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EXTRACTING MID-SUMMER TEMPERATURES FROM RING-WIDTH CHRONOLOGIES OF LIVING PINES AT THE NORTHERN FOREST LIMIT IN FENNOSCANDIA

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EXTRACTING MID-SUMMER TEMPERATURES FROM RING-WIDTH CHRONOLOGIES OF LIVING PINES AT THE NORTHERN FOREST LIMIT IN FENNOSCANDIA

Abstract

Reconstructions of mean July temperatures for the northern forest-limit region in Fennoscandia are made back to 1720 using ring-width chronologies of living Scots pine (Pinus sylvestris L.) as predictors. The results indicate that relative warmth prevailed in the region during the 1750's, 1826-1834 and 1849-1856. Cool summers were experienced by northern pines between years 1767-1776, 1782-1798, 1837-1844, and 1866-1871.

Introduction

The aim of the work is to identify and extract climatic signals from tree-rings of Scots pine (Pinus sylvestris L.) at the northern timber-line in Fennoscandia. Growth trends in ring-width records are modelled using two approaches, exponential and linear functions of both deterministic and stochastic components. The results presented in this paper demonstrate that the variability of critical seasonal climatic variables govern the relative growth rates of pines in the forest limit communities. Reconstructions are presented emphasizing high to medium frequency variability in ring-width records of past climate.

The research area has been limited to the northern forest-limit ecotone. This is the borderline terrain between the boreal forests and the tundra, where cold climate gradually weakens the growth and development of trees. The region is boarded by discernible phytogeographical margins, the Swedish Scandes in the west and the Kola peninsula in the east. The coniferous timberline represents an open environment, and as one moves from north to south, or to lower altitudes, the stand structure becomes more dense and e.g. near-neighbour competition increases. The more densely stocked forest stands in the south have more possible interactions between stand dynamics, aging of trees and for example fertilization and pollution.

Material

Ring-width data of Scots pine were collected at nine stands of relatively open and
Tree-ring data were collected at nine forest-limit stands (Figure 1 and Table 1). 258 pines in all were sampled. The number of trees per site ranged from 12 to 30.2. Climate variables used in this work represent the latitudes (Figure 1 and Table 2) were sampled. The number of trees per site ranged from 12 to 30.2.

Methods

Standardization, cross-dating and estimation of the mean chronology were used as basic tools in chronology building, (e.g. COOK ET ALII 1990). Data quality was assessed by procedures presented by VanDeusen (1992), Holmes (1983), Holmes et alii (1986), and Timonen (1995). Standardization was achieved by modelling noise related growth trends (Cook et alii 1990) as modified negative exponential functions (Fritts et alii 1969) of the form

\[ G_t = a \exp(-bt) + k, \]

where \( G_t \) is the expected growth in a given year \( t \), \( \exp \) is the base of natural logarithms and \( a, b, \) and \( k \) are all coefficients as a function of time \( t \) and vary from series to series. The modified negative exponential model is objective and biologically reasonable for application at the timber-line. It is assumed to preserve as much low-frequency climatic variance as is resolvable from the age trend. Linear regression lines were employed in combination with negative exponentials, as alternatives in cases where the negative exponential curves were not adequate (e.g. Graybill 1982; Cook et alii 1990). A model was fit to each measurement series, which was then divided by the modelled values to produce an indexed series. Means for each year were computed as biweight robust estimates (Cook 1985; Cook et alii 1990).

In addition, the methodology by the acronym ARSTAN (for AutoRegressive STANDARDization) developed by Cook (1985) and Holmes et alii (1986) was applied. This enables the use of both deterministic and stochastic modelling techniques, or combinations of them in attempts to remove time domain nonstationarity (Cook et alii 1990). Significant low-order (i.e., year-to-year) autocorrelation in each series was removed by fitting autoregressive models to each series, while long-term variation was preserved (Cook et alii 1990).

The ARSTAN procedure produces the following three versions of chronologies from tree-ring measurement series. (1) The standard version of the chronology is computed as usually. (2) The residual version is the average of the white noise series, the residuals from autoregressive modeling. This is a chronology without persistence. (3) In the ARSTAN chronology, the pooled model of autoregression is reincorporated into the residual version. The pooled autoregression contains the persistence that is common and synchronous among a large portion of series from a site. The resulting chronologies were then used in various response and transfer function experiments (Fritts 1976, 1990; Guiot 1990; Serre-Bachet, Tessier 1990). Spectral analysis (SPSS, 1993) was used as an alternative to digital filtering in an attempt to gain insight to the factors possibly causing periodicity in proxy as well as instrumental data (Mazepa 1990). Spectral analysis yields a description in terms of cycles of varying length or frequencies that generate the series (SPSS, 1993; Burroughs 1994). A periodogram shows an estimate of the amount of variance of the series accounted for by cycles at each frequency. Fourier frequencies are chosen so that the length of the series contains a whole number cycles at each frequency (SPSS, 1993).

Results

Individual site chronologies and regional master chronologies

Three sets of chronologies corresponding to the ARSTAN protocol were produced for each of the nine sites. Long-term growth patterns as well as the year-to-year variability between the site chronologies were highly consistent, which is usual in this region. Correlations between the nine chronologies produced by standard means of indexing are presented in Table 1. This matrix was calculated for the whole length of the individual series. The starting years of the chronologies are also shown in Table 1. The nine site chronologies were com-

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2 Samples from four sites, 75 trees in all, were provided by Prof. Matti Eronen from the University of Helsinki.
The longed cooling effect is reflected back to space and hence has a significant but negative effect of February precipitation on growth is that a prolonged spell of extreme weather can affect the underlying components long enough to yield smaller coefficient values than for example July mean temperatures alone. The partial regression coefficient is roughly at the level of mean temperatures in June. The result is in accordance with the few attempts to utilize more complex regressors, for example, June - July, April - August, or even May - September mean temperatures. Moreover, some workers have used wood densitometry to yield both ring-width and maximum-latewood-density time series.

**Comparison with other work**

Comparisons with other works are difficult. For example BRIFFA ET ALI (1990, 1992, 1995), BREFFA, SCHWEINGRUBER (1992), GRAYBILL, SHIYATOV (1992) have studied far more extensive regions than the work at hand, which concentrates strictly to the forest-limit zone. In addition, the authors have used broader time windows (predictand periods) in their reconstructions, for example, June - July, 2006-2013, or even May - September, 1880-1926. Also between approximately 7 and 20 years, two peaks are evident. In this work spectral analysis was limited to the 111 years calibration period (1880-1990), which is thus also a limit to the lowest frequencies.

**Periodicity**

Spectral analysis revealed notable concentrations of coinciding variance corresponding to cycles with periods of 2.2 - 2.5 years and 2.9 - 4 years (Figure 6). Also between approximately 7 and 20 years, two peaks are evident. In this work spectral analysis was limited to the 111 years calibration period (1880-1990), which is thus also a limit to the lowest frequencies.

In their reconstruction for northern Europe from A.D. 1580 to 1978, BRIFFA, SCHWEINGRUBER (1992) found significant

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**Table 3: Extreme summer temperatures in northern Fennoscandia**

<table>
<thead>
<tr>
<th>Anomaly (°C)</th>
<th>Year</th>
<th>Anomaly (°C)</th>
<th>Year</th>
</tr>
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<td>1769</td>
</tr>
<tr>
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<td>1739</td>
<td>-1.09</td>
<td>1784</td>
</tr>
<tr>
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<td>1737</td>
<td>-1.12</td>
<td>1786</td>
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<tr>
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<tr>
<td>1.11</td>
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<td>-1.24</td>
<td>1839</td>
</tr>
</tbody>
</table>

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**Figure 5: Reconstructed mean July temperatures**

- **A:** Reconstruction back to 1720 using Model (t) (t, t+1) in (A) and corresponding ARSTAN version of Model (t) in (B). The values are in normalized units, equal to degrees Celsius, as departures from the mean for 1880-1990. The smooth line illustrates filtered values. Observed July mean temperatures during 1880-1990 have a mean value of 12.6 °C. Calibration period (1880-1990) is indicated by a vertical line.

- **B:** Reconstruction back to 1720 using Model (t), using standard deviation units from the calibration period mean, which is 12.6 °C for 1880 – 1990.

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**Figure 6: Reconstructed mean July temperatures**

In the reconstruction BRIFFA ET ALI (1990), summers of years 1761 and 1831 have the largest positive temperature anomalies. These years are also indicated in Table 3.
Figure 3 - Growth responses. Arithmetic mean of the STANDARD (A) and RESIDUAL (B and C) versions of nine forest-limit site-chronologies have been used as the predictand. In diagram (C) the growing season, presented previously as mean July temperatures, is replaced by temperature sums, denoted as DD.

Since relatively large and significant autocorrelations were found, lagged ring-width variables were considered in the transfer models for climate reconstruction (FRITTS 1976; BRIFFA et alii 1983).

The regional average record of July mean temperatures was estimated by the two sets of regional master chronologies using Model (t, t+1) for standard master chronologies and Model (t) for corresponding ARSTAN chronologies fitted over the full 111 years of overlap account for 41% and 38% respectively of the dependent temperature variance. The two versions of variations in regional July temperatures in northern Pennoscanda since 1720 are shown in Figure 5. The data are plotted in normalized units, approximately equal to degrees Celsius, as anomalies from the calibration period mean. Observed July mean temperatures during 1880-1990 have a mean value of 12.6 °C. Linear equations, which were used to compute the reconstructions are presented below:

1. \( T_r = (2.675 \times TRW_1) + (0.232 \times TRW_{1+1}) - 2.725 \)
2. \( T_r = (2.874 \times TRW_2) - 2.980 \)

where \( T_r \) is the value of regional mean monthly July temperature departure and \( (TRW_1) \) and \( (TRW_2) \) are the standard and ARSTAN index values of corresponding master chronologies.

The estimated and observed data were also smoothed by a low-pass filter, a 8 year weighted moving average. Table 2 suggests that the low-frequency component in climate variation is less successfully reconstructed than the high-frequency one. The general levels of other statistics of model performance are relatively high in Table 2, especially when it is kept in mind that here only one monthly variable is considered. Reconstructions in Figure 5 includes predicions for years 1991 and 1992. These are included only to demonstrate the so-called
Figure 4. The observed (A) and reconstructed averages of July temperatures using the early calibrated/late verified model (B), the late calibrated/early verified model (C), and the full model (D). Standard versions of regional average chronologies using Model \( t+1 \) is the predictor. Vertical axis expresses departures from the mean in normalized units, equal to °C degrees. A weighted 8-year moving average was applied to the estimated as well as observed data (smoothed lines).

Table 2. The performance of Model \((t, t+1)\) and a master chronology of standard chronologies in predicting regional July temperatures. Calibration and verification statistics for the early (1880-1935), late (1936-1990) and full (1880-1990) periods.

Discussion

Response functions

In a previous work, it was concluded that patterns of growth response to intra-annual climate forcing are homogeneous throughout the forest limit region (LINDHOLM 1996). The conclusion was based on the considerable similarity of the response functions at all sites. In the present work, in Figure 3 it was demonstrated that the month with the statistically most significant total of positive response function elements is July. Mean temperature in June also has a positive and significant \((p < 0.05)\) effect on growth. This is generally the second best predictor using this data.

The conclusion may also be drawn that precipitation in May expresses a limiting factor as experienced by northern pine populations. The response functions also suggest that precipitation in July has a negative and significant effect on the radial growth of pines. A plausible explanation for the nega-
bined by arithmetic mean to form three sets of regional master chronologies corresponding to the ARSTAN procedure of chronology building. The three types of regional chronologies along with corresponding yearly variations in sample depth are illustrated in Figure 2. The master chronology produced by standard form of indexing, is seen in diagram (A). In diagram (B) the chronology with reincorporated persistence (autoregression) is shown. In diagram (C), a corresponding average curve of the nine residual chronologies is presented. The chronologies were not processed further. Yearly variations in the number of sampled trees, also called sample depth or replication, may be seen in diagram (D).

Even a visual inspection of Figure 2 clearly reveals the markedly instable variance during the first two or three centuries of the chronology. This is evident especially in diagrams A and B, but also in diagram C. The reason for this instability is poor replication, which becomes apparent in diagram D. This decrease in sample size causes a decrease in variance stability and chronology reliability as a function of time. The strength of the common signal in the chronologies was quantified by a correlation based technique, the sub-sample signal strength value (WIGLEY ET AL. 1984; BRIFFA, JONES 1990). This is denoted as SSS and it measures the increased uncertainty of a chronology when the number of its constituent core series drops in early periods (BRIFFA ET AL. 1988).

Four of the nine site chronologies were longer than others and their SSS values are over 0.85 since 1720. The remaining five shorter chronologies have SSS values over 0.85 since 1830. 0.85 is an arbitrary value, but it has been considered as satisfactory measure for chronology reliability through time (WIGLEY ET AL. 1984; BRIFFA ET AL. 1988). The above calculations were based on standard forms of the chronologies.

Determining tree-growth response to climatic factors

Growth responses in forest-limit pines to climatic factors are seen in Figure 3. The predictand variable is the regional average chronology of the nine STANDARD chronologies in plot (A) and corresponding RESIDUAL chronologies in (B) and (C). Predictors include monthly mean temperatures and total precipitations, viz. the regional averages of climate data for the 1880-1990 period. The removal of autocorrelation in tree-ring chronologies is assumed to improve regression performance (e.g. MON-SERUD 1986; VAN DEUSEN 1991; BIONDI 1993). The residual chronologies are white noise and have no persistence. Consequently, and contrary to what is usually done, no prior growth values are included in these regressions. The number of eigenvectors were delimited by the PVP criteria and the t-value (GUOY 1990). Autoregressive modelling was not applied to the climate data.

In Figure 3 diagram C, the main part of growing season that in diagrams A and B are presented by July mean temperatures is replaced by yearly temperature sums, the growing season degree-days above 5 °C. This is denoted as DD. The strongest predictor among monthly variables and temperature sums were analysed separately. It is noteworthy that practically the same results were achieved also from simple regressions, when thermal sums were used singly in predicting the same ring-width record.

The temperature variable, having the largest partial regression coefficient, was July (Figure 3). Also June temperatures seem to have a positive and significant (p < 0.05) impact on growth. Some monthly precipitation variables correlated significantly (p < 0.05) and either positively or negatively with growth. These included previous August, February, and concurrent May.

Reconstructions

After establishing the relationship between variations of recent tree growth and variations in present-day climate, past climate was estimated from past tree rings (FARRIS 1976, 1990; GUOY 1990). In this work only mean July temperatures have been reconstructed. Master chronologies for the whole study region were used as predictors. Both standard master chronologies based on negative exponentials and regression lines, and ARSTAN versions of them were used. These two types of chronologies were analyzed further in experiments involving more complicated model structures.
peaks corresponding to periods of 2.33, 2.89, 2.99, 3.02, 3.13, 3.59, 3.97, 4.16, 33.25, 38.0 and 88.7 years. BRIFFA, SCHWEINGRUBER (1992) also compared their results with those of SIREN, HARI (1971) from northern Finland and found that they both contained concentrations of variance corresponding to cycles with periods of about 3.6-33.0 and 80-96 years. BURROUGHS (1994) has reviewed widely dendroclimatological literature in a search for evidence of cycles. He concludes that the most frequently emerging observations include the so-called quasi-biennial-oscillation (QBO) of 2.1 – 2.8 years, cycles around 3 or 4 years, and 5 to 7 years. These cycles are also evident in Figure 6 (A).

The coherency spectrum of the actual and estimated mean July temperatures is shown in Figure 6 (B). The coherency may be considered good across the spectrum. The analyses revealed no reduced coherency for example between observed and estimated data at low frequencies relative to high frequencies. Only in one area, between 4 and 5 years is there relatively low coherency. The coherency is particularly high at the above mentioned periods of variance concentrations and above 20 years. In their work with larch, GRAYBILL, SHIYATOV (1992) found strong coherency at most periods less than 20 year frequency range, especially at periods of about 2.0-2.1 and 2.8 years.

**LITERATURE**


OJANSU R., HENTTONEN H., 1983. Estimation of local values of monthly mean temperature, effective temperature
SUMMARY

Extracing mid-summer temperatures from ring-width chronologies of living pines at the northern forest limit in Fennoscandia

Three types of ring-width chronologies were used in this work. The chronologies were built by standard means as well as by the ARSTAN protocol. Ring-width was modelled either as an exponential or linear function of both a deterministic component, the intrinsic growth trend and a stochastic component, the autoregressive process. These chronologies were then used in response and transfer function experiments. In response functions, the temperature variable having the largest partial regression coefficient was July. Also June temperatures have a positive and significant (p < 0.05) impact on growth. Some monthly precipitation variables correlated significantly (p < 0.05) and either positively or negatively with growth. These include preceding August, February, and concurrent May. Mean July temperatures have been reconstructed using regional master chronologies as predictors. The best models included ring-width data in both the concurrent and subsequent years, that is Model (t, t+1). The explained variance of these models over the calibration period range from 0.36 to 0.45.

ZUSAMMENFASSUNG

Rekonstruktion der Mittsommertemperatur aus den Jahrringchronologien von lebenden Kiefern an der nördlichen Baumgrenze in Fennoskandinavien