Climatic Signals Extracted from Ring-Width Chronologies of Scots Pines from the Northern, Middle and Southern Parts of the Boreal Forest Belt in Finland

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Climatic signals were extracted from ring-width chronologies of Scots pines (*Pinus sylvestris* L.) from natural stands of the northern, middle, and southern parts of the boreal forest belt in Finland. The strength of the common growth signals (forcing factors) were quantified as a function of time. This was achieved by mean inter-series correlations, calculated over a moving 30-year window, both within and between the regional chronologies. Strong regional signals and also evidence for common forcings were found, especially between northern and central, central and eastern, as well as central/eastern and southern chronologies. Response function analyses revealed that growing season temperatures govern the growth rates of northern pines, while towards south, pine growth becomes less affected by temperatures, and more affected by e.g. precipitation. During some periods, growing conditions seem to have been favorable in the south, while they have been unfavorable in the north (growth inversions). Going from the north to the south, the variability of radial growth clearly decreases, and the variance of ring-width series becomes smaller. Growth variability in the four regions was compared during the common interval of the chronologies, from 1806 to 1991. The spectral densities of the northern, central, eastern and southern chronologies were also compared as functions of frequency, viz. cycles per year. The variance is much greater and there is more periodic behavior in the north than in the south in high, medium, as well as lower frequencies.

Keywords boreal forest, Scots pine, tree-rings, ring-width chronologies, growth variability, growth responses, spectral analysis
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1 Introduction

1.1 Climatic Signal and Noise

In dendroclimatology, the general year-to-year agreement or synchrony between variations in tree-ring series taken from different sides of a tree, or between different trees or among different site chronologies is considered evidence for a limiting effect of climatic variation on tree growth (Fritts 1976). The building of tree-ring chronologies is often described as a noise reduction and signal enhancement process. Site and tree selection as well as standardization and averaging in building chronologies are the tools in signal extraction (Fritts 1976, Briffa and Jones 1990).

Climatic signal in a tree-ring chronology is a statistical quantity representing the common variability present in all of the tree-ring series at a particular site. The variance of any series of tree-ring indices will contain this common forcing signal, but in any one core it will be obscured by variability common only to the specific tree and core, viz. statistical noise (Briffa and Jones 1990). This noise is uncorrelated from core to core and site to site. The common growth variance (covariance, correlation) may be studied using either ANOVA method or correlation matrix (Fritts 1976, Briffa and Jones 1990).

Scots pines growing under extreme conditions in the northern timberline region are known to have a strong common 'signal', which is empirically linked to temperature forcing (e.g., Briffa et al. 1990, 1995, Lindholm 1996, Lindholm et al. 1996). Going from north to south, dendroclimatological work becomes more complicated. Tree-growth becomes less affected by growing-season temperatures, and more affected by e.g. precipitation (Lindholm et al. 1997) and a multitude of other factors. Compared with the northern timberline, factors related to stand dynamics increase in importance in controlling annual growth variability of southern pines.

1.2 Goals

- In order to identify the effects of climate change in the boreal forests, we need interregional comparisons of long-term growth variability, growth responses and spectral characteristics of tree-ring chronologies.
- In this work, we will identify and quantify the climatic 'signals' (growth forcings) in pine tree-ring chronologies from natural stands of the north, middle and south boreal zones in Finland. Signal strength will be measured as correlation calculated over a moving 30-year window both within and between ring-width chronologies.
- We will show to what degree the chronologies represent the hypothetical (perfect) population chronologies. To answer this question, it is necessary, first, to estimate the strength of the signal and second, to quantify how clearly this is expressed in the chronology.
- The qualities of the extracted climatic signals will be described by means of response function analysis. This is an empirical technique designed to display the relationships between tree growth and climate in terms of monthly climatic variables, thereby identifying the chronology climate signal.
- We will apply spectral analysis to the data in order to identify possible regularity and regional differences in the inter-annual, inter-decadal, and even inter-centennial scale modes of variance evident in tree-growth and growth forcing environmental factors (e.g. climate).

2 Material

2.1 Tree-Ring Data

Research areas represent the natural pine stands of the northern, middle, and southern parts in the boreal forest belt in Finland (Fig. 1). Table 1 describes the location of the 11 sampling sites. The northern and southeastern data sets were selected from larger data bases (Lindholm 1996, Lindholm et al. 1996, Lindholm et al. 1997).

The northern data (Fig. 1, Table 1) comes from four subareas including 85 living trees (2–3 cores per tree) growing between 68° N and 70° N, 21° E and 30° E (300–400 m a.s.l.). Sampling in the northern forest-limit region (sites 1, 2, 3, and 4), as well as sample preparation and measurement have been described in detail by Eronen et al. (1996) and Lindholm (1996, 1999).

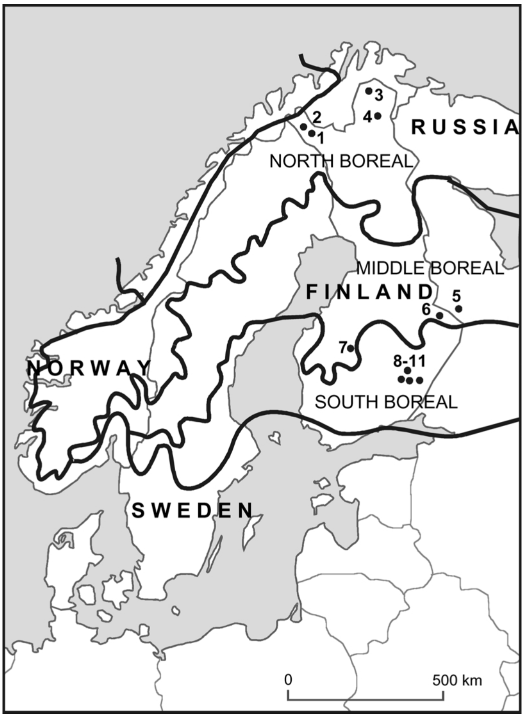

Fig. 1. The locations of the sampling sites in the four research regions in the north (1–4), the middle (5–7) and the south (8–11) boreal zones in Finland. The northern sites are located between approximate boundaries of 68°–70° N and 21°–30° E. The middle boreal zone is represented by three areas (5) 62°51' N, 25°29' E in the center, (6) 63°16' N, 30°40' E and (7) 63°30' N, 31° E in the east. The south-eastern region is located between 29°–30° E and 61°–62° N.

The middle boreal zone is represented by three subsets of data (sites 5–7 in Fig. 1, A and B in Table 1). The largest collection, samples from 54 living trees (one core per tree), comes from the westernmost area, the Pyhä Häkki national park, 62°51' N and 25°29' E (160–200 m a.s.l.). In the east, we have sampled 11 pines (2–3 cores per tree) located around 63°16' N, 30°40' E and 11 dead standing trees (snags) from around 63° 30' N, 31° E (150–235 m a.s.l.). The location

Table 1. A description of the 11 sampling sites from the northern, middle, and southern parts of the boreal forest belt in Finland. Total number of sampled trees as well as the number of samples accepted for chronology building and further analyses are shown. Threshold value is the criteria for acceptance for individual series to be included in the chronology. The middle boreal zone is represented by two eastern sites (A) and a central site (B).

Boreal part	Site names*	Latitude (N)	Longitude (E)	Threshold value	Total number of trees	Number accepted
Northern:				0.4	85	79
	1. Nunas	68° 30'	22° 00'		(25)	(25)
	2. Luspa	68° 35'	22° 05'		(10)	(10)
	3. Skallovaara	69° 47'	27° 20'		(20)	(20)
	4. Uusijoki	68° 35'	28° 00'		(30)	(24)
Middle:					76	50
A Eastern	5. Lentiera	63° 27'	32° 10'	0.3	(11)	(9)
	6. Lieksa	63° 16'	30° 40'		(11)	(10)
B Central	7. Pyhä-Häkki	62° 51'	25° 29'	0.3	(54)	(31)
Southern:				0.4	92	87
	8. Pitkäsaari	61° 80'	29° 10'		(16)	(14)
	9. Eteissaari	61° 81'	28° 68'		(27)	(26)
	10. Kyrönniemi	61° 86'	28° 88'		(22)	(21)
	11. Punkaharju	61° 80'	29° 40'		(27)	(26)
Total					253	216

* Numbers refer to Fig. 1. The names are used in original descriptions of the data in Lindholm (1996) for the northern sites and Lindholm et al. (1997) for the southern sites.

of site 5, Lentiera, (Fig. 1, Table 1) is only an approximation, since the snags were already used for construction purposes.

The south-eastern research areas (sites 8–11 in Fig. 1 and Table 1) cover a region surrounding the central parts of the Lake Saimaa basin, south-eastern Finland, between 29°–30° E and 61°–62° N (120–150 m a.s.l.). These samples were cored from 92 pines (two cores per tree) from two islands and two sites on mainland. The whole southeastern data base has been presented previously by Lindholm et al. (1997).

2.2 Climate Data

We have used data from actual meteorological stations together with modeled climate records based on the work of Ojansuu and Henttonen (1983), who have presented methods to produce unbiased estimates of the local values of monthly mean temperature and total precipitation from the observations made by the Finnish Meteorological Office. These records are available for a period from 1880 to 1993.

3 Methods

3.1 Ring-Width Measurements, Cross-Dating and Criteria for Sample Rejection

Samples from living trees were extracted by an increment borer at breast height (circa 1.3 m), one or two cores per tree. When sampling dead trees (snags and construction timber) we tried to approximate the same distance from the base. Ring widths were measured to the nearest 0.01 mm. Measured series were then cross-dated by visual comparison of ring-width graphs on the light table. Visual cross-dating were checked by computing cross-correlations between individual series and master chronologies using several procedures (Holmes et al. 1986, Van Deusen and Koretz 1988, Aniol 1989). After standardization (see next chapter), the measurement series became dimensionless indices and were once again checked on the computer screen, in order to detect possible distortions at the ends or at the beginnings of the series.

In dendrochronology, every ring in each sample core must be absolutely cross-dated in order to be included in the chronology (Fritts 1976). However, even the most careful sampling may include cores that are not cross-datable due to individual and local disturbances (Cook et al. 1990). Such cores may be rejected objectively by setting a threshold value for the synchrony (correlation) which is expected for inclusion in local and regional chronologies.

3.2 Standardization

The main goal in standardization is to emphasize the desired ‘signal’ and to reduce the unwanted elements of ‘noise’ in the tree-ring time-series (Fritts 1976, Cook and Briffa 1990). Standardization is generally achieved by dividing the measurement series by expected values as expressed by a deterministic or stochastic function (Cook et al. 1990). Since local variance of a non-stationary ring-width series is roughly proportional to its local mean, the procedure of dividing each ring-width by a fitted curve value is meant to stabilize the variance simultaneously with the mean (Fritts 1976, Cook et al. 1990). Part of ‘noise’, external and internal disturbances to a forest stand, is also reduced by averaging.

We have applied a pragmatic approach in modeling the growth trend, the ‘noise’ component to be discarded. These nonclimatic sources of variation in the data were modeled collectively as splines. It was assumed that the removed low frequency variance consists mainly of noise. However, there is a potential loss of meaningful long timescale variance. The 67 % n splines applied here, pass 50 % of the variance of the series at frequencies greater than two thirds of the series length (Cook and Peters 1981). For the purpose of comparison, we applied equal splines for each of the three data sets.

3.3 Sample Replication and Averaging

Sample depth or replication is a time-series variable which indicates the number of rings (total of individual, absolutely dated indices) averaged annually to form a chronology. The actual number of cores, trees and sites to be sampled for a particular investigation depends in part on the strength of the signal in the individual core samples and the strength of the signal-to-noise ratio desired in an analysis (Wigley et al. 1984). A certain amount of replication is needed not only for enhancing the signal of the chronology but also to provide an adequate number of specimens for cross-dating.

Integration of microclimatic effects throughout a tree and the averaging effects in a tree are central ideas of dendroclimatology and a basis for building chronologies. As Fritts (1976) points out, when several trees are sampled and the mean growth is obtained for each year, the variations in the yearly averages are less than the variations of ring widths from any one individual, because some of the noise in individual tree variation is cancelled in the averaging process. However, the variance of the signal which is the same in every tree is not lost by averaging, so the potential variance attributable to the signal grows with increasing sample size while the total variance of the mean chronology is reduced. The growth-limiting climatic conditions themselves are integrations of many different microclimates throughout the tree, and additional integration occur as their effects are averaged over time (Fritts 1976).

3.4 Measuring Signal Strength and Chronology Reliability

We have applied mean inter-series correlation, $\bar{r}_{bt}$, as a measure of the strength of the common growth 'signal' (climatic forcing) within the chronology. Wigley et al. (1984) and Briffa and Jones (1990) provide means to calculate this between-tree correlation between all possible pairs of indexed series drawn from different trees. For this calculation, we produced a single mean time series for each tree (mean-tree series), omitting within-tree variability. This index was calculated over a moving 30-year window, starting from the year, when sample depth (replication) is at least 4 in each of the four regional data sets.

We quantified the degree to which a particular sample chronology portrays the hypothetically perfect chronology using Expressed Population Signal (EPS), which is a function of $\bar{r}_{bt}$ and the series replication, according to the following equation (Wigley et al. 1984, Briffa and Jones 1990):

$$EPS(t) = \frac{\bar{r}_{bt}}{\bar{r}_{bt} + (1 - \bar{r}_{bt})/t} = \frac{t\bar{r}_{bt}}{t\bar{r}_{bt} + (1 - \bar{r}_{bt})}$$

where t is the number of tree series averaged (one mean core per tree) and $\bar{r}_{bt}$ is the mean between-tree correlation. EPS is expected to measure chronology confidence and reliability.

3.5 Response Function Analysis

Response function analysis (Fritts 1976, Briffa and Cook 1990) is a form of multiple regression analysis where the predictor variables are principal components, usually of a number of monthly mean temperature and total precipitation values. These climate predictor variables are frequently supplemented with some value(s) of the tree growth in the previous year(s). Thus, both climate and prior growth variables are generally used to calculate the amount of chronology variance explained and to quantify the relative importance of the original individual climate variables.

Response functions are widely used and there exist some modifications of the technique. These relate mainly to the manners in which relatively unimportant predictor principal components are removed from the consideration during the various regression screenings. We used a popular two stage screening in limiting the number of the principal component predictors entering regression. First we applied so-called PVP method (Briffa et al. 1983, Briffa and Cook 1990, Guiot 1985, 1990), which eliminates high-order PCs by including only those for which the cumulative multiple of eigenvalues is greater than 1.0. Secondly a cut-off T-value for a second regression was set to 1.0. Only PC-regressors with T-values greater than or equal to 1.0 were selected for the response functions. We have used period 1920–1990 for calibrations.

In our response function analyses, we have included 14 precipitation and temperature variables (from the previous July to the current August). Because of strong autocorrelation, they are supplemented with three variables representing prior growth years. The three 'standard' regional chronologies were used as the predictand variables.

3.6 Spectral Analysis

Spectral density functions are commonly estimated using the fast Fourier transform, which yields a description in terms of cycles of varying length or frequencies that generate the series (Chatfield 1989, SPSS 1993, Mazepa 1990, Burroughs, 1994). In this analysis, the spectral estimates were filtered using the Tukey-Hamming window spanning 5 years. A periodogram shows an estimate of the amount of variance of the series accounted for by cycles at each frequency. We have used spectral densities in a descriptive sense and no confidence limits have been calculated.

4 Results

4.1 Acceptance Criteria for Indices

Total number of sampled trees as well as the number of samples accepted for chronology building and further analyses in each region are shown in Table 1. Threshold value is the criteria for acceptance for individual indices (mean-tree series) to be included in the absolutely dated chronology. Only few indeces were rejected. The eliminated series synchronized poorly or not at all with the rest of the data in each region. These series had more individual and local disturbances and least common variance with the rest. Each mean-tree series was either accepted or rejected based on its correlation with a master chronology built from the rest of the series in each region. Table 1 lists the threshold correlation values; 0.4 for north, 0.3 for central and east, and 0.4 for south. In the north and south the criteria for inclusion could easily have been lifted to 0.45 without too many series dropping out.

4.2 Signal Strength within the Four Chronologies

Characteristics of the four regional chronologies built for the northern, middle (eastern and central), and southern parts are described in Table 2. The first and last years of the chronologies are shown as well as their length. The year when sample depth becomes at least 4 is marked, since it is the starting year for further analyses. Series inter-correlation is the average of the correlations of individual series with a master chronology. Table 2 shows that the northern trees clearly have highest correlations with each other as a group. This indicates strongest climatic signal. The southern pines come second and pines from the two middle regions third. Fig. 2 demonstrates changes in the strength of these signals (SS) as

Table 2. Characteristics of the four regional ring-width chronologies built for the northern, middle (eastern and central), and southern parts. The first and last years of the chronologies are shown as well as their length. The year when sample depth (size) becomes at least 4 is marked, since it is the starting point for further ananlyses. Series intercorrelation is the average of the correlations of individual series with a master chronology. Mean sensitivity measures the relative difference in width from one ring to the next.

Boreal part	First year	Last year	Length	Sample depth over 4	Series intercorrelation	Average mean sensitivity
Northern	1659	1992	334	1678	0.685	0.203
Middle:						
A Eastern	1413	1991	579	1615	0.433	0.188
B Central	1454	1996	543	1588	0.382	0.252
Southern	1685	1993	309	1806	0.547	0.217

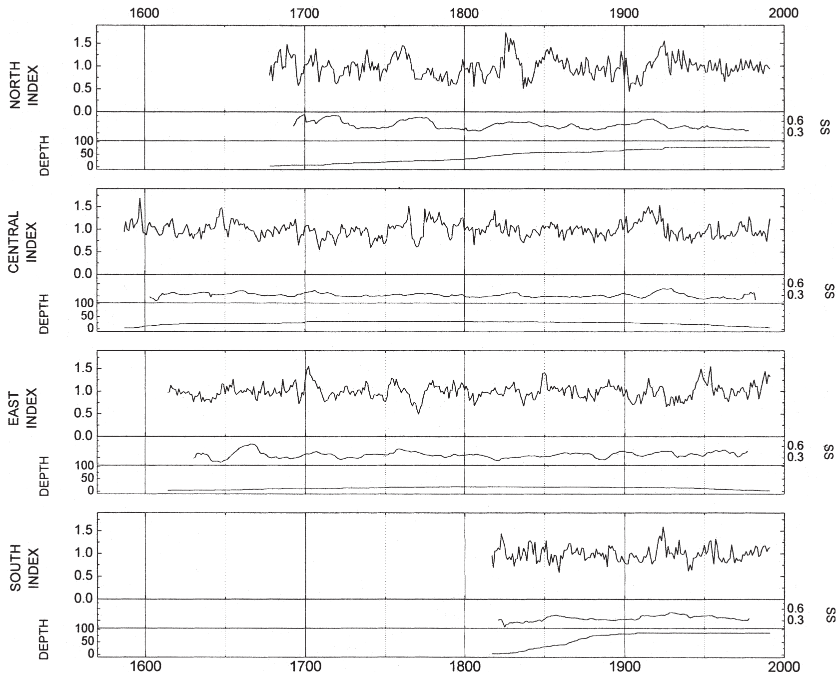

Fig. 2. Ring-width chronologies of Scots pine for the north, middle and south boreal zones. The mean inter-series correlation ($\bar{r}_{bt}$) is a measure of the strength of the common growth 'signal' (SS) in the chronologies. It is calculated over a moving 30-year window. The chronologies were built the same way, using equally stiff splines in standardization.

a function of time. Although there exists low frequency variation, no systematic trends are evident. On the other hand, mean sensitivity (Table 2) measures the relative difference in width from one ring to the next. Pines from the central region show highest sensitivity, although the signal is not clear and unambiguous.

In the four chronologies, the common 'signals', measured by $\bar{r}_{bt}$ (Fig. 2), may be considered rather strong for the whole length of the series. $\bar{r}_{bt}$ has highest values, with a mean of 0.51, in the northern data. Signal weakens towards south, $\bar{r}_{bt}$ being 0.31 in the central, 0.38 in the eastern and 0.36 in the southern data. After estimating the strength of the statistical signals, it is necessary to quantify the degree to which the chronology signal is expressed when the series are averaged.

Averaging reduces the noise while the common variance is unaffected. According to Briffa and Jones (1990) the chronology signal, expressed as a fraction of the total chronology variance, quantifies the degree to which this particular sample chronology portrays the hypothetically perfect chronology. This has been termed the EPS. Judged by high EPS values, a function of $\bar{r}_{bt}$ and series replication, the chronologies are also reliable. Wigley et al. (1984) and Briffa and Jones (1990) report values over 0.85 to be satisfactory for dendroclimatological purposes. EPS values for the north are well above 0.9 for the whole length of the chronology. The rest of the chronologies also stay mainly above 0.9, however they have occasional drops below that value for various intervals.

4.3 Comparison of Growth Responses

Response function analysis (Fritts 1976) identified the climatic origin of variability in the chronologies. In Fig. 3, growth responses of pines

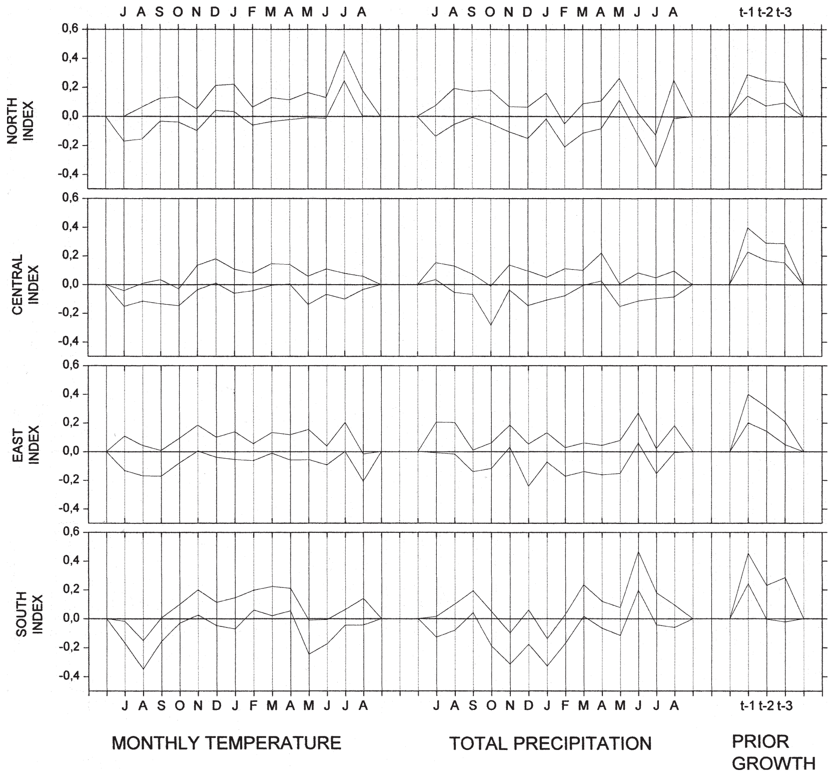

Fig. 3. A comparison of growth responses to climatic factors in pine stands from the northern, middle and southern boreal zones. The initials of each month are shown, starting from previous June. The upper and lower confidence limits, at 95 percent level, are shown.

growing in the northern, middle (central and eastern) and southern parts of the boreal forest belt are compared. The most visible feature in Fig. 3 is the shift from the determinance of growing season temperatures (July) in the north to prominence of early season precipitation (April, June) in central, eastern and southern regions. In addition to the importance of July temperatures in the north, precipitation in May seems to have a positive and significant effect on growth. In the central region, only April has a significant and positive effect. In the east, its position and influence has been replaced by June precipitation. In the south, rainfall in June is highly significant and positive.

There is no single monthly climate variable having a significant effect on tree growth in all four regions. While high-summer temperatures

Table 3. Bivariate correlations (Pearson's product moment) between the four ring-width chronologies over their 186-years common period from 1806 to 1991 (Cf. Table 2). Correlations which are significant at the 0.01 level are marked with asterisks.

	Northern	Middle Eastern	Middle Central	Southern
Northern	1			
Middle:				
A Eastern	0.305*	1		
B Central	0.207*	0.329*	1	
Southern	0.066	0.242*	0.087	1

Table 4. Total chronology variance explained (in %) by the response models in the four regions. Variance explained by climate and by prior growth are separated.

	Climate	Prior growth	Total
Northern	44.6	24.7	69.3
Middle:			
A Eastern	17.4	32.14	49.5
B Central	11.6	48.2	59.8
Southern	34.4	27.2	61.6

speed up growth in the north, early summer (May, June) temperatures seem to suppress growth in the south. A parallel phenomenon is apparent with precipitation. While growth in the south seem to favor early summer (June) rainfall, it has an opposite effect during high summer (July) in the north. These phenomena may be evidence climatic inversions. During some periods, growing conditions seem to have been favorable in the south, while they have been unfavorable in the north.

In Table 4, the total chronology variance explained by the response models in the four regions may be compared. Climate explains close to one half of the variance in the north and about one third in the south. The percentages for central and eastern chronologies are considerably less, about 12 and 17 percents respectively. The importance of prior growth variables in the models for middle regions is seen in Table 4 and Fig. 3. All three (prior growth variables) are significant except in the south. Autocorrelation and cyclic variation are often considered as characteristics of the growth of Scots pine (Henttonen 1984). Their importance increases at high latitudes and high altitudes (LaMarche 1974).

4.4 Signal Strength between the Four Chronologies

Correlation between the northern, middle (central and eastern) and southern chronologies for their common interval from 1806 to 1991, over the last 186 years, is shown in Table 3. The highest correlation is found in the middle region, between central and eastern chronologies, r = 0.329. Correlation between northern and eastern chronologies comes second with r = 0.305. The southern and middle chronologies correlate with r = 0.242. The northern chronology correlates with central chronology with r = 0.207. All the above values are significant at 0.01 level.

Fig. 4 demonstrates changes in signal strength (SS) as a function of time between north and central, central and east, as well as between east and south. Signals seem to drop drastically towards the end of last century between north and central, central and east. These two pairs of chronologies also seem to have other features in common, like the rise in mid 20th century. The east–south relationship clearly has developed differently. The origin of the trend-line requires further research.

4.5 Comparison of Growth Variability since 1806 in the Four Regions

We have compared growth variability, since 1806, between the northern, middle, and southern parts of the boreal forest belt in Finland (Fig. 2). The northern and southern regions represent the opposite ends of the boreal zone, the distance between them being over 800 km. It is seen in Fig. 2 and Table 2, that the variability of radial growth clearly decreases, the variance of ring-width series becomes smaller, going from the north to the south.

Growth variability in the four regions was compared during the common interval of the chronologies, from 1806 to 1991. The central and eastern chronologies have more pointer years in common than the rest (Table 5). Also the northern and middle chronologies have more in common than the southern chronology with either of them. Year 1806 among others is a pointer year in all three regions. Three of the chronologies extend back to the Mounder minimum and they all show marked growth suppressions especially during 1696, which is clearly evident in Fig. 2 as a peak of a depression lasting several years. Once again the southern chronology is most different from the rest.

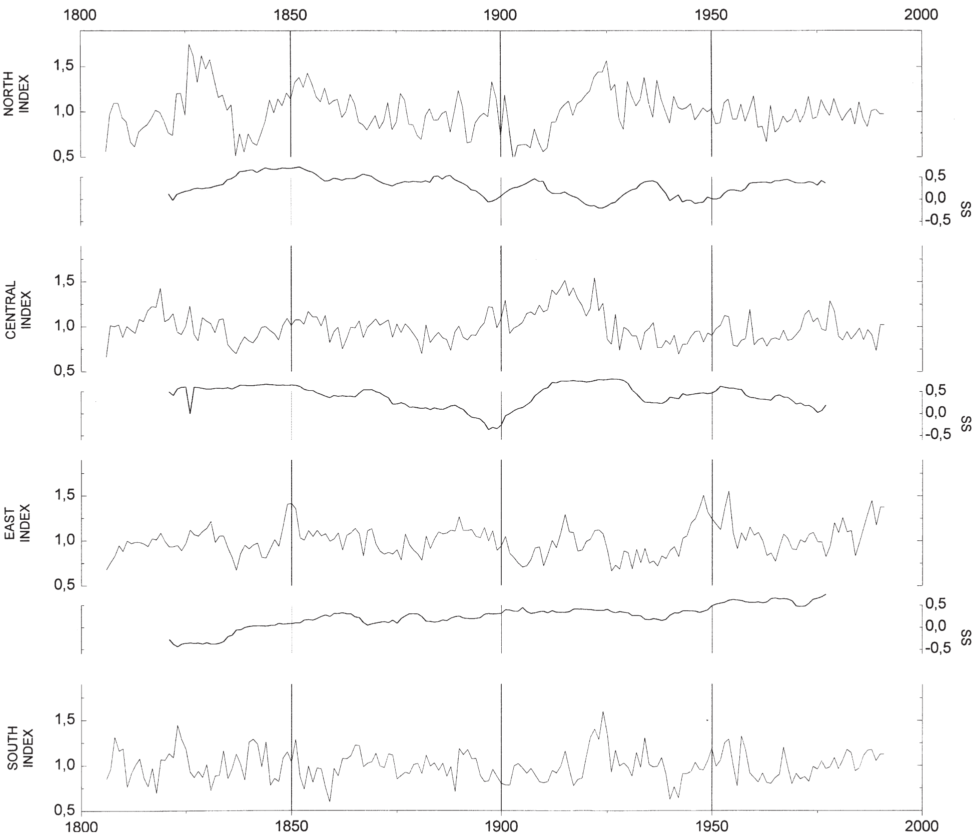

Fig. 4. Common growth variability between the four chronologies. Mean inter-series correlation ($\bar{r}_{bt}$) is a measure of signal strength (SS) between the regional chronologies. It is calculated over a moving 30-year window.

Table 5. 10 individual years when growth was most suppressed (during 1806–1991) in the four research regions sorted by ascending order. Values are expressed as deviations (s.d. units) from the comparison period mean, which is set at zero. Pointer years shared with neighbouring regions are in bold.

Year	North	Year	Middle Eastern	Year	Middle Central	Year	South
1903	–2.42	1926	–2.01	**1806**	–2.02	1859	–2.45
1837	–2.15	**1837**	–1.95	**1942**	–1.81	1940	–2.27
1839	–1.96	**1806**	–1.92	1881	–1.79	**1942**	–2.15
1806	–1.95	**1928**	–1.90	**1937**	–1.77	1818	–1.83
1910	–1.94	1931	–1.88	1989	–1.58	1889	–1.73
1911	–1.76	1905	–1.76	**1928**	–1.56	1831	–1.64
1907	–1.75	**1910**	–1.69	1888	–1.56	1853	–1.58
1813	–1.70	1906	–1.68	1933	–1.53	1858	–1.47
1904	–1.64	**1937**	–1.68	1836	–1.50	1811	–1.42
1842	–1.62	1927	–1.63	1862	–1.46	1841	–1.41

4.6 High- and Low-Frequency Signals; Comparison in the Frequency Domain

The longevity or duration of life of the individual trees, included in the chronology, will set an upper limit to the lowest frequencies that we can expect to extract from the resulting chronologies. Another limiting factor is standardization like the 67 % n splines used here. This procedure preserves the bulk of the variance, which is less than two thirds of the series length. In Fig. 5, the spectral densities of the northern, middle and southern chronologies are plotted as functions of frequency, viz. cycles per year. The variance in all four regional chronologies is concentrated in the lowest frequencies. Very generally, there are more periodic behavior in the northern chronology than in the middle and southern chronologies in high middle as well as low frequencies. The highest peak in concentrations of variance correspond roughly to periods of 54 years in the north, 161 years in the center, 54 years in the east, and 32 years in the south.

In their reconstruction for northern Europe from AD 1580 to 1978, Briffa and Scweingruber (1992) found significant 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 and Schweingruber (1992) also compared their results with those of Sirén and 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. By far the most significant concentration of variance in the temperature reconstructions of Briffa and Schweingruber (1992), however, corresponds to a period band between 33 to 38 years.

Burroughs (1994) has reviewed dendroclimatological literature in a search for evidence of cycles. He concludes that the most frequently emerging observations include the so-called quasi-biennal-oscillation (QBO) of 2.1–2.8 years, cycles around 3 or 4 years, and 5 to 7 years. In addition, there is generally some support for the 11-year (sunspot) cycle, and more importantly substantial evidence for the 20-year cycle. According to the above author, the evidence does not distinguish between this being the 18.6-year lunar cycle or the 22-year double sunspot cycle.

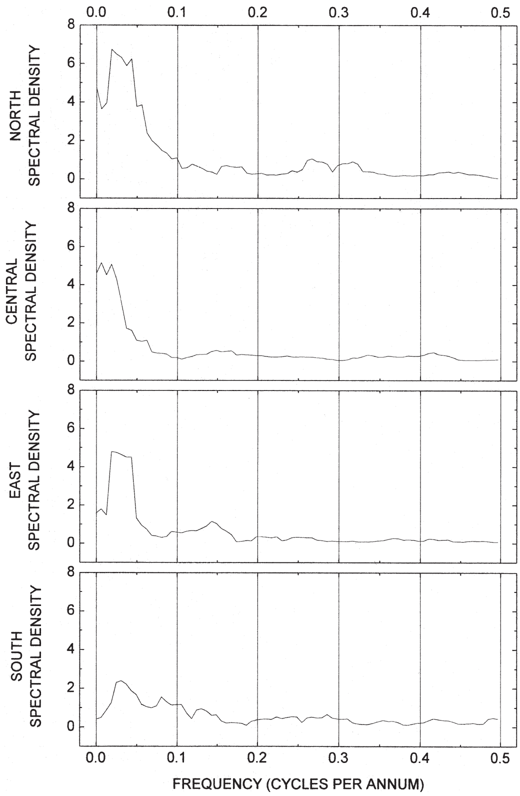

Fig. 5. A comparison of periodic behaviour of the northern (upper curve), middle and southern (lower curve) chronologies. The chronologies were smoothed using a 5-year Tukey-Hamming window.

Moreover, there exists also strong general support for 80- to 90-year and 180- to 200-year cycles (Burroughs 1994).

5 Discussion

5.1 Climatic Signals from the North, Middle and South Boreal Zones

We have extracted common growth signals (forcing factors) from the natural stands of the northern, middle, and southern parts of the boreal forest belt in Finland. We found strong regional signals and also evidence for common forcings, especially between northern and central, central and eastern, as well as central/eastern and southern chronologies. Response function analyses confirmed that growing season temperatures govern the growth rates of northern pines. We have also demonstrated that towards south, pine growth becomes less effected by temperatures, and more effected by e.g. precipitation. Problems with various response function approaches have been discussed by e.g. Henttonen (1984), Briffa and Cook (1990), Lindholm (1996).

Unlike the north and south, the middle zone did not yield any clear and unambiguous signals. It is possible that our samples from the middle zone contain a mixture of several signals, none of which dominates. Some of the signals may have their origin in other, nonclimatic, standwise sources. These other environmental signals may suppress climatic effects, since environmental variables often have serious multicollinearity problems.

5.2 Representativeness of Our Chronologies

In the north we have used a subset of a very large database in the region (Lindholm 1996, Eronen et al. 1996). The northern data set is considered very representative of the natural stands of the whole forest-limit region and northern part of the boreal belt in Fennoscandia (Lindholm 1996, Lindholm et al. 1996). Pine growth has very uniform patterns in the region (Lindholm 1996). We have used here a collection which comes from four subareas and includes samples from 85 living trees.

Our two data sets from the middle boreal zone are much more limited in their representativenes. The largest collection of the three subsets of data, samples from 31 (out of 54) living trees (one core per tree), comes from the westernmost area, the Pyhä Häkki national park. In the eastern part, we have now used 10 out of 11 pines from one area and 9 out of 11 dead standing trees (snags) from another. In addition to the limited sample size, these data come from borderline regions between middle and south zones (Fig.1, Table 1). Thus they are not expected to fully represent climatic signals from central and eastern parts of the middle zone.

The southern data set, samples from 92 pines (two cores per tree) is also part of a larger collection. It is definitely not representative of the whole southern boreal zone, but at best the natural stands in south-eastern Finland. Especially this body of data may be considered representative of shore forest stands of the central parts of the Lake Saimaa basin, south-eastern Finland (Lindholm et al. 1997).

In the future, we will be able to fill the gaps in our understanding of interregional differences in long-term pine growth and growth responses around the Baltic and in northern Europe. This is possible since more and more high-quality, millennial pine chronologies are being completed in Finland, Sweden, Norway and north-western Russia. Attempts will be made to detect abrupt as well as long-term changes in growth variability and growth forcing factors in international collaboration, using networks of chronologies.

5.3 Change from the North to the South

Pines, growing under extreme conditions, in the northern forest-limit regions, are known to have a strong common ‘signal’, which is empirically linked to temperature forcings (e.g., Briffa et al. 1990, 1995, Lindholm et al., 1996). Going from the north to the south, tree-growth becomes less effected by growing season temperatures, and more effected by e.g. precipitation (Lindholm 1997). Compared to the northern timberline, a multitude of factors related to stand dynamics, come to play an increasingly important role in controlling annual growth variability of southern pines. It is evident from Fig. 3 that towards the south, the correlations between the diameter growth of Scots pine and climate variables weaken. As demonstrated in Fig. 2, the variation in the width of the annual rings do become smaller. Interestingly, the comparison of the three chronologies shows similar as well as opposing features. During some periods, growth conditions seem to have been favorable in the south, while they have been unfavorable in the north. Growth responses to climatic factors seem to support this explanation, viz. climatic inversions. This means that climate has favored growth in one region while suppressing growth in the other.

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