in NESIB (Fig. 1). Correlations using June–August (JJA) mean temperatures over the 1951–1980 period ranged from 0.59 between WSIB stations to 0.80 between (proximal) NESIB stations. In all three regions, the station data were also highly correlated ($r > 0.98$) with JJA temperatures derived from corresponding grid points (shown in Fig. 1; Brohan *et al.*, 2006), supporting utilization of the long-term station data for calibration and trend analyses.

As for the tree-ring data, monthly temperature data showed a steep replication decline in the early 1990s, with data for only six stations in 1991 (Fig. 2). Maximum replication (13 stations × 12 months = 156) was only achieved consistently between 1943 and 1983. Replication declined gradually back in time, to 131 monthly values in 1930, 127 in 1900, and 76 in 1890. The number of missing values was overall much larger before 1940. Data from only three stations were available in 1882. As these changes not only affect the error of regional temperature records, but also modify the variance (larger with less data) of the mean timeseries (Frank *et al.*, 2007b), we adjusted this heteroscedasticity by removal of changing standard deviations in a 30-year running window.

Tree-ring detrending

To test the influence of age-trend removal on 20th century growth trends and DP emergence, we applied four different detrending techniques: regional curve standardization (RCS), Hugershoff (HUG), negative

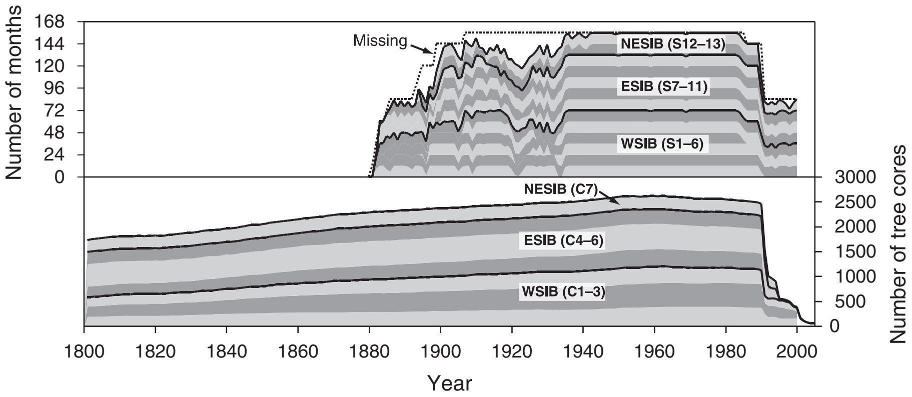

Fig. 2 Temperature and tree-ring data replication. Upper panel shows the number of monthly temperature readings recorded at the instrumental stations S1-6 in WSIB, S7-11 in ESIB, and S12-13 in NESIB (see Table S3 for station details). Dashed curve indicates the theoretical amount of monthly data if no values were missing. Lower panel shows the number of tree-ring series in clusters C1–C3 in WSIB, C4–C6 in ESIB, and C7 in NESIB.

exponential (EXP), and 300-year splines (SPL) (see supporting information: Detrending and chronology building). These methods were chosen as they were either typically used (HUG, EXP) for detrending of high latitude TRW and MXD data (e.g., Schweingruber *et al.*, 1979; Jacoby & D'Arrigo, 1989, 1995; Schweingruber & Briffa, 1995, 1996a; Briffa *et al.*, 1998; Wilson *et al.*, 2005; Helama *et al.*, 2008), or represent techniques that preserve varying low frequency variability (RCS, SPL) in resulting tree-ring chronologies (e.g., Briffa *et al.*, 1992; Cook *et al.*, 1995, 2004; Esper *et al.*, 2003b, 2007a; Luckman & Wilson, 2005; Büntgen *et al.*, 2005, 2006, 2007, 2008a).

The HUG detrending was specifically considered as it was used in the first work describing large-scale DP (Briffa *et al.*, 1998), and has been implemented in many subsequent hemispheric reconstructions (e.g., Briffa *et al.*, 2002b; Rutherford *et al.*, 2005; Mann *et al.*, 2008). On the opposing end of the spectrum, we considered RCS, which is one of the few methods that allows preservation of long time-scale information in tree-ring chronologies (Esper *et al.*, 2003a, 2007b). Given the data's age structure and the general characteristics of these methods (Fritts, 1976; Cook & Kairiukstis, 1990), we expected the RCS technique to preserve most low frequency variability, followed by EXP, HUG, and SPL. Note that while the differing detrending methods alter the low frequency spectra of timeseries – and thus the fit with 20th century climate data – the higher frequency, interannual to multidecadal variability remains largely unaffected.

Calibration and residual analysis

As with the detrending, we applied calibration approaches that were considered in the original literature on DP, and combined these techniques with alternative ways of fitting tree-ring data against instrumental measurements. All TRW and MXD cluster chronologies as well as the WSIB (C1–C3) and ESIB (C4–C6) mean timeseries were compared against regional JJA temperatures using the Pearson correlation coefficient. Tree-ring records were scaled to instrumental measurements, i.e. their mean and variance adjusted to the temperature data, over an early (pre-1941), late (post-1940), and full (1881–1990) window. In all cases we utilize scaling instead of least-squares regression as many studies have shown that long-term variability is suppress in most regression schemes (von Storch *et al.*, 2004; Esper *et al.*, 2005a; Lee *et al.*, 2008). We specifically considered the HUG-detrended timeseries that were calibrated over the pre-1941 period, and compared this approach with the RCS-detrended timeseries that were calibrated over the post-1940 (and full) period. This was done, as these approaches either follow methodology of Briffa *et al.* (1998) in their circumpolar DP assessment (HUG and early calibration), or represent techniques that tend to retain low frequency variance in proxy data (RCS) and reduce late 20th century offset between proxy and instrumental records (late calibration).

To estimate proxy uncertainty, and also quantify potential magnitude of DP, we calculated the residuals between the calibrated tree-ring and target instrumental timeseries. This approach provides relatively conservative estimates of the proxy uncertainty, as the tree-ring data were not fitted to temperatures based on ordinary least-squares but on scaling the mean and variance over some defined period of overlap. Instrumental uncertainty was expressed as the difference series between raw and adjusted GHCN temperature data. Similarly, residuals between differently detrended (RCS and HUG) and differently scaled (pre-1941 and post-1940 periods) tree-ring data quantified calibration uncertainty. The proxy, target, and calibration uncertainties (all in °C) were then compared to illustrate the relative importance of each factor throughout time. Scaled data and residual timeseries were occasionally smoothed using a 10-year Gaussian weighted moving average, or decadally averaged, to emphasize trends in the lower frequency domain.

Results

Trends and signals in the 1990s large-scale tree-ring network

To assess effects of tree-ring standardization on the preservation of long-term trends across Siberia, we compared the differently detrended tree-ring data after combining the spatial clusters C1–C7. The resulting mean timeseries revealed the RCS method retained most low frequency variance for both TRW and MXD data (Fig. 3). Linear fits to the timeseries displayed in the lower panel of Fig. 3 (regression calculated using annually resolved data; not shown) indicated that only the MXD RCS-detrended data contained a positive trend (+0.12 index/century) since 1800. All TRW chronologies, except for the HUG-detrended record (−0.25 index/century), showed positive trends. Timeseries were normalized over the 1881–1940 period to accentuate the difference between the various approaches towards the early 19th and late 20th centuries. For TRW, the HUG-detrended data had the lowest post-1960 values and among the highest (together with SPL) 19th century values. For MXD, SPL yielded the lowest post-1960 levels, followed by HUG and EXP. Highest post-1960 levels were retained with the RCS method.

These, often substantial, trend differences had little effect on assessments of climate response, as this signal is largely determined by high frequency associations. Calibration of the tree-ring records against regional temperature data revealed higher correlations for MXD (than TRW) and for the western C1 and C2 (than C3–C6) clusters (Fig. 4). The temperature signal for C7 was weak for the MXD data and nearly absent for TRW. This seemed to be related to the reduced number and coherence of the tree-ring data as well as the reduced number and increased distance to the corresponding instrumental stations. Correlations calculated over the maximum period of overlap with instrumental data were slightly higher when tree-ring data were averaged over the clusters C1–C3 and C4–C6, and ranged from 0.47 in ESIB (TRW) to 0.84 in WSIB (MXD). These values increased again slightly for decadally smoothed data to 0.72 (TRW) and 0.89 (MXD) in WSIB, and 0.65 (TRW) and 0.77 (MXD) in ESIB. Importantly, pre-1941 vs. post-1940 correlations revealed no significant change of climate sensitivity through time. While some clusters indicated a slight drop in correlation (up to $r = 0.2$) for the late period, other clusters and combinations of clusters showed virtually no change or even slight increases.

Scaling the RCS-detrended tree-ring data to regional JJA temperatures revealed that DP is not significant or widespread across Siberia (Fig. 5). Post-1960 differences between proxy and target data were either very small or nonexistent (WSIB), disappeared towards the end of the

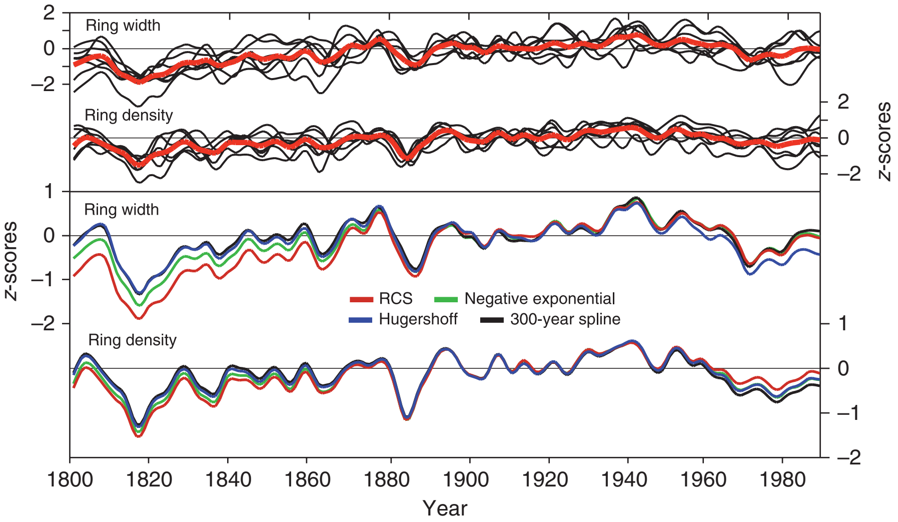

Fig. 3 Effect of tree-ring detrending. Upper panel shows the cluster chronologies C1–C7 (black) and their arithmetic mean (red) of the RCS-detrended TRW and MXD data. Lower panel shows the same arithmetic means (RCS) together with the mean timeseries derived from HUG, EXD, and SPL detrending. All timeseries were normalized over the 1881–1940 period. RCS, regional curve standardization; TRW, tree-ring width.

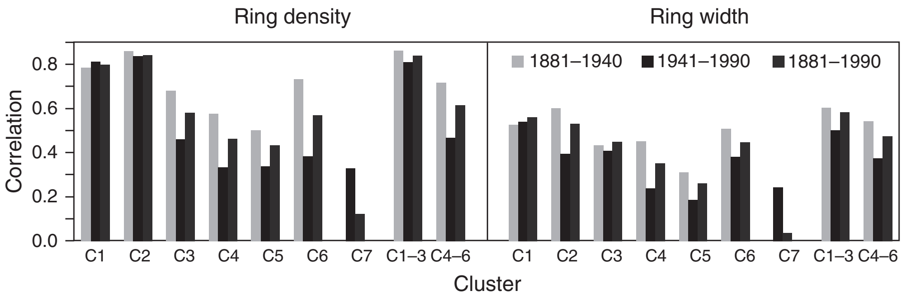

Fig. 4 Tree-ring data calibration. Pearson's correlation coefficients between RCS-detrended tree-ring chronologies and regional JJA temperature data for clusters C1–C7 and the arithmetic means of clusters representing WSIB (C1–C3) and ESIB (C4–C6). Instrumental station data reached back to 1881 in WSIB, 1883 in ESIB, and 1898 in NESIB. Correlations were calculated over different time periods. Results for other detrendings were similar, as the standardization methods applied here had virtually no effect on the high frequency characteristics of chronologies (not shown). RCS, regional curve standardization.

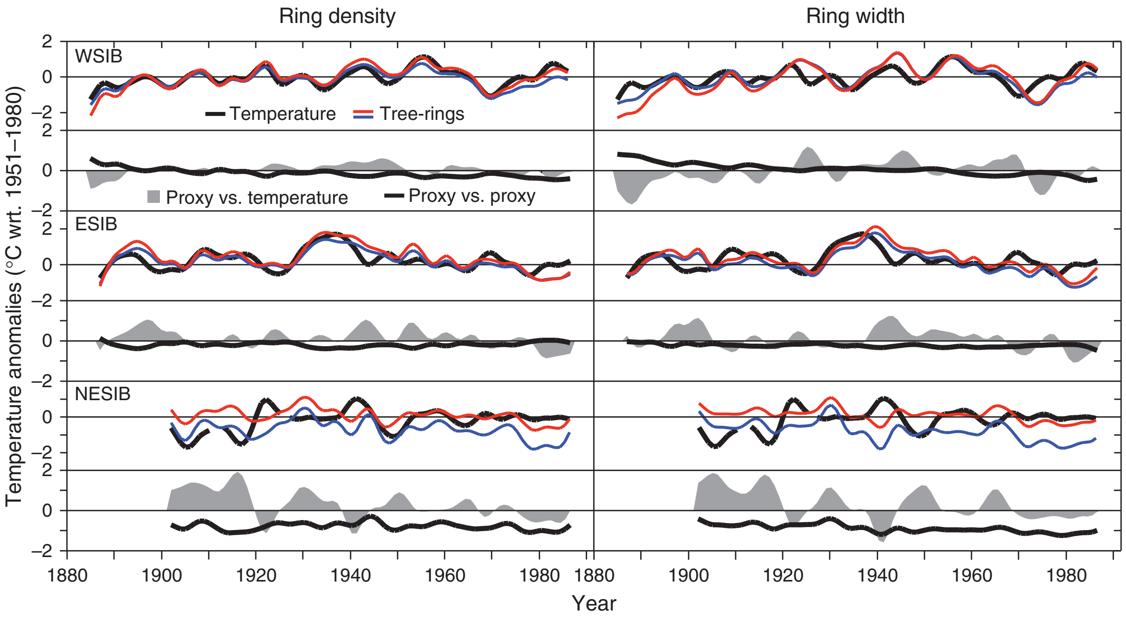

Fig. 5 Decadally smoothed tree growth and temperature trends in Siberia. Differently detrended (RCS in red, HUG in blue) MXD and TRW data are plotted together with JJA temperatures (black) derived from long instrumental station records in WSIB, ESIB, and NESIB. Tree ring data were scaled against regional temperatures over the 1941–1990 period (RCS) and over the early period of overlap up to 1940 (HUG). Bottom panels show the smoothed differences between the RCS tree-ring and JJA temperature data (grey), and between the RCS- and HUG-detrended tree-ring data (black). RCS, regional curve standardization; TRW, tree-ring width.

1980s (TRW in ESIB), or were of the same size as those before 1960 (MXD in ESIB). Results from NESIB were less significant, because of the overall lower coherence between proxy and temperature data. These data, however, nicely illustrate the sensitivity of DP evaluation to the period chosen for scaling. While the RCS-detrended data, scaled over the 1941–1990 period (shown in red in Fig. 5), indicated a sizeable positive difference before 1920, the HUG-detrended data, that were scaled over the pre-1941 period, indicated a similar but negative difference after 1950. The latter representing the classical notion of the DP. Besides the scaling period, the method chosen for detrending had an influence on the appearance of DP in some cases. For example, in WSIB the RCS-detrended timeseries started in the 1880s clearly below the HUG timeseries, but ended in the 1990s clearly above its counterpart. This greater positive trend preserved in the RCS data helped to avoid artificial DP detection in this region.

Proxy update to 2000

Recent field and laboratory work allowed an update of tree-ring data until 2000 including seven MXD and eight TRW site chronologies in WSIB (Fig. 6). These WSIB new records revealed very similar variations as the mean of the C1–C3 clusters ($r = 0.97$ for both MXD and TRW, 1881–1990 period), and thus allowed a straightforward assessment of DP over last decade of the 20th century.

The close fit between the MXD and TRW data with JJA temperatures indicated that there was no recent loss in high frequency coherence nor was lower frequency divergence found for the 1990s. The MXD timeseries matched post-1990 temperatures quite closely, and the TRW timeseries showed values higher than the corresponding temperatures in 1992, 1994, 1996, 1997, 1998, and 1999.

Proxy and climate data residuals

In order to compare proxy and instrumental (and calibration) uncertainties, decadally averaged residuals between the MXD and TRW data and their regional targets were calculated (Fig. 7). These timeseries indicated little trend in the proxy residuals of all regions in Siberia. The total error is on average about 0.16 °C smaller for MXD than for TRW, and increased from 0.51 °C in WSIB to 1.22 °C in NESIB (values indicated in the figure).

Similarly, the uncertainty in regional temperature data is shown in Fig. 8a. These timeseries indicated that both positive and negative corrections up to a few degrees Celsius were performed on the monthly station data. Mean corrections across the network (bold lines; Fig. 8a) generally increased back in time and were negative for most of the records length, including deviations of up to −0.56 °C in June 1897. The net adjustments thus increased warming over the 20th century in the region. The 1880s were, however, characterized by positive residuals (up to 1.1 °C in August

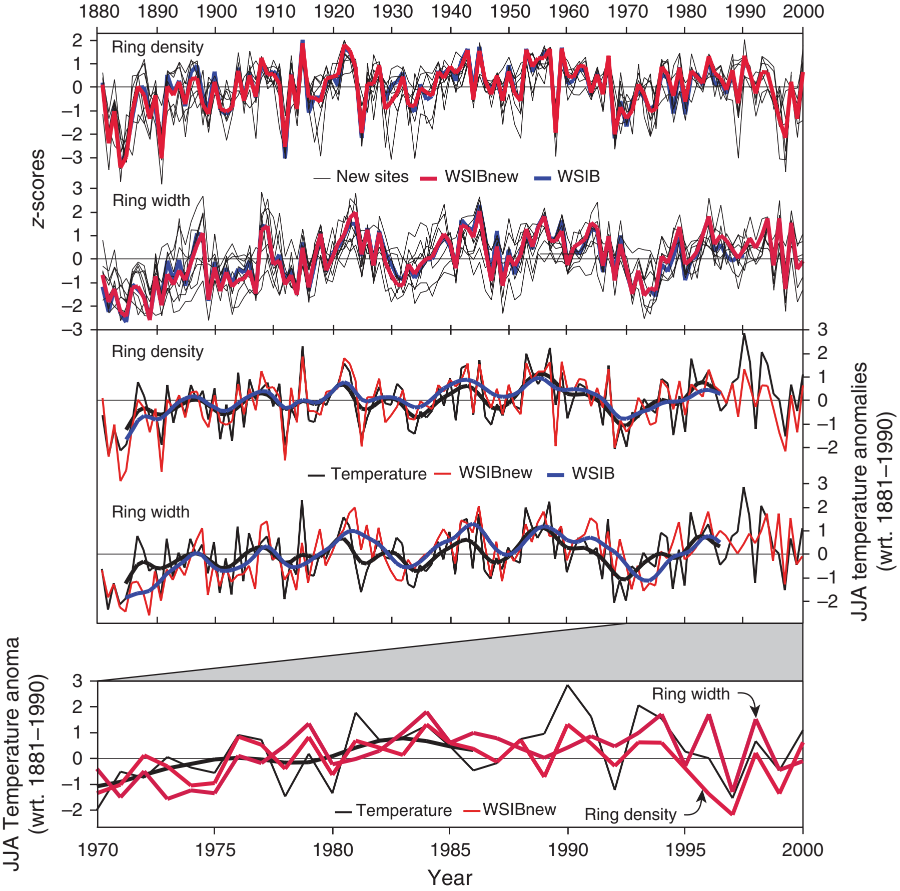

Fig. 6 Updated WSIBnew tree-ring data and coherence with regional temperatures. Top panel shows the seven new MXD and eight new TRW RCS-detrended site chronologies together with their mean (WSIBnew) and the mean of all records in the WSIB clusters C1-3 (WSIB). While the latter extended only until 1990, WSIBnew reached 2000. Middle panel shows the WSIB and WSIBnew tree growth data scaled over the 1881–1990 (WSIB) and 1881–2000 (WSIBnew) periods to regional JJA temperatures. JJA and WSIB data have been decadally smoothed. Bottom panel shows the WSIBnew MXD and TRW timeseries together with JJA temperatures over the 1970–2000 period. Details on the updated WSIBnew sites, and all other tree-ring locations, are listed in supplementary Table S2. RCS, regional curve standardization; TRW, tree-ring width.

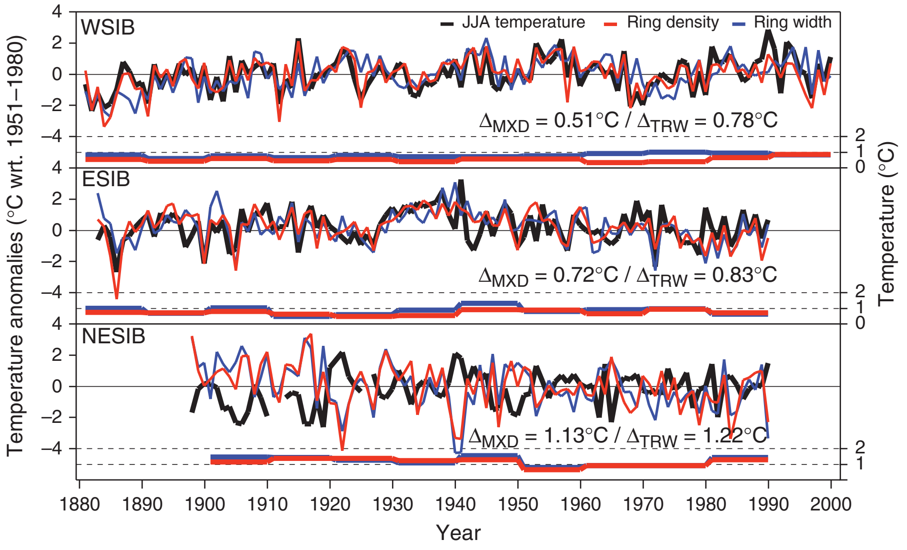

Fig. 7 Tree-ring proxy vs. target temperature differences. RCS-detrended MXD and TRW timeseries scaled to regional JJA temperatures in WSIB (over 1881–2000), ESIB (1883–1990), and NESIB (1898–1990). Periods represent the maximum overlap between proxy and target data. The WSIB TRW and MXD records are combinations of the C1–C3 mean timeseries with the WSIBnew update until 2000 (see Fig. 6). Curves at the bottom of the panels are the decadally averaged residuals MXD vs. temperature (red), and TRW vs. temperature (blue). Δ is the average residual over the periods of overlap. RCS, regional curve standardization; TRW, tree-ring width.

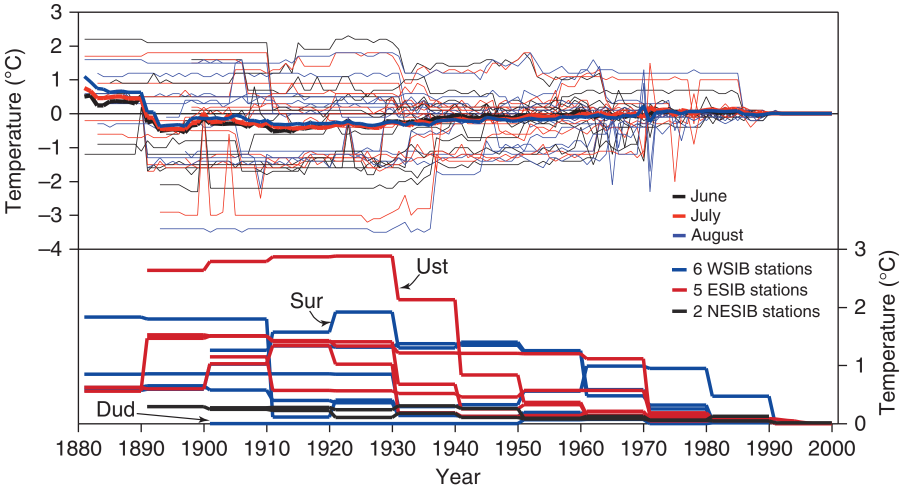

Fig. 8 Differences between raw and adjusted (GHCN) temperature station records. Upper panel shows the single June, July, and August adjustments of all 13 Siberian stations and their mean timeseries (bold). In the lower panel the adjustments were averaged to mean JJA mean timeseries and sorted by stations in WSIB, ESIB, and NESIB. Negative deviations were inverted, combined with positive values, and decadally averaged. Ust is Ust'-Maja, Sur is Surgut, and Dud is Dudinka (see Table S3).

1881), which was biased by the drop in station records over this early period (see Table S3). The absolute value of the warm-season (JJA) residuals, averaged decadally, indicated that the adjustments were significantly smaller in NESIB than WSIB or ESIB (Fig. 8b). It is also evident that certain stations, such as Ust'-Maja or Surgut underwent changes of up to 2–3 °C. Other stations, such as Dudinka in WSIB, received no substantial adjustments.

Aggregation of all station residuals from WSIB and ESIB, i.e. the average of the blue and red timeseries shown in Fig. 8b, indicate typical adjustments performed on the instrumental data across Siberian (Fig. 9). We compared these instrumental adjustments with the mean proxy residual, derived from the combined unexplained variance of TRW and MXD averaged over WSIB and ESIB (from Fig. 7), and the mean calibration uncertainty, derived from the residuals between differ-

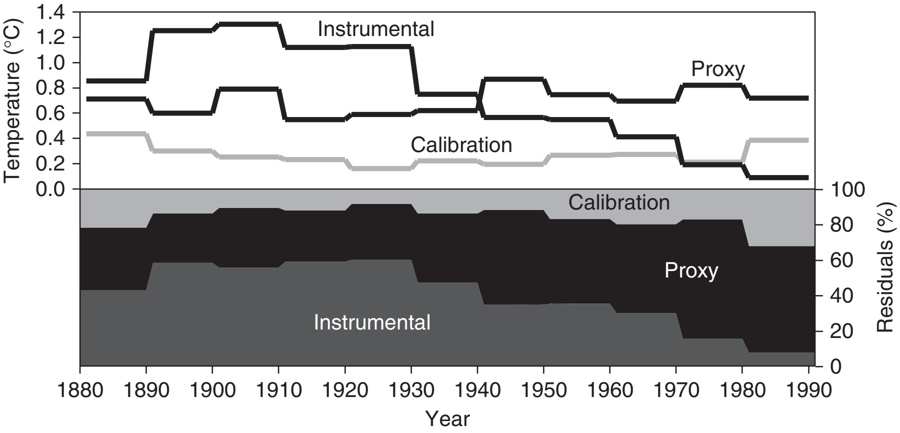

Fig. 9 Size of residuals. Upper panel shows the decadally smoothed instrumental, proxy, and calibration residuals averaged over western and eastern Siberia. 'Instrumental' refers to the difference between raw and adjusted JJA temperatures, 'proxy' to the difference between tree-ring and JJA temperature timeseries, and 'calibration' to the difference between the differently detrended (RCS, Hugershoff) and scaled (1881–1940, 1941–1990) MXD and TRW records. All residuals were calculated for WSIB and ESIB (and TRW and MXD), and then averaged to form larger scale estimates. Lower panel shows the same data expressed in percent. RCS, regional curve standardization.

ently detrended and scaled TRW and MXD data in WSIB and ESIB (from Fig. 5). NESIB data were not included in this comparison, as the proxy records did not correlate significantly with regional temperature data, i.e. the proxy error appeared to be biased by the large distance to the instrumental stations (see supporting information Fig. S1).

The mean temperature adjustments were larger – up to 1.3 °C for decadal means – than the proxy and calibration residuals until the 1940s, then steadily declined to about 0.1 °C until 1990, representing $<5\%$ of the overall uncertainty. The proxy uncertainty remained fairly stable between about 0.6 and 0.8 °C over the past 110 years, but predominated over the other uncertainties after the middle of the 20th century (up to about 60% in the 1980s), largely because of the reduced instrumental adjustments during that time. The calibration term was large at the beginning and the end of the overlapping period, i.e. about 0.4 °C in the 1880s and 1980s. However, the relative importance increased to about 35% in the 1980s, again mainly because of the relatively small temperature adjustments.

Discussion

Our analysis showed that the tree-ring data representative for high latitude environments of Siberia are closely coupled with temperature variations, and that they particularly do not suffer from a recently increased disassociation from regional instrumental data. This is the case for both TRW and MXD measurements. The proxy data can thus be utilized for long-term climate reconstruction, and should also be helpful to estimate the course of temperatures during earlier warm episodes such as the putative Medieval Warm Period. This being said, the data are seemingly prone to ill definition of late 20th century trends that can leave the erroneous impression of DP as was shown in previous publications (Briffa *et al.*, 1998). Our tests, however, demonstrated that consideration of various tree-ring detrending techniques and calibration methodologies resolved DP in this important archive of long-term environmental change. This conclusion was supported through the reanalysis of a large tree-ring network sampled in the early 1990s spanning most of Siberia, and confirmed by an update of tree-ring data in WSIB that revealed both TRW and MXD closely track recent temperatures. Notably, the detrending and calibration techniques shown to be free of the DP are those that are *a priori* known to be most suitable for retaining long-timescale information (e.g., Cook *et al.*, 1995; Esper *et al.*, 2002, 2005a; Rutherford *et al.*, 2005; Büntgen *et al.*, 2006, 2008a; Lee *et al.*, 2008). It seems important to note though that not a single consideration, such as the detrending method alone, was sufficient to avoid DP. Rather, a combination of factors – the balance depending on the region and tree-ring parameter – influenced 20th century growth trends and degree of disassociation from target temperature data (Esper & Frank, 2009).

The application of various detrending and calibration techniques showed that consideration of a standardization method that retains more low frequency variability in tree-ring chronologies, as well as scaling of the proxy data over the full (or recent) period of overlap with instrumental data influenced 20th century growth trends and coherence with post-1960 temperatures. A comparison of the residuals between proxy and target data with the residuals between differently detrended and scaled proxy data indicated that the uncertainty due to methodological choices (detrending and calibration) is about half the size of the unexplained (proxy vs. target) variance typical for the data analyzed here. A corresponding calculation of the residuals between raw and adjusted temperature data showed that these changes increased from about 0 °C to >1 °C back in time, and were largest before the 1940s. The association of all these influences and uncertainties suggests that more attention needs be paid to the (i) consequences of tree-ring detrending on the low frequency signal of mean chronologies, (ii) effect of calibrating proxy data over different time periods, and (iii) number of instrumental temperature readings as well as the size and temporally varying adjustments of these data (Frank *et al*., 2007a).

Greatest low frequency preservation and highest post-1960 tree-ring values were retained with the RCS method. Besides this notable finding, it seemed interesting that the four detrending methods tested here did not result in the same ranking of TRW and MXD chronologies when sorted by their low frequency loading. For example, the HUG-detrended TRW data clearly showed the lowest post-1960 values and most negative trend over the past two centuries. However, the same detrending applied to MXD produced post-1960 values comparable to EXP and larger than SPL. Trends and levels were even more heterogeneous, when smaller geographic regions and the differing tree-ring parameters within these regions were considered (not shown). Altogether it appeared obvious that the removal of long-term positive trends from the tree-ring data, as is most strongly the case with the HUG detrending, systematically increased the chance for divergence from increasing temperatures, and is thus not recommended for studies of long-term environmental change or DP in the far north.

The detrending tests also indicated that RCS applied on a site-by-site basis (Esper *et al*., 2007b), is a functional, alternative method, as we found common long-term trends among site chronologies and obtained the best fit with regional temperature data. It seems important to note, however, that RCS-detrended data generally contain greatest uncertainties, require large datasets, and are prone to biases caused by inhomogeneous sample collections (Esper *et al*., 2002, 2003a). Particularly relevant to the Siberian data analyzed here could be biases due to (i) the tendency that the oldest trees often grow most slowly (Melvin, 2004; Esper *et al*., 2007b; Wunder *et al*., 2008), and (ii) the composition of data from only living trees and relatively homogeneous age-structure (Esper *et al*., 2007a, 2009). The former bias is likely more relevant for TRW than MXD – because of the greater amount of variance contained by the age-trend (Schweingruber *et al*., 1979) – and would ultimately increase positive long-term trends in RCS chronologies. The latter bias potentially limits the preservation of low frequency climatic information and in particular the ability to capture 20th century warming. More research is needed to explore these potential and opposing sampling and age-structure biases in data collections from living trees.

Calibration of the Siberian tree-ring data confirmed that the climate signal is stronger in MXD than TRW, weaker in NESIB than WSIB and ESIB, equally good over early and late periods of overlap with instrumental data, and effectively independent of the method chosen for detrending. While these results were broadly in line with previous research (Briffa *et al*., 1998, 2002a), the sensitivity of DP to the period chosen for calibration, i.e. the early pre-1940 or late post-1940 periods, seemed to be relevant, as it indicated that the procedure chosen to transfer proxy data into temperature units affected recent trends and offsets. Calibration over only an early period of overlap with instrumental data minimizes the proxy/temperature residual over this period, and in turn increases the chance to detect offset over some later period. Early calibration is also problematic as the number of early temperature readings is reduced and uncertainty increased (Böhm *et al*., 2001; Frank *et al*., 2007a). The latter point is quantified for Siberia by the increasing residual between raw and adjusted station data back in time. Additional problems may arise if the proxy data are regressed, instead of scaled, against temperature data (Briffa *et al*., 2001), as regression-based procedures reduce the variability of the tree-ring time-series by some fraction of the unexplained variance (von Storch *et al*., 2004; Esper *et al*., 2005a). Such variance reductions systematically increase the chance to generate DP. Similarly, the season over which temperature data are considered might have an influence on DP, as in most high latitude regions summer temperatures show the weakest 20th century warming signal. Calibration against wider seasons including spring and fall months, or even winter months (e.g., annual temperatures), can thus change the trend of the target data, which in turn could contribute to DP detection.

Besides the calibration and possible seasonality influences, uncertainty in the target instrumental data adds to the complexity of estimating 20th century temperature trends and potential divergence of proxy data. At least some of this uncertainty has been considered here in the residual between raw and adjusted GHCN data. The way this term was calculated, by combining both the positive and negative adjustments back to 1881, yielded error estimates larger than those obtained when considering the difference between regional mean records integrating several stations. This is because most of the positive and negative adjustments per station cancel each other out when developing a regional record, a feature inherent to GHCN adjustment methodology (Peterson & Vose, 1997; Hansen *et al*., 1999). Interstation comparison and correction also reduce the number of statistically independent recordings in a given region. On the other hand, consideration of the residual between raw and adjusted station data, as done here, is also somewhat conservative, as changes in variance or step functions in the mean were often already adjusted in the source data. Other effects such as caused by changes of the physical properties of the environment surrounding the stations (Landsberg, 1981), including the urban heat island effect (Hinkel *et al*., 2003), are not specifically considered in the GHCN procedure. The latter might, however, be quite large in Siberia, as the number of inhabitants in 11 (of the 13) villages and cities from which the long-term temperature records originate increased from about 20 000 between 1897 and 1930 (most data from a census in 1897) to about 710 000 in the 21st century (supporting information Table S3). No early 20th century census data were found for Ust′-Maja in ESIB (3800 inhabitants in 1999) and Markovo NESIB (ca. 600 inhabitants in 2000). These considerable changes, together with the reduced number of early station data, the large distance between individual stations particularly before 1920, and the increased number of missing values before about 1940 made the identification and correction of nonclimatic long-term trends over the past 120 years difficult in Siberia. In addition, the homogenization methodologies currently applied particularly in large-scale approaches, have difficulties in identifying and correcting for systematic biases that simultaneously affect data across larger regions (Parker, 1994; Frank *et al*., 2007a; Thompson *et al*., 2008). If we, for example, consider the substantial changes of instrumental summer temperatures that were recently applied to early station data in Europe and elsewhere (see both Frank *et al*., 2007a; Böhm *et al*., 2009, and references therein), it appears premature to solely use early temperature readings for proxy transfer and evaluation of DP in remote high latitude regions.

While a recently published analysis of several thousand tree-ring series from the European Alps revealed DP to be inexistent in a major mid latitude mountain system (Büntgen *et al*., 2008b), this current analysis, for the first time, showed that DP does not affect tree growth in a large area of high latitude Asian taiga forests. From this perspective and the various tests applied in this analysis, several recommendations can be derived that might help studying 20th century growth trends and potential DP in tree-ring data. These include to (i) preserve low frequency variability when detrending tree-ring data, (ii) not allow positive growth curves to be fit in the detrending process (Hugershoff), (iii) calibrate over the full (or late) period of overlap with instrumental climate data, (iv) avoid regression-based approaches for proxy transfer, (v) carefully examine early instrumental data, and not base DP on uncertain temperature data, and (vi) consider tree-ring sites with a clear climatic signal.

Acknowledgements

We thank F. H. Schweingruber for stimulating discussions. Supported by the European Community project Millennium (grant 017008) and the Swiss National Science Foundation through the National Centre for Competence in Climate Research (NCCR-Climate).

References

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, **23**, 1–26.

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.

Böhm R, Auer I, Brunetti M, Maugeri M, Nanni T, Schöner W (2001) Regional temperature variability in the European Alps: 1760–1998 from homogenized instrumental time series. *International Journal of Climatology*, **21**, 1779–1801.

Böhm R, Jones PD, Hiebl J, Brunetti M, Frank D, Maugeri M (2009) The early instrumental warm-bias: a solution for long central European temperature series 1760–2007. *Climatic Change*, in press.

Briffa KR, Jones PD, Bartholin TS *et al*. (1992) Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Climate Dynamics*, **7**, 111–119.

Briffa KR, Osborn TJ, Schweingruber FH, Harris IC, Jones PD, Shiyatov SG, Vaganov EA (2001) Low-frequency temperature variations from a northern tree ring density network. *Journal of Geophysical Research*, **106**, 2929–2941.

Briffa KR, Osborn TJ, Schweingruber FH, Jones PD, Shiyatov SG, Vaganov EA (2002a) Tree-ring width and density data around the Northern Hemisphere: part 1, local and regional climate signals. *The Holocene*, **12**, 737–757.

Briffa KR, Osborn TJ, Schweingruber FH, Jones PD, Shiyatov SG, Vaganov EA (2002b) Tree-ring width and density data around the Northern Hemisphere: part 2, spatio-temporal variability and associated climate patterns. *The Holocene*, **12**, 759–789.

Briffa KR, Schweingruber FH, Jones PD, Osborn TJ, Shiyatov SG, Vaganov EA (1998) Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature*, **391**, 678–682.

Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *Journal of Geophysical Research*, **111**, D12106, doi: 10.1029/2005JD006548.

Büntgen U, Esper J, Frank DC, Nicolussi K, Schmidhalter M (2005) A 1052-year tree-ring proxy for Alpine summer temperatures. *Climate Dynamics*, **25**, 141–153.

Büntgen U, Frank DC, Grudd H, Esper J (2008a) Long-term summer temperature variations in the Pyrenees. *Climate Dynamics*, **31**, 615–631.

Büntgen U, Frank DC, Kaczka RJ, 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.

Büntgen U, Frank DC, Nievergelt D, Esper J (2006) Summer temperature variations in the European Alps, A.D. 755–2004. *Journal of Climate*, **19**, 5606–5623.

Büntgen U, Frank DC, Wilson R, Carrer M, Urbinati C, Esper J (2008b) Testing for tree-ring divergence in the European Alps. *Global Change Biology*, **14**, 2443–2453.

Cook ER, Briffa KR, Meko DM, Graybill DS, Funkhouser G (1995) The 'segment length curse' in long tree-ring chronology development for paleoclimatic studies. *The Holocene*, **5**, 229–237.

Cook ER, Esper J, D'Arrigo R (2004) Extra-tropical Northern Hemisphere temperature variability over the past 1000 years. *Quaternary Science Reviews*, **23**, 2063–2074.

Cook ER, Kairiukstis LA (1990) *Methods of Dendrochronology – Applications in the Environmental Science*. Kluwer, Dordrecht.

D'Arrigo R, Wilson R, Liepert B, Cherubini P (2008) On the 'divergence problem' in northern forests: a review of the tree-ring evidence and possible causes. *Global and Planetary Change*, **60**, 289–305.

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. *Geophysical Research Letters*, **32**, L20703, doi: 10.1029/2005GL024258.

Esper J, Cook ER, Krusic PJ, Peters K, Schweingruber FH (2003a) Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Research*, **59**, 81–98.

Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree-ring chronologies and the reconstruction of past temperature variability. *Science*, **295**, 2250–2253.

Esper J, Frank D (2009) Divergence pitfalls in tree-ring research. *Climatic Change*, in press.

Esper J, Frank DC, Büntgen U, Verstege A, Luterbacher J, Xoplaki E (2007a) Long-term drought severity variations in Morocco. *Geophysical Research Letters*, **34**, L17702, doi: 10.1029/2007GL030844.

Esper J, Frank DC, Wilson RJS, Briffa KR (2005a) Effect of scaling and regression on reconstructed temperature amplitude for the past millennium. *Geophysical Research Letters*, **32**, doi: 10.1029/2004GL021236.

Esper J, Frank DC, Wilson RJS, Büntgen U, Treydte K (2007b) Uniform growth trends among central Asian low and high elevation juniper tree sites. *Trees*, **21**, 141–150.

Esper J, Krusic P, Peters K, Frank D (2009) Exploration of long-term growth changes using the tree-ring detrending program Spotty. *Dendrochronologia*, doi: 10.1016/j.dendro.2008.07.003.

Esper J, Shiyatov SG, Mazepa VS, Wilson RJS, Graybill DA, Funkhouser G (2003b) Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. *Climate Dynamics*, **8**, 699–706.

Esper J, Wilson RJS, Frank DC, Moberg A, Wanner H, Luterbacher J (2005b) Climate: past ranges and future changes. *Quaternary Science Reviews*, **24**, 2164–2166.

Frank D, Büntgen U, Böhm R, Maugeri M, Esper J (2007a) Warmer early instrumental measurements versus colder reconstructed temperatures: shooting at a moving target. *Quaternary Science Reviews*, **26**, 3298–3310.

Frank D, Esper J, Cook ER (2007b) Adjustment for proxy number and coherence in a large-scale temperature reconstruction. *Geophysical Research Letters*, **34**, L16709, doi: 10.1029/2007GL030571.

Friedrichs DA, Neuwirth B, Winiger M, Löffler J (2008) Methodologically induced differences in oak site classifications in a homogeneous tree-ring network. *Dendrochronologia*, doi: 10.1016/j.dendro.2008.02.001.

Fritts HC (1976) *Tree Rings and Climate*. Academic Press, London.

Hansen J, Ruedy R, Glascoe H, Sato M (1999) GISS analysis of surface temperature change. *Journal of Geophysical Research*, **104**, 30997–31022.

Hantemirov RM, Shiyatov SG (2002) A continuous multimillennial ring-width chronology in Yamal, northwestern Siberia. *The Holocene*, **12**, 717–726.

Helama S, Vartiainen M, Kolström T, Peltola H, Meriläinen J (2008) X-ray microdensitometry applied to subfossil tree-rings: growth characteristics of ancient pines from the southern boreal forest zone in Finland at intra-annual to centennial time-scales. *Vegetation History and Archaeobotany*, **17**, 675–686.

Hinkel KM, Nelson FE, Klene AE, Bell JH (2003) The urban heat island in winter at Barrow, Alaska. *International Journal of Climatology*, **23**, 1889–1905.

Houghton RA (2003) Why are estimates of the terrestrial carbon balance so different? *Global Change Biology*, **9**, 500–509.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*. Cambridge University Press, Cambridge, UK and New York.

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. *Quaternary Research*, **53**, 312–318.

Jacoby GC, D'Arrigo R (1995) Tree-ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles*, **9**, 227–234.

Jacoby GC, D'Arrigo RD (1989) Reconstructed northern hemisphere annual temperature since 1671 based on high latitude tree-ring data from North America. *Climatic Change*, **14**, 39–59.

Karl TR, Diaz HF, Kukla G (1988) Urbanization: its detection and effect in the United States climate record. *Journal of Climate*, **1**, 1099–1123.

Kirdyanov A, Vaganov E, Hughes MK (2007) Separating the climatic signal from tree-ring width and maximum. *Trees*, **21**, 37–44.

Knorre AA, Kirdyanov AV, Vaganov EA (2006) Climatically-induced interannual variation in aboveground biomass productivity in the forest-tundra and northern taiga of central Siberia. *Oecologia*, **147**, 86–95.

Lamb HH (1965) The early medieval warm epoch and its sequel. *Palaeogeography, Palaeoclimatology and Palaeoecology*, **1**, 13–37.

Landsberg HE (1981) *The Urban Climate*. Academic Press, New York.

Lee TCK, Zwiers FW, Tsao M (2008) Evaluation of proxy-based millennial reconstruction methods. *Climate Dynamics*, **31**, 263–281.

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

Lloyd AH, Bunn AG (2007) Response of the circumpolar boreal forest to 20th century climate variability. *Environmental Research Letters*, **2**, O45013, doi: 10.1088/1748-9326/2/4/045013.

Luckman BH, Wilson RJS (2005) Summer temperature in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics*, **24**, 131–144.

Malhi Y, Meir P, Brown S (2002) Forests, carbon and global climate. *Philosophical Transactions of the Royal Society of London Series A*, **360**, 1567–1591.

Mann ME, Zhang Z, Hughes MK, Bradley RS, Miller SK, Rutherford S, Ni F (2008) Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences*, **105**, 13252–13257.

Melvin TM (2004) *Historical growth rates and changing climatic sensitivity of boreal conifers*. PhD Thesis, University East Anglia, Norwich, UK.

Parker DE (1994) Effects of changing exposure of thermometers at land stations. *International Journal of Climatology*, **14**, 1–31.

Peterson TC, Vose R, Schmoyer R, Razuvaev V (1998) Global Historical Climatology Network (GHCN) quality control of monthly temperature data. *International Journal of Climatology*, **18**, 1169–1179.

Peterson TC, Vose RS (1997) An overview of the Global Historical Climatology Network temperature database. *Bulletin of the American Meteorological Society*, **78**, 2837–2849.

Rutherford S, Mann ME, Osborn TJ, Bradley RS, Briffa KR, Hughes MK, Jones PD (2005) Proxy-based Northern Hemisphere surface temperature reconstructions: sensitivity to methodology, predictor network, target season and target domain. *Journal of Climate*, **18**, 2308–2329.

Schweingruber F (2002) Jahrringforschung und Klimawandel in den borealen Wäldern. *Schweizerische Zeitschrift für Forstwesen*, **153**, 29–32.

Schweingruber FH (1993) Dendrochronological sampling strategies for radiodensitometric networks in northern hemisphere subalpine and boreal zones. *European Palaeoclimate and Man*, **4**, 205–209.

Schweingruber FH, Bräker OU, Schär E (1979) Dendroclimatic studies on conifers from central Europe and Great Britain. *Boreas*, **8**, 427–452.

Schweingruber FH, Briffa KR (1995) X-ray densitometry as a tool for reconstructing Northern Hemispheric summer temperatures. In: *Tree Rings. From the Past to the Future. Proceedings of the International Workshop on Asian and Pacific Dendrochronology* (eds Ohta SFujii T, Okada N *et al*.), pp. 267–272. Tokyo University, Tokyo.

Schweingruber FH, Briffa KR (1996a) Reconstruction of summer temperatures with a circumpolar tree ring network. In: *Fire in Ecosystems of Boreal Eurasia* (eds Goldammer GJ, Furyaev V), pp. 105–111. Kluver, Dordrecht.

Schweingruber FH, Briffa KR (1996b) Tree-ring density networks for climate reconstruction. In: *Climatic Variations and Forcing Mechanisms of the Last 2000 Years* (eds Jones PD, Bradley RS, Jouzel J), pp. 43–66. Springer, Berlin.

Thompson DWJ, Kennedy JJ, Wallace JM, Jones PD (2008) A large discontinuity in the mid-twentieth century in observed global-mean surface temperature. *Nature*, **453**, 646–649.

von Storch H, Zorita E, Jones JM, Dimitriev Y, González-Rouco F, Tett SFB (2004) Reconstructing past climate from noisy data. *Science*, **306**, 679–682.

Wilmking M, D'Arrigo R, Jacoby G, Juday G (2005) Divergent growth responses in circumpolar boreal forests. *Geophysical Research Letters*, **32**, L15715, doi: 10.1029/2005GLO23331.

Wilson R, D'Arrigo R, Buckley B *et al*. (2007) A matter of divergence – tracking recent warming at hemispheric scales using tree-ring data. *Journal of Geophysical Research*, **112**, D17103, doi: 10.1029/2006JD008318.

Wilson RJS, Frank DC, Topham J, Nicolussi K, Esper J (2005) Problems and opportunities for the spatial reconstruction of summer temperatures in central Europe. *Boreas*, **34**, 490–497.

Wunder J, Brzeziecki B,-ybura H, Reineking B, Bigler C, Bugmann H (2008) Growth-mortality relationships as indicators of life-history strategies: a comparison of nine tree species in unmanaged European forests. *Oikos*, **117**, 815–828.

Supporting Information

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

Table S1. Tree-ring data statistics of clusters C1 to C7, their regional means C1-3 and C4-6, and the mean of all data C1-7. MTA is mean tree age, Rbar is mean interseries correlation, and AC(1) is first year autocorrelation. Rbar and AC(1) were derived from 32-year spline and RCS detrended data (since 1800 AD), respectively.

Table S2. Tree-ring site statistics.

Table S3. Siberian long-term climate stations.

Fig. S1. Decadally averaged residuals of the raw *versus* adjusted JJA temperature data (black), the MXD *versus* JJA temperature data (red), and the TRW *versus* JJA temperature data (blue).