Oikos 123: 559–566, 2014
doi: 10.1111/j.1600-0706.2013.00836.x

Subject Editor: Robin Pakeman. Accepted 1 November 2013

Detection and evaluation of an early divergence problem in northern Fennoscandian tree-ring data

Lea Schneider, Jan Esper, Mauri Timonen and Ulf Büntgen

L. Schneider (l.schneider@geo.uni-mainz.de) and J. Esper, Dept of Geography, Johannes Gutenberg Univ., DE-55099 Mainz, Germany. – M. Timonen, Finnish Forest Res. Inst., Rovaniemi Research Unit, FI-96301 Rovaniemi, Finland. – U. Büntgen, Swiss Federal Res. Inst. WSL, CH-8903 Birmensdorf, Switzerland, and Oeschger Centre for Climate Change Research (OCCR), Univ. of Bern, CH-3012 Bern, Switzerland, and Global Change Research Centre AS CR, v.v.i., Bêlidla 986/4a, Cz-60300 Brno, Czech Republic.

Although not yet fully understood, reduced sensitivity of tree growth to temperature at high northern latitudes during the last ~40 years is often linked to concurrent anthropogenic changes of atmospheric composition and global warming. The idea that a temporal localization of the problem could improve its understanding initiated a search for erratic growth-patterns in earlier periods of high quality dendrochronological archives.

An extensive network of maximum latewood density (MXD) measurements from northern Fennoscandia likely represents one of the most reliable regional summer-temperature reconstructions. The strong coherence between proxy and instrumental data is, however, interrupted by a short, but significant correlation decrease from ~1900 till 1925, a period of distinct summer-temperature warming. Here we analyze this early 20th century divergence period (EDP). We therefore use long instrumental station records and tree-ring density chronologies including 878 *Pinus sylvestris* and 126 *Picea abies* samples. Our results indicate that EDP was accompanied by a simultaneous decline of inter-site and inter-station correlations. This could be ascribed to substantially reduced inter-annual summer temperature variability from 1905–1919. Stable correlations of the MXD network with high-pass filtered sea level pressure and precipitation records imply tree-growth to be additionally controlled by other factors, e.g. light conditions, in periods of low summer temperature variability. Within the scope of this study, the causes for EDP could be confined to a limited area and a short period. Calibration of proxy data and reconstruction skills thus remain unaffected in this case of divergence.

Tree-rings are an important proxy for the reconstruction of high-resolution climate variability over past centuries to millennia. A constantly increasing network of chronologies containing regional scale synchronous growth patterns as well as the application of rigorous statistical techniques are distinct characteristics testifying the great palaeoclimatic potential of this archive (Carrer and Urbinati 2006, Frank et al. 2010). Pre-instrumental climate conditions are inferred from dendrochronological data by applying the principle of uniformitarianism (Fritts 1976). This vital assumption implies a robust relationship between tree growth and climate throughout time. However, tree-rings are a biological archive and physiological-induced thresholds and/or non-linear growth responses often result in an ambiguous interpretation of climate reconstructions.

Evidence for reduced sensitivity of tree growth to temperature, for example, has been reported from multiple forest sites along the mid to high northern latitudes and from some locations at higher elevation (Büntgen et al. 2008, Esper and Frank 2009). This alleged large-scale phenomenon reflects the inability of temperature sensitive tree-ring width and density chronologies to track increasing temperature trends in instrumental measurements since around the mid-20th century (Briffa et al. 1998, D'Arrigo et al. 2008, Esper et al. 2010). In addition to such low-frequency trend offsets the formerly temperature sensitive trees become potentially unable to reflect high-frequency climate signals. As causes and scales of these two observations have been widely discussed recently, the phenomenon was coined the 'divergence problem' (DP). If the DP turns out to be a real and widespread phenomenon (coincidentally) paralleling anthropogenic-induced changes of atmospheric composition as well as global warming, it would not only have a substantial effect on biomass productivity rates, but it would further question the overall ability of tree ring-based temperature reconstructions to capture earlier periods of putative warmth, such as the so-called Medieval Warm Period, and subsequently to model possible reactions of forest ecosystems in a warming world. However, it remains to be proven that similar correlation decays are a result of human impact and thus absent in earlier, i.e. ideally preindustrial times.

In order to test the singularity of the late 20th century divergence, we here addressed one of the most important dendrochronological archives for the assessment of long-term European climate variability. The recently extended network of MXD measurements from northern Fennoscandia provides a unique test bed for analyses at the northern tree line (Büntgen et al. 2011). Despite its rather remote setting, the region additionally offers long and continuous instrumental climate records of up to 150 years, which subsequently allowed summer temperatures to be reconstructed over the past two millennia (Esper et al. 2012a). Northern Fennoscandia thus represents ideal conditions to verify the robustness of the growth-climate correlation in times of only initial atmospheric human impact (i.e. late 19th and early 20th century).

Indeed, we detected a shorter, but more pronounced period of correlation decay during the first decades of the 20th century in this essential dataset. Since tests with all underlying site-chronologies suggest a systematic deficiency in the climate records, the phenomenon was defined as the early divergence period (EDP). We herein explore features and causes of EDP in northern Fennoscandia to determine its significance in contrast to the 'common' divergence problem. Since EDP possibly affects the robustness of regional long-term climate reconstructions a systematical assessment of the coherence within and between the updated MXD proxy and instrumental temperature networks is carried out. Results are discussed with respect to all possibly contributing factors, including non-climatic noise in instrumental temperature data and further climate parameters, to conclude on the significance of EDP and its underlying forces in the region.

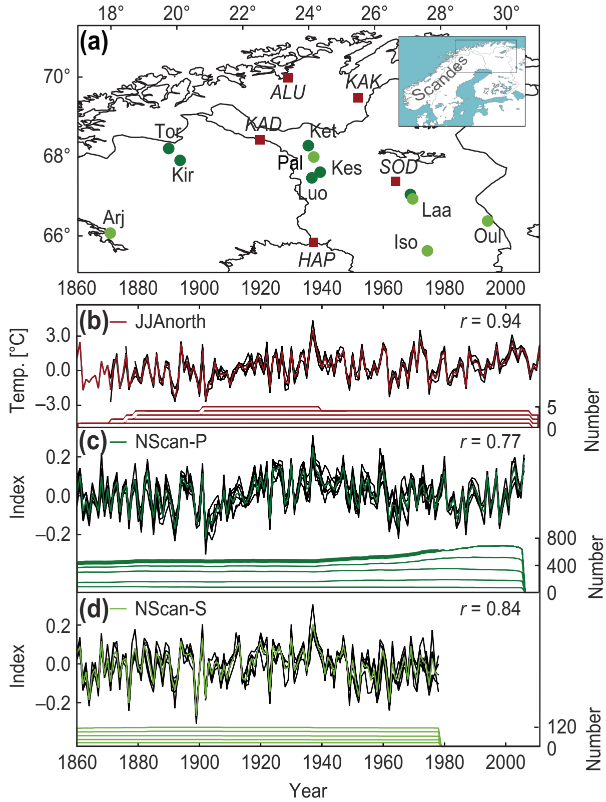

Figure 1. Fennoscandian temperature and MXD records. (a) Location of five meteorological stations (red), six *Pinus sylvestris* (dark green, Tor including Tor-old) and five *Picea abies* (light green) MXD sites in northern Fennoscandia. (b) JJA temperatures recorded at the five stations (black) and their arithmetic mean (red). Bottom panel shows the station replication. (c) and (d) *Pinus sylvestris* and *Picea abies* site chronologies (black) and their arithmetic means (pine in light green, spruce in dark green). Bottom panels indicate the replication (number of MXD measurement series) of the site chronologies. Correlation coefficients in (c)–(d) were calculated over the common 1879–1978 period.

Material and methods

The northern Fennoscandian MXD network contains seven *Pinus sylvestris* and five *Picea abies* sites located between 65–69°N and 17–21°E in northern Sweden and Finland (Fig. 1a).

All MXD timeseries were derived from high-resolution X-ray densitometry measurements (Schweingruber et al. 1988) conducted at the WSL in Birmensdorf (Switzerland) in cooperation with the Finnish Forest Research Institute in Rovaniemi (Finland). The pine network consists of 878 measurement series including five more recently developed, and much better replicated sites (Supplementary material Appendix 1 Table A1, Büntgen et al. 2011), as well as two older sites sampled in the late 1970s and early 1980s. The spruce network is smaller and consists of only 126 measurement series, all developed in the late 1970s. The common period of overlap with regional instrumental data is limited to 1879–1978 AD, during which at least 477 *Pinus sylvestris* and 114 *Picea abies* MXD series are available. Temporal replication and coherency changes within and between the individual MXD chronologies are shown in Fig. 1c–d.

To remove non-climatic, tree-age related, trends from the MXD data, the raw measurement series were detrended using negative exponential curves (no positive slopes). The detrending comprised the calculation of residuals between the raw timeseries and fitted exponential functions (Esper et al. 2010) and averaging of these indices using the arithmetic mean (Cook 1985) (see black curves in Fig. 1c–d). Variance changes that can arise from varying sample sizes and coherence changes had to be adjusted with a spline function (Frank et al. 2007a), before all pine (NScan-P) and spruce (NScan-S) site chronologies could be averaged to build the regional means (green curves in Fig. 1c–d).

We used five meteorological station records (Alta Lufthavn, Haparanda, Karasjok, Karesuando, Sodankylä) to assess the spatiotemporal homogeneity in regional summer temperature variability back to at least the early 20th century (Fig. 1b, Supplementary material Appendix 1 Table A2). Maximum replication of these five stations occurs from 1901–1939 AD. An additional set of five independent stations from southern Sweden and Finland (Helsinki, Jyvaskylä, Stockholm, Turku, Uppsala; mean = JJA_{south}) is used as a reference to assess early 20th century temperature patterns throughout space.

Growing seasons in northern Fennoscandia are usually short and restricted to the summer months June to August (D'Arrigo et al. 2008, Büntgen et al. 2011, Esper et al. 2012b). For the temperature record these months were extracted over the common period, which is confined to 1879–1978 as the first year with ≥ four station records = 1879, and the recent end of the spruce records = 1978.

The analysis of temporally changing coherence patterns, including EDP centered at 1905–1919, is based on Pearson correlations calculated in running windows along the time axis. For the assessment of coherency among tree sites and among stations, the single site chronologies and station records were correlated against an average of all other records after removal of the respective site record from the mean (MXD: NScan-P and NScan-S; temperature: JJA_{north} and JJA_{south}). The significance of deviating correlations was estimated using a bootstrap approach (Gershunov et al. 2001). We generated two sets of 1000 artificial red-noise series using a second order autoregressive model of JJA_{north} and NScanP, respectively. Each generated proxy times-series was built to correlate with $r = 0.70 \pm 0.05$ against the corresponding temperature time-series over the 1879–1978 period. Running correlations (15 years) of these pairs drop below 0.12 in only 0.5% of the 86 000 cases. All timeseries were also decomposed into high and low frequency components using first differences and 15-years moving averages, respectively. Unless otherwise specified, all values are displayed as indices or anomalies. Analyses of additional climate parameters including precipitation and sea-level pressure were performed on the basis of gridded datasets. For precipitation, we used the average of 25 grid points within 65–70°N and 22–27°E from the CRU TS 3.10 (land) dataset at 1° resolution (Mitchell and Jones 2005), and for sea-level-pressure, the average of two grid points within the same region from the Trenberth and Paolino (1980) dataset at 5° resolution.

Results

Early divergence period (EDP)

Correlations of proxy data with JJA-temperature of 0.78 and 0.66 with NScan-P and NScan-S, respectively, confirm the high predictive skills of the MXD network during the common period. Higher correlations for spruces with an extended growing season from May to August ($r_{1879-1978} = 0.72$) indicate deviating ecophysiological properties of this species, but for reasons of uniformity our analyses focus on June to August (a detailed assessment of growing season effects is included in the Discussion). Despite these evidences for a strong climate signal in the proxy data, a distinct correlation decline with regional JJA temperature data centered ~1912 was revealed after applying running correlations (Fig. 2). The value decreases to a minimum of 0.13 in this period, which stochastically corresponds to the 0.5 percentile of the bootstrap analysis. EDP is defined by the minimum correlation in this period detected between 1905 and 1919, although this definition is partly affected by the window length used herein. As the most distinct patterns are achieved using a 15-year window this became default for all subsequent running correlations. Tests with 10 or 20 years in the running window, however, produced similar results, but the shorter period results in a more fluctuating running value, while the divergence tends to level out with the longer window.

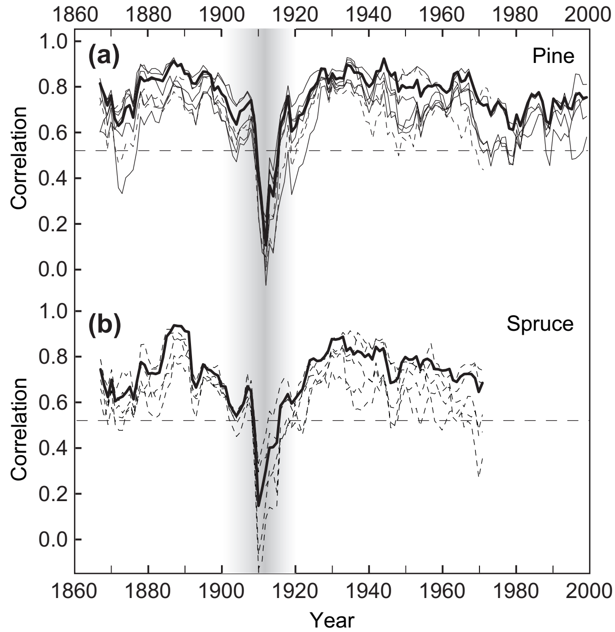

Figure 2. Running correlations between temperature and MXD records computed in 15 years windows. (a) Shows correlations with *Pinus sylvestris*, (b) with *Picea abies* MXD data. The bold curves show the correlations for the NScan-P and NScan-S mean records. The thin curves show the correlations of the single site chronologies. Dashed curves indicate sites with a replication < 20 MXD series. EDP is highlighted with grey shading.

Throughout most periods of the past 130 years, the 15-year running correlations stay well above the 95% confidence level (= 0.51), thereby emphasizing the sudden decoupling between tree-ring proxy and instrumental temperature data during EDP. The correlation decline, approaching zero in 1912, is not only revealed in the NScan-P and NScan-S regional mean timeseries, but also reflected in each single MXD site chronology. Whereas all distinct 15-year periods prior and after 1905–1919 indicate highly significant correlations between proxy and instrumental data ($R^2_{pine} = 0.47–0.79$, $R^2_{spruce} = 0.53–0.71$), this persistent JJA temperature signal falls apart during EDP ($R^2_{pine} = 0.02$, $R^2_{spruce} = 0.10$; Supplementary material Appendix 1 Fig. A1).

MXD inter-site correlations

Even though our MXD network is spread over an area of about 100 000 km², short- and long-term density variations are common among the spruce and pine sites signifying sensitivity to a common, unifying forcing throughout space (Fig. 1c–d). Importantly, both species reveal decreasing inter-site correlations in the early 20th century (Fig. 3a–b), a period coinciding with a gradual increase of MXD values. In NScan-P the lowest value of the last 150 years occurred in 1902, and the highest in 1937. In NScan-S, the increase is less accentuated (lowest value in 1899) though the inter-site correlation decline is overall similar to the pine portion of the network. Although the low inter-site correlations during EDP appear distinct and fairly synchronous throughout the Fennoscandian MXD network, their

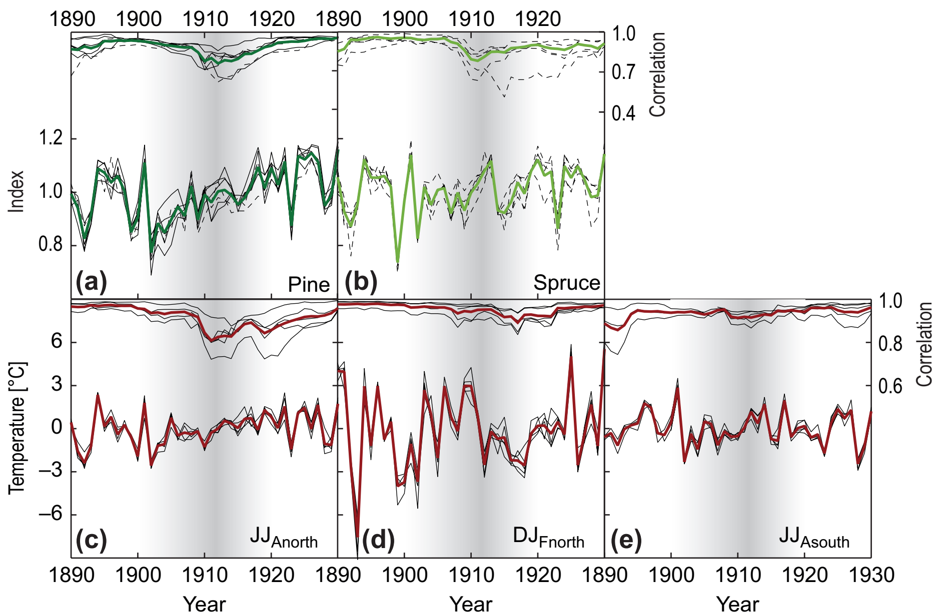

Figure 3. Inter-site and inter-station correlations. (a) Pine site chronologies (bottom panels) over the 1890–1930 period together with a running correlation (15 year window) of each site against an average of all others (top panel). The colored curve in the bottom panel is the NScan-P mean chronology; the colored curve in the top panels is the arithmetic mean of the inter-site correlations. Black curves represent the data on a site-by-site basis, while black dashed curves indicate sites with a replication of $n<20$ MXD series. (b) Same as in a but for spruce sites. (c) to (e), Same as in (a), but for June–August station temperature records (c), December–February temperature records (d), and June–August temperature records from southern Fennoscandia (e). Black curves represent each single record. For station locations see Fig. 1 and Supplementary material Appendix 1.

mean values do not differ significantly from the full-period mean inter-site correlation (green curves in upper panels of Fig. 3a–b; $r_{1879-1978} = 0.77$ for pines and 0.84 for spruces).

Temperature inter-station correlations

The EDP coherence decline seen in the MXD network is also revealed in the temperature station network (Fig. 3c). The observational summer temperature data show minimum correlation (= 0.78) during 1904–1918, a value clearly deviating from the value calculated over the full period ($r_{1879-1978} = 0.94$). The correlations among the winter season (Fig. 3d) and annual mean temperatures (not shown) appear largely unaffected during EDP, however, indicating 1) the coherence loss is restricted to the warm season, and 2) the observational data are not affected by quality issues identified elsewhere in early instrumental temperature readings (Frank at al. 2007b). The distinct summer temperature coherence loss in northern Fennoscandia is further emphasized by comparison with JJA temperatures recorded at five stations located south of the study area (Supplementary material Appendix 1 Fig. A2). In contrast to the northern stations, the southern stations show no sign of correlation decay during EDP (Fig. 3d). The mean distance among the southern stations is 309 km compared to 257 km for the northern stations, and the north-south gradient of both station networks is ~900 km.

Differentiation of the northern summer temperature data into high and low frequency components (see Methods) clearly shows that the station records are 1) coherent in both frequency domains, and 2) accompanied by substantial loss in year-to-year variability during EDP (Fig. 4). The early decadal scale warming trend seen in the northern temperature data from 1890–1930 ($JJA_{north} = +0.30$°C/decade) is not revealed in the southern station records ($JJA_{south} = -0.02$°C/decade). Similarly, the variance reduction, found during EDP in the JJA temperatures, is limited to northern Fennoscandia.

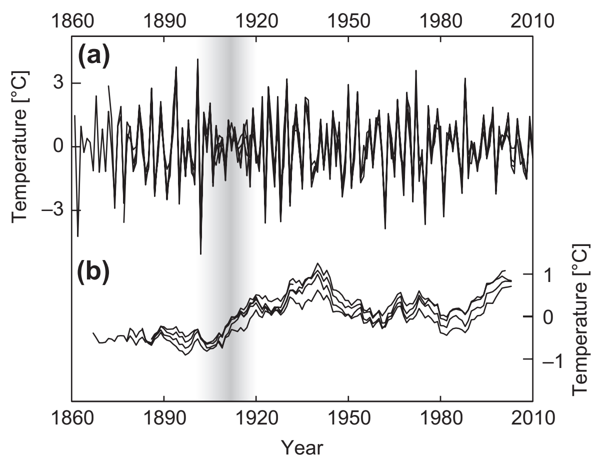

Figure 4. High- and low-pass filtered northern Fennoscandian summer temperature records. (a) First-difference timeseries of JJA temperatures recorded at five stations in northern Fennoscandia (see Fig. 1a for locations). (b) Same as in (a), but after low-pass filtering the original timeseries using 15-year running means. Low-pass filtered anomalies refer to the 1890–1930 period. EDP is highlighted with grey shading.

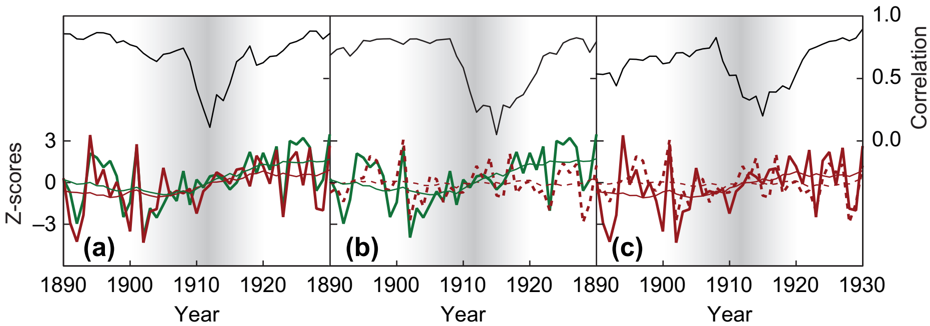

Figure 5. Comparisons of NScan-P with (a) northern and (b) southern JJA temperatures as well as (c) the two temperature records. Bottom panels show the mean timeseries of all *Pinus sylvestris* MXD chronologies (green; NScan-P) together with the mean JJA temperatures of all stations in northern (red; JJA_{north}) and southern Fennoscandia (red, dashed; JJA_{south}). All records were standardized to a mean of zero and a standard deviation of one over 1905–1919. To emphasize low-frequent signals a 15-year running mean was added. Top panels show the 15-year running correlations (black). EDP is highlighted with grey shading.

Proxy calibration against JJA_{north} and JJA_{south}

Calibration of the MXD network against mean summer temperatures recorded in northern (JJA_{north}) and southern Fennoscandia (JJA_{south}) is considered to support identification of the underlying causes of EDP (Fig. 5). JJA_{south} revealed high correlations with MXD records regarding the full calibration period, despite its distant setting (0.67 with NScan-P and 0.59 with NScan-S). It also confirms distinct coherence decay for a period overlapping with EDP if compared to NScan-P (Fig. 5b). Although divergence seems to be maintained by low-frequent disagreement evident in the decadal trends, it remains of similar magnitude after removing trends (Supplementary material Appendix 1 Fig. A3). A more stationary coherence between NScan-P and JJA_{south} would have suggested biased early recordings for the northern summer temperatures. Analog divergence patterns in an independent temperature network, however, are another evidence for a true decoupling of target- and proxy-data.

Discussion

The 1905–1919 EDP in northern Fennoscandia is characterized by a strong warming of summer temperatures accompanied with a distinct reduction of year-to-year variance. Both the temperature increase as well as the variance reduction are displayed in regional MXD pine and spruce chronologies, though the correlation of these proxy data against summer temperatures display an all-time low approaching zero during EDP. This apparent loss of summer temperature signal is associated with the loss of inter-annual variance in both the proxy and instrumental data. It subsequently appears challenging for the trees to reproduce an invariable temperature signal that fluctuates closely around its mean value. The reduced inter-annual variance during EDP not only explains the misfit between tree-rings and temperature, but is also an underlying cause for a distinct reduction of coherence among the instrumental station records in northern Fennoscandia. EDP thus reflects a period during which local temperature deviations are predominating at the inter-annual timescale, while larger scale, synoptic patterns are predominating at the decadal timescale.

When assessing EDP we strictly limited our analyses to the JJA season, as this has been reported to be the key period controlling latewood density variability in Fennoscandia (Esper et al. 2012b). Further evaluation of the seasonality of temperature signals in the pine and spruce components of the network, however, suggests slightly deviating maximum responses during varying growing season months (Fig. 6). Whereas both species indicate significant correlations with spring season months – including May and even April – over the 1879–1978 common period, extension of the season (beyond JJA) does not improve the temperature signals throughout the pine network. For spruce, however, the May signal seems particularly important, as the correlation exceeds the signals recorded in June and July. Importantly, during the 1905–1919 EDP, the correlation with May temperatures approaches the 95% significance level, and May–August would be the only season retaining a significant signal throughout the spruce MXD network. These findings, together with the assessment of coherence decline in the northern Fennoscandian instrumental station network, suggest that the EDP is limited to the summer season months.

The EDP detailed here in northern Fennoscandia fulfills a number of requirements identified for a proper definition of the modern, post-1960 divergence problem seen in a number of high latitude tree-ring sites (Esper and Frank 2009). It, for example, 1) shows a clear deviation in correlation from an otherwise highly significant summer temperature signal, 2) is consistent among a number of MXD sites in a given region (network), and 3) is not associated with methodological (detrending or transfer) biases that can cause artificial divergence towards the end of tree-ring chronologies (Esper and Frank 2009). However, the phenomenon identified here is restricted to abrupt correlation decay, and is not revealed in diverging lower frequency trends, i.e. the proxy and instrumental data both show a coherent decadal-scale warming signal in the early 20th century. Interestingly, this warming trend is similar to the increasing temperatures recorded in a number of high latitude regions during the late 20th century, though the underlying forces that have been hypothesized to cause (late 20th century) divergence – including stratospheric ozone depletion (Briffa et al. 1998), irradiance

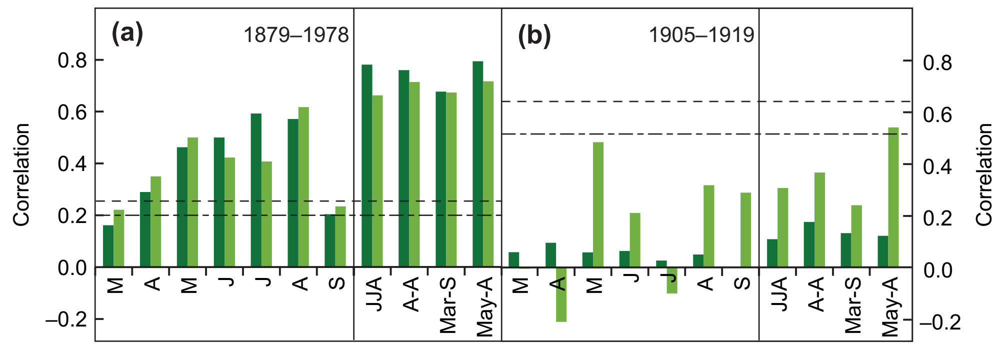

Figure 6. Correlations of NScan-P (dark green) and NScan-S (light green) with monthly and seasonal temperature data recorded at five stations in northern Fennoscandia over (a) 1879–1978, and (b) 1905–1919. Coefficients for single months from May (M) to September (S), and seasons including JJA, April–August, March–September, and May–August are shown. Dashed lines indicate the confidence levels (95% and 99%).

changes due to global dimming (Wild et al. 2007), or an unprecedented increase of CO_2 concentrations (Barber et al. 2000) – can, obviously, not account for a similar observation identified some 50 years before the onset of modern divergence (D'Arrigo et al. 2008).

Another reason for the occurrence of EDP in the early 20th century could be related to biases in early temperature readings that have been identified in other regions of the world (Frank et al. 2010) to constrain the reliability of instrumental data for proxy calibration purposes (Frank et al. 2007b). In order to assess this potential cause, we additionally compared the northern Fennoscandian MXD data with precipitation and sea level pressure recordings (Fig. 7). This evaluation indicates that the correlation decay during EDP centered in the 1910s is not limited to only the temperature readings. Also the early sea level pressure and precipitation data show exceptionally low correlations against the MXD data whereas a synoptical association between temperature and pressure/precipitation is unlikely in this period since correlations

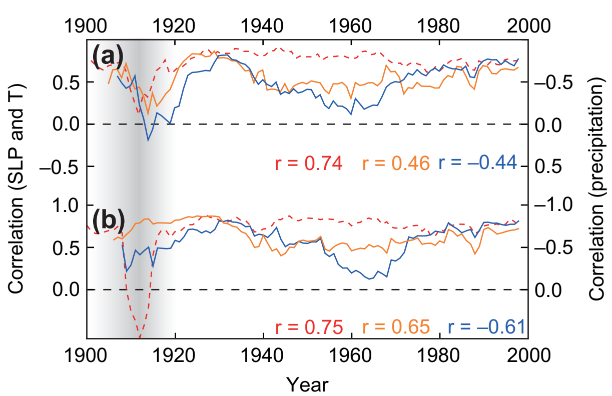

Figure 7. Coherence of NScan-P with other climate parameters. (a) Fifteen-year running correlations of NScan-P with regional summer temperature (red, dashed), sea-level-pressure (orange), and precipitation records (blue). See text for details on the instrumental data. (b) The same as (a), but using first-difference records (proxy and instrumental) instead of the original timeseries. Correlation values refer to the 1901–2006 common period. EDP is highlighted with grey shading.

between these parameters decrease in a similar manner. The deviation is, however, distinct only in the temperature data after the proxy and instrumental records are high pass filtered using first differencing (Fig. 7b), again suggesting the diminished inter-annual variance inherent to the regional temperature field (but not to the pressure and precipitation data) is the key driver of EDP in northern Fennoscandia. For the original and high-pass filtered data the weakest correlations increase/decrease from 0.13 to 0.59 (pressure) and from 0.19 to –0.22 (precipitation) over the (common) 1909–1930 period, whereas the correlation with summer temperatures decreases from 0.11 to –0.57.

The trigger for the persistent high frequency correlation between tree growth and sea level pressure could be related to the correlation between cloud cover and surface pressure. Cloud dissipation, associated with anticyclonic (high) pressure patterns, increases irradiance and promotes enhanced photosynthetic rates. Even though assimilation is not necessarily directly coupled with MXD, this hypothesis is corroborated by the strong coherence of photosynthetic rate with growing-season sunlight amounts in Fennoscandia (Nemani et al. 2003). This hypothesis is supported by the negative correlation with precipitation, reflecting decreased cell wall growth in summers predominated by rainy (and cloudy) weather. It is also in line with one of the potential explanations for the late 20th century divergence problem, where global dimming is considered as a trigger for the decoupling between tree-ring and instrumental data (D'Arrigo et al. 2008, Stanhill and Cohen 2001). Assuming that anthropogenic pollution was a rather local phenomenon at that time, large scale dimming and an increasing amount of indirect radiation could e.g. be induced by a stratospheric volcano-ash injection. This might either directly affect tree-growth (Farquhar and Roderick 2003) or trigger a distortion of the temperature field. However, the only potential event documented in the first decade of the 20th century is the Icelandic volcano Grimsvötn, which erupted with a VEI of 4 in 1903 (Siebert et al. 2010). Although tephra volume is not specified it was more likely an effusive eruption with long duration (two years) and mainly lava flows.

As other potential explanations, including volcanoes, did not yield convincing results, we suggest the low temperature variance during summer warming associated with high sensitivity to light exposure to be the most likely explanation for the EDP in northern Fennoscandia. Although our bootstrap analysis could not exclude that divergence occurs by chance, it appears very unlikely to detect patterns of such high magnitude and spatial spread without physical explanation. The intension to test this hypothesis also against corresponding tree-ring width chronologies was abandoned due to the high amount of biological memory and noise in this proxy (Franke et al. 2014). Some initial approaches revealed generally much lower correlations within the network and against climate as well as indistinct correlation patterns during EDP.

Conclusions

Our results imply conceptual advancements for the evaluation of temporal instable growth-climate relationships. Based on correlation analyses with 10 summer temperature records, seven pine- and five spruce-MXD-chronologies as well as gridded climate data for precipitation and sea level pressure we can conclude on the extent and the causes for EDP. Within the scope of this study, the early divergence between proxy and climate data could be temporally and spatially confined to northern Fennoscandian summers between ~1900 and 1925 AD. The cause for the reduced coherence among northern summer temperatures and against tree-growth is decreased interannual temperature variability on a large spatial scale, which allows temperature records to be dominated by less variable local conditions yielding an indistinct forcing for tree-growth. By including other climate parameters (sea level pressure and precipitation), we could show that the high frequent MXD-signal is a clear response to light availability, while the low frequent positive trend during EDP mirrors the summer temperature warming recorded at the northern stations. Despite EDP this dataset is thus not prone to introduce any bias using traditional reconstruction techniques (e.g. ordinary least squares regression). This is the most significant difference to the divergence problem found in the most recent decades, which is often accompanied by deviating decadal trends. There, the ability to reconstruct climate using tree-rings is seriously questioned, since these trends were observed to disturb calibration schemes.

While this 'modern' divergence is often associated to reduced physiological climate sensitivity in a warming world, we here found growth response to recover after the warming period and being as strong during warmer conditions as before. Thus, EDP is obviously not a result of non-linear behavior of the proxy, but can be attributed to a diminishing temperature signal during a period of summer warming. Consequently further research should focus on the causes for altering temperature variance in records with strong multidecadal trends and the potential of proxy records to track such variance changes. The expected outcome will likely stimulate new research questions, such as the relevance of changing temperature variance for the 'modern' divergence. To raise the awareness of divergence problems not only in the most recent decades we generally suggest that climate/growth associations of existing and new chronologies should be tested for robustness with high temporal resolution, additional to existing calibration and verification assessments. This could spread the current focus on modern divergence to a broader conception of temporal discrepancies between tree-growth and climate.

Acknowledgements – Supported by the Mainz Geocycles Research Cluster. UB was supported by the Czech project 'Building up a multidisciplinary scientific team focused on drought' (no. CZ.1.07/2.3.00/20.0248).

References

Barber, V. A. et al. 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. – Nature 405: 668–673.

Briffa, K. R. et al. 1998. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. – Nature 391: 678–682.

Büntgen, U. et al. 2008. Testing for tree-ring divergence in the European Alps. – Global Change Biol. 14: 2443–2453.

Büntgen, U. et al. 2011. Causes and consequences of past and projected Scandinavian summer temperatures, 500–2100 AD. – PloS ONE 6.

Carrer, M. and Urbinati, C. 2006. Long-term change in the sensitivity of tree-ring growth to climate forcing in *Larix decidua*. – New Phytol. 170: 861–871.

Cook, E. R. 1985. A time series analysis approach to tree-ring standardization. – PhD thesis, Univ. of Arizona.

D'Arrigo, R. et al. 2008. On the 'divergence problem' in northern forests: a review of the tree-ring evidence and possible causes. – Global Planetary Change 60: 289–305.

Esper, J. and Frank, D. 2009. Divergence pitfalls in tree-ring research. – Climatic Change 94: 261–266.

Esper, J. et al. 2010. Trends and uncertainties in Siberian indicators of 20th century warming. – Global Change Biol. 16: 386–398.

Esper, J. et al. 2012a. Orbital forcing of tree-ring data. – Nature Climate Change 2: 862–866.

Esper, J. et al. 2012b. Variability and extremes of northern Scandinavian summer temperatures over the past two millennia. – Global Planetary Change 88–89: 1–9.

Farquhar, G. D. and Roderick, M. L. 2003. Atmospheric science: Pinatubo, diffuse light, and the carbon cycle. – Science 299: 1997–1998.

Frank, D. et al. 2007a. Adjustment for proxy number and coherence in a large-scale temperature reconstruction. – Geophys. Res. Lett. 34.

Frank, D. et al. 2007b. Warmer early instrumental measurements versus colder reconstructed temperatures: shooting at a moving target. – Quat. Sci. Rev. 26: 3298–3310.

Frank, D. et al. 2010. A noodle, hockey stick, and spaghetti plate: a perspective on high-resolution paleoclimatology. – Wiley Interdisciplinary Rev. Climate Change 1: 507–516.

Franke, J. et al. 2014. Spectral biases in tree-ring climate proxies. – Nature Climate Change 3: 360–364.

Fritts, H. C. 1976. Tree rings and climate. – Academic Press.

Gershunov, A. et al. 2001. Low-frequency modulation of the ENSO–Indian monsoon rainfall relationship: signal or noise? – J. Climate 14: 2486–2492.

Mitchell, T. D. and Jones, P. D. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. – Int. J. Climatol. 25: 693–712.

Nemani, R. R. et al. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. – Science 300: 1560–1563.

Schweingruber, F. et al. 1988. Radiodensitometric-dendroclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). – Boreas 17: 559–566.
Siebert, L. et al. 2010. Volcanoes of the world. – Smithsonian Inst.
Stanhill, G. and 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.
Trenberth, K. E. and Paolino, D. A. 1980. The Northern Hemisphere sea-level pressure data set: trends, errors and discontinuities. – Monthly Weather Rev. 108: 855–872.
Wild, M. et al. 2007. Impact of global dimming and brightening on global warming. – Geophys. Res. Lett. 34.

Supplementary material (available as Appendix oik-00836 at <www.oikosoffice.lu.se/appendix>). Appendix 1.