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Tree-ring records from central Fennoscandia: the relationship between tree growth and climate along a west–east transect

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Abstract: Nine Scots pine tree-ring-width chronologies were compared regarding growth variability and response to climate along a gradient of oceanicity–continentality at 62–64°N in central Fennoscandia. The study revealed higher growth variance and stronger response to climate in the oceanic area west of the Scandinavian Mountains, compared to the more continental areas further east. However, there was a gradual change in radial tree growth and response to climate along the gradient, where tree growth in a transition zone between oceanic and continental climate showed positive correlations with radial tree growth in both oceanic and continental areas. Pine growth responded positively to summer temperatures in the western areas, and positively to summer precipitation in the east. Generally, pine growth showed a weaker relationship with the North Atlantic Oscillation (NAO) than with temperature and precipitation. During the summer, pine responded to the NAO only in western Fennoscandia, while during the winter pine responded to the NAO in both western and eastern Fennoscandia. This suggests that, during winter, the NAO is an adequate measure for climatic variations important for pine radial growth along the whole studied gradient, while, in the summer, the NAO is an inadequate measure for climatic variations important for pine radial growth east of the Scandinavian Mountains. During the second half of the twentieth century, pine growth in western Fennoscandia displayed reduced sensitivity to climate, while the opposite was found in the east. Indications of growth stress were found in one site east of the Scandinavian Mountains, and, as increasing temperatures have been accompanied by increasing precipitation in Fennoscandia throughout the twentieth century, we suggest that a change in climate regime from subcontinental to suboceanic caused those trees to experience climatic stress. However, trees in either oceanic or more continental areas did not seem to respond negatively to recent climatic change.

Key words: Tree rings, dendrochronology, dendroclimatology, *Pinus sylvestris*, Scots pine, North Atlantic Oscillation, NAO, climatic change, Fennoscandia.

Introduction

Tree-ring records are valuable indicators of past climates as they have an extensive coverage, are precisely dated and may contain a highly resolved climate response (Briffa, 2000). Depending on the location and strength of the climate forcing, information concerning different climatic variables (e.g., temperature and precipitation) can be recovered on yearly to decadal or centennial timescales. Trees growing close to the altitudinal or latitudinal treeline respond to summer temperatures and several regional reconstructions of high-latitude temperatures have been made using tree-ring data from the northern boreal zone (D'Arrigo and Jacoby, 1993; D'Arrigo *et al.*, 1999; Hughes *et al.*, 1999; Lindholm and Eronen, 2000). Furthermore, recent global or hemispheric temperature reconstructions have largely relied on tree-ring data (Jones *et al.*, 1998; Mann *et al.*, 1999; Briffa *et al.*, 2001).

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Along the altitudinal and latitudinal treeline in Fennoscandia, annual to decadal Scots pine (*Pinus sylvestris* L.) growth patterns are highly correlated and the growth-climate relationship is similar over large areas (e.g., Briffa *et al.*, 1990; Lindholm, 1996; Kirchhefer, 2001; Gunnarson and Linderholm, 2002). Below the altitudinal and latitudinal treeline a diminishing growth influence of summer temperature and increasing influences of other climatic variables, such as precipitation and competition among trees, is expected (Fritts, 1976: Lindholm *et al.*, 2000).

In Fennoscandia, a significant proportion of the interannual precipitation and temperature variability is attributed to the dynamics of the North Atlantic Oscillation (NAO), which is a measure of the pressure difference between the Azores and Iceland and hence affects westerly winds blowing across the North Atlantic. Seasons of high positive NAO are associated with warming and increased rainfall over northwest Europe (Hurrell, 1995). This relationship is most pronounced in winter and early spring and substantially weaker in summer (Rogers, 1990).

Since the late 1960s there has been a strengthening of the wintertime NAO, with unprecedented strongly positive NAO index values since the 1970s (Hurrell, 1995). This may account for some of the wintertime warming in recent decades and the steady increase in storminess in winter over the northeast Atlantic and the North Sea since the 1960s (Ulbrich and Christoph, 1999). Increased warming, as well as increased precipitation, indicates that the climate of Fennoscandia is becoming more oceanic (e.g., Tuomenvirta *et al.*, 2000).

As the strengthening of the NAO coincides with late twentieth-century global warming, the influence of large-scale atmospheric circulation on a variety of ecosystems has gained increased attention in the North Atlantic region (e.g., D'Arrigo *et al.*, 1993; Post and Stenseth, 1999; Weyhenmeyer *et al.*, 1999; Mysterud *et al.*, 2000; Solberg *et al.*, 2002). As a consequence, several recent studies have focused on making multiproxy reconstructions of the NAO (e.g., Cook *et al.*, 1998; 2002; Glueck and Stockton, 2001). However, few attempts have been made to understand the influence of the atmospheric circulation on tree growth in the Atlantic region (but see D'Arrigo *et al.*, 1993). It is our opinion that a reasonable understanding of these mechanisms is fundamental before using tree-ring data as proxies for NAO.

Lately, several accounts of reduced tree growth sensitivity to climate in the Northern Hemisphere have been presented (Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998; Linderholm, 2002). Although the mechanism behind this loss of climate sensitivity has yet to be confirmed, the evidence suggests that the temperature increase, especially in the last two to three decades, has caused trees to respond differently to climate than during earlier decades of the twentieth century.

In a joint Fennoscandian project, growth patterns and growth-climate responses during the last 150 years of a Scots pine tree-ring-width chronology network from central Fennoscandia (61°N to 64°N, 10°E to 30°E) are compared. Climate regions range from oceanic at the west coast of Norway to highland climate in the Scandinavian Mountains and subcontinental to continental in Sweden and eastern Finland. Local studies of tree growth response to climate have been conducted in central Fennoscandia (e.g., Lindholm *et al.*, 1997; Kalela-Brundin, 1999; Linderholm, 2002), and regional comparisons of growth-climate relationships have been made along north–south gradients in Finland and Sweden (Lindholm *et al.*, 2000; Mäkinen *et al.*, 2000; Linderholm *et al.*, 2002). The present work is the first comparative study of climate influence on tree growth along a west–east transect through central Fennoscandia. Our aims with this investigation were to:

(1) make interregional comparisons of Scots pine growth-pattern variations across Fennoscandia from oceanic western Norway to continental eastern Finland;
(2) determine the influence of temperature and precipitation on Scots pine growth across central Fennoscandia;
(3) detect a signature of a large-scale atmospheric circulation system (i.e., the NAO) in tree growth along this west–east transect;
(4) detect possible changes in growth-climate relationships in the twentieth century.

Material and methods

Regional climate and growth conditions

The regional climate in the studied region ranges from oceanic conditions in the west to a relatively continental climate in the east (Wallén, 1970). The oceanic climate is characterized by mild, wet winters, cool summers, high precipitation with maximum in autumn and winter, and relatively low variance in temperature between summer and winter. The more continental climate is characterized by colder winters, warmer summers and considerably lower precipitation with maximum in summer and autumn, and higher variance in temperature between summer and winter. The strong impact of the westerlies is responsible for the oceanic climate in the west and several of the sites in and east of the Scandinavian mountain range are also strongly influenced by Atlantic air masses.

Site descriptions

We used Scots pine tree-ring-width chronologies from nine sites in the boreal forest of central Fennoscandia. The sampled sites represent mature and natural pine stands ranging from the west coast of Norway to eastern Finland (Figure 1; Table 1). The four westernmost sites (N1, N2, N3 and S1) are characterized by an oceanic–suboceanic climate with high amounts of precipitation, and together with N4 and S2 they are situated close to the local forest line. Furthermore, N4 and S2 lie in a transition zone between oceanic and continental climates. All Norwegian and Swedish sites are characterized by open forests dominated by Scots pine and Norway spruce (*Picea abies* (L.) Karst.). Furthermore, the sampled trees at these sites grew on relatively thin soil layers, mainly till. In this environment, pine occupies dry, convex microsites while spruce occupies wetter, concave microsites. The

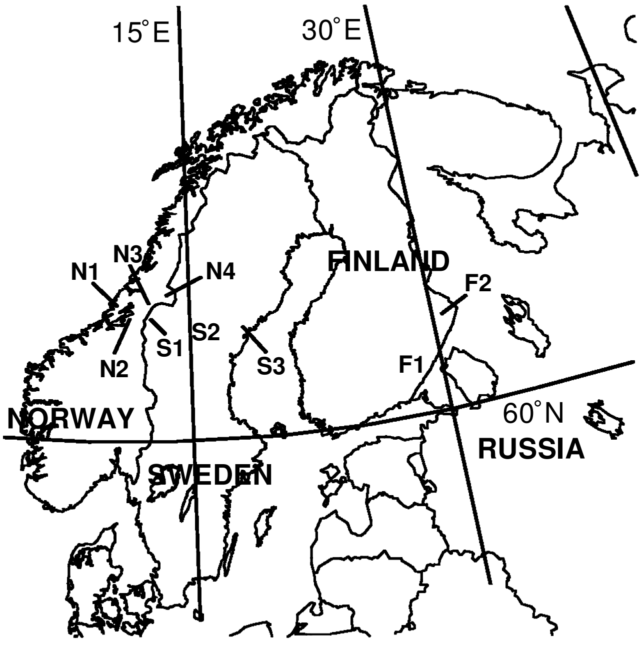

Figure 1 Map of Fennoscandia, showing locations of sampled sites. Further details are given in Table 1.

Table 1 Site description

Site	Country	Length of chronology	Elevation (m a.s.l.)	Lat. (N)	Long. (E)	No. of trees	Temp. Jan.*	Temp. Jul.*	Precip. year*
N1	Norway	1655–1997	250	64°19′	10°55′	41	−2.4	13.3	1565
N2	Norway	1500–2000	425	63°15′	10°37′	26	−4.0	13.0	1260
N3	Norway	1754–1997	350	64°09′	12°33′	48	−6.3	12.9	934
S1	Sweden	1472–1998	700	63°07′	13°20′	38	−7.7	10.8	902
N4	Norway	1635–1997	470	64°27′	13°58′	49	−10.4	11.8	630
S2	Sweden	1471–1999	270	63°59′	16°32′	34	−8.6	13.4	483
S3	Sweden	1452–1998	250	62°20′	18°29′	36	−7.0	15.5	703
F1	Finland	1794–1993	90	61°80′	28°50′	87	−8.5	16.0	589
F2	Finland	1413–1991	170	63°16′	30°40′	52	−10.4	15.0	536

*1961–1990; temperature in °C and precipitation in mm.

N1, N3, N4 and S1 are composite chronologies, each containing trees from two sites. The individual sites in each chronology are situated close to each other and are strongly correlated. At N1, N3 and N4, samples were taken at the upper boundary of Scots pine as well as 100 m below. At S1, trees were collected at the Scots pine tree limit from two sites approximately 30 km apart. The two Finnish sites represent typical growing conditions for Scots pine in eastern Finland, i.e., well-drained, pine-dominated heaths with coarse mineral soils and a thin humus layer. Most of the bedrock in the region is covered by glacial till, but bare bedrock terrain occurs frequently. The topography is characterized by high relative altitudes, due to the unevenness of the bedrock and various glacial features.

Chronology building

All tree-ring chronologies were mainly based on samples from living trees, sampled with standard dendrochronological techniques. Ring widths of the samples were measured with a precision of 0.01 mm, and then cross-dated both manually and by computing cross-correlations between individual series using customary procedures (Holmes *et al.*, 1986; Aniol, 1989). In order to strengthen the common signal in the tree-ring data and to reduce unwanted ‘noise’ (e.g., Fritts, 1976), the individual tree-ring series were standardized before averaging, by using procedures in the software ARSTAN (Holmes *et al.*, 1986; Cook *et al.*, 1990a). The use of negative exponential functions or regression lines (Cook *et al.*, 1990a), allowed for chronologies with interannual- to centennial-scale properties to be built. Autocorrelation was removed from individual tree-ring series through autoregressive modelling (Cook *et al.*, 1990b), and the pooled autoregression model is reincorporated into the residual chronology to produce the arstan chronology. The arstan chronologies were used for correlation analyses and comparisons of long-term growth trends. Correlation analyses were computed for the period 1840–1993. The residual chronologies were used for analyses of growth-climate relationships, as they proved to yield more climatic information than the arstan chronologies. It should be noted that, due to low sample size in the end of the two Finnish chronologies (Figure 2), reduced analysis periods were used: 1840–1991 for F1 and 1840–1982 for F2. These reduced periods are consistent for all analyses. Generally, we anticipate for the analyses from 1840 to the present that the reduced periods do not influence the analyses substantially. However, for growth-climate analyses the shortened period at F2 is expected to have an influence on the result, especially for the temporal analyses (see below).

Dendroclimatic analysis

Response function analysis (Fritts, 1976; Briffa and Cook, 1990) is a form of multiple regression analysis where the predictor variables are replaced by principal components, as climatic parameters are often intercorrelated (Guiot *et al.*, 1982). Principal components do not correlate with each other and can thus be used to express the real, independent relationships between tree growth and climate (e.g., Briffa and Cook, 1990). In our investigation we used a 12-month analysis period, extending from September of the year preceding growth to August of the growth year, with the residual tree-ring chronologies as predictand and monthly mean temperature and monthly total precipitation values as predictors. Response function analyses were performed with software PRECON, version 5.17b (Fritts *et al.*, 1991).

A regional temperature and precipitation index for central Norway was representative for climate in Norway as well as westernmost Sweden (S1). This record dates back to 1896 (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer and Nordli, 1998). For S2 and S3, we used homogenized data from Östersund and Härnösand, respectively. These data cover the period 1860 to present and were obtained from the Swedish Meteorological and Hydrological Institute. Finnish climate series were modelled by a method based on the work of Ojansuu and Henttonen (1983). This method produces unbiased estimates of local values from observations made by the Finnish Meteorological Office (1880–1993). Growth-climate responses were analysed for a period where both meteorological and tree-ring data were available for all sites: 1897–1993 (note the shorter periods for the Finnish chronologies as described above). To determine whether the growth-climate relationship was stable through the twentieth century, additional analyses were performed in two subperiods (1897–1944 and 1945–1993). By doing so, we were able to discover changes in growth sensitivity to climate. Finally, to detect possible signals of the NAO in the ring-width patterns, residual chronology indices were compared to monthly indices of the NAO (Jones *et al.*, 1997) for the period 1897–1993 and two subperiods in the same manner as for the temperature and precipitation data.

Results

Growth variance and long-term growth patterns

Chronology statistics, which summarize the quality of the chronologies, are shown in Table 2. All series surpassed expressed population signal >0.85 (Figure 2; Table 2) within the period 1840–1993 and so showed inherent qualities making the chronologies applicable for growth-climate analyses (Briffa and Jones, 1990). Correlation analyses showed a strong coherent growth pattern among the sites west of the Scandinavian Mountains, including S1 and N4 (henceforth referred to as the western sites) (N1–N4; $r^{mean} = 0.52$; Table 3). East of the Scandinavian Mountains (henceforth referred to as the eastern sites), F1 was fairly well correlated to F2 and S3, but F2, S2 and S3 were not well correlated. Instead, there was a gradual transition where tree growth in

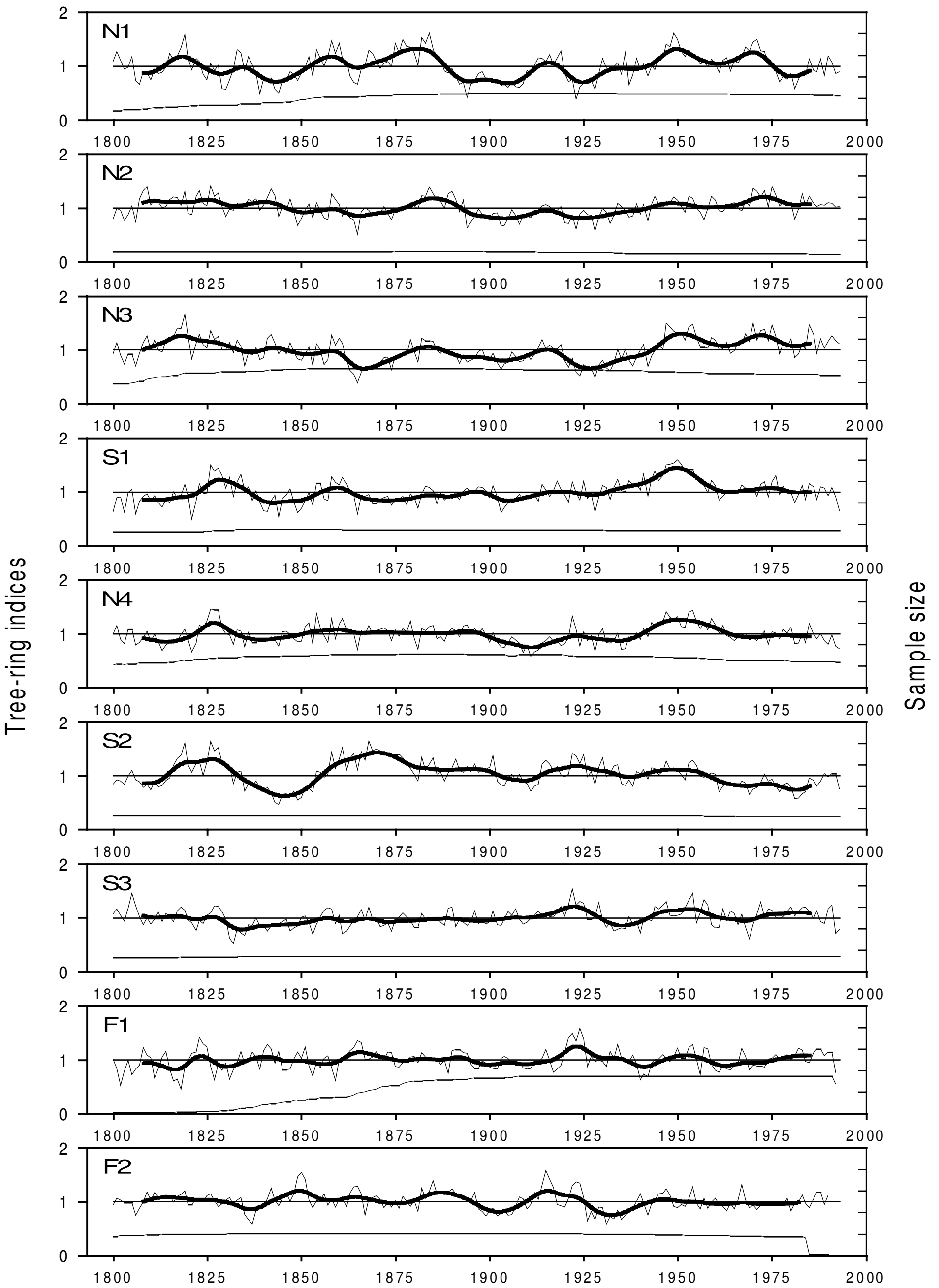

Figure 2 Standardized Scots pine tree-ring-width chronologies (arstan version, thin lines), smoothed with a Gaussian filter with $\delta = 3$ corresponding to a 10-year running mean (thick lines). Lower lines indicate sample size over time (right y-axis) with a scale of 50.

the transition zone between oceanic and subcontinental areas (N4 and S2) was positively correlated to both western and eastern sites. Generally, the high covariance among the western sites gave evidence for common growth forcing environmental factors (Table 3).

The low-frequency growth patterns along the west–east gradient were characterized by relatively high variance at the western sites and considerably lower variance at the eastern sites (Figure 2). There were no periods where a common growth pattern with above- or below-average growth occurred simultaneously at all sites in central Fennoscandia. At the western sites, common periods of above-average growth were found around 1820, 1880, 1950 and 1970, where the periods around 1880 and 1970 were unique for the three westernmost sites (N1–N3). Common below-average growth was found around 1900–1910 for all sites, and around 1925 for the three westernmost sites. The low variance in the low-frequency growth patterns at the eastern sites did not indicate any clear common decadal growth trends. One exception is a period of above-average growth in the 1920s. The S2 and S3 sites showed some similar characteristics with the western sites with above-average growth around 1820 for S2 and around 1950 for both sites. The S2 site showed an individual and characteristic pattern between 1810 and 1880, where the below-average growth from 1835 to 1845 was unique. Below-average growth in the 1930s was seen at F2, and to some degree S3, coinciding with the temperature maximum for the twentieth century.

Growth-climate relationships

The most distinct significant growth response to climate was a positive response to summer temperature at all Norwegian sites, S1, S2 and F2, while F1 had a negative response to summer (June) temperature (Figure 3). At the three westernmost sites, the main response was in June, while at the other sites it was in July. A negative response to summer precipitation was found at N1, N3 and S1. At the most oceanic site (N1), where precipitation is very

Table 2 Chronology statistics for the arstan chronologies with 1840–1993 as common period

	Common period	MS	SD	1PC%	SNR	EPS	Mean corr. between trees	No. of trees*
N1	1840–1993	0.17	0.26	34.5	8.5	0.90	0.30	20/41
N2	1840–1993	0.14	0.18	47.7	12.2	0.92	0.43	16/26
N3	1840–1993	0.15	0.22	38.5	21.9	0.96	0.35	40/48
S1	1840–1993	0.15	0.21	36.4	17.1	0.95	0.32	36/38
N4	1840–1993	0.14	0.19	32.3	13.2	0.93	0.29	33/49
S2	1840–1993	0.13	0.23	54.8	33.8	0.97	0.52	31/34
S3	1840–1993	0.13	0.17	33.8	14.7	0.94	0.30	34/36
F1	1840–1991	0.16	0.19	41.9	9.1	0.90	0.36	16/87
F2	1840–1982	0.14	0.19	40.3	25.8	0.96	0.37	44/52

*Number of trees included in the common period divided by number of total trees in the chronology.

MS = mean sensitivity, a measure of the relative change in ring widths from one year to the next.

SD = standard deviation.

1PC% = the percentage of variation explained by the first principal component expresses the variation held in common among the trees included in the chronology.

SNR = signal to noise ratio, measurement of the degree to which the chronology signal is expressed when tree-ring series are averaged.

EPS = expressed population signal.

Table 3 Correlations among the arstan chronologies for the common period 1840–1993. The common period is adjusted for the Finnish chronologies due to low sample size (Figure 2) in some periods (R > 0.4 in bold; *sign. at p = 0.05; **sign. at p = 0.01)

	N1	N2	N3	S1	N4	S2	S3	F1[a]	F2[b]
N1	1								
N2	__0.56**__	1							
N3	__0.58**__	__0.76**__	1						
S1	__0.45**__	__0.42**__	__0.56**__	1					
N4	__0.42**__	0.37**	__0.42**__	__0.67**__	1				
S2	0.31**	–0.04	–0.15	0.29**	__0.46**__	1			
S3	0.08	0.08	0.13	0.27**	0.29**	0.20*	1		
F1[a]	–0.17*	–0.10	–0.16	–0.05	0.11	0.19*	0.33**	1	
F2[b]	0.07	0.12	0.13	–0.01	0.22**	0.17*	0.26**	0.36**	1

[a]1840–1991.

[b]1840–1982.

high, the negative response to precipitation seemed to be stronger than the positive response to temperature. Furthermore, all western sites, except N3, had positive growth responses to spring precipitation. Trees at the western sites and S2 showed positive responses to previous autumn/early winter temperature. At the remaining eastern sites, pine growth showed positive responses to June precipitation. Also, all eastern sites displayed negative growth responses to previous autumn precipitation. Additionally, F1 showed a negative response to January precipitation. Pines close to the Baltic Sea in Sweden (S3) had few and weak significant growth responses to climate, and the lowest R^2 value of all sites (Figure 3).

At all western sites except N4, there was a marked decrease in sensitivity to climate in the last subperiod (1945–1993) (Table 4). The most prominent change in growth response to climate in the last subperiod is the lack of significant negative responses to precipitation at the western sites. The response to temperature, however, turned out to be quite similar between the two analysed subperiods along the entire west–east transect. The eastern sites and N4 showed a slight increase in growth sensitivity to climate in the last subperiod, especially at S2 where R^2 became highest of both western and eastern sites (Table 4). At N4 and S2, there was an increase in significant responses to temperature.

Generally, tree growth in central Fennoscandia was less correlated to monthly indices of the NAO compared to temperature and precipitation (Figures 3 and 4). The strongest growth response to NAO was found at the west coast of Norway (N1 and N3) and in southeastern Finland (F1) (Figure 4). At the west coast of Norway, there was a negative response to both January and July NAO, while in southeastern Finland there was a positive response to winter NAO (December–March). A positive relationship between radial tree growth and one winter month NAO (December or January) was also present at N4, S2 and S3. Only at three sites did the importance of the NAO increase in 1945–1993, where R^2 values at N1, N4 and F2 reached around 0.3 (Table 5). At the remaining sites R^2 values decreased in 1945–1993, except at N3 where there was no change. The most prominent reductions in growth responses to the NAO were seen at N2 and S1, where responses were more or less halved.

Discussion

This study revealed higher growth variance and stronger responses to climate in the oceanic area west of the Scandinavian Mountains compared to the flatter and more continental area east of the mountains. Several of the decadal growth variations for the last 150 years are held in common by the sites from Norway to central Sweden (N1–S2), but also with other pine tree-ring series from northern and central Fennoscandia (Lindholm, 1996; Kalela-Brundin, 1999; Kirchhefer, 2001; Linderholm, 2002). On the other hand, the low decadal growth variations for the three most eastern sites (S3–F2) indicate a different climate forcing on radial tree growth. The eastern sites share common decadal growth variations with radial tree growth from central and southern Finland, especially the period with increased growth around 1925 (Lindholm *et al.*, 2000). Increased growth from 1930 to 1950 at the western sites coincides with the highest summer temperature recorded since 1770 from the Trondheim meteorological station (Kalela-Brundin, 1999). On the contrary, the eastern sites have tendencies for reduced growth in the 1930s, which is also found in continental mountain valleys in northern Norway (Kirchhefer, 1999). Our results do not give evidence for a well-defined border between sites with oceanic or continental growth patterns. Instead, there is a gradual change in growth patterns and climate responses from oceanic western Norway to the more continental climate of eastern Finland, where a couple of the central sites (N4 and S2) have positive correlations to both western and eastern sites.

The differences in pine growth along the Fennoscandian transect are ultimately caused by differences in climate. The dominance of Atlantic air masses and proximity to the North Atlantic current in western Fennoscandia results in relatively mild winters and cool summers. In the more continental parts of Fennoscandia, air masses from the interior of Asia have a stronger influence on climate, resulting in colder winters and warmer/drier summers. Furthermore, during summer cool maritime air masses are heated and dried out as they subside on the leeward side of the Scandinavian Mountains (Wallén, 1970). High air temperatures are therefore a rather usual phenomenon in summer in eastern Norway, Sweden and Finland, even for the westerly type of circulation. Cool summers in western Fennoscandia give response patterns with positive responses to summer temperature, while warm and dry summers in the east cause pine to respond positively to summer precipitation. This is especially convincing at the southernmost eastern site (F1), where pine had an additional negative response to June temperature. It is well known that when

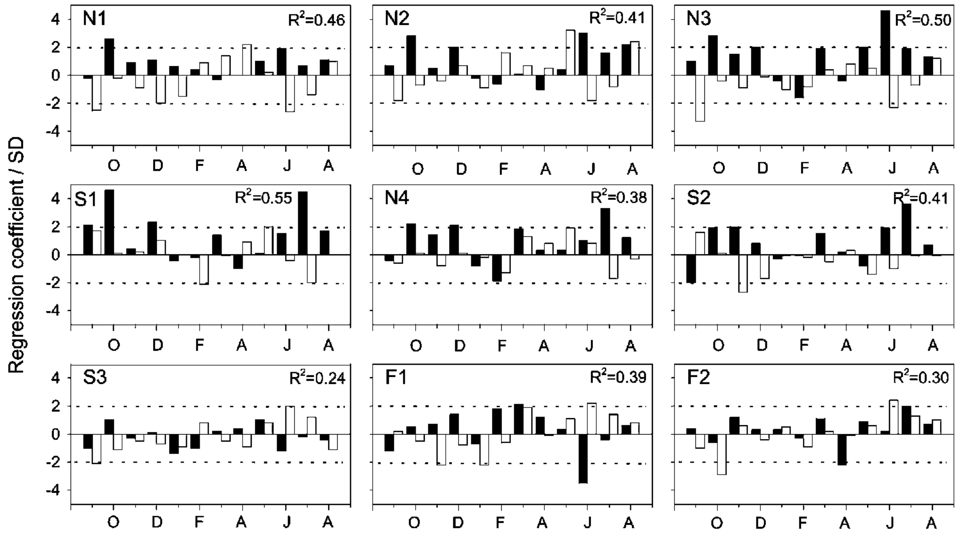

Figure 3 Effect of temperature (black bars) and precipitation (white bars) on ring-width indices shown by the regression coefficients divided by its standard deviation for the period 1901–90. Dotted horizontal lines indicate significance level ($p < 0.05$) above and below mean.

Table 4 The course of R^2 and number of significant response variables for the residual chronologies and climate variables between the two subperiods 1897–1944 and 1945–1993. For the F1 and F2 chronologies, the last subperiods ended in 1982 and 1991, respectively

	N1	N2	N3	S1	N4	S2	S3	F1	F2
R^2 1897–1944	0.59	0.66	0.63	0.75	0.53	0.49	0.34	0.50	0.41
R^2 1945–1993	0.50	0.39	0.53	0.51	0.58	0.67	0.41	0.50	0.66*
No. of sign. resp. P 1897–1944	3	4	3	2	2	1	0	1	1
No. of sign. resp. P 1945–1993	1	1	0	0	0	2	1	1	0
No. of sign. resp. T 1897–1944	0	2	2	4	0	1	0	1	0
No. of sign. resp. T 1945–1993	0	0	2	3	2	2	0	1	0

*This figure is not comparable with the other R^2 values because the regression equation contains considerably fewer years.
P = precipitation.
T = temperature.

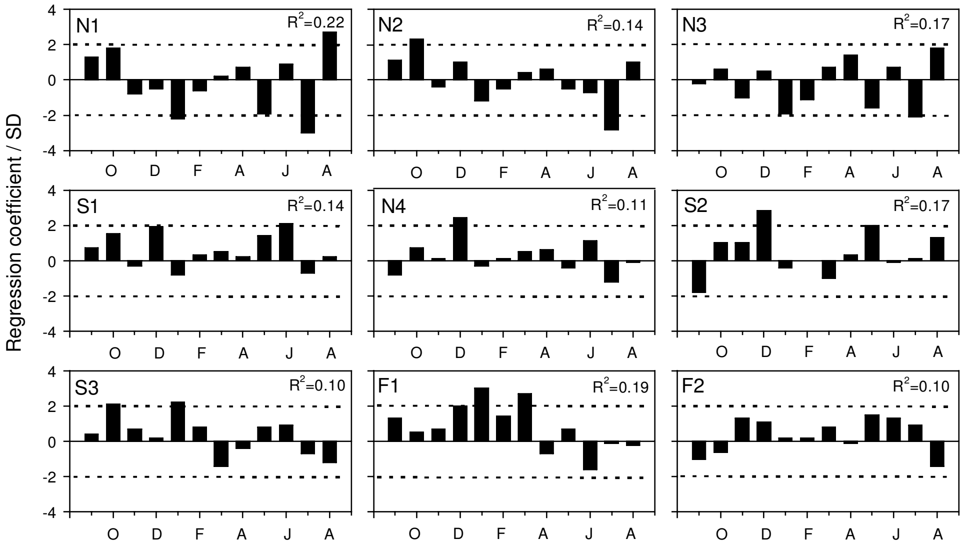

Figure 4 Effect of the NAO on ring-width indices shown by the regression coefficients divided by its standard deviation for the period 1901–90. Dotted horizontal lines indicate significance level ($p < 0.05$) above and below mean.

going from north (cold) to south (warmer) trees shift their response to climate from being temperature-limited to being precipitation-limited (Fritts, 1976; Lindholm *et al.*, 2000). In this west–east gradient, there is probably the same effect because the eastern sites are under influence from warmer and drier air masses during the summer season.

Generally, trees are more sensitive to temperature close to the treeline than at lower altitudes (Fritts, 1976). This contributes to the stronger emphasis on temperature in the western sites, and to more distinct decadal growth variations. Furthermore, in the west, the sampled pines grew close to their western distribution limit, while in the east they grew in a more central part of the distri-

Table 5 The course of R^2 and number of significant response variables for the residual chronologies and the NAO between the two subperiods 1897–1944 and 1945–1993. For the F1 and F2 chronologies, the last subperiods ended in 1982 and 1991, respectively

	N1	N2	N3	S1	N4	S2	S3	F1	F2
R^2 1897–1944	0.25	0.24	0.29	0.31	0.25	0.36	0.16	0.31	0.17
R^2 1945–1993	0.31	0.10	0.28	0.16	0.29	0.26	0.11	0.25	0.31*
No. of sign. resp. 1897–1944	1	1	2	1	0	2	1	2	0
No. of sign. resp. 1945–1993	1	0	0	0	1	0	0	0	1

*This figure is not comparable with the other R^2 values because the regression equation contains considerably fewer years.

bution area of the species (Nikolov and Helmisaari, 1992). It is expected that species close to the distribution limit will be more sensitive to climate compared to the situation in more central parts of the distribution area, and this will potentially influence the sensitivity to climate for pines at the different sites along the west–east transect.

Kirchhefer (1999) showed that Scots pine along a transect across the Scandinavian Mountains of 10° longitude in northern Norway (69°N), displayed a strong and coherent growth pattern and growth response to climate (PC1: R^2~0.70, positive responses to July temperatures at all sites). Consequently, despite the large climatic variability across the mountains, pine at all eight sites shared strong common growth variability (Kirchhefer, 1999). The strong common variability along the northern Norway transect is probably caused by its northerly position with a short growing season along the entire transect. The larger dissimilarities along the central Fennoscandian transect may have several explanations. First, the west–east transect in the central area extends over 20° in longitude compared to 10° in the north. Second, the Scandinavian Mountains are higher and more massive in the central area, which has implications for the distribution and dominance of different large-scale air masses, which strongly influence climate (Wallén 1970; Hanssen-Bauer and Førland, 2000). Consequently, our results showed that it is not possible to combine tree-ring-width chronologies from eastern and western parts of central Fennoscandia expecting them to yield a common climate signal.

The negative relationship between radial tree growth and summer NAO is an exclusive pattern for the three westernmost sites, indicating that the NAO also influences climate in summer in this area. Thus, during high NAO index summers, high precipitation combined with relatively low temperatures will have a negative influence on radial growth. This supports the positive/negative correlation between summer temperature/precipitation and radial growth in the west. The lack of a negative correlation between summer NAO and radial tree growth further east suggests that the NAO index is an inadequate measure of the atmospheric circulation over the more continental parts of central Fennoscandia during summer (Slonosky *et al.*, 2001). This is in agreement with the findings of Chen and Hellström (1999) that there is only a weak relationship between summer temperatures and the NAO. During winter, the NAO has a considerable influence on Fennoscandian climate, and influences tree growth over a large area despite pines being dormant during winter (D'Arrigo *et al.*, 1993; Lindholm *et al.*, 2001). In the oceanic part of west-central Scandinavia, there are indications for a negative relationship between NAO for both pine and spruce radial tree growth (see Solberg *et al.*, 2002). Periods of high winter temperatures at oceanic sites, associated with high NAO index, may potentially represent a stress factor for pine (Kirchhefer, 2001). Also, high NAO index in oceanic environments during winter results in unstable weather with possible increases in freeze-thaw cycles and more unfavourable soil conditions (Kramer and Kozlowski, 1979). Mild spells in winter with precipitation falling as rain instead of snow would increase snow-free periods, particularly at low elevations (Mysterud *et al.*, 2000), and further expose the ground to frost in coming cold periods (Kramer *et al.*, 2000). This could lead to a prolongation of ground frost in spring, but also to winter desiccation (Tranquilini, 1979). In the areas with a more continental climate character (N4-F2), there are positive relationships between winter NAO and radial growth (D'Arrigo *et al.*, 1993; Lindholm *et al.*, 2001), and negative tree growth departures were found in low NAO index winters when conditions are unusually cold in Scandinavia. Evidently, the influence on radial tree growth in central Fennoscandia of the NAO is dependent on habitat, local climate and exposure to the North Atlantic Ocean.

Reduced tree growth sensitivity to climate has been reported from large areas in the Northern Hemisphere during the last 30–50 years of the twentieth century (e.g., Briffa *et al.*, 1998). Furthermore, in dry, continental areas in North America, reduced radial tree growth has been associated with increased drought stress caused by increased temperatures during the last decades (Jacoby and D'Arrigo, 1995; Barber *et al.*, 2000; Biondi, 2000; Lloyd and Fastie, 2002). In the central Fennoscandian tree-ring data, reduced climate sensitivity in the last half of the twentieth century was only present west of the Scandinavian Mountains, while at the remaining sites climate sensitivity increased. The reduced climate sensitivity at the western sites is probably an effect of increasing temperatures. However, positive effects on tree growth of increased temperatures were only seen at the two Norwegian inland sites (N2, N3). As precipitation (annually as well as in summer) in western Fennoscandia has increased in the twentieth century, causing increased oceanic conditions (Hanssen-Bauer and Førland, 1998; Tuomenvirta *et al.*, 2000), we suggest that increased precipitation has counteracted the positive effects of increased temperatures at the remaining western sites. This can be seen in the N4 and S1 chronologies, where the growth optimum around 1950 is followed by a slightly declining growth trend. However, the effect of increased oceanic conditions is most evident at S2, which is the only central Fennoscandian chronology displaying a clear negative growth trend in the twentieth century contemporary with an increase in tree growth sensitivity to climate. We suggest that, just east of the Scandinavian Mountains, the wetting and warming in the twentieth century has altered the climate regime from subcontinental (due to the sheltering effect of the mountains) to be more suboceanic, causing decreased growth of the trees at the S2 site. The increased response to temperatures at S2 in 1945–91, together with a decreasing growth trend, implies that the change in climate regime in this area caused the trees to suffer from increased oceanic conditions. As there was no evidence for increased growth stress at either the oceanic, western, sites or the more continental, eastern sites, we suggest that presently the twentieth-century climatic change has only had a negative effect on Scots pine in areas where a marked change in climate regime occurs, e.g., from subcontinental to suboceanic. Consequently, provided that future increases in temperature are accompanied by increases in precipitation, Scots pines in central Fennoscandia are unlikely to be subjected to drought stress similar to that of North American trees.

Conclusion

Our main conclusions from this investigation are as follows.

(1) Growth variability, as well as correlation among sites, was higher in the western, oceanic, area of central Fennoscandia, compared to the eastern, more continental, areas. However, there was a gradual transition between western and eastern sites.

(2) Trees in western Fennoscandia showed a stronger response to climate, mainly to summer temperatures, than those in the eastern parts, which mainly responded to summer precipitation.

(3) The relationship between pine growth and the NAO was generally low. Pines at western sites responded both to summer and winter NAO, while the eastern sites only responded to winter NAO.

(4) Reduced growth sensitivity to climate in the second half of the twentieth century was found in the western parts, while the opposite was the situation in the east. Only at one site just east of the Scandinavian Mountains was evidence of growth stress found.

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References

Aniol, R.W. 1989: *Computer aided tree ring analysis system. User's Manual.* Schleswig, Germany.

Barber, V.A., Juday, G.P. and **Finney, B.P.** 2000: Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature* 405, 668–73.

Biondi, F. 2000: Are climate-tree growth relationships changing in North-Central Idaho, USA? *Arctic, Antarctic and Alpine Research* 32, 111–16.

Briffa, K.R. 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Reviews* 19, 87–105.

Briffa, K.R. and **Cook, E.R.** 1990: Methods of response function analysis. In Cook, E.R. and Kairiukstis, L., editors, *Methods of dendrochronology. applications in the environmental science*, Dordrecht: Kluwer, 240–47.

Briffa, K.R. and **Jones, P.D.** 1990: Basic chronology statistics and assessment. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of dendrochronology. applications in the environmental science*, Dordrecht: Kluwer, 137–52.

Briffa, K.R., Bartholin, T.S., Eckstein, D., Jones, P.D., Karlén, W., Schweingruber, F.H. and **Zetterberg, P.** 1990: A 1.400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346, 434–39.

Briffa, K.R., Osborn, T.J., Schweingruber, F.H., Harris, I.C., Jones, P.D., Shiyatov, S.G. and **Vaganov, E.A.** 2001: Low-frequency temperature variations from a northern tree ring density network. *Journal of Geophysical Research* 106, 2929–41.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Shiyatov, S.G. and **Vaganov, E.A.** 1998: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391, 678–82.

Chen, D. and **Hellström, C.** 1999: The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. *Tellus* 51A, 505–16.

Cook, E., Briffa, K., Shiyatov, S. and **Mazepa, V.** 1990a: Tree-ring standardization and growth-trend estimation. In Cook, E. and Kairiukstis, L., editors, *Methods of dendrochronology. applications in the environmental sciences*, Dordrecht: Kluwer, 104–22.

Cook, E.R., Shiyatov, S. and **Mazepa, V.** 1990b: Estimation of the mean chronology In Cook, E. and Kairiukstis, L., editors, *Methods of dendrochronology: applications in the environmental sciences*, Dordrecht: Kluwer, 123–32.

Cook, E.R., D'Arrigo, R.D. and **Briffa, K.R.** 1998: A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene* 8, 9–17.

Cook, E.R., D'Arrigo, R.D. and **Mann, M.E.** 2002: A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since AD 1400. *Journal of Climate* 15, 1754–64.

Dario, R.D. and **Jacoby, G.C.** 1993: Secular trends in high northern latitude temperature reconstructions based on tree rings. *Climatic Change* 25, 163–77.

D'Arrigo, R.D., Cook, E.R., Jacoby, G.G. and **Briffa, K.R.** 1993: NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews* 12, 431–40.

D'Arrigo, R.D., Jacoby, G.G., Free, M. and **Robock, A.** 1999: Northern hemisphere temperature variability from the past three centuries: tree-ring and model estimates. *Climatic Change* 42, 663–75.

Fritts, H.C. 1976: *Tree-rings and climate*. London: Academic Press.

Fritts, H.C., Vaganov, E.A., Sviderskaya, I.V. and **Shaskin, A.V.** 1991: Climatic variation and tree-ring structure in conifers: empirical and mechanistic models of tree-ring width, number of cells, cell size, cell-wall thickness and wood density. *Climate Research* 1, 97–116.

Glueck, M.J. and **Stockton, C.W.** 2001: Reconstruction of the North Atlantic Oscillation 1429–1983. *International Journal of Climatology* 21, 1453–65.

Guiot, J., Berger, A.L. and **Munaut, A.V.** 1982: Response functions. In Hughes, M.K., Kelly, P.M., and Pilcher, J.R., editors, *Climate from tree rings*, Cambridge: Cambridge University Press, 38–45.

Gunnarson, B.E. and **Linderholm, H.W.** 2002: Low-frequency summer temperature variation in central Sweden since the tenth century inferred from tree rings. *The Holocene* 12, 667–71.

Hanssen-Bauer, I. and **Førland E.J.** 1998: *Annual and seasonal precipitation variations in Norway 1896–1997.* DNMI report 28/98, klima, Oslo: Norwegian Meteorological Institute.

—— 2000: Temperature and precipitation variations in Norway 1900–1994 and their links to atmospheric circulation. *International Journal of Climatology* 20, 1693–708.

Hanssen-Bauer, I. and **Nordli, P.Ø.** 1998: *Annual and seasonal temperature variations in Norway 1876–1997.* DNMI report 25/98, klima, Oslo: Norwegian Meteorological Institute.

Holmes, R.L., Adams, R.K. and **Fritts, H.C.** 1986: Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin, with procedures used in the chronology development work, including user manuals for computer programs COFECHA and ARSTAN. Chronology Series VI. Laboratory of Tree-Ring Research, University of Arizona, Tucson, 50–65.

Hughes, M.K., Vaganov, E.A., Shiyatov, S., Touchan, R. and **Funkhouser, G.** 1999: Twentieth-century summer warmth in northern Yakutia in a 600-year context. *The Holocene* 9, 629–34.

Hurrell, J.W. 1995: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269, 676–79.

Jacoby, G.C. and **D'Arrigo, R.D.** 1995: Tree ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles* 9, 227–34.

Jones, P.D., Briffa, K.R., Barnett, T.P. and **Tett, S.F.B.** 1998: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *The Holocene* 8, 455–71.

Jones, P.D., Jonsson, T. and **Wheeler, D.** 1997: Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *International Journal of Climatology* 17, 1433–50.

Jones, P.D., Osborn, T.J. and **Briffa, K.R.** 2001: The evolution of climate over the last millennium. *Science* 292, 662–67.

Kalela-Brundin, M. 1999: Climatic information from tree-rings of *Pinus sylvestris* L. and a reconstruction of summer temperatures back to AD 1500 in Femundsmarka, eastern Norway, using partial least squares regression (PLS) analysis. *The Holocene* 9, 59–77.

Kirchhefer, A.J. 1999: Dendroclimatology on Scots pine (*Pinus sylvestris* L.) in northern Norway. PhD thesis, Department of Biology, University of Tromsø.

—— 2001: Reconstruction of summer temperatures from tree-rings of Scots pine (*Pinus sylvestris* L.) in coastal northern Norway. *The Holocene* 11, 41–52.

Kramer, K., Leinonen, I. and **Loustau, D.** 2000: The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. *International Journal of Biometeorology* 44, 67–75.

Kramer, P.J. and **Kozlowski, T.T.** 1979: *Physiology of woody plants.* Orlando: Academic Press.

Linderholm, H.W. 2002: Twentieth-century Scots pine growth variations in the central Scandinavian Mountains related to climate change. *Arctic, Antarctic, and Alpine Research* 34, 440–49.

Linderholm, H.W., Moberg, A. and **Grudd, H.** 2002: Peatland pines as climate indicators? A regional comparison of the climatic influence on Scots pine growth in Sweden. *Canadian Journal of Forest Research* 32, 1400–10.

Lindholm, M. 1996: Reconstruction of past climate from ring-width chronologies of Scots pine (*Pinus sylvestris* L.) at the northern forest limit in Fennoscandia. PhD thesis, University of Joensuu, Publications in Sciences 40.

Lindholm, M. and **Eronen, M.** 2000: A reconstruction of mid-summer temperatures from ring-widths of Scots pine since AD 50 in northern Fennoscandia. *Geografiska Annaler* 82A, 527–35.

Lindholm, M., Eggertson, O., Lovelius, N., Raspopov, O., Shumilov, O. and **Laanelaid, A.** 2001: Growth indices of North European Scots pine recorded the seasonal North Atlantic Oscillation. *Boreal Environment Research* 6, 275–84.

Lindholm, M., Lehtonen, H., Kolström, T., Meriläinen, J., Eronen, M. and **Timonen, M.** 2000: Climatic signals extracted from ring-width chronologies of Scots pines from the northern, middle and southern parts of the boreal forest belt in Finland. *Silva Fennica* 34, 317–30.

Lindholm, M., Meriläinen, J., Timonen, M., Vanninen, P. and **Eronen, M.** 1997: Effects of climate on the growth of Scots pine in the Saimaa Lake district, south eastern Finland, in the southern part of the boreal forest belt. *Dendrochronologia* 15, 151–68.

Lloyd, A.H. and **Fastie, C.L.** 2002: Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. *Climate Change* 52, 481–509.

Mäkinen, H., Nöjd, P. and **Mielikäinen, K.** 2000: Climatic signal in annual growth variation of Norway spruce (*Picea abies*) along a transect from central Finland to the Arctic timberline. *Canadian Journal of Forest Research* 30, 769–77.

Mann, M.E., Bradley, R.S. and **Hughes, M.K.** 1999: Northern Hemisphere temperatures during the past millennium: inferences, uncertainties and limitations. *Geophysical Research Letters* 26, 759–62.

Mysterud, A., Yoccoz, N.G., Stenseth, N.C. and **Langvatn, R**. 2000: Relationship between sex ratio, climate and density in red deer: the importance of spatial scale. *Journal of Animal Ecology* 69, 959–74.

Nikolov, N. and **Helmisaari, H.** 1992: Silvics of the circumpolar boreal forest tree species. In Shugart, H.H., Leemans, R. and Bonan, G.B., editors, *A systems analysis of the global boreal forest*, Cambridge: Cambridge University Press, 13–84.

Ojansuu, R. and **Henttonen, H.** 1983: Kuukauden keskilämpösumman ja sademäärän paikallisten arjoven johtaminen ilmatieteen laitoksen mittaustiedoista. *Silva Fennica* 17, 143–60.

Post, E. and **Stenseth, N.C.** 1999: Climatic variability, plant phenology, and northern ungulates. *Ecology* 80, 1322–39.

Rogers, J.C. 1990: Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cyclone frequencies. *Journal of Climate* 3, 1364–79.

Slonosky, V.C., Jones, P.D. and **Davies, T.D.** 2001: Atmospheric circulation and surface temperature in Europe from the 18th century to 1995. *International Journal of Climatology* 21, 63–75.

Solberg, B.Ø., Hofgaard, A. and **Hytteborn, H.** 2002: Shifts in radial growth responses of coastal *Picea abies* induced by climatic change during the 20th century, Central Norway. *Ecoscience* 9, 79–88.

Tranquilini, W. 1979. *Physiological ecology of the Alpine timberline. Tree existence at high altitudes with special reference to the European Alps*. Ecological Studies 31. Berlin: Springer Verlag.

Tuomenvirta, H., Alexandersson, H., Drebs, A., Frich, P. and **Nordli, P.Ø.** 2000: Trends in Nordic and Arctic temperature extremes and ranges. *Journal of Climate* 13, 977–90.

Ulbrich, U. and **Christoph, M.** 1999. A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dynamics* 15, 551–59.

Wallén, C.C. 1970: *Climates of northern and western Europe.* World survey of climatology vol. 5. Amsterdam: Elsevier.

Weyhenmeyer, G.A., Bleckner, T. and **Pettersson, K.** 1999: Changes of the plankton spring outburst related to the North Atlantic Oscillation. *Limnology and Oceanography* 44, 1788–92.