PINE GROWTH AND CLIMATE AD 1800-1992 ALONG A TRANSECT ACROSS THE SCANDES AT 69°N

Andreas J. Kirchhefer, Department of Biology, University of Tromsø, N-9037 Tromsø, Norway

Abstract: A total of eight ring-width chronologies of Scots pine, *Pinus sylvestris* L., was constructed in northern Norway 69°N along a west-east transect from the Atlantic coast across the Scandes. During AD 1800-1992, the first principal component (PC 1) reflected about 70% variability in common for the chronologies, while about 10% of the variability was related to the west-east gradient (PC 2). July temperature explained about 56% of the variability in PC 1. Growth of Scots pine at the coast was determined by July-August temperatures (R^2_{adj} = 45%), while inland growth was mainly limited by July temperatures alone (R^2_{adj} = 48%). In the inner Scandes, pine experienced a growth reduction during the temperature optimum of the 20th century in the 1930s, while the growth maximum was delayed until about 1950. Possible causes might relate to a high year-to-year variability of summer temperature and allocation of assimilates for reproduction, to mid-winter climate, late winter precipitation, or a combination of these factors. Regional variations of pine growth during the 20th century thermal optimum suggests a division of the study area into three dendroecological regions: 1) a coastal region, 2) the inner Scandes, and 3) the Finnmarksvidda, east of the Scandes.

Keywords: Tree rings, *Pinus sylvestris* L., climate, dendroclimatology, Norway

INTRODUCTION

The high latitudes are recognised as areas strongly affected by climate change (Kattenberg *et al.*, 1996; Nicholls *et al.*, 1996; Watson *et al.*, 1998). Tree rings form as a natural record of environmental changes in the north-boreal forests, particularly for the annual variability of summer temperatures (Fritts, 1976; Cook and Kairiukstis, 1990). Consequently, analyses of tree-ring chronologies have become a well-established tool for the reconstruction of past temperatures along the northern tree line (Guiot, 1985b; Briffa *et al.*, 1988; 1992; 1994; 1996; D'Arrigo *et al.*, 1992b; Graybill and Shiyatov, 1992; Jacoby and D'Arrigo, 1995). Used alone or in combination with other high-resolution climate proxies, tree-ring chronologies allow inferences to be made on past arctic, northern hemispheric and global temperatures (Overpeck et al., 1997; Jones et al., 1998; Mann et al., 1998; 1999; D'Arrigo et al., 1999). In a circum-arctic perspective, northern Fennoscandia occupies a unique geographic position. Situated at the north-western edge of the Eurasian continent, the region of main heat transfer between the low latitudes and the Arctic, northern Fennoscandia is exposed to climate influences both from the Arctic and the North Atlantic Ocean. In addition, the Scandes affect the regional pattern of climate by enhancing the gradient of continentality, directing the flow of air masses and causing local montane climates (Barry, 1992; Aune, 1993).

In recent decades, the construction of multi-millennial chronologies of Scots pine in northern Sweden and Finland have been the main focus of dendroclimatic research in northern Fennoscandia (Bartholin and Karlén, 1983; Briffa *et al.*, 1990; 1992; Briffa, 1994; Eronen and Zetterberg, 1996; Lindholm *et al.*, 1999). Concurrently, studies have been carried out on the spatial variability of pine growth along the northern pine tree-line and its dependence on climate (Briffa *et al.*, 1988; Lindholm *et al.*, 1996). As part of this work, five pine chronologies were constructed in Norway north of the Arctic Circle (Schweingruber *et al.*, 1987). Short tree-ring series from Porsanger in Finnmark (Ruden, 1935) and the chronologies from Steigen and Sørfold in Nordland (Aandstad, 1939; Ording, 1941) previously existed. Independent of these studies, dendroclimatological work commenced in the Vesterålen archipelago and inner Troms, Norway (Ruden, 1987; Kirchhefer and Vorren, 1995; Thun and Vorren, 1996). Several of the northern Fennoscandian chronologies have been used in large-scale reconstructions of the North-Atlantic sea-surface temperatures and the North-Atlantic Oscillation (D'Arrigo *et al.*, 1992a; 1993; Cook *et al.*, 1998). This documents the relevance of the region for globally significant climate features. Together with northern Fennoscandia’s potential for multi-millennial tree-ring chronologies and its spatial heterogeneity in terms of climate and climate-growth response of Scots pine (Schweingruber, 1985; Thun and Vorren, 1996), it showed the need for a systematic survey of the spatial variability of radial growth and climate-growth response of Scots pine along the Norwegian coast and the gradient of continentality. The present investigation focused on a west-east transect in Norway, 69°N.

THE STUDY AREA

Topographically, the study region (Figure 1) comprises the Scandes with mean maximum heights around 1400 m a.s.l. in the west and the Finnmarksvidda in the east, gently undulating between ca. 300 and 650 m a.s.l. According to phytogeography, climate varies from oceanic (O2) in the Vesterålen archipelago and the outer coastline of Troms, to subcontinental (C1) on the Finnmarksvidda, including the eastern valleys of the Scandes (Moen, 1998). The annual amplitude of monthly mean temperatures increases from about 14°C at the coast to 18°C inland, with maximum and minimum temperatures slightly delayed from July (13°C) and January (–15°C) inland towards August (12°C) and February (–2°C) at the coast, respectively (Table 1). The annual

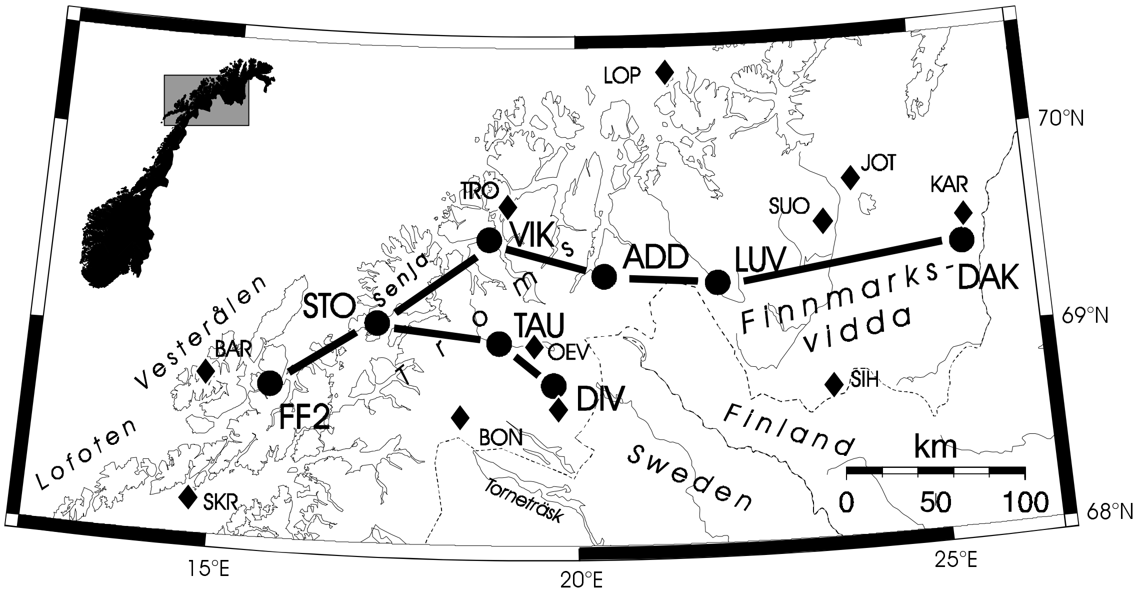

Figure 1: Map of the study area with the locations of the tree-ring chronologies (●) and climate stations (♦). The codes for chronologies and climate stations are explained in Tables 1 and 2, respectively.

precipitation varies from more than 1000 mm at the coast to less than 500 mm inland, with an autumnal maximum at the coast and a summer maximum inland (Aune, 1993). The valleys of Skibotn and Dividalen are sheltered by the highest summits in Troms (Jiekkevarre 1833 m and Njunes 1713 m a.s.l.) and consequently experience little cloudiness and low precipitation. Isolated forests of Scots pine (*Pinus sylvestris* L.) appear 30 km from of the outer coast line. The upper pine tree-line rises from near sea level at the coast to 450 m a.s.l. in Dividalen, inner Troms, and reaches 350 m a.s.l. in Karasjok, Finnmark. According to Moen (1998), the low-elevation forests belong to the middle boreal zone, whereas the tree-line stands are considered to belong to the northern boreal zone.

MATERIAL AND METHODS

DENDROCHRONOLOGY

The chronology network consisted of eight localities placed along a coastal axis and two west-east transects at approximately 69° and 69°30'N (Figure 1, Table 2). South- to west-sloping sites were preferred, but for practical reasons, the sites near Tromsø and Karasjok were at north-facing slopes. Open-canopy stands were selected in dry habitats, i.e. rock outcrops and glacial till, close to the tree line. Two cores were taken from each

Table 1: The meteorological stations in the study area (Figure 1) contributing to the regional climate series (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer and Nordli, 1998). Selected climate parameters for the period 1961-1990 are indicated: mean temperatures of July and August, mean temperatures of the coldest month (min; J: January, F: February), Conrad’s continentality index (CI; Conrad, 1946; Tuhkanen, 1980), annual precipitation (sum), month of minimum (min) and maximum precipitation (max). The climate stations of Skrova Fyr to Øverbygd represent the coastal climate series, while Dividalen to Karasjok represent the inland region. The first contributing year is indicated for temperature and precipitation (1^{st}).

	station	latitude N,	m	temperature (°C)				CI	precipitation			
		longitude E	a.s.l.	1^{st}	July	August	min		1^{st}	sum	min	max
SKR	Skrova Fyr	68°09', 14°39'	11	1933	12.5 ±1.7	12.5 ±1.3	-0.8 F	9	-	802	May	Oct
BAR	Barkestad	68°49', 14°48'	3	-	-	-	-	-	1896	1505	May	Oct
BON	Bones i Bardu	68°39', 18°15'	230	-	-	-	-	-	1907	846	May	Oct
LOP	Loppa	70°20', 21°28'	10	1920	11.6 ±1.8	11.0 ±1.2	-2.0 J/F	9	-	914	May	Oct
TRO	Tromsø	69°39', 18°56'	100	1867	11.8 ±1.8	10.8 ±1.2	-4.4 J	14	1873	1031	May	Oct
OEV	Øverbygd	69°01', 19°17'	78	-	13.2 ±1.7	11.5 ±1.4	-10.2 J	27	1895	657	May	Oct
DIV	Dividalen	68°47', 19°43'	228	1936	12.7 ±1.7	10.9 ±1.3	-9.4 J	24	-	282	Apr	Jul
SUO	Suolovuopmi	69°35', 23°32'	374	1963	11.5 ±1.8	9.5 ±1.2	-14.3 J	30	1908	456	Apr	Jul
JOT	Jotkajavre	69°45', 23°56'	389	-	-	-	-	-	1923	452	Apr	Jul
SIH	Sihcajavri	68°45', 23°32'	382	1913	11.8 ±1.7	9.7 ±1.2	-15.9 J	34	1912	366	Feb	Jul
KAR	Karasjok	69°28', 25°31'	129	1876	13.1 ±1.8	10.7 ±1.2	-17.1 J	38	1877	366	Feb	Jul

of at least 20 dominant living Scots pines (*Pinus sylvestris*). In order to extend the tree-ring records, cores or cross-sections were sampled from dead trees and tree remains preserved on dry forest ground.

The ring widths were measured to the nearest 0.001mm on two radii of each tree. In order to detect measuring errors and missing rings, tree-ring patterns on the samples and ring-width curves were compared within trees, between trees, and with the continuously developing chronologies (Fritts, 1976; Wigley *et al.*, 1987). This cross-dating procedure was assisted by correlation analysis (COFECHA; Holmes et al., 1986). Wood remains were dated by the same means. In order to enhance the common tree-ring signal, abnormal growth rings such as compression wood and abrupt growth reductions were excluded from further analysis. Short series, in practice < 94 years, were discarded. To remove the age-related growth trend, negative exponential functions or non-ascending straight lines were fitted to the raw ring-width series of the individual radii (ARSTAN; Holmes et al., 1986; Cook *et al.*, 1990a). The chronologies represent the bi-weight robust mean of the detrended and standardised radius series (Cook *et al.*, 1990b). White-noise tree-ring series were produced by autoregressive modelling, and averaged to RESIDUAL chronologies (Cook, 1985). Autoregressive models were selected according to

Table 2: Site location, elevation above sea level, slope inclination and aspect, and continentality according to vegetation (Moen, 1998). O2: oceanic, O1: sub-oceanic, OC: oceanic-continental transition zone, C1: sub-continental.

	locality	lat. N	long. E	m a.s.l.	slope		continentality
FF2	Forfjorddalen / Vesterålen	68°48'	15°44'	50 - 170	15°	W	O2
STO	Stonglandseidet / Senja	69°05'	17°13'	80 - 210	25°	SE	O1
VIK	Vikran / Tromsø	69°32'	18°44'	80 - 120	5°	NE	O1
TAU	Tauskjerringa / Målselvdalen	69°02'	18°55'	280 - 360	17°	S	OC
DIV	Devdisvarri / Dividalen	68°50'	19°38'	320 - 450	15°	SW	C1
ADD	Addjet / Skibotn	69°22'	20°23'	300 - 350	11°	SW	OC
LUV	Luvdiidvuopmi / Nordreisa	69°17'	22°02'	300 - 400	25°	SW	C1
DAK	Dakteoaivi / Karasjok	69°26'	25°30'	260 - 340	6°	N	C1

the Akaike Information criterion (Akaike, 1974). Re-introducing the pooled autocorrelation into the individual RESIDUAL series resulted in ARSTAN chronologies which were homogeneous in terms of autocorrelation (Cook, 1985). The expressed population signal (EPS 85%) defined the number of trees required for chronologies which contain a sufficient signal strength (Wigley et al., 1984). Thereby, the temporal limits of this investigation were determined to AD 1800-1992. Chronology homogeneity and signal strength were assessed for this common time period (ARSTAN; Holmes et al., 1986; Briffa and Jones, 1990). Principal component analysis (PCA) was performed on the chronologies in order to detect main regional tree-ring signals (3Pbase; Guiot and Goeury, 1996). The principal components were selected according to the PVP criterion, i.e. accepted if the cumulative product was greater than 1 (Guiot, 1985a).

DENDROCLIMATOLOGY

Standardised regional series of monthly mean temperatures and precipitation sums for 1895-1992 were applied for the analysis of climate-growth response (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer and Nordli, 1998). The four western chronologies (FF2, STO, VIK and TAU; Figure 1) belong to the coastal climate region extending from the Polar Circle to the North Cape. The four eastern chronologies (DIV, ADD, LUV, DAK) lie within the range of the continental climate series representing inner Troms and Finnmark.

The climate-growth relationship was assessed by bootstrap orthogonal regression (Guiot, 1990; Till and Guiot, 1990; Guiot and Goeury, 1996) on the tree-ring chronologies and climate data of the biological year, defined as from the previous to the current August. The bootstrap routine (Efron, 1979), in this case randomly drawing one thousand subsamples, reduces the effects of outlier values and non-normal distribution of the data. At each iteration, the data (years) not selected for the calibration provided verification statistics. The mean bootstrap multiple correlation coefficients and their standard deviation of the calibration and the verification procedure were used as criteria for the quality of the response functions. The significance of the regression coefficients for monthly climate parameters were defined by their 5th and 95th percentiles as well as their standard deviation.

The high-frequency climate signal in tree rings was investigated by applying the RESIDUAL chronologies. Because the first principal component for northern Norway of the RESIDUAL chronologies was serially correlated, that series was additionally whitened by an ARMA (2,0)-process. For the assessment of the climate signal in the ARSTAN chronologies, several previous rings were added as explanatory variables. Three regional climate reconstructions were produced by bootstrap orthogonal regression on the principal components of the ARSTAN chronologies. These were 1) northern Norway, 2) the coastal region (FF2, STO, VIK, TAU) and 3) the inland region (ADD, DIV, LUV, DAK).

RESULTS

TREE-RING CHRONOLOGIES

The individual STANDARD chronologies are shown in Figure 2. The regional mean growth trend is represented by the first principal component (PC 1) for northern Norway (Figure 3). Below-average growth occurred during most of the period AD 1800-1910. The first part of the 19th century experienced strong fluctuations with minima around 1815 and 1837, followed by a distinct negative trend from the 1850s towards the 1900-10 minimum. A sudden growth release occurred about 1912 and, except for a few years, growth rates stayed at or above average since then. The growth maximum was reached during 1940-60. The lowest ring indices were recorded in 1837 and 1903, the greatest indices in 1950, 1960 and 1985. A particularly high year-to-year variability occurred in the 1930s.

The first principal component, PC 1, for northern Norway explained approximately 68% of the variance among the STANDARD and ARSTAN chronologies and almost 75% of the variance among the RESIDUAL chronologies (Table 4). PC 1 best represented the central localities (Tromsø VIK, Målselvdalen TAU, and Dividalen DIV), with r = 0.38 to 0.39.

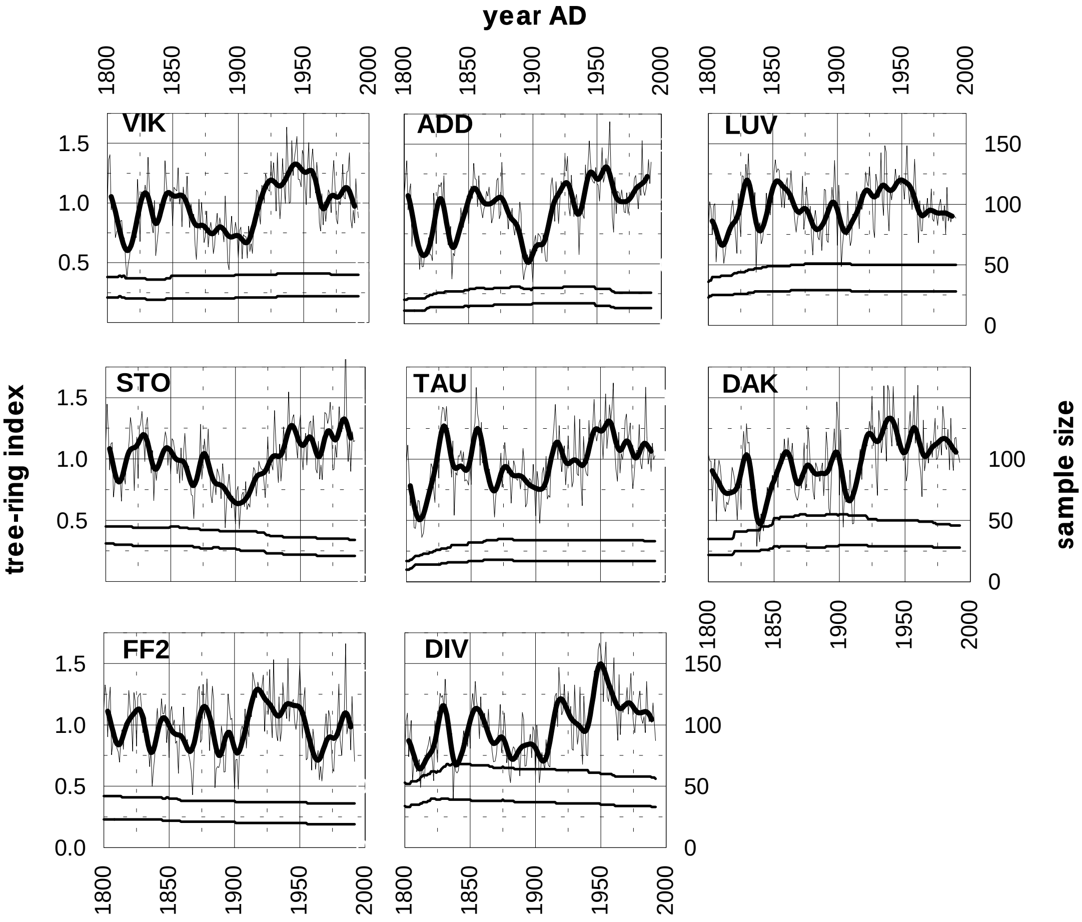

Figure 2: STANDARD tree-ring width chronologies 1800-1992. Left row: the coastal series (VIK Tromsø, STO Senja, FF2 Forfjorddalen); middle row: the inner Scandes (ADD Skibotn, TAU Målselvdalen, DIV Dividalen,); right: Finnmarksvidda (LUV Nordreisa, DAK Karasjok). The bold lines represent the 10-year low-pass filtered chronologies. Below each chronology the number of trees (lower line) and radii (upper line) are shown.

On the other hand, the chronology from Forfjorddalen shared considerably less common variability (r = 0.28). Third principal component (PC 3) expressed a signal which was common among the central versus the marginal localities, i.e. the most oceanic sites (Forfjorddalen FF2, Senja STO in part) and the Finnmarksvidda (LUV, DAK). The second PC represented the west-east gradient, being strongly negatively correlated with the two south-western chronologies (FF2, STO), whereas positively correlated with the three eastern chronologies (Dividalen DIV, Nordreisa LUV and Karasjok DAK). This component explained 9.0 to 9.5% of the total variation between the chronologies.

The major changes in pine growth along the coast-inland transect may be seen in the differences between PC 1 of both the western (FF2, STO, VIK, TAU) and the eastern

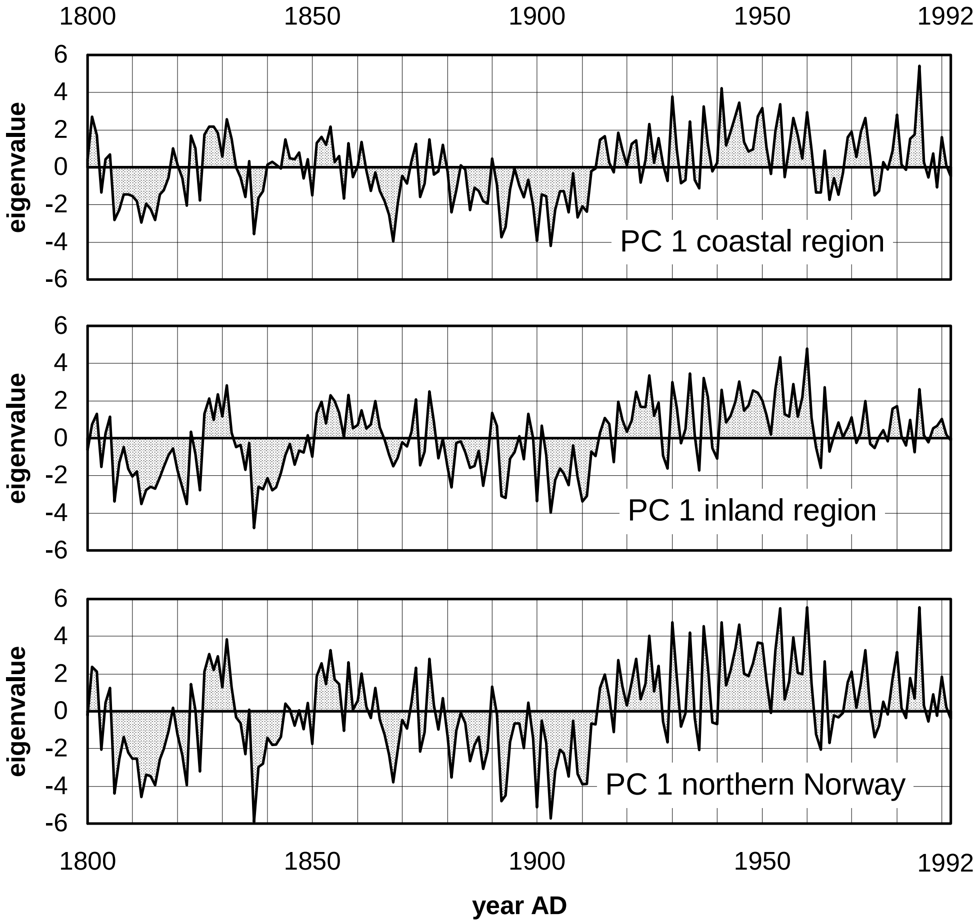

Figure 3: The first principal components derived from the four western (PC 1 coastal region: FF2, STO, VIK, TAU), the four eastern (PC 1 inland region: DIV, ADD, LUV, DAK) and all eight northern Norwegian ARSTAN chronologies (PC 1 northern Norway).

(DIV, ADD, LUV, DAK) chronology group (Figure 3). For example, the minimum growth period of the 1830s was more persistent inland, while the extremely narrow ring of 1868 was restricted to the coastal group. However, the individual chronologies (Figure 2) revealed that this simple west-east division is not sufficient to describe all spatial growth patterns. For instance, the 1810-20 growth minimum was less distinct in the south-west (FF2, STO) as well as at Karasjok (DAK). Positive growth anomalies which were not prominent in the regional series appeared in the 1870s in the south-west and in the 1890s on the Finnmarksvidda (LUV, DAK). An anomalous growth pattern occurred in the inner Scandes (TAU, ADD, DIV), with the minimum of the 1930s and the maximum around 1950. At Karasjok (DAK) on the contrary, the absolute growth maximum occurred in the 1930s. Of single year events, the 1985 ring was most conspicuous, being extremely broad in the three south-western chronologies from Forfjorddalen, Senja and Målselvdalen (FF2, STO, TAU).

Table 3: Chronology statistics. For the STANDARD chronologies: total time span (first year, last year), number of trees (n) required to reliably represent the pine population (EPS 85%) and first year when the chronology reaches EPS 85% (Wigley *et al.*, 1984), first order autocorrelation (r_{AR1}) and variance due to autoregression (VAR_{AR}). For the common time period, separately for the detrended (STANDARD and ARSTAN) and RESIDUAL tree-ring series: Mean correlation between trees (r_{TRE}) and between radii and chronology (r_{RM}), signal-to-noise ratio (SNR), expressed population signal (EPS), and variance in the first eigenvector (VAR_{PC1}) (Holmes *et al.*, 1986; Briffa and Jones, 1990). The common interval is 1800-1992 for all chronologies except TAU (1838-1992) and ADD (1859-1992).

Chronology	FF2	STO	VIK	TAU	DIV	ADD	LUV	DAK
first year AD	877	1403	1599	1697	1186	1579	1152	1693
last year AD	1994	1997	1992	1994	1994	1992	1995	1992
EPS 85% since AD	1358	1548	1700	1799	1504	1740	1757	1705
n trees at EPS 85%	9	9	8	10	8	9	11	6
r_{AR1}	.53	.58	.68	.62	.71	.69	.72	.66
VAR_{AR} (%)	28.2	38.2	50.8	47.1	47.9	53.5	47.5	47.1
Common interval								
n trees (radii)	19 (35)	17 (25)	18 (33)	15 (28)	23 (39)	11 (22)	28 (42)	18 (25)
detrended series								
r_{TRE}	.41	.39	.42	.37	.44	.41	.35	.49
r_{RM}	.65	.64	.67	.63	.66	.66	.60	.70
SNR	13.1	10.9	13.2	8.9	17.7	7.8	14.8	17.2
EPS	.93	.92	.93	.90	.95	.89	.94	.95
VAR_{PC1} (%)	43.8	43.6	45.7	41.5	48.0	46.7	38.5	54.4
RESIDUAL series								
r_{TRE}	.51	.44	.49	.47	.48	.42	.51	.57
r_{RM}	.72	.67	.70	.70	.69	.67	.72	.75
SNR	20.0	13.1	17.2	13.0	21.2	8.0	29.2	23.4
EPS	.95	.93	.95	.93	.96	.89	.97	.96
VAR_{PC1} (%)	53.7	46.5	51.0	49.5	50.3	46.4	52.9	59.1

Clear spatial trends in chronology characteristics were not observed across the sampling area at large (Table 3). However, the easternmost chronology, Karasjok (DAK), gained highest values for most chronology statistics, and two other eastern localities, Dividalen (DIV STANDARD chronology) and Nordreisa (LUV RESIDUAL chronology) reached highest signal-to-noise ratios (SNR). For individual statistics, low values were achieved for the least replicated chronologies (Målselvdalen TAU and Skibotn ADD), but also for Senja (STO) and Nordreisa (LUV). Highest similarity occurred between the eastern chronologies, with maximum correlation coefficients between the Dividalen and the Målselvdalen STANDARD (DIV-TAU, r = 0.84) and the Nordreisa RESIDUAL chronology

Table 4: Results from principal component analysis on the chronologies, 1800-1992. PCs selected according to the PVP criterion (cumulative product > 1; Guiot, 1985a).

	STANDARD chronology			RESIDUAL chronology			ARSTAN chronology		
	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3
eigenvalue	5.48	.76	.56	5.97	.72	.37	5.41	.76	.59
R^2 (%)	68.5	9.4	7.0	74.6	9.0	4.6	67.6	9.5	7.3
cum. product	5.48	4.14	2.31	5.99	4.28	1.57	5.41	4.13	2.41
FF2	.27	-.72	-.55	.34	.45	-.23	.28	-.66	-.56
STO	.33	-.43	.45	.33	.48	-.43	.33	-.48	.35
VIK	.38	-.11	.14	.35	.34	.39	.38	-.11	.16
TAU	.38	.04	.22	.37	.05	.16	.38	-.02	.20
DIV	.39	.24	.04	.38	-.24	.09	.39	.24	.14
ADD	.36	.14	.34	.36	-.15	.59	.35	.16	.40
LUV	.36	.29	-.44	.36	-.41	-.24	.36	.33	-.39
DAK	.34	.35	-.34	.34	-.45	-.41	.34	.35	-.42

(DIV-LUV, r = 0.87), respectively. The largest ‘Gleichläufigkeit’ values (Glk; Eckstein, 1969) were computed between the Nordreisa and the Dividalen STANDARD (LUV-DIV, Glk = 87%) and the Karasjok RESIDUAL chronology (LUV-DAK, Glk = 88%), respectively. Least agreement occurred between the most distant sites, i.e. the STANDARD chronologies of Karasjok and Forfjorddalen (DAK-FF2, r = 0.41, Glk = 70%), and the RESIDUAL chronologies of Karasjok and Senja (DAK-STO, r = 0.57; Glk = 70%).

CLIMATE-GROWTH RESPONSE OF SCOTS PINE

Multiple regression of the first principal component of the RESIDUAL chronologies with the mean climate series for northern Norway showed a dominant influence of July temperatures on radial growth, with a mean bootstrap regression coefficient of $\beta = 0.46$ (Table 5). July precipitation was negatively correlated with ring width ($\beta = -0.29$), while May precipitation showed a significantly positive correlation ($\beta = 0.16$). July temperature also dominated the response functions of the individual chronologies. In agreement with the *a priori* assignment of the chronologies to the two climate regions, the western chronologies (FF2, STO, VIK, TAU) achieved higher calibration and verification statistics when calibrated with coastal rather than with inland climate. Here, except for Vikran, also August temperature was significantly positively correlated with growth. The four eastern chronologies (ADD, DIV, LUV, DAK) correlated best with the

Table 5: Climate-growth response of Scots pine, 1896-1992, derived by bootstrap orthogonal regression on the RESIDUAL chronologies: Mean correlation coefficients (×100) and standard deviation SD for the calibration (cal) and the verification procedure (ver); regression coefficients β (upper row, ×100) and the ratio β:SD (italics) for individual months displayed if within the 90% confidence interval. The chronologies FF2 to TAU are related to the coastal, and DIV to DAK to the inland climate series. Lowest function (PC 1): Regional growth response for northern Norway, computed from regional climate (coast-inland mean) and the first eigenvector of the RESIDUAL chronologies.

	mean r		temperature									precipitation				
coast	cal	ver	Aug	Oct	Nov	Feb	Apr	May	Jun	Jul	Aug	Aug	Oct	Jan	May	Jul	Aug
FF2	76	43	-17				18			33	16		-18			-21	
	±4	*±12*	*-2.1*				*2.3*			*4.3*	*2.4*		*-2.1*			*-3.0*	
STO	75	41			14	-14		16		30	19		-21	19			17
	±4	*±12*			*2.1*	*-1.9*		*2.2*		*3.8*	*2.5*		*-2.3*	*2.3*			*2.3*
VIK	76	42		-14			16			35			-18		16	-17	
	±5	*±12*		*-1.8*			*1.9*			*4.3*			*-1.9*		*1.8*	*-2.5*	
TAU	77	46	-16			-13				32	15		-15	17	16	-12	
	±4	*±12*	*-1.9*			*-1.8*				*4.4*	*2.0*		*-1.8*	*2.1*	*2.0*	*-1.8*	
inland	cal	ver	Aug	Oct	Nov	Feb	Apr	May	Jun	Jul	Aug	Aug	Oct	Jan	May	Jul	Aug
DIV	78	46							16	41		18				-32	
	±4	*±11*							*2.2*	*5.9*		*2.7*				*-4.0*	
ADD	73	35							16	31		25		21		-32	
	±4	*±12*							*2.2*	*4.1*		*3.0*		*2.2*		*-3.5*	
LUV	81	56		11			15			45					12	-20	
	±4	*±10*		*1.6*			*2.2*			*6.8*					*1.7*	*-3.0*	
DAK	83	61							12	52		14		18	18	-19	
	±3	*±10*							*2.0*	*8.3*		*2.4*		*2.1*	*2.6*	*-2.9*	
PC 1	81	58								46					16	-28	
	±4	*±10*								*5.7*					*2.0*	*-3.5*	

inland climate series. Of the inland chronologies, Skibotn (ADD) and Nordreisa (LUV) were significantly correlated with June and July temperatures, while Dividalen (DIV) and Karasjok (DAK) with July temperature only. The regression coefficients for July temperature increased from maximum β = 0.35 at the coast (Vikran, VIK) to β = 0.52 in the east (Karasjok, DAK).

In the response functions based on the ARSTAN chronologies, up to four leading rings were significantly positively correlated with the current ring (Tables 6 and 7). All coastal ARSTAN chronologies were significantly correlated with July and August temperatures, and all inland chronologies exclusively with July temperatures. The latter sites also showed a significant response to precipitation in previous August (positive

Table 6: Climate-growth response computed from the ARSTAN chronologies 1900-92. A total of four prior rings were included as explanatory variables. PC 1 and PC 2: Response functions for the first and second principal components derived from the coastal and inland chronologies, respectively. Further explanations are given in Table 5.

	mean r		temperature								precipitation									prior rings			
coast	cal	ver	Aug	Sep	Oct	Nov	Jan	Apr	Jul	Aug	Aug	Nov	Jan	Feb	Mar	Apr	May	Jul	Aug	t-1	t-2	t-3	t-4
FF2	82	61		-10				14	30	20					-13			-17		29	9		10
	±2	*±9*		*-2.1*				*2.4*	*4.7*	*3.5*					*-2.1*			*-3.3*		*5.4*	*2.1*		*1.8*
STO	85	66							23	15						7			13	27	16	10	
	±2	*±10*							*4.0*	*2.5*						*1.6*			*2.0*	*5.3*	*3.2*	*2.2*	
VIK	88	71						13	31	14		9								18		14	21
	±2	*±8*						*2.0*	*5.2*	*2.6*		*1.7*								*4.3*		*2.6*	*3.5*
TAU	83	59				13	-11	13	33	16				-10						21		15	19
	±3	*±11*				*2.2*	*-1.8*	*1.9*	*5.8*	*2.8*				*-1.7*						*3.6*		*2.4*	*3.3*
PC 1	86	67						11	35	19								-9		19		11	17
	±2	*±9*						*2.1*	*6.1*	*3.7*								*-1.9*		*4.5*		*2.0*	*2.9*
PC 2	87	71	-10									-10		11	-18			-10		38	27	12	
	±3	*±11*	*-1.8*									*-1.7*		*1.9*	*-3.3*			*-1.7*		*7.0*	*7.5*	*2.2*	
inland	cal	ver	Aug	Sep	Oct	Nov	Jan	Apr	Jul	Aug	Aug	Nov	Jan	Feb	Mar	Apr	May	Jul	Aug	t-1	t-2	t-3	t-4
DIV	89	67							33		15							-23		23		20	21
	±3	*±12*							*5.5*		*2.9*							*-3.3*		*3.5*		*3.8*	*3.6*
ADD	89	68							24		17		10			-9		-23		25	14	19	17
	±3	*±16*							*3.7*		*2.8*		*2.0*			*-1.9*		*-3.4*		*4.4*	*2.5*	*4.4*	*3.7*
LUV	88	69	11			14	10	12	43		17							-13		19		21	15
	±2	*±8*	*2.1*			*2.4*	*1.8*	*2.1*	*9.3*		*3.4*							*-2.4*		*3.2*		*4.8*	*3.0*
DAK	89	72					9		48		13		12			-11	14	-13		20		19	16
	±3	*±10*					*1.9*		*9.7*		*2.7*		*1.8*			*-2.6*	*2.5*	*-2.5*		*3.3*		*3.5*	*2.5*
PC 1	90	73							43		18					-9		-21		15		21	22
	±2	*±10*							*8.2*		*4.0*					*-1.9*		*-3.8*		*2.5*		*3.9*	*4.2*
PC 2	89	66			10		13		20											36	22	18	
	±4	*+18*			*1.7*		*1.9*		*3.4*											*5.1*	*3.5*	*4.0*	

Table 7: Climate-growth response based on the first three principal components, derived from the eight northern Norwegian ARSTAN chronologies 1900-92. A total of three prior rings were included as explanatory variables. Further explanations are given in Table 5.

	mean r		temperature						precipitation						prior rings		
	cal	ver	Oct	Dec	Apr	Jun	Jul	Aug	Aug	Sep	Dec	Jan	Feb	Jul	t-1	t-2	t-3
PC 1	89	71					40	13	15			12	-10	-20	24		22
	±3	*±9*					*7.0*	*2.2*	*2.6*			*1.9*	*-1.7*	*-3.2*	*4.1*		*3.1*
PC 2	79	47	14	-11		-14				23					42		
	±3	*±12*	*2.1*	*-1.6*		*-1.8*				*2.8*					*4.7*		
PC 3	92	77			14		17				-14				34	27	19
	±2	*±8*			*2.4*		*2.8*				*-2.5*				*6.2*	*7.3*	*4.1*

correlation) and current July (negative correlation). The response functions for the first PCs showed the same pattern. The second PCs mainly accounted for autocorrelation of up to three years (t-1 to t-3). The first principal component for northern Norway reflected mainly July temperatures with a weaker, but significant, August signal (Table 7) and the third principal component for northern Norway accounted for autocorrelation of three years.

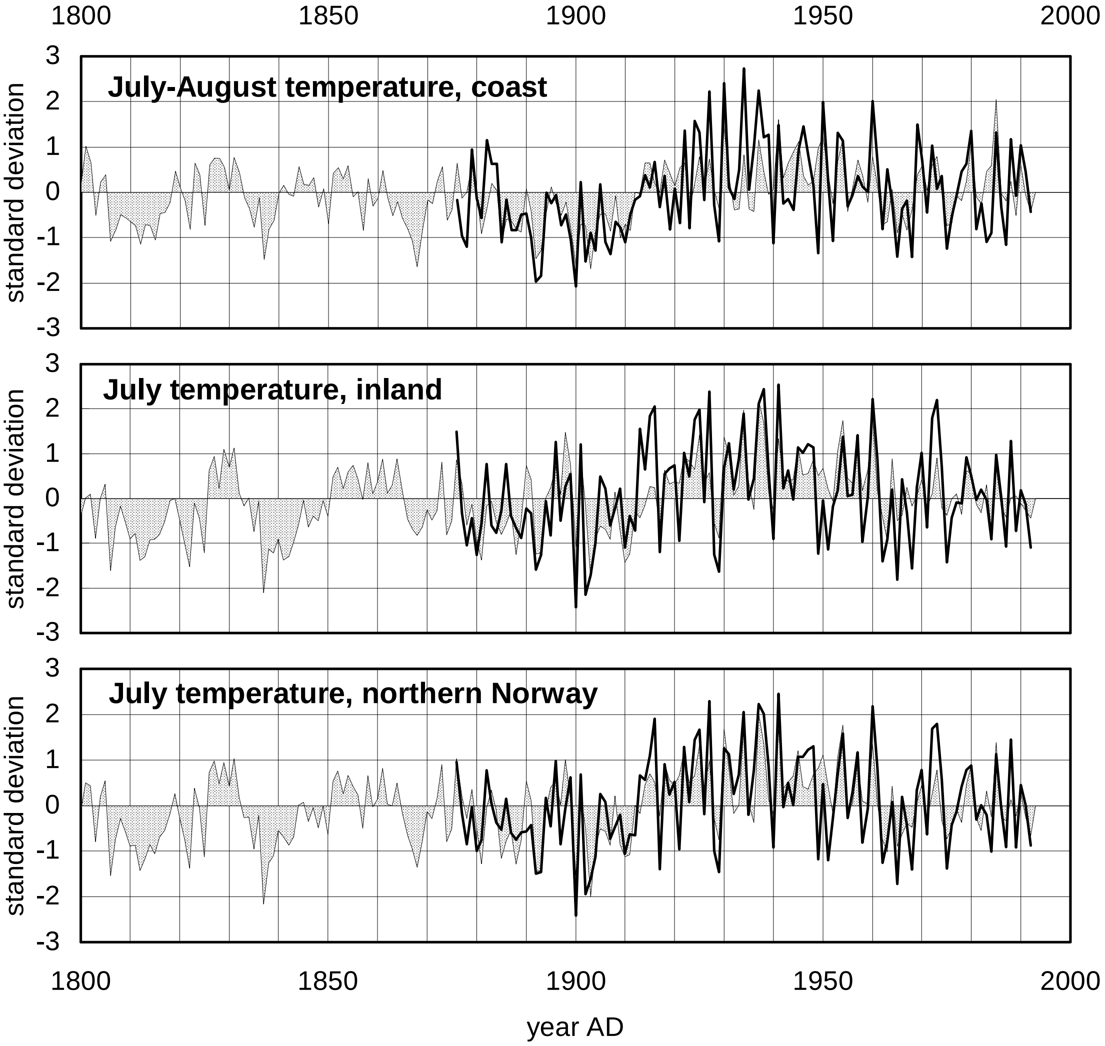

Figure 4: Three climate reconstructions for northern Norway back to 1800 (shaded): July-August temperatures for the coastal region, and July temperatures for the inland region and for northern Norway. Temperatures are expressed as standard deviations from the observed mean 1961-1990 (Table 1). The observed temperatures are shown as bold lines.

Table 8: Calibration and verification statistics of the climate reconstructions: mean bootstrap multiple correlation coefficients and their standard deviation for the calibration and the verification procedure (Guiot, 1990), variance explained adjusted for degrees of freedom (R^2_{adj}), Product-Means test (PM t), numbers of incorrect signs (sign test) and incorrect first differences (1st diff.), and reduction of error statistics (RE) (Fritts, 1976; Cook and Kairiukstis, 1990). PM t, sign test and 1st diff. are significant at $p < 0.05$ in all cases except where marked by (n.s.).

	coast July-August PC 1, PC 2		inland July PC 1, PC 2		northern Norway July PC 1, PC 3	
calibration:	early 1876-1934	late 1935-1992	early 1876-1934	late 1935-1992	early 1876-1934	late 1935-1992
mean r_{CAL}	.75 ± .05	.58 ± .07	.71 ± .05	.75 ± .04	.77 ± .04	.74 ± .05
mean r_{VER}	.71 ± .10	.52 ± .14	.68 ± .09	.72 ± .09	.74 ± .08	.72 ± .10
R^2_{adj}	.54	.32	.49	.54	.58	.54
PM t	4.00	3.00	4.76	4.13	5.07	4.08
sign test	17	17	13	15	15	14
1st diff.	14	17	19	14	14	13
verification:	1935-1992	1876-1934	1935-1992	1876-1934	1935-1992	1876-1934
r	.56	.73	.63	.63	.72	.75
RE	.36	.54	.31	.37	.55	.55
PM t	3.94	4.43	3.69	5.13	3.58	5.33
sign test	20	11	23 (n.s.)	16	15	17
1st diff.	17	16	13	16	14	15
main calibration:	1876-1992		1876-1992		1876-1992	
mean r_{CAL}	.68 ± .04		.70 ± .04		.76 ± .03	
mean r_{VER}	.67 ± .07		.68 ± .07		.74 ± .06	
R^2_{adj}	0.45		0.48		0.56	
PM t	4.72		6.65		6.54	
sign test	29		34		31	
1st diff.	33		29		25	

CLIMATE RECONSTRUCTION

Based on the response functions, three reconstructions of summer temperature were obtained back to AD 1800. These comprise July temperatures for northern Norway, July temperatures for the inland and July-August temperatures for the coastal region (Figure 4). The first two regional principal components of the ARSTAN chronologies were selected as predictors for the coastal and inland reconstructions. Including lagging rings into the transfer functions did not improve the reconstructions. The reconstruction for northern Norway was based on PC 1 and PC 3 derived from all eight chronologies. The latter reconstruction yielded the highest mean bootstrap correlation coefficients ($r = 0.76$) and highest explained variance adjusted for degrees of freedoms $R^2_{adj} = 56\%$ (Table 8). These statistics were lowest for the coastal reconstruction. The high similarity between the multiple correlations coefficients for the calibration and the verification iterations, as well as their small standard deviations, indicated a high stability of the transfer functions. The validity of the reconstructed high-frequency variability was strongly supported by the results for the Product Means test, the sign test and the first difference test (Table 8). These tests were all significant at $p < 0.05$, except the sign test for one verification of inland temperatures.

The reconstructions of July temperatures between 1800-75 for northern Norway and the inland region were similar (Figure 4), as they are based on a similar data set. Temperatures above the 1961-90 mean occurred during 1826-32 and 1851-64, while below-average temperatures prevailed during the years 1806-17, 1835-43(50) and 1866-71. The coldest summer of the 19th century was 1837, with temperatures two standard deviations below the 1961-90 mean. Inland, the 1837 cold event persisted until 1843. Other strongly negative anomalies occurred in 1809, 1812/13, 1822, 1825 and 1867/68. The coastal reconstruction of July-August temperatures differed from the inland reconstruction by a more severe early 19th century temperature depression (1806-17), a shorter cool event in the 1830s (1835-39), a more distinct 1868 anomaly, and longer-lasting warm intervals in the 1820s and 1840-62. A steady cooling trend was observed from the 1820s towards the 1900s. In general, the reconstructed temperature amplitude was smaller at the coast than inland.

DISCUSSION

The presented tree-ring chronologies extend the Fennoscandian-Eurasian dendroclimatological network at its north-western edge, approaching the coastal limit of Scots pine, though not the arctic tree line of Scots pine, *Pinus sylvestris*. Although spanning a distance of 400 km along a west-east transect from the Atlantic Ocean across the Scandes, the common variability of radial growth during 1800-1992 was high (PC 1 ≈ 70%). It is evident that this strong common signal is caused by July temperature, being the dominant growth-determining factor at the tree-limit of Scots pine on both sides of the Scandes. This in turn provided the basis for a reconstruction of July temperatures for the entire study area, northern Norway at 69°N, which explained more than half (57%) of the observed variability of July temperatures. The reconstruction does not differ significantly from previous reconstructions of July temperatures for northern Fennoscandia, i.e. temperature minima occurring in the 1810s, 1830s and late 1860s, and maxima in the late 1820s and the 1850s (Briffa *et al.*, 1988; 1990; Lindholm *et al.*, 1996). This reflects the homogeneity of the northern Fennoscandian climate, particularly east of the Scandes, from where the majority of chronologies were derived in previous investigations. Indeed, the climate fluctuations of the early 19th century were fairly consistent around the Arctic, while the minimum around 1900 was particularly well-developed in northern Fennoscandia (Graybill and Shiyatov, 1992; Schweingruber and Briffa, 1996; Jones et al., 1998; Mann et al., 1999).

As expected from previous knowledge of regional climate and pine growth, a systematical spatio-temporal variability in radial growth along the west-east gradient of continentality could be demonstrated (PC 2, $R^2 \approx 10\%$). However, this west-east variability clearly plays a secondary role in relation to the main regional signal (PC 1, $R^2 \approx 70\%$). At least in part, this variability is caused by differences in the climate-growth responses, i.e. to July-August temperatures at the coast and (June-) July temperatures inland. These differences in climate-growth response are a direct effect of the regional climate regimes, i.e. a coastal advective climate versus an inland climate, which is influenced to a greater degree by radiation.

Inland, the thermally favourable, second half of the midnight sun period, June 21st to about July 20th, is of major importance for pine growth. The short and early time-window of pine response to temperatures is well-known from previous studies in northern Finland and Sweden (Erlandsson, 1936; Bartholin and Karlén, 1983; Aniol and Eckstein, 1984; Briffa *et al.*, 1988; Lindholm, 1996). A significant response to June temperatures is only evident from the pre-whitened (RESIDUAL) chronologies in Dividalen (DIV) and Karasjok (DAK) and not from the ARSTAN chronologies at the same sites. This suggests that preconditioning of Scots pine by high temperatures in the previous summer enables a positive response to early summer temperatures.

At the coast, due to the delayed temperature maximum and minor temperature amplitudes, the risk of early frosts is reduced. Thus pine growth can terminate later, at relatively shorter day-lengths compared to inland pine. This supports earlier investigations in Forfjorddalen which showed that August temperatures have considerable influence on pine growth at the coast (Ruden, 1987; Kirchhefer and Vorren, 1995; Thun and Vorren, 1996).

The difference in climate-growth response between coast and inland region complicate potential spatial analyses of summer temperatures across the Scandes and related atmospheric circulation patterns over northern Europe and the Norwegian Sea. Ideally, such analyses should be based on chronologies which represent an identical climatic time-window on both sides of the Scandes. Because previously significant responses to July-August temperatures have been found in northern Sweden and Finland (Erlandsson, 1936; Briffa *et al.*, 1990; 1992; Lindholm, 1996), it is likely that a coast-inland synthesis of July-August temperatures will be possible in future studies.

The present study also shows the existence of a common July-temperature signal. Within the coastal and inland region respectively, Vikran (VIK) and Karasjok (DAK) do not only display the most significant chronology statistics, but also a distinct July-temperature window. Because those chronologies were derived from the northernmost and only north-facing sites of the northern Norwegian network, this suggests an increase in the tree-ring and climate signal, as well as a restriction of the vegetation period to the month of July, towards higher latitudes and/or at north-facing slopes. Considering the short latitudinal distance between the chronologies, the slope aspect is the most plausible explaining variable, i.e. a short growing season, depending on high temperatures during the second half of the midnight sun period. Prior to the present study, a considerable influence of the slope aspect on the length of the period of cambial activity and cell differentiation of Scots pine was deduced from a single-year tree-ring analysis in Finnmark (Kirchhefer, 1998). Thus, north-facing slopes in the coastal region might provide chronologies which mainly reflect July temperatures and thus enable a direct comparison with July temperatures reconstructed for the continental climate region.

For the climate-response analysis, northern Norway was divided into a coastal and an inland region along the highest summits of the Scandes. Thereby, Skibotn (ADD) and Dividalen (DIV) were assigned to continental, and Målselvdalen (TAU) to oceanic northern Norway. This classification might at least partly be affected by the *a priori* clustering of original climate series into regional climate groups (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer and Nordli, 1998). An indicator for the existence of a third climatic or dendroecological region is the growth of Scots pine in the inner valleys of the Scandes in the middle of the 20th century, with reduced growth in the 1930s and the growth maximum about 1950 in Skibotn (ADD), Målselvdalen (TAU) and Dividalen (DIV) (Figure 2, Figure 5). On the contrary, at the coast, the 1930s growth depression was only weakly developed and on the Finnmarksvidda it is missing (Nordreisa, LUV) or even replaced by the highest growth indices of the period 1800-1992 (Karasjok, DAK). The present study is the first to show this particular growth pattern. Moreover ecologically, it is remarkable because it coincides with the 20th century’s temperature optimum (Hanssen-Bauer and Nordli, 1998).

The response functions did not offer any plausible explanation for the 20th century growth deviation observed in the inner Scandes. Thus also in the inner Scandes, summer temperature principally determined the year-to-year tree-ring variability. As factors related to summer temperatures and reducing decade-scale growth in the 1930s, one might discuss the high year-to-year variability of summer temperatures, or a non-linear response to increased temperatures, as drought stress in the unusually warm summers 1927, 1930, 1934, 1937/38 and 1941, and allocation of assimilates for reproductive rather than vegetative growth (Hustich, 1969; Hustich, 1978; Kozlowski *et al.*, 1991). The decadal variability of climate (Figure 5) indicates that also mid-winter climate conditions and spring precipitation might influence pine growth. Mid-winter temperatures and precipitation were high during the 1930s (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer and Nordli, 1998), indicating dominant zonal air flow, likely associated with weather conditions exerting stress on Scots pine. Mild periods in winter might break the dormancy and cause dehardening, followed by frost damage during subsequent cold spells. Also, mild periods might cause melting of the sparse snow cover and subsequent deep freezing of the soils. One indicator for such mechanisms is the heavy needle loss observed after the mild winter 1932/33 (Bathen, 1935). Loss of photosynthetic tissue reduces tree-ring growth until a sufficient number of needle sets are re-established. This event is likely to have triggered the difference between observed and reconstructed coastal temperatures during 1933-40 (Figure 4). In general at the coast, Scots pine appears to be more vital during periods of cold winters (Figure 5c). In contrast on the Finnmarksvidda, growth closely followed the decadal trend of summer temperatures. It is likely that here winter temperatures did not rise high enough to cause stress on pine even in the warm 1930s.

The only climatic parameter showing a marked maximum about 1950, simultaneously with pine growth, is precipitation of March to May (Figure 5). This suggests that in these dry intra-montane valleys during warm summers, pine profits from precipitation prior to the vegetation period, i.e. by preventing water deficit and/or early snow melt and soil warming. The hypothesis of reduced pine increment due to water deficit is supported by previous Fennoscandian studies which reported drought stress in individual years in dry habitats (Mikola, 1950; Slåstad, 1957; Kärenlampi, 1972; Damsgård, 1998; Kirchhefer, 1998). Also in boreal North-America, evidence was found for drought stress reducing conifer growth under climate warming (Jacoby and D'Arrigo, 1995; Brooks *et al.*, 1998). The decadal scale variability of growth and climate implies that there is a slight drought effect on the Finnmarksvidda, but not along the coast (Figure 5).

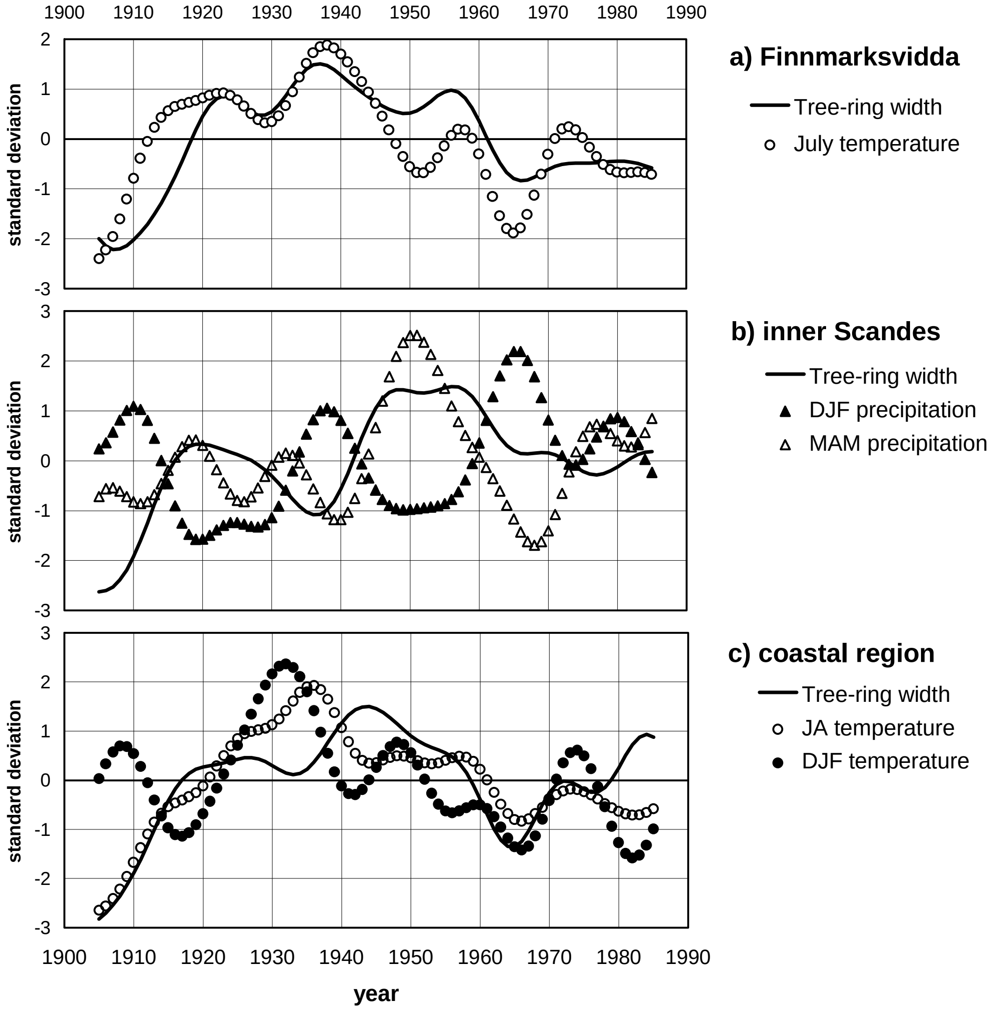

Figure 5: The decadal-scale variability (10-year low-pass filter) of the three regional mean tree-ring chronologies (bold lines) and selected climate parameters. a) The Finnmarksvidda chronology (LUV-DAK mean) is compared with inland July temperatures, b) the Scandes chronology (ADD-DIV-TAU mean) is compared with December-to-February (DJF) and March-to-May mean precipitation (MAM) for northern Norway, and c) the coastal chronology (FF2-STO-VIK mean) is compared with coastal July-August (JA) and December-to-February temperatures (DJF).

The response functions suggest a division of northern Norway into a coastal region with a main response of pine growth to July-August temperatures, and an inland region with the response restricted to July temperatures. On the other hand, the growth patterns during the thermal optimum of the 20th century suggest a division of northern Norway into three dendroecological regions: 1) the coastal district with a slightly negative response to winter temperatures, 2) the intra-montane valleys with a negative response to oceanic winters and a positive response to March-May precipitation, and 3) the Finnmarksvidda with the dominant response to July temperatures slightly enhanced by high precipitation in late winter and spring. However, the present study cannot offer a conclusive explanation for the observed growth deviations in the inner Scandes during the 1930s to 1950s. Detailed investigations will profit from the application of local climate data, including information about short-term weather events, and records of pine phenology, including reproductive functions and tree damages. During the 20th century thermal optimum, the radial growth of Scots pine appeared to be influenced by several inter-related factors rather than responding to summer temperatures alone. A further understanding of these relationships will provide valuable information for predicting the response of northern Fennoscandian pine forests to future climate change.

Regarding reconstructions of summer temperatures from tree-rings in northern Norway, the present study implies that pine chronologies from the Finnmarksvidda are relatively straightforward to interpret. However, at the coast, a constant modifying influence of winter temperatures must be taken into account. In the inner valleys of the Scandes, both winter climate and spring precipitation appear to affect the climate reconstructions during warm periods. Although complicating reconstructions of past climate, these factors represent a challenge for future dendroclimatic investigations in terms of a) amplifying the major summer-temperature signal and b) providing additional information, such as winter temperatures and late winter to spring precipitation.

CONCLUSIONS

1. A total of eight tree-ring chronologies of Scots pine, *Pinus sylvestris*, were constructed in northern Norway at about 69°N along the gradient of continentality from the Atlantic coast to the inland east of the Scandes.
2. During AD 1800-1992, these eight chronologies shared about 70% variability, while nearly 10% of the ring-width variability was related to the west-east gradient.
3. At the coast, radial growth of Scots pine was limited by July-August temperatures. Inland pine was limited by July temperatures alone, with a weak June signal. Summer temperatures explain about 50% of the tree-ring variability, i.e. a minimum of $R^2_{adj} = 45\%$ in the coastal July-August reconstruction, and maximum $R^2_{adj} = 56\%$ in the reconstruction of July temperatures for northern Norway.
4. During the temperature optimum of the 20th century in the 1930s, radial growth was reduced in the inner Scandes, and the growth maximum was delayed until about 1950. This indicates a non-linear response to summer temperatures in unusually warm periods. The growth reduction was most likely due to high mid-winter temperatures and precipitation, high year-to-year variability of summer temperatures,

heavy needle loss in 1933 and allocation of assimilates to reproductive growth. The growth maximum at approximately 1950 coincides with increased late winter and spring precipitation.

5. The response function analysis suggests that northern Norway may be divided into a coastal and an inland region. However, the spatial pattern of pine growth during the 20th century implies the existence of three dendroecological regions: 1) the coastal region, 2) the inner valleys of the Scandes and 3) the Finnmarksvidda, east of the Scandes.

REFERENCES

Aandstad, S. 1939: Die Jahresringbreiten einiger seltenen Kiefern in Steigen, Nordland. *Nytt Magasin for Naturvitenskapene* 79, 127-40.

Akaike, H. 1974: A new look at the statistical model identification. *IEEE Transactions on Automatic Control* AC-19, 716-23.

Aniol, R.W. and **Eckstein, D.** 1984: Dendroclimatological studies at the northern timberline. In Mörner, N.-A. and Karlén, W., editors, *Climatic changes on a yearly to millennial basis*. Dordrecht: D. Reidel Publishing Company, pp. 273-9.

Aune, B. 1993: *Klima*. Nasjonalatlas for Norge. Hønefoss: Statens kartverk, 10 maps, 64 pp.

Barry, R.G. 1992: *Mountain Weather and Climate*. Routledge Physical Environment Series. London: Routledge, 2nd ed., 402 pp.

Bartholin, T.S. and **Karlén, W.** 1983: Dendrokronologi i Lapland. *Meddelanden fra det Dendrokronologiska Sällskapet* 5, 3-16.

Bathen, R. 1935: Våre polare furuskoger. *Tidsskrift for Skogbruk* 43, 75-83.

Briffa, K.R. 1994: Mid and late Holocene climate change: evidence from tree growth in northern Fennoscandia. In Funnell, B.M. and Kay, R.L.F., editors, *Palaeoclimate of the last glacial/ interglacial cycle*. *Natural Environment Research Council Special Publications* 94/2, 61-5.

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, 434-9.

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 Academic Publishers, pp. 137-52.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P. and **Eronen, M.** 1992: Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Climate Dynamics* 7, 111-9.

Briffa, K.R., Jones, P.D., Pilcher, J.R. and **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(4), 385-94.

Briffa, K.R., Jones, P.D. and **Schweingruber, F.H.** 1994: Summer temperatures across northern North America: Regional reconstructions from 1760 using tree-ring densities. *Journal of Geophysical Research* 99(D12), 25835-44.

Briffa, K.R., Jones, P.D., Schweingruber, F.H., Shiyatov, S.G. and **Vaganov, E.A.** 1996: Development of a north Eurasian chronology network: rationale and preliminary results of comparative ring-width and densitometric analyses in northern Russia. In Dean, J.S., Meko, D.M. and Swetnam, T.W., editors, *Tree rings, environment and humanity*. Proceedings of the International Conference, Tucson, Arizona, 17-21 May 1994. *Radiocarbon* 1996, 25-41.

Brooks, J.R., Flanagan, L.B. and **Ehleringer, J.R.** 1998: Responses of boreal conifers to climate fluctuations: indications from tree-ring widths and carbon isotope analyses. *Canadian Journal of Forest Research* 28, 524-33.

Conrad, V. 1946: Usual formulas of continentality and their limits of validity. *Transactions of the American Geophysical Union* 27, 663-4.

Cook, E.R. 1985: *A time-series analysis approach to tree-ring standardization*. PhD thesis, University of Arizona, Tucson, 171 pp.

Cook, E.R., Briffa, K.R., Shiyatov, S.G. and **Mazepa, V.** 1990a: Tree-ring standardization and growth-trend estimation. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 104-23.

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(1), 9-17.

Cook, E.R. and **Kairiukstis, L.A., editors** 1990: *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, 394 pp.

Cook, E.R., Shiyatov, S.G. and **Mazepa, V.** 1990b: Estimation of the mean chronology. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 123-32.

Damsgård, H. 1998: Årringundersøkelser på furu (*Pinus sylvestris*) fra Sørlandet og Setesdal, Sør-Norge. In Griffin, K. and Selsing, L., editors, *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 65-108.

D'Arrigo, R.D., Cook, E.R., Jacoby, G.C. and **Briffa, K.R.** 1993: NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews* 12(6), 431-40.

D'Arrigo, 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., Jacoby, G.C. and **Cook, E.R.** 1992a: Impact of recent North Atlantic anomalies on surrounding land areas based on dendroclimatic evidence. *Geophysical Research Letters* 19(23), 2321-4.

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

D'Arrigo, R.D., Jacoby, G.C. and **Free, R.M.** 1992b: Tree-ring width and maximum latewood density at the North American tree line: parameters of climate change. *Canadian Journal of Forest Research* 22, 1290-6.

Eckstein, D. 1969: *Entwicklung und Anwendung der Dendrochronologie zur Altersbestimmung der Siedlung Haithabu*. Dissertation, University of Hamburg, 114 pp.

Efron, B. 1979: Bootstrap methods: another look at the jackknife. *Annals of Statistics* 9, 139-72.

Erlandsson, S. 1936: *Dendro-Chronological Studies*. Uppsala: Almqvist & Wiksells Boktrykkeri. Stockholm Högskolas Geokronologiska Institution, *Data* 23, 119 pp.

Eronen, M. and **Zetterberg, P.** 1996: Climatic changes in northern Europe since late glacial times, with special reference to dendroclimatological studies in northern Finnish Lapland. *Geophysica* 32(1-2), 35-60.

Fritts, H.C. 1976: *Tree Rings and Climate*. London: Academic Press, 567 pp.

Graybill, D.A. and **Shiyatov, S.G.** 1992: Dendroclimatic evidence from the northern Soviet Union. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. London: Routledge, pp. 393-414.

Guiot, J. 1985a: The extrapolation of recent climatological series with spectral canonical regression. *Journal of Climatology* 5, 325-35.

— 1985b: Reconstruction of seasonal temperatures and sea-level pressures in the Hudson Bay area back to 1700. *Climatological Bulletin / Bulletin climatologique* 19(2), 11-59.

— 1990: Methods of calibration. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 165-78.

Guiot, J. and **Goeury, C.** 1996: PPPBase, a software for statistical analysis of paleoecological and paleoclimatological data. *Dendrochronologia* 14, 295-300.

Hanssen-Bauer, I. and **Førland, E.J.** 1998: *Annual and seasonal precipitation variations in Norway 1896-1997*. Norwegian Meteorological Institute, Oslo. *DNMI report* 27/98 klima, 37 pp.

Hanssen-Bauer, I. and **Nordli, P.Ø.** 1998: *Annual and seasonal temperature variations in Norway 1876-1997*. Norwegian Meteorological Institute, Oslo. *DNMI report* 25/98 klima, 29 pp.

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 users manuals for computer programs COFECHA and ARSTAN*. Laboratory of Tree-Ring Research, University of Arizona, Tucson. *Chronology Series* VI, 182 pp.

Hustich, I. 1969: Notes on the growth of pine in northern Finland and Norway. *Reports from the Kevo Subarctic Research Station* 1969(4), 159-70.

— 1978: The growth of Scotch pine in northern Lapland, 1928-77. *Annales Botanici Fennici* 15, 241-52.

Jacoby, G.C. and **D'Arrigo, R.D.** 1989: Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climatic Change* 14, 39-59.

— 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(4), 455-71.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J. and **Wigley, T.M.L.** 1996: Climate models - projections of future climate. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., editors, *Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 285-357.

Kirchhefer, A.J. 1998: Climate and site effects on tree-rings of *Pinus sylvestris* L. in northernmost Norway - an exploratory pointer-year study. In Griffin, K. and Selsing, L., editors, *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 15-28.

Kirchhefer, A.J. and **Vorren, K.-D.** 1995: Årringer på furu, *Pinus sylvestris* L., som kilde for klimainformasjon i Vesterålen, Nord-Norge (Tree rings of Scots pine, *Pinus sylvestris* L., a source of climate information in Vesterålen, northern Norway). In Selsing, L., editor, *Kilder for klimadata i Norden, fortrinnsvis i perioden 1860-1993 (Sources for climatic data in Norden, mainly in the period 1860-1993)*. Museum of Archaeology, Stavanger. *AmS-Varia* 24, 79-85.

Kozlowski, T.T., Kramer, P.J. and **Pallardy, S.G.** 1991: *The Physiological Ecology of Woody Plants*. Physiological Ecology. San Diego: Academic Press, 657 pp.

Kärenlampi, L. 1972: On the relationships of the Scots pine annual ring width and some climatic variables at the Kevo Subarctic Station. *Reports of the Kevo Subarctic Research Station* 9, 78-81.

Lindholm, M. 1996: *Reconstructions 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, 169 pp.

Lindholm, M., Eronen, M., Timonen, M. and **Meriläinen, J.** 1999: A ring-width chronology of Scots pine from northern Lapland covering the last two millennia. *Annales Botanici Fennici* 36, 119-26.

Lindholm, M., Timonen, M. and **Meriläinen, J.** 1996: Extracting mid-summer temperatures from ring-width chronologies of living pines at the northern forest limit in Fennoscandia. *Dendrochronologia* 14, 99-113.

Mann, M.E., Bradley, R.S. and **Hughes, M.K.** 1998: Global scale temperature patterns and climate forcing over the past six centuries. *Nature* 392, 779-87.

— 1999: Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* 26(6), 759-62.

Mikola, P. 1950: Puiden kasvun vaihteluista ja niiden merkityksestä kasvututkimuksissa (On variations in tree growth and their significance to growth studies). *Communicationes Instituti Forestalis Fenniae* 38(5), 1-131.

Moen, A. 1998: *Vegetasjon.* Nasjonalatlas for Norge. Hønefoss: Statens kartverk, 200 pp.

Nicholls, N., Gruza, G.V., Jouzel, J., Karl, T.R., Ogallo, L.A. and **Parker, D.E.** 1996: Observed climate variability and change. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., editors, *Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 133-92.

Ording, A. 1941: Årringundersøkelser på gran og furu. *Meddelelser fra Det Norske Skogforsøksvesen* VII(25), 101-354.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R.S., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G.C., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J.C., Retelle, M., Smith, S., Wolfe, A. and **Zielinski, G.A.** 1997: Arctic environmental change of the last four centuries. *Science* 278, 1251-6.

Ruden, T. 1935: Om årlige forandringer i trærnes tilvekst. *Tidsskrift for Skogbruk* 43, 272-5.

— 1987: *Hva furuårringer fra Forfjorddalen kan fortelle om klimaet i Vesterålen 1700-1850 (What annual rings of Scots pine (Pinus sylvestris) from Forfjorddalen can tell about the climate in Vesterålen 1700-1850).* Norwegian Forest Research Institute, *NISK rapport* 4/87, 12 pp.

Schweingruber, F.H. 1985: Dendro-ecological zones in the coniferous forests of Europe. *Dendrochronologia* 3, 67-75.

Schweingruber, F.H. and **Briffa, K.R.** 1996: Tree-ring density networks for climate reconstruction. In Jones, P.D., Bradley, R.S. and Jouzel, J., editors, *Climatic variations and forcing mechanisms of the last 2000 years*. Berlin: Springer-Verlag, *NATO ASI Series* I 41, 43-66.

Schweingruber, F.H., Bräker, O.U. and **Schär, E.** 1987: Temperature information from a European dendroclimatological sampling network. *Dendrochronologia* 5, 9-22.

Slåstad, T. 1957: Årringundersøkelser i Gudbrandsdalen (Tree-ring analyses in Gudbrandsdalen). *Meddelelser fra Det Norske Skogforsøksvesen* 14(48), 571-620.

Thun, T. and **Vorren, K.-D.** 1996: Short dendroseries from northern Norway reflect oceanic and subcontinental climates. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag, *Palaeoclimate Research* 20, 120-6.

Till, C. and **Guiot, J.** 1990: Reconstruction of precipitation in Morocco since 1100 A.D. based on *Cedrus atlantica* tree-ring widths. *Quaternary Research* 33, 337-51.

Tuhkanen, S. 1980: Climatic parameters and indices in plant geography. *Acta Phytogeographica Suecica* 67, 1-110.

Watson, R.T., Zinyowera, M.C., Moss, R.H. and **Dokken, D.J., editors** 1998: *The Regional Impacts of Climate Change: An Assessment of Vulnerability. A special report of IPCC Working Group II*. Cambridge: Cambridge University Press, 517 pp.

Wigley, T.M.L., Briffa, K.R. and **Jones, P.D.** 1984: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology* 23, 201-13.

Wigley, T.M.L., Jones, P.D. and **Briffa, K.R.** 1987: Cross-dating methods in dendrochronology. *Journal of Archaeological Science* 14, 51-64.

Submitted to *Climatic Change*, January 28th 2000