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Growth Variability of Scots Pine (Pinus sylvestris) along a West-East Gradient across Northern Fennoscandia: A Dendroclimatic Approach

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Abstract

We performed a spatiotemporal analysis of a network of 21 Scots pine (Pinus sylvestris) ring-width chronologies in northern Fennoscandia by means of chronology statistics and multivariate analyses. Chronologies are located on both sides (western and eastern) of the Scandes Mountains (67°N–70°N, 15°E–29°E). Growth relationships with temperature, precipitation, and North Atlantic Oscillation (NAO) indices were calculated for the period 1880–1991. We also assessed their temporal stability. Current July temperature and, to a lesser degree, May precipitation are the main growth limiting factors in the whole area of study. However, Principal Component Analysis (PCA) and mean interseries correlation revealed differences in radial growth between both sides of the Scandes Mountains, attributed to the Oceanic-Continental climatic gradient in the area. The gradient signal is temporally variable and has strengthened during the second half of the 20th century. Northern Fennoscandia Scots pine growth is positively related to early winter NAO indices previous to the growth season and to late spring NAO. NAO/growth relationships are unstable and have dropped in the second half of the 20th century. Moreover, they are noncontinuous through the range of NAO values: for early winter, only positive NAO indices enhance tree growth in the next growing season, while negative NAO does not. For spring, only negative NAO is correlated with radial growth.

Introduction

The north of Fennoscandia (Fig. 1) constitutes an excellent source of information for dendroclimatologists due to the clear response of tree growth to climate in the region. Control of annual growth by environmental factors, particularly climate, is strong and clearly discernible in areas where trees grow in marginal environments (Fritts, 1976). Scots pines (Pinus sylvestris L.) growing under extreme conditions in the northern timberline region are known to have a strong “common” signal, which is empirically linked to summer temperature forcing (mainly July) (Briffa et al., 1990; Lindholm, 1996).

Northern Fennoscandia extends from the shores of the north Atlantic Ocean in Norway in the west to the White Sea and Kola Peninsula in Russia in the east, and from the Arctic Circle in the south to the Barents Sea in the north. The Gulf Stream influences climate in the area, making it milder than in other regions at the same latitude. Climate in the area is greatly influenced by the presence of the northeast Atlantic Ocean and the Scandes Mountains. Cool, moist Atlantic air masses are trapped along northern Norway by the high mountains very close to the coast. As a result, the climate is extraordinarily wet in that area, with precipitation up to 2500 mm yr⁻¹.

There is a gradient of continentality towards the east, enhanced by the presence of the mountains, which also create local montane climates in the Scandes (Barry, 1992). The climate east of the Scandes is rather continental. In the far north, continentality declines under the influence of the Arctic Ocean (Tuukanen, 1980).

Few studies have been carried out using chronologies from both sides of the Scandes (Kirchhefer, 1999; Linderholm et al., 2003). Although tree-growth limiting factors are mainly related to summer temperature in the entire range, the growing season differs slightly from the east and continental side of the mountain range, where it is earlier and shorter (July, sometimes June) (Lindholm, 1996), to the Scandes and Atlantic coast, where the season is later and longer (July, August) and is influenced by more climatic parameters (Kirchhefer, 2001).

The North Atlantic Oscillation (NAO) is a large-scale seesaw between the Icelandic Low and the Azores High (Van Loon and Rogers, 1978). It is one of the Northern Hemisphere’s major multimodal climate fluctuations (Appenzeller, 1999). NAO indices are calculated by computing the difference between the SLP (sea level pressure) in these two areas (SLP Azores–SLP Iceland). NAO is most clearly expressed during the winter (Van Loon and Rogers, 1978).

High positive NAO situations imply a large SLP difference between the two air masses. When the gradient of pressure is large, there is an increase in the western (maritime) winds in northern Europe, where winters are wetter and milder. The stronger the wind, the more of the Gulf Stream’s heat is delivered to Eurasia. A negative NAO situation brings a relaxation of the western winds over northern Europe (less Gulf Stream influence), with a consequently drier and colder winter in the area (Hurrell, 1995).

NAO indices have been calculated from as far back as 1860 up to the present using SLP data from Azores and Iceland. Despite a high annual variability, the indices tend to show periods when they are mostly positive and periods when they are mostly negative. The last 25 yr of the 20th century were characterized by an unrecorded series of high positive values (Hurrell, 1995).

Diverse proxy data have been used in order to reconstruct NAO indices back in time, up to 350 yr long for a proxy NAO index from ice accumulation records in Greenland (Appenzeller, 1999). Tree-ring data have also been used in reconstructing NAO indices back to the year A.D.
1700 (Cook et al., 1998). Northern Fennoscandian chronologies have been used in these reconstructions. Some studies have focused on the study of the correlation among NAO indices and Fennoscandia tree rings, finding significant correlations between tree-ring indices and winter and summer NAO indices (D’Arrigo et al., 1993; Lindholm et al., 2001).

AIMS OF THE STUDY

The primary objectives of this research are to:

1. conduct spatial-temporal comparison of the variability of several chronologies from northern Fennoscandia, on both sides of the Scandes Mountains (67°N–70°N, 15°E–29°E), in order to detect differences in tree growth due to different climatic conditions in the studied area and during the studied period.

2. analyze the relationships of ring-width chronologies with temperature, precipitation, and NAO indices, and of the evolution of these relationships during the time.

Data

TREE-RING DATA

A network of 21 ring-width chronologies of Pinus sylvestris from the north of Fennoscandia on both sides of the Scandes, with latitudes ranging from 67N to 70N and longitudes ranging from 15°E to 29°E, was used. Fourteen of these chronologies have been previously published (Lindholm, 1995, 1996; Kirchhefer, 2000, 2001). Seven chronologies, corresponding to the Finnish Lapland, were built by Mauri Timonen in 2001, and have not yet been published (Table 1, Fig. 1). Tauskjerring/Rønninglia and Devdiselva/Høgskardet are “pairs of chronologies” (site chronologies representing slope aspect).

CLIMATIC DATA

For the studies with mean monthly temperature and monthly precipitation we have selected six meteorological stations distributed evenly in the study area. These stations are Sodankylä, Finland; Karesuando, Sweden; Karasjok, Norway; Andenes, Norway; Frihetsli (Dividalen), Norway; and Tromsø, Norway. Station names, locations, and lengths of the data records are shown in Table 2 and displayed in Figure 1.

Andenes records are not homogeneous in 1963 due to a relocation of the station. No corrections were made in this case, because this relocation implied a temperature change far smaller than the year-to-year variability (Kirchhefer, 2001). Frihetsli (Dividalen) records have some gaps. Kirchhefer (2000) estimated missing data by taking the precipitation data from the nearby Oeverbygd station. Temperature and precipitation data for Tromsø, Karasjok, Sodankylä, and Karesuando were taken from the NordKlim data set (Tuomenvirta et al., 2001).

There are several NAO indices available, obtained by slightly different calculation methods and from different climate stations (Rogers, 1984; Hurrell, 1995; Jones et al., 1997). In this study we have used the NAO indices obtained by Hurrell (1995). Monthly, seasonal, and annual NAO indices are based on the difference of normalized SLP between Ponta Delgada, Azores, and Stykkisholmur/Reykjavik, Iceland, since 1865 (Hurrell, 1995).

Methods

CHRONOLOGY DEVELOPMENT

Individual measurement series were divided by the values of negative exponential functions or nonascending straight lines to remove the age-related growth trend. The resulting dimensionless indices were averaged to form master chronologies for each of the locations. Negative exponential functions maximize low-frequency variability, and are thus well suited for climatic reconstruction (Cook.
Residual chronologies, computed after removing autocorrelation from the individual series, were used in all response analysis.

### DESCRIPTIVE STATISTICS AND GROWTH VARIATIONS

Expressed Population Signal (EPS), which is a function of the series replication and the mean interseries correlation, was used as a measure of the strength of the common signal within the chronology (Wigley et al., 1984). In order to have EPS values >85% in the entire study period for all chronologies, the period analyzed was set to 1880–1991. Interseries Pearson correlations and evolution of these correlations along a 30-yr overlapping period were also calculated.

Some other descriptive statistics were calculated for each chronology to allow comparisons among the chronologies analyzed in this study as well as to permit comparisons with other dendroclimatic data sets (Fritts, 1976; Briffa and Jones, 1990). These statistics are standard deviation (SD), mean sensitivity (MS), first order autocorrelation (r1), the percentage of variation explained by the first principal component (VARpc1), as well as signal-to-noise ratio (SNR) as a measure of the common variance in a chronology scaled by a measure of the total variance of the chronology (Wigley et al., 1984).

### METEOROLOGICAL STATIONS USED IN THE STUDY OF TEMPERATURE AND PRECIPITATION RELATIONSHIPS WITH TREE GROWTH

| Site            | Country | Start | End   | Span   | Latitude  | Longitude | No. of cores | Author            |
|-----------------|---------|-------|-------|--------|-----------|-----------|--------------|-------------------|
| ATLANTIC COAST AND SCANDES |         |       |       |        |           |           |              |                   |
| 1 Forfjordalen  | Norway  | 1877  | 1994  | 1118   | 68°48'N   | 15°44'E  | 71           | A. J. Kirchhefer   |
| 2 Stonglandseidet | Norway  | 1403  | 1997  | 595    | 69°05'N   | 17°13'E  | 66           | A. J. Kirchhefer   |
| 3 Vikran        | Norway  | 1599  | 1992  | 394    | 69°32'N   | 18°44'E  | 44           | A. J. Kirchhefer   |
| 4 Tauskjerring  | Norway  | 1545  | 1994  | 450    | 69°02'N   | 18°35'E  | 37           | A. J. Kirchhefer   |
| 5 Ronningshag  | Norway  | 1620  | 1994  | 375    | 68°58'N   | 18°35'E  | 36           | A. J. Kirchhefer   |
| 6 Høgskardet    | Norway  | 1498  | 1995  | 498    | 68°50'N   | 19°33'E  | 36           | A. J. Kirchhefer   |
| 7 Devadsevla    | Norway  | 966   | 1992  | 1027   | 68°51'N   | 19°37'E  | 38           | A. J. Kirchhefer   |
| EAST OF THE SCANDES |        |       |       |        |           |           |              |                   |
| 8 Karesuvanto   | Finland | 1698  | 1992  | 295    | 68°29'N   | 22°09'E  | 26           | M. Lindholm       |
| 9 Leppajärvi    | Finland | 1789  | 1991  | 203    | 68°31'N   | 23°17'E  | 35           | M. Lindholm       |
| 10 Kolari       | Finland | 1861  | 2000  | 140    | 67°21'N   | 23°50'E  | 19           | M. Timonen        |
| 11 Pakasaivo    | Finland | 1761  | 2000  | 240    | 67°35'N   | 24°E     | 29           | M. Timonen        |
| 12 Pitkajärvi   | Finland | 1780  | 2000  | 221    | 68°18'N   | 24°E     | 28           | M. Timonen        |
| 13 Nunnanen     | Finland | 1786  | 1991  | 206    | 68°24'N   | 24°31'E  | 56           | M. Lindholm       |
| 14 Karasjok     | Norway  | 1803  | 1992  | 190    | 69°35'N   | 25°38'E  | 29           | M. Lindholm       |
| 15 Taastti      | Finland | 1682  | 2000  | 319    | 68°09'N   | 25°46'E  | 21           | M. Timonen        |
| 16 Skallovära  | Finland | 1711  | 1991  | 281    | 69°48'N   | 27°10'E  | 20           | M. Lindholm       |
| 17 Klevelande   | Finland | 1755  | 2000  | 246    | 68°25'N   | 27°16'E  | 29           | M. Timonen        |
| 18 Karhunpesäkivi | Finland | 1397  | 1993  | 597    | 68°59'N   | 27°18'E  | 23           | M. Lindholm       |
| 19 Lokka        | Finland | 1773  | 2000  | 228    | 67°47'N   | 27°42'E  | 29           | M. Timonen        |
| 20 Peuravuonon  | Finland | 1659  | 1992  | 334    | 68°32'N   | 28°00'E  | 26           | M. Lindholm       |
| 21 Kessi        | Finland | 1789  | 2000  | 212    | 69°05'N   | 28°50'E  | 28           | M. Timonen        |

### TABLE 2

Meteorological stations used in the study of temperature and precipitation relationships with tree growth.

| Meteorological station | Latitude | Longitude | Altitude (m a.s.l.) | P (mm) | T (°C) |
|------------------------|----------|-----------|---------------------|--------|--------|
| Andenes (N)            | 69°19'N  | 16°06'E   | —                   | 1910–1992 | 1868–1992 |
| Tromsø (N)             | 69°39'N  | 18°56'E   | 100                 | 1880–1999 | 1880–1999 |
| Divaldalen (N)         | 68°43'N  | 19°33'E   | 228                 | 1912–1993 | 1922–1992 |
| Karesuando (S)         | 68°26'N  | 22°31'E   | 327                 | 1890–1999 | 1890–1999 |
| Karasjok (N)           | 69°28'N  | 25°31'E   | 129                 | 1895–1999 | 1890–1999 |
| Sodankylä (FIN)        | 67°22'N  | 26°39'E   | 179                 | 1908–1999 | 1908–1999 |

### MULTIVARIATE TECHNIQUES

Cluster (UPGMA, an Agglomerative Hierarchical clustering method that uses Euclidean distances as a measure of dissimilarity) analysis was used as a first multivariate approach to examine the structure of the relationships between the residual tree-ring series.

PCA was performed in order to evaluate the shared variance among residual chronologies. PCAs for successive overlapping periods (1880–1910, 1890–1920, 1900–1930, 1910–1940, 1920–1950, 1930–1960, 1940–1970, 1950–1980, and 1960–1991) and for the whole period (1880–1991) were calculated in order to evaluate the temporal stability of this shared variance (Tardif et al., 2002).

### TREE-GROWTH RESPONSES TO CLIMATIC FACTORS

Growth responses to temperature and precipitation were assessed using the data of the six meteorological stations mentioned above together with the indices of six chronologies closest to the meteorological stations: Forfjordalen (coastal northern Norway) for the meteorological data of Andenes, Divaldalen (Inner Troms valleys, Norway) for Frihetsli, and Tromsø (coastal northern Norway) for Vikran (Kirchhefer, 2001); Karesuvanto (east of the Scandes, Sweden) for Karesuando, Karasjok (east of the Scandes, Finnmarksvidda, northern Norway) for Karasjok (Lindholm, 1996), and finally Lokka (Finnish Lapland) for the Sodankylä meteorological data (Table 2).

The climate-growth relationship was assessed by a bootstrap orthogonal regression (Till and Guiot, 1990) on the chronologies and mean monthly temperature, total monthly precipitation, and monthly and seasonal (3 mo) NAO indices from the previous September through the current August (PPP-base; Till and Guiot, 1990). As a simpler alternative to assess these relationships, Pearson correlations were also computed between the ring-width series and the climatic data.

Pearson Correlation coefficients were used in analyzing the relationship between only negative (<zero) NAO index series and the corresponding tree-ring indices. The same was done for only positive

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TABLE 3
Chronology characteristics: expressed population (Eps), mean sensitivity (MS), standard deviation (SD), first order autocorrelation (r1), signal-to-noise ratio (SNR), and variance explained by the first principal component (VARpc1). The common period was set as 1880–1991

| Study site | Eps >85% since | Standard chronology | Residual chronology | Common interval: 1880–1991 | Detrended series |
|------------|----------------|---------------------|---------------------|-----------------------------|-----------------|
| ATLANTIC COAST AND SCANCES | | | | | |
| 1 Forfjordalen | 1242 | 0.19 0.26 0.70 | 0.20 0.18 | 28.84 58.40% | |
| 2 Stonglandseidet | 1538 | 0.17 0.23 0.58 | 0.19 0.16 | 15.39 50.15% | |
| 3 Vikran | 1671 | 0.17 0.25 0.68 | 0.19 0.17 | 15.46 48.14% | |
| 4 Tauskjerring | 1766 | 0.19 0.26 0.62 | 0.21 0.19 | 10.14 43.43% | |
| 5 Rønningla | 1705 | 0.19 0.27 0.63 | 0.22 0.19 | 9.47 44.43% | |
| 6 Høgskardet | 1666 | 0.16 0.24 0.67 | 0.19 0.17 | 6.46 42.36% | |
| 7 Devdselva | 1611 | 0.17 0.23 0.62 | 0.20 0.17 | 12.84 52.33% | |
| EAST OF THE SCANCES | | | | | |
| 8 Karesuvanto | 1740 | 0.17 0.26 0.70 | 0.20 0.18 | 31.47 54.80% | |
| 9 Leppajõri | 1835 | 0.20 0.35 0.76 | 0.20 0.19 | 33.30 77.62% | |
| 10 Kolari | 1871 | 0.15 0.23 0.67 | 0.19 0.16 | 5.01 45.66% | |
| 11 Packaisvo | 1865 | 0.15 0.37 0.83 | 0.19 0.20 | 4.97 39.57% | |
| 12 Pitkajõri | 1796 | 0.16 0.26 0.73 | 0.19 0.17 | 4.75 48.30% | |
| 13 Nunnanen | 1796 | 0.17 0.25 0.69 | 0.20 0.17 | 50.00 74.80% | |
| 14 Karasjok | 1870 | 0.19 0.33 0.85 | 0.15 0.15 | 7.91 42.58% | |
| 15 Taatsi | 1815 | 0.16 0.31 0.79 | 0.19 0.19 | 8.90 54.00% | |
| 16 Skalvoaara | 1760 | 0.19 0.31 0.71 | 0.25 0.21 | 19.86 55.89% | |
| 17 Riekkoera | 1804 | 0.14 0.25 0.71 | 0.17 0.16 | 24.97 53.61% | |
| 18 Karhupeoksivi | 1727 | 0.15 0.26 0.73 | 0.19 0.17 | 16.74 51.04% | |
| 19 Lokka | 1784 | 0.13 0.29 0.84 | 0.16 0.15 | 14.51 49.34% | |
| 20 Peuravuonon | 1690 | 0.15 0.26 0.71 | 0.19 0.17 | 23.96 52.81% | |
| 21 Kessi | 1865 | 0.16 0.24 0.62 | 0.16 0.15 | 16.44 46.62% | |

(>zero) NAO index series. This analysis was conducted with monthly and seasonal NAO index series that showed significant correlation (>99%) with the chronologies.

The purpose of the later analysis was to determine if the correlation with NAO shown by tree growth in Fennoscandia is reflecting both phases of NAO (positive and negative) or, on the contrary, if only specific NAO situations are forcing tree growth.

Results and Discussion

CHRONOLOGY CHARACTERISTICS AND GROWTH VARIATIONS

Chronology statistics are shown in Table 3. No clear spatial trends in chronology statistics were observed across the study area at large.

Most of the correlations among standard chronologies taken in pairs are significant, with the mean correlation coefficient for all sites being 0.58. Highest similarity occurred among the standard series from the northeastern area, with 10 pairs having correlation values over 0.8 and 2 over 0.9 (Peuravuonon-Pitkajõri, r = 0.902; Peuravuonon-Karhupeoksivi, r = 0.922). Chronologies located in the Scandes and Atlantic coast are also highly correlated, with several pairs showing r > 0.8 (Tauskjerring-Rønningla, r = 0.867; Stonglandseidet-Vikran, r = 0.819; Høgskardet-Devdselva, r = 0.843; Tauskjerring-Devdselva, r = 0.813; Tauskjerring-Høgskardet, r = 0.825). Lowest correlations appear among pairs from the two different sides of the Scandes (Rønningla-Karhupeoksivi, r = 0.072; Kolari-Stonglandseidet, r = 0.051; Riekkoeraara-Rønningla, r = 0.066). Kolari chronology (east of the Scandes) shows the lowest correlation with the rest of the studied series, with values never reaching 0.4 with any series. This could be due to the fact that it is the youngest and the least replicated chronology (Time span: 1861–2000; 19 series [Table 1]).

The study of the evolution of correlations between chronologies among the overlapping successive 30-yr periods shows a drop in the mean interseries correlation during the second half of the 20th century (from r values around 0.65 in the first half of the century to values of 0.5 in the last 30 yr of the period analyzed).

Cluster analysis (Fig. 2) shows two well-defined groups, corresponding to Scandes-and-Atlantic-coast (Western Subregion) and East-of-the-Scandes (Eastern Subregion) sets of chronologies. However, inside the eastern group, two chronologies, Pakaisvo and Kolari, are separated from the rest, probably because of their anomalous growth pattern in the 1970s. As recommended in multivariate studies, we did not include these two chronologies in the PCA in order to avoid axis deformations due to the presence of outliers (Gauch, 1995).

Principal Component Analysis was computed from the variance-covariance matrix of the 19 chronologies (all except Pakaisvo and Kolari) and for the common time period 1880–1991. The explained cumulative variance by the first two principal components is 78.70%. Figure 3 shows a two-dimensional plot for the loadings of the first two PC for each chronology. The first component, explaining 66.33% of variance, is interpreted as an indicator of the similarity among the series, and is positively correlated with all the chronologies. The second component (VARpc2 = 12.36%) is interpreted as a West-East gradient and segregates the chronologies according to their location west or east of the Scandes Mountains, and is positively correlated with the chronologies on the Western Subregion and negatively correlated with the eastern sites.
The study of the eigenvalues associated to each year of the two PCs for the 19 chronologies yields the following result: years with low eigenvalues for the first PC correspond to years of low radial growth for all the chronologies and years with high eigenvalues correspond to years with large generalized radial growth in the whole area. Years with high and positive eigenvalues for the second PC correspond to wide rings in the Western Subregion chronologies and narrow rings in the Eastern Subregion chronologies, and vice versa (see Table 4 for some specific examples). This confirms the interpretation of the first PC as an indicator of the common signal among all series and of the second PC as an indicator of a west-east gradient that separates chronologies from the two sides of the Scandes.

Results from the PCAs calculated for successive overlapping 30-yr periods indicate that the percentage of variance extracted by the first and second principal components is not constant through time (Fig. 4). The variance held in common (first component) was at its peak at the beginning of the century and has dropped to a minimum in the last period analyzed (1961–1991). This result indicates less common variation in tree-ring indices for the entire study area. Accordingly, the variance explained by the second component, which represents a west-east gradient, has increased during all the period, with a maximum in the last subperiod computed (1961–1991, VARpc2 = 23.34%). This means an intensification of the differences in tree growth between the two sides of the Scandes, and can be interpreted as a strengthening of the west-east (oceanic-continental) climatic gradient in northern Fennoscandia during the last half of the period analyzed. This supports the above-mentioned results of the evolution of correlations among the series.

CLIMATE GROWTH RESPONSE OF SCOTS PINE

Temperature and Precipitation

Bootstrap orthogonal regression coefficients for the period 1923–1991 are shown in Table 5. Only the common general features will be commented.

As expected, the most significant growth-limiting factor is July mean temperature, with positive and significant relationships at all sites. The same result has been found in many studies in the area (Briffa et al., 1988; Lindholm, 1996; Kirchhefer, 2001). August temperature is also significant in Forfjordalen (northern coastal Norway).

May precipitation has a positive and significant effect on growth at all sites except at Devdiselva (Inner Troms valleys, northern Norway). Precipitation in spring thus seems to be a general limiting factor. The positive response to May precipitation is probably caused by rain induced early snowmelt and soil warming, enabling an early start of the vegetation period (Kirchhefer, 2001).

No clear spatial trends arise from the study of the relationships of chronologies with temperature and precipitation data for the six meteorological stations.

Pearson correlations were also performed (not shown) on temperature and precipitation/series. These results agree with the ones

TABLE 4

|               | High eigenvalues 1st PC | Low eigenvalues 1st PC | High eigenvalues 2nd PC | Low eigenvalues 2nd PC |
|---------------|-------------------------|------------------------|-------------------------|------------------------|
|               | 1930 1934 1937 1941     | 1892 1900 1903 1928    | 1969 1980 1985          | 1920 1923 1975         |
| Eastern Subregion | Mean index            | 1.45 1.37 1.37 1.28   | 0.71 0.73 0.67 0.72    | 0.96 0.91 1.13 1.18    |
|                | Std. Dev.              | 0.12 0.11 0.10 0.05    | 0.08 0.11 0.07 0.11    | 0.13 0.06 0.06 0.07    |
| Western Subregion | Mean index            | 1.43 1.26 1.37 1.38   | 0.67 0.71 0.72 0.80    | 1.17 1.22 1.48 0.95    |
|                | Std. Dev.              | 0.06 0.08 0.10 0.11    | 0.04 0.07 0.07 0.10    | 0.10 0.07 0.21 0.09    |

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yielded by bootstrap regression. The bootstrap does not yield significant correlations due to randomness by artificially increasing the number of observations, and as a result there are less significant multiple regression coefficients than correlation coefficients for the same set of data analyzed.

NAO Indices

As seen before, it is possible to separate the chronologies east of the Scandes (Eastern Subregion) from the chronologies on the Scandes and Atlantic coast (Western Subregion), according to different radial growth patterns.

A Principal Component Analysis was performed taking only the seven residual chronologies located on the Western Subregion (Forfjorddalen, Stonglandeiset, Vikran, Tauskjerring, Rønninglia, Devdiselva, and Høgskardet). The first component of this PCA explains the variance held in common among the seven combined chronologies (78.42% of the common variability) and can be interpreted as a regional chronology for the Western Subregion. Another PCA was performed then for the 12 chronologies of the Eastern Subregion. The first PC explains 73.24% of the variance and is also interpreted as a regional chronology for the Eastern Subregion.

Bootstrap regression analyses were conducted separately based on both subregional chronologies and monthly NAO data from the previous September to the current August (Table 6a). The same was done with seasonal (3-mo mean) data from the previous September-October-November (SON) to the current August-September-October (ASO) NAO indices (Table 6b).

Subregional chronologies using PCA were also computed for the two sets of chronologies and the subperiods 1880–1930 and 1931–1991. The variance held in common in these new PCs ranges between 72.48% and 79.79%, so they can also be considered as regional chronologies.

As a control, Pearson correlations (not shown) were computed between NAO series and tree-ring chronologies.

 Period 1880–1991: Tree-growth is mostly related (positively) with NAO indices corresponding to the previous early winter (November, December) and to the end of the spring/beginning of the summer (May, June, July) in all the study area (Table 6a).

The individual monthly NAO value best related with the series is May for the East and June for the West, and the most significant 3-mo period is MJJ (May-June-July) (for the Eastern regional chronology). Although NAO is most clearly expressed during the winter (Van Loon and Rogers, 1978), trees are showing strong sensitivity to NAO values representing end of spring/beginning of summer. This season is of extreme importance for the end of their dormancy and the beginning of their vegetation period. Nonbiological proxy data, such as ice cores, might show better correlations with winter NAO values. Positive NAO values at the end of spring imply an increased moist western winds activity. As seen in the relationships with precipitation, a rainy May is highly positively correlated with growth, probably because of rain causing early snow melt, enabling an early start of the vegetation period (Kirchhefer, 2001).

TABLE 5
Response functions based on bootstrap orthogonal regression on residual chronologies and monthly climate data from previous September to current August, for the period 1923–1991. Mean bootstrap correlation coefficients and their standard deviations are shown. When significant at 90% confidence level, mean bootstrap regression coefficients (above) and the ratio mean correlation coefficients/standard deviation (below) are shown for individual months. When this ratio is greater than 1.645, there is 90% of confidence. When the value exceeds 1.96, the degree of confidence is 95%

|                | Temperature | Precipitation |
|----------------|-------------|---------------|
|                | S  | O  | N  | D  | J  | F  | M  | A  | M  | J  | A  | S  | O  | N  | D  | J  | F  | M  | A  | M  | J  | A  |
| WESTERN SUBREGION | Forfjorddalen | 0.42 | 0.24 | 0.41 | 0.24 | 0.18 | 0.13 | 0.18 | 0.19 |
| Vikran         | 5.04 | 2.81 | 5.01 | 2.79 | 2.30 | 2.10 | 2.00 | 1.70 |
| Devdiselva     | 0.23 | 0.33 | 0.22 | 0.31 | 0.17 | 0.16 | 0.16 | 0.15 |
|                | 2.30 | 4.20 | 3.88 | 5.20 | 1.71 | 2.26 | 2.00 | 1.87 |
| EASTERN SUBREGION | Karasjok | 0.40 | 0.18 | 0.40 | 0.17 | 0.21 | 0.18 | 0.21 | 0.16 |
| Karensuvanto   | 3.77 | 1.91 | 3.77 | 1.91 | 1.74 | 1.72 | 1.74 | 1.72 |
| Lokka          | 1.70 | 2.50 | 1.70 | 2.50 | 0.18 | 0.16 | 0.18 | 0.16 |
|                | 1.74 | 1.74 | 1.74 | 1.74 | 0.17 | 0.17 | 0.17 | 0.17 |
The last months of the previous fall (N, D) NAO values are also significant. Significant and positive correlation coefficients of radial growth and December temperatures have been found in this study for most chronologies (Pakasaivo, Kolari, Kessi, Riekkovaara, Pitkäjärvi, Taatsi, Karesuvanto, Karhunpesakivi, Leppäjärvi, Nunnanen, Skallovaara, Karasjok, Forfjorddalen, Devdiselva, Høgskardet, and Tauskjer). Positive NAO indices during the early winter imply a mild beginning of the winter. D’Arrigo et al. (1993) already found that some Scots pine tree-ring series from Fennoscandia were significantly related to winter NAO and Oslo winter temperatures. Rogers and Van Loon (1979) and Rogers (1990) indicate that anomalies in North Atlantic sea-surface temperatures, sea-ice extent and sea-level pressure associated with extreme NAO conditions can persist into the spring and summer months, when climate is exerting a more direct influence on tree growth (Cook et al., 1998).

Subperiods 1880–1930 and 1931–1991: During 1880–1930, subregional chronologies (Eastern and Western) yield the same correlations with NAO indices as described for the whole period 1880–1991. The two tree-growth–sensitive seasons for NAO (end of the spring and previous early winter) are very clearly defined, especially in the monthly data analysis. However, in the analysis for the subperiod 1931–1991, no pattern of correlation between NAO indices and subregional chronologies is observed. Some significant coefficients appear, only in the Eastern subregion chronology. When appearing, significant coefficients are stronger than during the first period (previous November and July), but compared with the first period analyzed, a drop in the NAO-series relationship strength is evident. This drop is strongest in the Western subregion chronology. Pearson correlations between individual chronologies and NAO series (not shown) agree with these results.

In their study of NAO dynamics recorded in Greenland Ice cores, Appenzeller et al. (1998) used a Morlet wavelet analysis. The observed power spectrum of the proxy index suggested that the NAO is an intermittent climate oscillation characterized by temporally active (coherent) and passive (incoherent) phases. Atmosphere-ocean interaction on the typical time scales of 5 to 15 yr might occur during active phases, although spatially coherent phases still might exist (Appenzeller et al., 1998). Despite noting that there is a possibility that the proxy NAO index simply represents stochastic variability, they identified as very active NAO phases the periods 1870–1900 and 1900–1930, while the period 1960 onward is a weaker phase. It is noteworthy to consider the similarity between high NAO indices/radial–growth relationship values during active NAO phases and the very low NAO indices/radial–growth relationship during the passive NAO phases.

### Table 6a
Response functions based on bootstrap orthogonal regression on Eastern and Western subregion chronologies and monthly NAO data from previous September to current August. Mean bootstrap correlation coefficients and their standard deviations are shown. When significant at 90% confidence level, mean bootstrap regression coefficients (above) and the ratio mean correlation coefficients/standard deviation (below) are shown for individual months. When this ratio is greater than 1.645, there is a 90% degree of confidence. When the value exceeds 1.96, the degree of confidence is 95%. The periods analyzed are 1880–1991, 1880–1930, and 1931–1991.

| Monthly NAO indices | S | O | N | D | J | F | M | A | M | J | J | A |
|---------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1880–1991           |   |   |   |   |   |   |   |   |   |   |   |   |   |
| PC1 East            | 0.20 | 0.17 | 0.24 | 0.17 | 0.19 | 2.48 | 1.91 | 2.42 | 1.68 | 2.24 |   |   |   |
| PC1 West            | 0.16 | 0.18 | 1.84 | 2.21 |   |   |   |   |   |   |   |   |   |
| 1880–1930           |   |   |   |   |   |   |   |   |   |   |   |   |   |
| PC1 East            | 0.19 | 0.18 | 0.25 | 0.39 | 0.15 | 2.06 | 1.68 | 2.6 | 3.53 | 1.64 |   |   |   |
| PC1 West            | 0.29 | 0.22 | 3.2 | 1.99 | 2.5 |   |   |   |   |   |   |   |   |
| 1931–1991           |   |   |   |   |   |   |   |   |   |   |   |   |   |
| PC1 East            | 0.23 | 0.28 |   |   | 0.28 | 1.7 | 2.09 |   |   |   |   |   |   |

### Table 6b
Response functions based on bootstrap orthogonal regression Eastern and Western chronologies and seasonal NAO data from previous September-October-November (SON) to current August-September-October (ASO). Mean bootstrap correlation coefficients and their standard deviations are shown. When significant at 90% confidence level, mean bootstrap regression coefficients (above) and the ratio mean correlation coefficients/standard deviation (below) are shown for individual months. When this ratio is greater than 1.645, there is a 90% degree of confidence. When the value exceeds 1.96, the degree of confidence is 95%. The periods analyzed are 1880–1991, 1880–1930, and 1931–1991.

| Seasonal NAO indices | Year | SON | OND | NDJ | DJF | JFM | FMA | MAM | AMJ | MJJ | JJA | JAS | ASO |
|----------------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1880–1991            |      |     |     |     |     |     |     |     |     |     |     |     |     |
| PC1 East             | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.2 |   |   |   |   |   |   |   |
| PC1 West             | 0.15 | 0.17 | 0.17 | 0.17 | 0.17 | 0.13 |   |   |   |   |   |   |   |
| 1880–1930            |      |     |     |     |     |     |     |     |     |     |     |     |     |
| PC1 East             | 0.23 | 0.21 | 0.21 | 0.21 | 0.21 | 2.12 | 1.77 | 1.86 |   |   |   |   |   |
| PC1 West             | 0.29 | 0.22 | 0.22 | 0.22 | 0.22 | 2.12 | 1.77 | 1.86 |   |   |   |   |   |
| 1931–1991            |      |     |     |     |     |     |     |     |     |     |     |     |     |
| PC1 East             | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 2.3 |   |   |   |   |   |   |   |

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TABLE 7
Significant Pearson correlations between residual chronologies and only positive (>0) or only negative (<0) NAO indices series. PC1E, as PC1 East in Table 6. PC1W, as PC1 West in Table 6. Numbers marked with a plus (+) have a degree of confidence >95%, and those marked with an asterisk (*) have a degree of confidence >99%

| Sites          | November (+) | December (+) | NDJ (+) | May (+) | June (+) | AMJ (+) |
|----------------|--------------|--------------|---------|---------|----------|---------|
| Eastern Subregion |              |              |         |         |          |         |
| Pakasavo       | 0.26*        | 0.28*        | 0.29    | 0.40*   | 0.24*    |         |
| Koltari        |              |              |         |         | 0.23     | 0.24    |
| Kessi          | 0.27*        | 0.29        | 0.35*   | 0.32*   | 0.32*    | 0.28*   |
| Riekkovaara    | 0.35*        | 0.28*        | 0.31    | 0.24    | 0.26*    | 0.34*   |
| Pitkäjärvi     | 0.34*        | 0.38*        | 0.32*   | 0.24*   | 0.29*    | 0.33*   |
| Taatsi         | 0.29*        | 0.27*        | 0.37    | 0.28    |          | 0.32*   |
| Lokka          |              |              |         |         | 0.29     | 0.24    |
| Karesuvanto    | 0.26*        | 0.31*        | 0.34*   | 0.33*   | 0.24     | 0.24    |
| Karhunpesakiivi| 0.38*        | 0.31*        | 0.25*   | 0.32*   | 0.23*    | 0.32*   |
| Leppajarvi     | 0.23*        | 0.25*        | 0.33*   | 0.40    |          |         |
| Nunnanen       |              | 0.30         | 0.35*   | 0.41    | 0.28     | 0.23    |
| Peuravuonon    | 0.27*        | 0.31*        | 0.34*   | 0.30    | 0.30     | 0.25*   |
| Skallovaara    |              |              | 0.35*   | 0.33*   | 0.28     | 0.36*   |
| Karasojk       | 0.29*        | 0.31*        | 0.22*   | 0.23*   | 0.35*    | 0.28    |
| PC1E           | 0.30*        | 0.26*        | 0.32*   | 0.34*   | 0.29*    | 0.27    |
| Western Subregion |            |              |         |         |          |         |
| Vikran         |              |              |         |         | 0.24     | 0.34    |
| Stonglandeiset |              |              |         |         |          |         |
| Fortjorddalen  | 0.26*        | 0.26         | 0.32    | 0.23    | 0.27     |         |
| Deavdselva     | 0.27*        | 0.23         |         | 0.26    |          |         |
| Hogskeidet     |              |              |         |         | 0.24     |         |
| Romingla       | 0.22*        |              |         |         |          |         |
| Tauskjerrind   |              |              |         |         | 0.30     | 0.23    |
| PC1W           |              |              |         |         | 0.24     |         |

We also calculated the correlations between a subset of >zero NAO indices and the tree-ring series corresponding to the years in which NAO values are only positive for different NAO month and season indices. The objective was to find out if correlations of NAO indices with chronologies are due to both positive and negative NAO situations or, on the contrary, only specific NAO situations are limiting tree growth. The same was done for <zero NAO series. The resulting series are formed by years which are ordered in time but that are not necessarily contiguous. As we are working with residual chronologies and there is no autocorrelation within them, it is possible to split the years of the series and look at the correlation of the newly created tree-ring series with the newly created >zero or <zero NAO series.

The same analysis was performed using the Western and Eastern subregional chronologies previously defined.

The results of this analysis for November, December, and November-December-January (NDJ) (previous early winter); and for May, June, and April-May-June (AMJ) (spring) are displayed in Table 7. Positive correlations of previous early winter NAO indices and chronologies are mostly found in >zero NAO series. When NAO is positive at the previous early winter, the climatic patterns in northern Fennoscandia (mild beginning of winter) enhance tree growth in the next growth season, while when NAO at the previous early winter is negative, the climatic patterns in northern Fennoscandia (nonmild beginning of winter) do not affect tree growth in the next growing season.

On the other hand, positive correlations of spring NAO indices and chronologies are mostly found in <zero NAO series. NAO being negative at the spring in northern Fennoscandia can limit tree growth, while positive NAO values at the spring do not affect tree growth. A more detailed explanation of this would relate negative NAO springs with later snowmelt and later beginning of the vegetation period (as Kirchhefer [2001] proposes). During negative NAO springs, snowmelt timing constitutes a limiting factor for tree growth. Higher than normal temperatures associated with positive NAO springs often favor an early snowmelt. Under these conditions, ground starts to warm up earlier than during negative NAO springs. Low spring temperatures in soil may limit tree growth in the next summer. Soil temperatures might not be a limiting factor if they are high enough before trees start to be active, as probably happens during positive NAO springs, which are uncorrelated with tree growth. It is a widely known ecological rule that when a factor is not limiting anymore, other limiting factors appear (Fritts, 1976).

The same method was done using the PC representing the eastern set of chronologies and the PC representing the western one giving similar results, with a much better fit for the eastern set of series.

Conclusions and Significance

(1) In accordance with previous studies (Briffa et al., 1990; Lindholm, 1996), the main limiting climatic factor in the northern Fennoscandian forests is July temperature. May precipitation is another key factor for tree growth, and it is caused by rain inducing early snowmelt and soil warming, enabling an early start of the vegetation period (Kirchhefer, 2001).

(2) Although having a major common climatic signal, tree-ring chronologies from both sides of the Scandes Mountains during the common period 1880–1991 show growth differences, detectable by the study of (1) standardized series, (2)
correlations among the chronologies along time, and (3) multivariate comparisons.

(3) The second half of the period studied, corresponding to 1931–1991, is characterized by an enhancing of the east-west differences in northern Fennoscandia. There is an increase in the variance explained by the second component of the PCA of the residual series, which represents a strengthening of radial growth differences between the Western and the Eastern Subregions. These enhanced growth differences are also detected in the study of the evolution of the correlations among chronologies.

(4) Northern Fennoscandia forests are most sensible to previous early winter and end of the spring-summer NAO indices. They show significant positive relationships with these NAO season values.

(5) During the first half of the period analyzed (1880–1930), NAO indices and residual chronologies are very highly correlated, while in the second half (1931–1991), the correlations of radial growth with NAO indices drop, especially in the west.

(6) Positive previous early winter NAO indices enhance tree growth in the next growing season, while negative previous early winter NAO indices do not have any correlation with tree growth. On the other hand, positive NAO spring values are not correlated with radial growth, while negative NAO spring values show a significant correlation with them.

Multivariate techniques (PCA in particular) have proven to be very useful in tree-ring studies when applied to a climatic gradient. The combined interpretation of loadings, eigenvalues and cumulative variance expressed by the analysis has allowed a detailed description of the information tree rings in the area contain about the climatic gradient. The use of the 1st PC series as a regional chronology was possible due to the high common variance it expresses and to the fact that all chronologies have positive loadings with the 1st PC. The eigenvalues associated to each year of the PC series can be used as a way to identify pointer years. For the 1st PC, years of extreme growth for the whole area correspond to extreme eigenvalues. For the 2nd PC, it is possible to identify what could be called relative or gradient pointer years: that is, years that are conspicuous because of being wide (narrow) in one side of the gradient and narrow (wide) in the other extreme of it. Such relative pointer years could not be detected by classical pointer year methods, and will be further analyzed in future studies, as they contain the clues to describe situations where the climatic gradient peaks.

When studying climatic gradients, it is basic to take into account that these gradients fluctuate, they are time variable, and they can increase or decrease in intensity during the period under study. This is why an analysis by subperiods is strongly recommended and widely used (Tardif et al. 2003). In this study, the subperiod analysis of the relationships between chronologies along the gradient has revealed a general decrease in the variability they hold in common, especially in the second half of the 20th century. This decrease is coinciding with a significant loss of correlation between the chronologies and the NAO indices. In a study on wood density/air temperature relationships, Briffa et al. (1998) already described a loss of sensitivity of wood density to temperature changes during the late 20th century. To determine whether this is a result of NAO active/passive phase dynamics, a consequence of an anthropogenic induced climatic change, or if it is caused by a combined effect of both, is something beyond the scope of this paper, but it is without doubt one of the main lines of our future research in this topic. Identifying which of the NAO-affected climatic parameters has been changing in the area will help us to answer these questions. However, the change is most probably affecting not one but many combined precipitation and temperature parameters.

Describing and understanding such temporal changes in the strength with which NAO affects tree rings in the area is of vital importance when using tree rings as proxy data in dendroclimatic reconstructions.

This study also reveals the fact that NAO/tree-ring relationships are not continuous along all range of NAO values. It is important to realize that NAO can affect tree growth in a given season only if it is positive (i.e. end of previous fall) or negative (i.e. end of spring/beginning of summer). That is, the combined effects of NAO on temperature and precipitation over the area are limiting tree growth only in certain NAO situations, whereas in other NAO phases, its effects over tree growth for a given season are simply nonexistent.

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