BOREAL ENVIRONMENT RESEARCH 6: 275–284 ISSN 1239-6095
Helsinki 20 December 2001

Growth indices of North European Scots pine record the seasonal North Atlantic Oscillation

Markus Lindholm[1)], Ólafur Eggertsson[2)], Nikolay Lovelius[3)], Oleg Raspopov[4)], Oleg Shumilov[4)] and Alar Läänelaid[5)]

[1)] *Saima Centre for Environmental Sciences, Linnankatu 11, FIN-57130 Savonlinna, Finland*
[2)] *Laboratory for Wood Anatomy and Dendrochronology, Lund University, P.O. Box 117, SE-22100 Lund, Sweden*
[3)] *Botanical Institute of Russian Academy of Science, Prof. Popova Street 2, 197376 St. Petersburg, Russia*
[4)] *St. Petersburg Filial of Institute of Terrestrial Magnetism, Ionosphere and Radiowaves Propagation of Russian Academy of Sciences, P.O. Box 188, 191023 St. Petersburg, Russia*
[5)] *Institute of Botany and Ecology, University of Tartu, Lai Street 40, 2400 Tartu, Estonia*

Lindholm, M., Eggertsson, Ó., Lovelius, N., Raspopov, O., Shumilov, O. & Läänelaid, A. 2001. Growth indices of North European Scots pine record the seasonal North Atlantic Oscillation. *Boreal Env. Res.* 6: 275–284. ISSN 1239-6095

A network of 30 ring-width chronologies of Scots pine (*Pinus sylvestris* L.) from various parts of the boreal forest belt in north Europe were calibrated against seasonal indices of the North Atlantic Oscillation (NAO). The northernmost pines, from the forest-limit region, proved to be sensitive to summertime variations of the NAO, while most southern pines respond to winter variations in the NAO index. Going from the north to the south, growth responses demonstrate that this drastic shift occurs directly south of the northern part of the boreal belt. The southern part of the pine network was used for building a transfer model of wintertime NAO between 1893 and 1981. Although the final model explains only one quarter of the variance of the predictand winter NAO index, the verification statistics show reasonable reconstruction skill. This preliminary work will complement the increasing number of proxy experimental reconstructions of the NAO.

Introduction

The goal of this work was to test the potential of a network of 30 ring-width chronologies of Scots pine (*Pinus sylvestris* L) from north Europe for use in reconstruction of the North

Atlantic Oscillation (NAO). Tree-ring chronologies have recently provided important new information about the dynamics of the NAO (Overpeck *et al.* 1997, Cook *et al.* 1998, Briffa 2000, Glueck and Stockton 2001, Jones *et al.* 2001). The NAO is characterized by a north–south difference in sea level pressure (Rogers 1984, Van Loon and Rogers 1978, Rogers and Van Loon 1979). A low-pressure region is centered near Iceland and a high-pressure region is situated in the subtropics near the Azores. This pressure contrast drives the surface winds and wintertime storms from west to east across the North Atlantic. When the pressure is lower than normal near Iceland, it tends to be higher than normal near the Azores and vice versa. This out-of-phase relation defines the NAO index. In North America, Europe, and North Africa, precipitation patterns and wintertime temperatures can be attributed to the NAO's phases (Rogers 1984). Since the mid-1970s, the NAO index has generally been very high. During this time, winters have been relatively warm in Europe and cold in the northwest Atlantic while the Mediterranean has been particularly dry.

The distinct climate anomaly patterns associated with opposite phases of the NAO suggest that tree-ring chronologies in certain key regions should capture at least part of its variability (Cook *et al.* 1998, Briffa 2000). During seasons of high positive NAO there is a strong pressure gradient between Iceland and the Azores, resulting in enhanced westerly flow into western Europe (Rogers 1984). These seasons are associated with relative warmth over northwestern Europe, Siberia and the southeast United States;

Table 1. The pine chronology network. Locations of the sampling sites for the pine ring-width chronologies. The number of trees and their temporal span are included.

No.	Site name	Country	Start	End	Span	Longitude (E)	Latitude (N)	No. of trees
1	Nunas	Finland	1786	1991	206	68°30´	22°00´	24
2	Leppäjärvi 1	Finland	1789	1991	203	68°30´	23°20´	13
3	Leppäjärvi 2	Finland	1789	1991	203	68°30´	23°20´	13
4	Luspa	Finland	1792	1992	201	68°30´	22°00´	10
5	Kaaresuvanto	Sweden	1803	1992	190	68°28´	22°15´	26
6	Karasjok	Norway	1698	1992	295	69°28´	25°30´	27
7	Skallovaara	Finland	1711	1991	281	69°47´	27°20´	19
8	Karhunpesäkivi	Finland	1398	1993	596	68°50´	27°15´	23
9	Uusijoki	Finland	1659	1992	334	68°35´	28°00´	26
10	Pääjärvi 1	Russia	1548	1993	448	66°00´	31°00´	20
11	Pääjärvi 2	Russia	1471	1993	523	66°15´	30°30´	26
12	Pääjärvi 3	Russia	1707	1993	287	66°15´	30°00´	10
13	Kandalacha	Russia	1687	2000	314	67°10´	33°10´	15
14	North-Karelia	Finland	1413	1991	579	63°16´	30°40´	19
15	Central Finland	Finland	1454	1996	543	62°51´	25°29´	31
16	Huvilasaari	Finland	1685	1993	309	61°75´	29°20´	17
17	Pitkäsaari	Finland	1794	1993	200	61°80´	29°10´	14
18	Sauvasaari	Finland	1783	1993	211	61°85	29°00´	19
19	Eteissaari	Finland	1825	1993	169	61°81´	28°68´	26
20	Kyrönniemi	Finland	1863	1992	130	61°86´	28°88´	21
21	Punkaharju	Finland	1815	1992	178	61°80´	29°40´	26
22	Raskov	Russia	1588	2000	413	62°00´	32°25´	7
23	Velikiy	Russia	1598	2000	403	66°10´	35°40´	8
24	St. Petersburg	Russia	1830	2000	171	60°00´	30°25´	11
25	Lake Onega	Russia	1586	1999	414	61°28´	35°08´	21
26	Medvegorsk	Russia	1778	1999	222	62°54´	34°36´	17
27	Lake Sam	Russia	1733	1998	266	61°55´	33°00´	26
28	Kivach	Russia	1813	1999	187	62°15´	34°00´	16
29	Nemdeo	Estonia	1775	1997	223	59°20´	22°10´	47
30	Gotland	Sweden	1734	1981	248	57°10´	18°30´	22

cold in northeast Canada; higher rainfall over Scandinavia and northern Egypt and relatively drier conditions in the north and west Mediterranean. These relationships are most pronounced in winter and early spring but are much less apparent in summer.

The major advantage of using tree-rings in the reconstruction of paleoclimates is the annual resolution of the resulting record. In order to identify NAO variability at different frequencies, the instrumental records (e.g. Hurrell 1995, Jones *et al.* 1997) need to be extended back in time. The NAO is expected to go through active and passive phases, but although the NAO is considered to be a decadal feature, it is not yet known whether there are fundamental NAO frequencies during active phases that would enhance predictability (Cook *et al.* 1998, Jones *et al.* 2001). The interrelationship between large-scale patterns of temperature, precipitation and atmospheric pressure variability mean that networks of climate sensitive tree-ring chronologies can be used to make statistical inferences about the past behaviour of circulation patterns or important circulation indices (Fritts 1976, Jones *et al.* 2001).

This initial experiment with the North European pine chronology network is used to study its potential usefulness for inclusion in NAO reconstruction efforts. However, the chronologies are temporally too limited to allow for a transfer model to be applied beyond the calibration period. In addition, none of the chronologies were specifically developed with the reconstruction of the NAO in mind. Cook *et al.* (1998) call these kinds of chronologies ‘chronologies of opportunity’. Thus the results of this work will be used as guidelines for future sampling strategies and methodological developments.

Data

We used a network of 30 ring-width chronologies of Scots pine (*Pinus sylvestris* L.) from the boreal forest belt in north Europe (Table 1). Nine of the chronologies come from the northern forest-limit region, six from the middle boreal region and the remaining 15 from the southern boreal zone (Fig. 1 and Table 1). Twenty of these site chronologies have been previously published. The building of these chronologies, analyses of them in terms of common growth variability and growth responses to climatic factors were described by Lindholm (1996) for the northern, Lindholm *et al.* (2000) for the middle, and Lindholm *et al.* (1997, 1998–1999) for the southern parts of the boreal forest belt in north Europe. The remaining ten, unpublished, site chronologies come from Russian Karelia (7 sites) and two islands in the Baltic Sea: Nemdeo, belonging to Estonia (1 site), and the island of Gotland, belonging to Sweden (1 site).

Seasonal NAO indices were calculated from the monthly values of sea level pressure differences between stations on the Azores and Iceland (Jones *et al.* 1997). These data can be downloaded from the Internet site of the Climatic Research Unit, University of East Anglia: http://www.cru.uea.ac.uk/cru/data/nao.htm. Continuous NAO indices are available from 1825 to the present. However, because of the limited time span of the shorter chronologies (110 years minimum), the calibration period in this work was limited to 89 years (1893 to 1981). This procedure also ensures adequate replication.

Methods

Building the ring-width chronologies

Ring widths of the samples were measured to the nearest 0.01 mm. Measured series were then cross-dated (Fritts 1976) and the annual resolution verified by several procedures (Holmes *et al.* 1986, Deusen and Koretz 1988, Aniol 1989). The measured tree-ring time-series were standardized to emphasize the desired signal and to reduce the unwanted noise (Fritts 1976, Cook and Briffa 1990, Cook *et al.* 1990). The noise component, the nonclimatic sources of variation in the data, were modelled and then removed using flexible spline functions. It was assumed that the removed low frequency variance consists mainly of noise. In standardisation, there remains a risk of loss of meaningful long timescale variance. The 89-year calibration period also sets a limit to the lowest extractable fre-

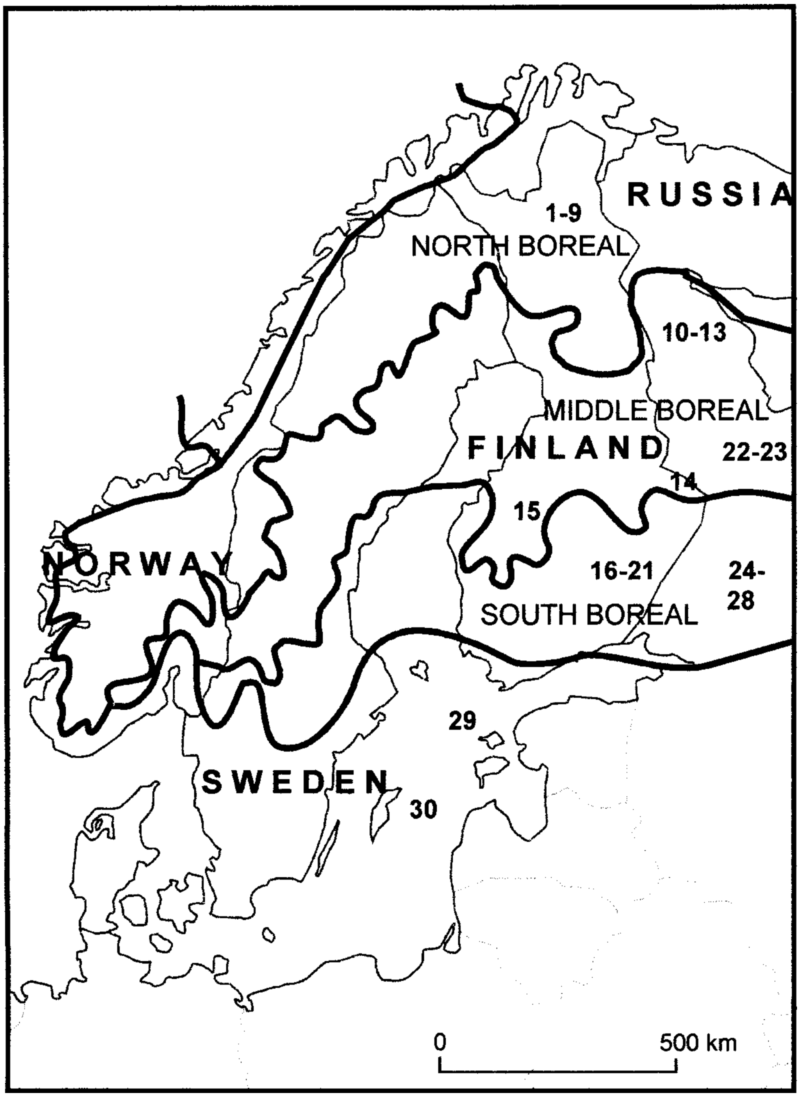

Fig. 1. Distribution of the 30 ring-width chronologies over North Europe. Chronology numbers refer to Tables 1, 2, and 5. The boreal forest belt has been divided into northern, middle and southern parts. As in Tables 1 and 2, site numbers start from the North and go to the South.

quencies. The splines applied here, pass 50% of the variance of the series at frequencies greater than two thirds of the series length (Cook and Peters 1981). Equal splines were applied to all 30 data sets.

Calibration

Growth responses of pines to seasonal NAO indices were studied by correlation analysis (Pearson product moment *r*). The transfer models were developed using multiple regression after extracting the Principal Components (PCs) of the predictor variables. A correlation matrix was used without any rotation. Previous studies have shown that ring-width chronologies of northern pines show relatively high autocorrelations up to order three (Lindholm *et al.* 2000). Autocorrelation is generally linked to lagged growth responses to climate (e.g. Fritts 1976). In dendroclimatological reconstructions (e.g. Briffa *et al.* 1983, 1988, 1990, Lindholm 1996), the growth in year *t* is expected to depend on the climate in year *t* and in the previous years. Consequently, a model structure including three additional predictors from years immediately lagging year *t*, was applied in this work. The model may be written as:

$$C_t = f(W_t, W_{t+1}, W_{t+2}, W_{t+3}), \qquad (1)$$

where C_t is the seasonal NAO index in year *t*, and W_{t+1}, W_{t+2}, and W_{t+3} are the lagged tree-ring predictors. This procedure increases the number of variables to four times the original.

Fritts (1976) and Guiot (1990) recommend the use of PCs and the limiting of their number in calibration. The objective is not only to reduce the number of predictors but also to exclude the smallest scale variations that are least likely to represent the signal of large-scale climatic variations. The largest-scale PCs are also analogous to the mean value of many climate data sets (Fritts *et al.* 1971); and as mean values, the larger PCs have a reduced error component. The effects of occasional extreme values and other minor abnormalities become a part of the smallest PCs that are left out of the analyses. Thus, the largest PCs are likely to be distributed normally even if some of the individual chronologies are not (Fritts 1990).

Various criteria have been presented for selecting the PCs to enter regression (Fritts 1976, Guiot 1985, 1990, Briffa *et al.* 1983, 1988, Cook *et al.* 1998). In this work, a two-stage procedure was followed for screening the PC predictor variables for limiting their number in regression. In the first stage, the cumulative sum of loading of the acceptable PCs was set to 95%. In the second stage, the number of remaining PCs was further delimited based on the cut-off *t*-value set at 0.8.

Verification

A cross-calibration/verification procedure, frequently applied in dendroclimatology (e.g. Briffa *et al.* 1988, 1990, Lindholm 1996, Cook *et al.* 1998), was exercised to test the general form of the reconstruction equation. The NAO index was divided into two periods of roughly equal length, 1893–1936 and 1937–1981. The division allows for three models to be developed: an early calibrated (late verified), a late calibrated (early verified) and a final model utilizing the total length of the available data from 1893 to 1981.

Calibration and verification statistics (Reduction of Error, Coefficient of Efficiency) were described by Fritts (1976, 1990), Briffa *et al.* (1988), Gordon *et al.* (1982), and Cook *et al.* (1994). According to Fritts (1976), Reduction of Error (RE) is calculated as follows:

$$\mathrm{RE} = 1 - \mathrm{SSR/SSM}, \qquad (2)$$

where SSR is the sum of the squares of the differences between actual data and the statistical estimates (the residuals) and SSM is the sum of the squares of the differences of the actual data from the mean of the dependent data set used for calibration. Coefficient of Efficiency (CE) differs from RE only in that the calibration period mean of measured climate data is replaced by the mean of the verification period (Briffa *et al.* 1988).

Results

Growth responses of boreal pine chronologies to seasonal variation in the NAO

Growth responses of pine were revealed by correlating (Pearson, 2-tailed) each of the available chronologies with seasonal NAO indices, viz. winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). Included were 89 years of data, 1893 to 1981 (Table 2).

Eight of the nine forest-limit chronologies (sites 1–9 in Table 2) correlate significantly (at least $p < 0.01$ level) with the summertime NAO index. Only site 2 (Leppäjärvi 2) shows a lesser forcing, although it is still significant at $p < 0.05$ level. No other NAO season seems to yield any growth responses in forest-limit pines. In this sub-region, all chronologies correlate with summer NAO index with *r* values above 0.24 and most of them above 0.3. The springtime NAO index yields the lowest overall correlations.

Moving southward, a remarkable change occurs in growth responses right below the forest-limit region, between sites 9 and 10 (Uusijoki and Pääjärvi 1 in Table 2). This borderline is located between the northern and middle boreal parts (Fig. 1). Table 2 clearly demonstrates that pines from the middle and southern parts of the boreal belt are much more sensitive to NAO variability during winter. Most chronologies have highly significant (at least $p < 0.01$ level) correlations with the wintertime NAO index. With only four exceptions, the 21 chronologies, south of the forest-limit region, correlate significantly (at least $p < 0.05$) with the wintertime NAO index. Four of the southern and middle boreal chronologies also correlate simultaneously with the summertime NAO index, although less significantly. As was true of the more northern chronologies, chronologies from these middle and southern regions show little common variability with the spring and autumn NAO indices.

Reconstruction model for winter NAO variability

The total calibration period (1893–1981) was

Table 2. Growth responses of North European pines to the seasonal NAO variation in sites ordered from north to south. Correlations (Pearson, 2-tailed) between the 30 site chronologies and seasonal NAO data. D-J-F (December, January, February), M-A-M (March, April, May), J-J-A (June, July, August), and S-O-N (September, October, November) denote winter, spring, summer, and autumn modes of the NAO respectively. Calibration period is 1893–1981, spanning 89 years. Significant values at the 0.05 and 0.01 level are marked with one or two asterisks correspondingly.

No.	Site name	D-J-F	M-A-M	J-J-A	S-O-N
1	Nunas	0.13	–0.05	0.38**	–0.00
2	Leppäjärvi 1	–0.04	–0.11	0.24*	–0.04
3	Leppäjärvi 2	0.07	–0.11	0.30**	0.08
4	Luspa	0.16	– 0.06	0.30**	–0.06
5	Kaaresuvanto	0.1	–0.04	0.28**	–0.01
6	Karasjok	–0.01	–0.07	0.30**	0.00
7	Skallovaara	0.12	–0.12	0.34**	0.06
8	Karhunpesäkivi	0.13	–0.13	0.41**	0.03
9	Uusijoki	0.08	–0.13	0.41**	0.05
10	Pääjärvi 1	0.35**	0.01	0.17	0.05
11	Pääjärvi 2	0.32**	–0.10	0.28**	0.12
12	Pääjärvi 3	0.36**	0.18	0.06	0.12
13	Kandalacha	0.30**	0.02	–0.08	0.07
14	North-Karelia	0.10	–0.06	0.10	0.04
15	Central Finland	0.21*	0.16	0.09	0.04
16	Huvilasaari	0.34**	0.00	0.17	0.03
17	Pitkäsaari	0.30**	–0.06	0.04	0.06
18	Sauvasaari	0.35**	0.05	0.02	0.02
19	Eteissaari	0.24*	0.00	0.12	0.00
20	Kyrönniemi	0.41**	0.05	0.21*	0.11
21	Punkaharju	0.30**	–0.03	0.08	0.16
22	Raskov	0.10	0.01	–0.08	0.04
23	Velikiy	0.12	0.07	–0.12	0.14
24	St. Petersburg	0.20*	0.18	0.07	–0.07
25	Lake Onega	0.09	–0.03	0.04	0.20
26	Medvegorsk	0.30**	0.12	0.26*	0.16
27	Lake Sam	0.27**	0.04	0.08	0.15
28	Kivach	0.21*	0.05	0.21*	0.20
29	Estonia	0.38**	–0.03	0.16	–0.08
30	Gotland	0.29**	–0.08	–0.02	–0.04

divided for early (1893–1936) and late (1937–1981) periods in order to test the time stability of the regression coefficients. The 17 southern chronologies (south of the forest-limit region, starting from site 10 in Table 2), yielding at least significant correlations ($p < 0.05$), were used in regression against the winter NAO index after extracting the PCs. The three lagged values, together with concurrent chronology values, produce a pool of 68 candidate predictor PCs in total. A two-stage screening procedure of the PC predictor variables was used for limiting their number in regression (Table 3). In the first stage, 30 PCs out of 68 were extracted as the cumulative sum of loading was set to 95%. In the second stage, 7 PCs (1, 3, 6, 7, 11, 27, 30) were further retained based on the cut-off *t*-value set at 0.8.

The selected 7 PCs were first used as predictors of the winter NAO in the two submodels (early and late calibrated). Their regression coefficients, calibration and verification statistics were relatively similar justifying the calibration of the final model over the entire period from 1893–1981 (Table 4). The selected 7 PCs represent 44.5% of the total variance in the chronology network. Only less than one half of the original ring-width variance was utilized in the reconstruction models. The final model extracted 25% of the dependent NAO variance. The calibration and verification statistics, RE and CE in Table 4, are positive (0.262–0.413), which is generally considered an indication of reasonable skill in reconstruction. In Fig. 2 the wintertime NAO index is superimposed on the modelled values. Only interannual to decadal

Table 3. Screening of the PC predictor variables for limiting their number in regression. In the first stage, 30 PCs of the 68 were extracted as the cumulative sum of loading was set to 95%. In the second stage 7 PCs (1, 3, 6, 7, 11, 27, 30) were retained based on the cut-off *t*-value (0.8). Using the selected 7 PCs, 44.5% of the total variance in the chronology network was utilized in the actual reconstruction model.

PC and % variance explained		*t*-value in various models		
PC	Variance explained	Early calibration–late verification	Late calibration–early verification	Final
1	21.6	1.9	1.6	2.7
3	8.2	2.2	1.8	2.8
6	5.3	1.7	0.9	1.9
7	5.0	1.4	1.0	1.1
11	3.1	1.4	1.8	2.4
27	0.7	0.9	1.4	1.8
30	0.6	1.0	1.2	0.9
Total	44.5			

Table 4. Results of the calibration and verification. Reduction of Error (RE) and Coefficient of Efficiency (CE) statistics are positive.

	Calibration			Verification	
Period	R^2	r	F	RE	CE
1893–1936	0.26	0.512	2.3*	0.262	0.374
1937–1981	0.3	0.551	2.6*	0.303	0.413
1893–1981	0.25	0.5	4.2**		

R^2 = explained NAO variance, CE = coefficient of efficiency, F = F-ratio of model, * = statistically significant ($p < 0.05$), r = Pearson correlation, ** = statistically significant ($p < 0.01$), RE = reduction of error, RE or CE > 1 = significant (*)

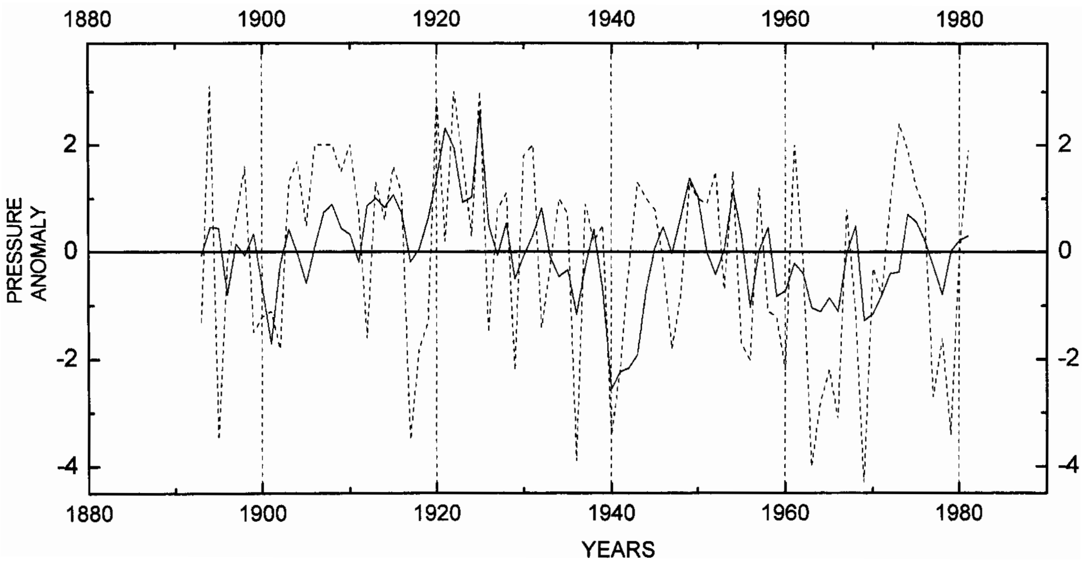

Fig. 2. The actual winter NAO index (dash) plotted together with the modelled values (solid). The anomalies are normalised sea level pressure differences between stations on the Azores and Iceland. Interannual-to-decadal changes are evident.

scale variability (the high- and mid-frequencies) was extracted.

Discussion

The pine network from the boreal region of North Europe clearly responds to the seasonal variability in the NAO, especially winter and summer modes of variation. Wintertime NAO seems to influence the growth of southern boreal pines, south of the northern forest-limit region. The mechanism of this influence is not yet entirely clear. However, Rogers and Van Loon (1979) and Rogers (1990) indicate that winter 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.

Table 5. The potential of the present network for extended reconstruction of the NAO. Four pine chronologies from Finland already have a temporal dimension beyond the present work. The site chronologies from living trees used here form the modern part of these master chronologies.

Region	Span in years	Related to sites
Northern forest-limit	7500	1–9
Eastern	600	14
Central	700	15
South-eastern	1750	16–21

The northern forest-limit pines respond to the summer manifestation of the NAO. Summertime NAO is known to have large pressure anomalies of one sign over Greenland and the eastern Mediterranean, and anomalies of opposite sign across eastern North America, the Labrador Sea, and over northern Europe (Rogers 1984). The belt of high pressure that extends across the Atlantic from the southern United States into western Europe, is weaker, northward shifted, and discontinuous in the central Atlantic in the summer (Van Loon and Rogers 1978).

The final model shows reasonable reconstruction skill (RE and CE > 0), although only 25% of the dependent variance could be extracted. This may be considered as an encouraging result as the chronology network was not specifically developed for NAO reconstruction. The short temporal span of the chronologies presented here effectively prevents the use of the transfer model for actual reconstruction. However, the present tree-ring databases are growing and the chronologies reaching backwards in time. Table 5 shows the recent temporal cover of some of the Finnish chronologies.

Only interannual and decadal variations (the high-to-mid-frequencies) are presented in this work. Fig. 2 shows that the high-frequency variability is slightly more faithfully reproduced than the low-frequency changes. Several peaks do coincide, although the reconstruction often seems to lag behind in magnitude of the measured values. However, the downward trend during the 1920s and 1930s is evident in the actual values as well as in the reconstruction. The most recent decades, the 1960s and 1970s, are very much out of phase. The actual values have greater variance than the reconstruction, 2.08 and 0.84 respectively.

Cook *et al.* (1998) were able to characterise persistent oscillatory behaviour in the NAO, particularly at periods near 2.1, 8 and 24 years during the last 300 years and they suggest that a near 70-year ‘oscillation’ apparent in the post-1850 instrumental period, may not have existed in the previous 150 years. Another preliminary, though not exclusively tree-ring based (including δ^{18}O and accumulation data from Greenland Ice Sheet Project 2-GISP2), reconstruction of winter NAO has been produced for the period from 1429 onwards by Glueck and Stockton (2001), who consider this reconstruction to be a somewhat more reliable indication of multidecadal NAO variability. It indicates generally high values for 1741–1758, supporting the idea that the observed period of high NAO indices in the last two decades may not be unprecedented.

The final model in this work has comparatively less predictive power than the above-cited two works by Cook *et al.* (1998) and Glueck and Stockton (2001). The Cook *et al.* (1998) prediction equation accounted for some 45% of the observed index variability when tested against various independent periods of data, while the Glueck and Stockton (2001) regression explained slightly less (0.31). The northern European reconstruction presented here implies that future development and inclusion of northern pine chronologies is very likely to produce an even more reliable winter NAO reconstruction. Similarly, it is also likely that good reconstructions of the summer manifestation of the NAO will be recoverable from northern tree-ring data. As Cook *et al.* (1998) stated, the North Atlantic climate patterns may hold clues for climate trends over long time periods and may help in identifying the human impact on climate change. International efforts are now under way to improve the monitoring network for the NAO, with a view to forecasting its long-term evolution.

Acknowledgements: This work was funded by the Academy of Finland (grant 40962 to Prof. Matti Eronen) and an EC research program EXTRATERRESTRIAL (Contract ERBIC15CT980123). We acknowledge the sampling work, sample preparation, and careful measurement of ring-widths by a number of skilful assistants in several national laboratories. We are also grateful to Dr. Mary F. Glueck for a fruitful review of the manuscript and several other colleagues worldwide for enlightening discussions about the characteristics of the NAO phenomenon.

References

Aniol R.W. 1989. *Computer aided tree ring analysis system*. User’s Manual. Schleswig, Germany, stencil, 20 pp.

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

Briffa K.R., Bartholin T.S., Eckstein D., Jones P.D., Karlén W., Schweingruber F.H. & Zetterberg P. 1990. A 1400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346: 434–439.

Briffa K.R., Jones P.D., Pilcher J.R. & Hughes M.K. 1988. Reconstructing summer temperatures in northern Fennoscandia back to A.D. 1700 using tree-ring data from Scots pine. *Arctic and Alpine Research* 20: 385–394.

Briffa K.R., Jones P.D., Wigley T.M., Pilcher J.R. & Bailie M. 1983. Climate reconstruction from tree rings: Part 1. Basic methodology and preliminary results for England. *Journal of Climatology* 3: 233–242.

Cook E. & Briffa K. 1990. Data analysis. In: Cook E. & Kairiukstis L. (eds.), *Methods of dendrochronology: applications in the environmental science*. Kluwer Academic Publishers, Dordrecht, pp. 97–162.

Cook E.R., Briffa K.R. & Jones P.D. 1994. Spatial regression methods in dendroclimatology: a review and comparison of two techniques. *International Journal of Climatology* 14: 379–402.

Cook E.R., Briffa K., Shiyatov S. & Mazepa V. 1990. Tree-ring standardization and growth-trend estimation. In: Cook E. & Kairiukstis L. (eds.), *Methods of dendrochronology: applications in the environmental science*. Kluwer Academic Publishers, Dordrecht, pp. 104–123.

Cook E.R., D'Arrigo R.D. & 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. & Peters K. 1981. The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41: 45–53.

Deusen Van P.C. & Koretz J. 1988. *Theory and programs for dynamic modeling of tree rings from climate*. General Technical Report, SO-70. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 18 pp.

Fritts H.C. 1976. *Tree rings and climate*. Academic Press, London, 567 pp.

Fritts H.C. 1990. Statistical reconstruction of spatial variations in climate. In: Cook E. & Kairiukstis L. (eds.), *Methods of dendrochronology: applications in the environmental science*. Kluwer Academic Publishers, Dordrecht, pp. 193–210.

Fritts H.C., Blasing T.J., Hayden B.P. & Kutzbach J.E. 1971. Multivariate technique for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. *Journal of Applied Meteorology* 10: 845–864.

Glueck M.F. & Stockton C.W. 2001. Reconstruction of the North Atlantic Oscillation, 1429–1983. *International Journal of Climatology*. [In press].

Gordon G.A., Gray B.M. & Pilcher J.R. 1982. Verification of dendroclimatic reconstructions. In: Hughes M.K., Kelly P.M., Pilcher J.R. & LaMarche V.C.Jr. (eds.), *Climate from tree rings*. Cambridge University Press, pp. 58–62.

Guiot J. 1985. The extrapolation of recent climatological series with spectral canonical regression. *Journal of Climatology* 5: 325–335.

Guiot J., 1990: Methods of calibration. In: Cook E. & Kairiukstis L. (eds.), *Methods of dendrochronology: applications in the environmental sciences*. Kluwer Academic Publishers, Dordrecht, pp. 165–178.

Holmes R.L., Adams R.K. & Fritts H.C. 1986. T*ree-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, pp. 50–65.

Hurrell J.W. 1995. Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science* 269: 676–679.

Jones P.D., Jónsson T. & Wheeler D. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *Int. J. Climatol.* 17: 1433–1450.

Jones P.D., Osborn T.J. & Briffa K.R. 2001. The evolution of climate over the last millennium. *Science* 292: 662–667.

Lindholm M. 1996. *Reconstruction of past climate from ring-width chronologies of Scots pine (Pinus sylvestris L.) at the northern forest limit in Fennoscandia*. Ph.D. thesis, University of Joensuu, Publications in Sciences 40, 169 pp.

Lindholm M., Lehtonen H., Kolström T., Meriläinen J., Eronen M. & Timonen M. 2000. Climatic signals extracted from ring-width chronologies of Scots pine from the Northern, Middle and Southern parts of the boreal forest belt in Finland. *Silva Fennica* 34: 317–329.

Lindholm M., Meriläinen J. & Eronen M. 1998–1999. A 1250-year ring-width chronology of Scots pine for south-eastern Finland, in the southern part of the boreal forest belt. *Dendrochronologia* 16–17: 183–190.

Lindholm M., Meriläinen J., Timonen M., Vanninen P. & 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: 151–168.

Overpeck J., Hughen K., Hardy D., Bradley R., Case R., Douglas M., Finney B., Gajewski K., Jacoby G., Jennings A., Lamoureux S., Lasca A., MacDonald G., Moore J., Retelle M., Smith S., Wolfe A. & Zielski G. 1997. Arctic environmental changes of the last four centuries. *Science* 278: 1251–1256.

Rogers J.C. 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Monthly Weather Review* 112: 1999–2015.

Rogers J.C. 1990. Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cyclone frequencies. *Journal of Climate* 3: 1364–1379.

Rogers J.C. & Van Loon H. 1979. The seesaw in winter temperatures between Greenland and northern Europe: Part II: Some oceanic and atmospheric effects in middle and high latitudes. *Monthly weather Review* 107: 509–519.

Van Loon H. & Rogers J.C. 1978. The seesaw in winter temperatures between Greenland and northern Europe: Part 1: general description. *Monthly Weather Review* 106: 296–310.

Received 4 June 2001, accepted 18 September 2001