THE INFLUENCE OF SLOPE ASPECT ON TREE-RING GROWTH OF *PINUS SYLVESTRIS* L. IN NORTHERN NORWAY AND ITS IMPLICATIONS FOR CLIMATE RECONSTRUCTION

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Abstract: The influence of slope aspect on radial growth of Scots pine, *Pinus sylvestris* L., was studied in the valleys Dividalen and Målselvdalen, northern Norway. Both localities were represented by two tree-ring chronologies each. July temperature was the main growth-determining climate factor at all sites. Scots pine at the two north-facing sites also responded positively to June temperatures, most likely due to the influence of the midnight sun. A positive response to March temperatures and precipitation in recent decades at the south-facing slopes was interpreted as stress during periods of anticyclonic weather conditions due to strong insulation at low temperatures, high diurnal temperature amplitudes and winter desiccation. Based on regional mean growth, July temperatures were reconstructed back to AD 1799 (R^2_{adj} = 38%). June temperatures were reconstructed back to 1776, utilising the growth differences between the north-facing and the south-facing sites (R^2_{adj} = 26%). Both reconstructions would have gained from the existence of long climate series in the inner Scandes of northern Norway. The growth response to June temperature, its time-stability and its applicability to climate reconstruction requires further investigation.

Key words: Tree rings, climate, *Pinus sylvestris* L., slope aspect, Norway

INTRODUCTION

Tree-ring analysis is a widely applied tool for the reconstruction of past climate (Fritts, 1976; Cook and Kairiukstis, 1990). At the northern tree line, tree-ring chronologies generally reflect summer temperatures as the principal growth-limiting factor (Briffa *et al.*, 1988; D'Arrigo *et al.*, 1992; Lindholm *et al.*, 1996; Hughes *et al.*, 1999). A common approach in dendroclimatology is to extract temperature information from regional mean chronologies, which reduces the effect of random stand-specific events such as wind-fall, fires, insect outbreaks or local climate events. Thereby, also habitat-related differences in the climate response of trees are averaged out. On the other hand, such differences might yield information on past climate, adding to the signal of the regional growth-limiting factor.

The present study focuses on the influence of slope aspect on radial growth. Slope exposition primarily affects the radiation budget, and thus also the heat and water balance (Barry, 1992). The resulting differences in the thermal sums and the length of the vegetation period are expressed for example in the lower position of the alpine timberline at north-facing sites. North of the Polar Circle, the significance of the slope aspect is altered by the midnight sun. Thus in northern Norway, north-facing pine forests preferably occur where the northern skyline is low.

In Finnmark, differences in slope-related climate-response of Scots pine were observed in a single-year analysis, both in terms of the duration and the timing of the growing season and the influence of summer precipitation (Kirchhefer, 1998). Similar results have been achieved in the European Alps (Kienast *et al.*, 1987; Desplanque *et al.*, 1999). The aim of the present study was to explore to what extent the slope-aspect modifies the climate signal of tree-ring time series, and whether potential differences in the climate-growth response are applicable to a differentiation of climate reconstructions from tree-ring widths in high latitudes.

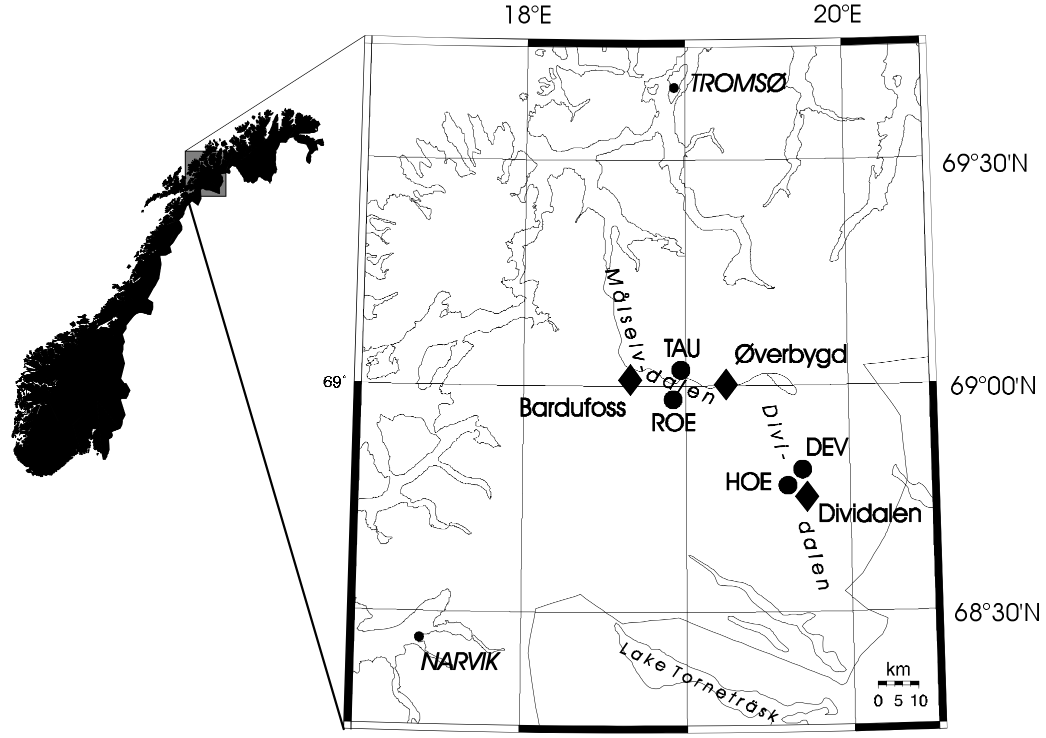

Figure 1: Map of the study area, Målselvdalen and Dividalen in inner Troms, northern Norway, showing the positions of the pine sites Devdiselva DEV, Høgskardet HOE, Tauskjerringa TAU and Rønninglia ROE (●) and the climate stations Bardufoss, Øverbygd and Dividalen (♦).

MATERIAL AND METHODS

THE SITES

The two main localities for the present investigation were situated in the valleys Målselvdalen and Dividalen in inner Troms, northern Norway (Figure 1). Phytogeographically, Målselvdalen belongs to the oceanic-continental transition of the middle boreal zone (Mb-OC) and Dividalen to the sub-continental section of the northern boreal zone (Nb-C1) (Moen, 1998). Climatically, the valleys differ mostly in the precipitation regime, with 652 mm annual precipitation and an autumnal maximum in Målselvdalen and 282 mm annually and a July maximum in Dividalen (Figure 2). In each valley, a pair of sites was selected from opposing slopes, close to the upper tree line of Scots pine, *Pinus sylvestris* L. (Table 1). In Målselvdalen, the slopes faced south and north-east, with the main valley orientation in a west-east direction. In Dividalen, the sites were facing south-west and north, respectively, with the main valley direction NNW–SSE.

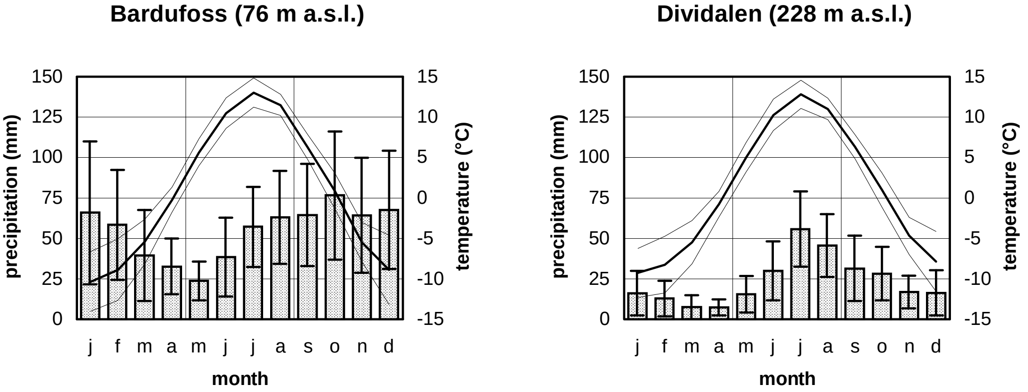

Figure 2: Climate diagrams for Bardufoss and Dividalen showing monthly mean temperatures (lines) and precipitation (bars) for the period 1961-1990 (Aune, 1993; Førland, 1993). Standard deviations are indicated.

TREE-RING ANALYSIS

Two cores were extracted from each of a minimum of 17 dominant, solitary Scots pines, *Pinus sylvestris*, in dry habitats. Tree rings were measured with an resolution of 0.001 millimetres. The ring-width series of the individual samples were cross-dated by visual comparison of cores and tree-ring graphs within trees, between trees, and with the developing chronology (Stokes and Smiley, 1968; Fritts, 1976). This process was assisted by correlation analysis (COFECHA; Holmes *et al.*, 1986; Wigley *et al.*, 1987).

Table 1: Site description: latitude and longitude, elevation above sea level, slope aspect and inclination, and number of samples.

	Målselvdalen Tauskjerringa TAU	Målselvdalen Rønninglia ROE	Dividalen Devdiselva DEV	Dividalen Høgskardet HOE
latitude N, longitude E	69°02', 18°55'	68°58', 18°53'	68°51', 19°37'	68°50', 19°33'
elevation m a.s.l.	280-360	260-340	380-450	320-370
slope angle, aspect	17°S	15°NE	11°SW	8°N
no. trees + tree remains	18 + 6	17	21	19 + 2

The raw tree-ring series were standardised by fitting negative exponential functions or non-ascending straight lines (Cook *et al.*, 1990a). This conservative technique removes the age-related growth trend, but preserves a maximum of climatically induced long-term trends. The resulting tree-ring index series were averaged to STANDARD chronologies by bi-weight robust means, thereby preventing exceptionally broad or narrow tree-rings of individual trees from affecting the chronology (Cook *et al.*, 1990b).

In order to enhance the year-to-year tree-ring signal for the climate-growth response analysis, serial correlation between tree-rings was removed from the individual series by autoregressive modelling, before computing the so-called RESIDUAL chronologies (Cook, 1985). ARSTAN chronologies, which are regarded as containing a maximum of low-frequency climate information, were computed after re-introducing the pooled autoregression into the RESIDUAL radius series (Cook, 1985). Mean chronologies were computed for each slope aspect (DEV-TAU and HOE-ROE mean) and a regional mean chronology was constructed from all four site chronologies, normalised for the period 1776-1992 (RESIDUAL chronologies) and 1799-1992 (ARSTAN chronologies).

RESPONSE-FUNCTION ANALYSIS

The climate-growth relationship was assessed by bootstrap orthogonal regression (Guiot, 1990; Till and Guiot, 1990) on the RESIDUAL chronologies and monthly mean temperature and precipitation for the 13 months from previous to current August. This method includes principal component analysis (PCA) on the climate variables. The regression analysis was repeated one thousand times by bootstrapping (Efron, 1979). The strength and stability of the regression results were evaluated by the mean multiple correlation coefficients and their standard deviation. In each iteration, the years not selected for calibration were used for verification. The significance of the regression coefficients for the climate variables were evaluated by their standard deviation (2 SD) and the 90% confidence band, represented by the 5th and 95th percentiles.

The site chronologies were related to the local climate series from Bardufoss back to 1947 and Dividalen back to 1936 (Figure 1, Figure 2). Missing data at Dividalen were estimated from the nearest station, Øverbygd. The slope mean chronologies and the regional mean chronology were related to Dividalen-Bardufoss mean climate 1947-1992, i.e. the mean of the standardised climate series from Bardufoss and Dividalen. Regional climate series for coastal (NNC) and inland northern Norway (NNI) and their mean (NN, northern Norway excluding the Varanger peninsula) facilitated an extension of the analysis period back to 1896 (NNI, NN) and 1876 (NNC) (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer and Nordli, 1998).

CLIMATE RECONSTRUCTION

The climate variables for the reconstruction were chosen on the basis of the response function analyses, assisted by all-subset multiple regression. Transfer functions for the most suitable models were calibrated by orthogonal bootstrap regression (Guiot, 1990; Till and Guiot, 1990; Guiot and Goeury, 1996) applying Målselv and NN temperature data of 1947-1992 and 1876-1992, respectively. The latter data set was divided into an early (1876-1934) and a late calibration period (1935-1992) in order to assess the temporal model stability.

The first differences test, the sign test, the Product Means test, the reduction of error (RE) (Fritts, 1976; Fritts *et al.*, 1990) and explained variance adjusted for degrees of freedom (R^2_{adj}) yielded information on the model performance. The first differences test compares the first difference series of the observation and reconstruction, the sign test is based on the number of cases where the estimated and the observed values have the same sign in relation to the observed mean, whereas the Product Means test additionally considers the absolute temperature deviations. The RE is similar to the explained variance statistic, but the total squared error is obtained using the mean of the dependent period as the only estimate. Applied software was VERIFY (Dendrochronological Program Library, DPL), 3Pbase (Guiot and Goeury, 1996) and Statistica (StatSoft, 1996).

RESULTS AND DISCUSSION

THE CHRONOLOGIES

The STANDARD chronologies (Figure 3) were very similar, with low tree-ring indices around 1810 and 1880-1910 and high indices about 1830, in the 1850s, 1920s and particularly around 1950. At all sites, growth was repressed in the 1930s, during the thermal optimum of the 20th century. This feature is unique for the valleys of the inner Scandes and appeared only weakly, if at all, in other northern Fennoscandian chronologies (Briffa and Schweingruber, 1992; Kirchhefer and Vorren, 1995; Lindholm, 1996). The most prominent growth difference between the valleys was the strongly negative anomaly around 1810 in Målselvdalen. The relatively high growth indices in Målselvdalen before 1800 and between 1825-1860 may be regarded as an artefact of the standardisation procedure, triggered by the 1810 anomaly. In Dividalen, growth was below average during most of the period 1770-1910.

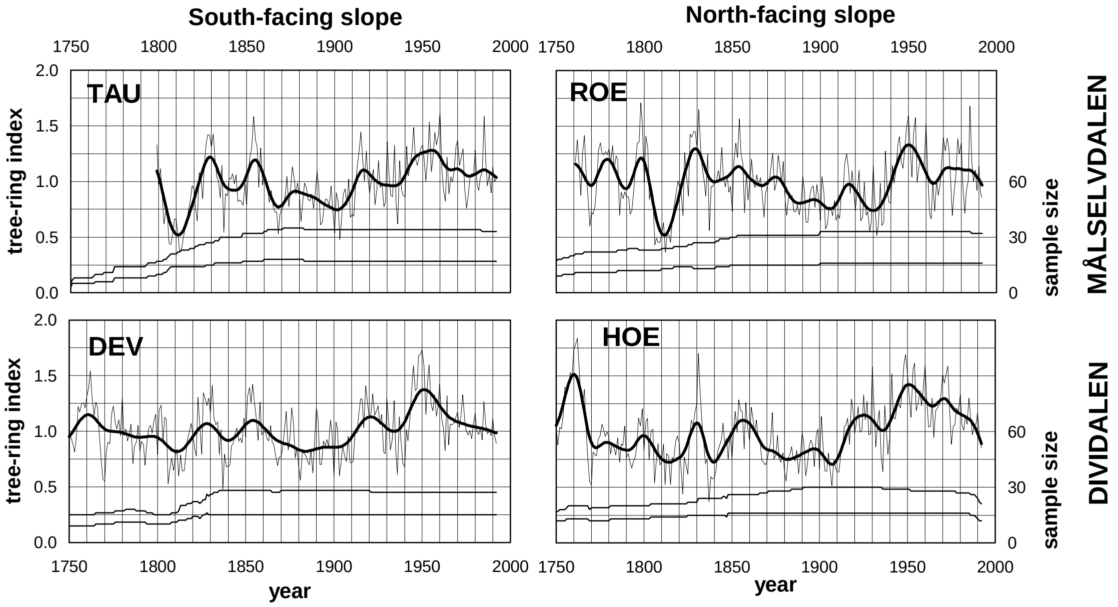

Figure 3: STANDARD ring-width chronologies from Dividalen and Målselvdalen, AD 1650-1992. The low-frequency variability is indicated by a 10-year low-pass filter (bold line). The sample size is shown below the chronologies (upper line: number of radii; lower line: number of trees). The chronologies from Devdiselva (DEV) and Tauskjerringa (TAU) comprise trees from south-facing sites, and Høgskardet (HOE) and Rønninglia (ROE) trees from north-facing sites, respectively. Only the chronology sequences that expressed 85% of the population signal (EPS) are shown.

Table 2: Chronology statistics, describing chronology length, replication, homogeneity and signal strength: MS = mean sensitivity, SD = standard deviation (chronology mean = 1), AR1 = first order autocorrelation, $\mathrm{VAR}_{\mathrm{AR}}$ = variance due to autocorrelation, SNR = signal-to-noise-ratio, EPS = expressed population signal (Wigley *et al.*, 1984), $\mathrm{VAR}_{\mathrm{PC1}}$ = variance in the first principal component (Fritts, 1976; Cook and Kairiukstis, 1990).

	DEV	HOE	TAU	ROE
Total time span	1501-1992	1377-1995	1697-1994	1637-1994
Number of trees (radii)	18 (38)	19 (38)	18 (35)	16 (34)
Mean series length (years)	229	226	229	198
Ring-width median (mm)	0.75	0.46	0.89	0.83
STANDARD chronology				
MS	0.17	0.16	0.19	0.19
SD	0.23	0.24	0.26	0.27
AR 1	0.62	0.67	0.62	0.63
$\mathrm{VAR}_{\mathrm{AR}}$	44.6 %	50.6 %	47.1 %	42.2 %
RESIDUAL chronology (AR model)	AR 3	AR 5	AR 3	AR 3
MS	0.20	0.19	0.21	0.22
SD	0.17	0.17	0.19	0.19
Common interval analysis 1838-1992:				
Number of trees (radii)	15 (26)	10 (16)	15 (28)	13 (26)
STANDARD and ARSTAN series				
r between trees	0.44	0.43	0.38	0.35
r radii versus mean	0.69	0.67	0.64	0.62
SNR	12.0	7.4	9.1	7.0
EPS	0.92	0.88	0.90	0.88
EPS 85% since (trees)	1656 (8)	1652 (8)	1799 (10)	1761 (11)
$\mathrm{VAR}_{\mathrm{PC1}}$	48.4 %	48.3 %	41.8 %	42.1 %
RESIDUAL series				
r between trees	0.51	0.46	0.47	0.50
r radii versus mean	0.72	0.68	0.70	0.72
SNR	15.3	8.6	13.0	12.8
EPS	0.94	0.90	0.93	0.93
EPS 85% since (trees)	1611 (6)	1655 (7)	1776 (7)	1720 (6)
EPS 90% since (trees)	1681 (9)	1736 (11)	1807 (11)	1755 (10)
$\mathrm{VAR}_{\mathrm{PC1}}$	53.4 %	50.5 %	49.5 %	53.0 %

Ring width, mean sensitivity (MS) and standard deviation (SD) were greater in Målselvdalen than in Dividalen (Table 2), most likely due to the shorter chronology lengths in Målselvdalen. The Dividalen chronologies were more homogeneous, as reflected by the correlation between tree-ring series, by the expressed population signal

(EPS; Wigley *et al.*, 1984), the signal-to-noise-ratio (SNR) and the variance represented by the first principal component (VAR_{PC1}).

In addition, several tree-ring statistical parameters varied in relation to slope aspect. At the south-facing slopes, higher values were achieved for mean series length, ring width, correlation between tree-ring series and SNR for both chronology versions, and EPS for the RESIDUAL series. The north-facing slopes reached larger values for standard deviations and first-order autocorrelation. In conclusion, the trees from north-facing sites expressed more variability, whereas south-facing pine stands contained a stronger common tree-ring signal. However, the mean tree-ring sensitivity, i.e. the mean difference between consecutive rings, which is regarded as a measure for the climatic severity of a site (Fritts, 1976) did not show any clear differences between the slopes.

CLIMATE RESPONSE

At all sites and for all periods analysed, radial growth of Scots pine was most strongly correlated with July temperatures (Table 3). This confirmed the previously observed dominant influence of summer temperatures on pine growth close to the alpine and arctic limit of its distribution in Målselvdalen (Thun and Vorren, 1996) and in northern Fennoscandia in general (Erlandsson, 1936; Mikola, 1950; Sirén, 1961; Bartholin and Karlén, 1983; Aniol and Eckstein, 1984; Briffa *et al.*, 1988; Eckstein *et al.*, 1991; Kirchhefer and Vorren, 1995; Lindholm, 1996; Lindholm *et al.*, 1996). The cambium of Scots pine in northern Finland is active from mid or late June to early or mid August (Hustich, 1956; Hari and Sirén, 1972), with the onset varying up to one month (Romell, 1925). Accordingly, also June and/or August temperatures were significant for the radial growth of Scots pine in several of the named northern Fennoscandian dendroclimatic investigations. The present study revealed only a secondary response to June, but not to August, temperatures.

The importance of climate conditions during the vegetation period was further emphasised by the response functions computed from the NNI climate data, where significant values appeared exclusively within the June-August time window (Table 3). The negative influence of July precipitation during 1896-1992 can be explained by its inverse relationship with air and soil temperatures as well as light. However, the fact that no significant precipitation response occurred when applying local climate data might be interpreted as a sign of moderate drought stress. Further, this casts doubt upon the applicability of precipitation data derived from stations east of the Scandes (NNI) for dendroclimatic analyses in the inner Scandes.

Table 3: Climate-growth response of Scots pine derived from the individual RESIDUAL chronologies (DEV Devdiselva, HOE Høgskardet, TAU Tauskjerringa, ROE Rønninglia), slope mean chronologies (S south-facing; N north-facing) and the four-chronology mean (mean), and climate from Bardufoss (bar), Dividalen (div), the Målselv mean (mål) and the regional climate series for inland northern Norway (NNI). The quality of the response functions are assessed by the mean bootstrap multiple correlations (×100) and their standard deviations SD for the calibration (cal) and verification procedure (ver). All response functions include temperatures and precipitation from the previous (pAug) to the current August, but only regression coefficients β (×100) within the 90% confidence interval are displayed, together with the ratio β:SD (italics).

			mean r		temperature						precipitation				
			cal	ver	Sep	Nov	Feb	Mar	Jun	Jul	pAug	Jan	Mar	Jul	Aug
TAU	bar	1947-92	90	32		34	-23	17		42					
			±5	±20		*2.5*	*-2.0*	*1.6*		*3.5*					
ROE	bar	1947-92	86	31		23	-23		19	39					
			±5	±19		*2.0*	*-2.1*		*1.9*	*3.4*					
DEV	div	1947-92	87	22	29			27		39					
			±5	±21	*2.3*			*2.4*		*3.1*					
HOE	div	1947-92	90	29			-22		25	42					
			±4	±21			*-2.3*		*2.2*	*3.6*					
DEV	div	1936-92	83	30	25			26		39		20	18		
			±5	±19	*2.1*			*2.5*		*3.5*		*1.7*	*1.7*		
HOE	div	1936-92	84	30	20		-21			44					
			±5	±18	*1.8*		*-2.3*			*3.8*					
S	mål	1947-92	89	35	26	29	-17	26		42					18
			±4	±22	*2.1*	*2.3*	*-1.8*	*2.5*		*4.0*					*1.9*
N	mål	1947-92	88	34	19	23	-23		24	43					
			±5	±21	*1.6*	*1.9*	*-2.6*		*2.2*	*4.2*					
mean	mål	1947-92	88	35	22	26	-21	20		44					
			±5	±21	*1.8*	*2.1*	*-2.2*	*1.9*		*4.3*					
S	NNI	1947-92	83	7				21		35				-25	
			±6	±22				*1.6*		*2.4*				*-2.1*	
N	NNI	1947-92	84	12						30				-23	
			±6	±21						*2.1*				*-1.8*	
mean	NNI	1947-92	83	8						33				-25	
			±6	±21						*2.3*				*-2.0*	
S	NNI	1896-1992	76	41						35	18			-33	
			±4	±12						*5.0*	*2.4*			*-4.2*	
N	NNI	1896-1992	76	43					23	34	16			-31	
			±4	±12					*3.3*	*4.9*	*2.2*			*-3.8*	
mean	NNI	1896-1992	76	42					18	35	17			-33	
			±4	12					*2.5*	*5.0*	*2.3*			*-4.0*	

When applying the NNI climate data, south- and north-facing slopes responded significantly to precipitation of previous August. This might be interpreted in terms of cloudiness and advective heat reducing the risk of early frosts. Also, high precipitation might cause a proper cessation of the vegetation period due to reduced light early inducing growth cessation and winter-hardening, and a water balance supporting the necessary physiological functions (Kozlowski *et al.*, 1991). However, statistically, this phenomenon merely may be an expression of the tendency for a cool, i.e. wet, summer to be followed by a warm summer.

The clearest difference in climate response between the valleys occurred in November, when pine reacted significantly positively to temperature only in Målselvdalen. Because at this time of the year the mean temperatures are well below freezing point (Figure 2), this response might be related to the higher climate oceanity of Målselvdalen compared to Dividalen, causing a lower tolerance of pine to low early-winter temperatures. This may also indicate a higher frequency of snow-free conditions in early winter, which in combination with low temperatures, leads to deeply frozen ground and, consequently, reduced growth in the following vegetation period (Kullman, 1991). On the other hand, the negative response to February temperatures at all sites except the south-facing Devdiselva (DEV) may indicate stress due to warm spells in mid winter.

Significant slope-related temperature responses occurred in the months of March and June. In March, a positive correlation appeared at the south-facing slopes (DEV, ROE) during 1947-1992, whereas the north-facing sites were unaffected. Although at this time of the year the sun has reached a considerable height above the horizon, it is unlikely that solar radiation directly triggered this response. This is because clear skies at this time of the year are associated with cold, continental air masses and extremely low night temperatures of about –30°C. Strong insulation raise needle temperatures above zero at noon. This might cause winter desiccation due to the frozen ground (Jalkanen, 1993) and mechanical damage to needle tissue due to the extreme diurnal temperature amplitudes (Kozlowski *et al.*, 1991). High light intensity in combination with below-zero air temperatures can induce damage to photosynthetic pigments (Kozlowski *et al.*, 1991). Therefore, the positive response to mean temperature in March is likely to be related to heat advection by moist south-western air masses. This interpretation was supported by the positive response to March precipitation at Devdiselva (DEV) during 1936-1992.

In June, a positive temperature response was observed at the north-facing slopes (Rønninglia ROE, Høgskardet HOE). Where the northern horizon is low, these slopes are exposed to midnight sun from late May to mid July. The cambial activity of pine commences between early and late June (Romell, 1925; Hustich, 1956; Hari and Sirén, 1972; Schmitt *et al.*, 1999), at the time when the sun stands highest above the northern horizon. Particularly if pine is adapted to the red light of low-angle sun, solar radiation in June directly triggers photosynthesis during long days. The midnight sun contributes to relatively high night-time temperatures of the tree and soil and thereby promotes root activity and water conductivity. Also the reflected light from snow-covered mountains must be considered as a energy source, contributing to the thermal sum necessary for an early start of cambial activity is attained. For these reasons, the first half of the midnight sun period appears to be essential for an optimal growth of pine during the short growing season at northern slopes.

The regional and slope mean chronologies yielded larger multiple correlation coefficients for the verification procedure (r_{VER}) than the individual chronologies (Table 3). This means that averaging site chronologies to mean chronologies suppressed the non-climatic, random variability in tree-ring series. On the other hand, the application of the NNI climate series 1947-1992 gave lower coefficients. Thus, local climate data were more representative and revealed more detailed climate-growth relationships than NNI climate data. However, the loss of information due to the application of NNI data was outweighed by their series length.

TEMPERATURE RECONSTRUCTION

July temperature was selected as the main variable for climate reconstruction. The optimal transfer function comprised the ring width of the current year (t) and one following ring (t+1) of the regional mean ARSTAN chronology as predictors. The calibration based on Dividalen-Bardufoss mean climate 1947-1991 yielded a mean multiple correlation coefficient $r_{CAL} = 0.65$ and an explained variance adjusted for degrees of freedom $R^2_{adj} = 0.39$ (Table 4). The loss of explained variance when applying the northern Norwegian mean temperature data (NN) for 1947-91, was approximately 25%. However, extending the calibration period to 1876-1991 again yielded a relatively high value of $r_{CAL} = 0.63$ (Table 4). The explained variance $R^2_{adj} = 0.38$ was slightly lower than $R^2_{adj} = 0.41$ obtained in northern Finland (Lindholm *et al.*, 1996), and distinctly lower than $R^2_{adj} = 0.48$ observed in northern Sweden (Briffa *et al.*, 1990). Despite this, the positive reduction of error statistics (RE = 0.23 to 0.45) indicated sufficient skill of the model (Fritts, 1976). One reason for the relatively low explained variance was the lack of long local climate series. Another reason may be the systematic deviations between observed and reconstructed July temperatures during 1930-60 (Figure 3), which inferred a non-linear climate response of Scots pine during exceptionally warm periods (Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998). The latter effect may also be seen in the lower correlation coefficient for the late calibration period in the present study (1934-1991) and at Lake Torneträsk (Figure 1) (Briffa *et al.*, 1990).

Table 4: Calibration results for the reconstruction of June and July temperatures. Calibration and verification statistics of the transfer functions for an early (1876-1933), a late calibration period (1934-1991) and the entire calibration period (1876-1991): mean bootstrap multiple correlation coefficients for the calibration (r_{CAL}) and verification sub-samples (r_{VER}) within the calibration period (Guiot, 1990; Till and Guiot, 1990), explained variance adjusted for degrees of freedom (R^2_{adj}), t-value for the Product Means test (PM), sign test (s: number of incorrect signs), number of incorrect first differences (d), number of years (n), multiple correlation coefficients (r) and reduction of error (RE) (Fritts, 1976; Fritts *et al.*, 1990). * Calibrated with the Målselv mean climate series. PM, s and d significant at $p < 0.05$, if not indicated by n.s.

	calibration							verification						
period	r_{CAL}	r_{VER}	R^2_{adj}	PM	s	d	n	period	r	RE	PM	s	d	n
June														
1947-1991*	.57±.11	.49±.19	.28	4.2	n.s.	8	45							
1876-1933	.60±.07	.52±.13	.30	4.1	15	18	58	1934-1991	.46	.20	1.8	15	15	58
1934-1991	.53±.07	.50±.14	.25	3.2	22	17	58	1876-1933	.37	.19	3.4	n.s.	n.s.	58
1876-1991	.53±.05	.52±.10	.26	3.8	37	37	116							
July														
1947-1991*	.65±.09	.61±.17	.39	2.3	11	7	45							
1876-1933	.69±.05	.67±.11	.46	5.0	18	17	58	1934-1991	.50	.23	2.3	15	10	58
1934-1991	.57±.09	.52±.15	.28	1.8	13	12	58	1876-1933	.63	.45	3.6	15	19	58
1876-1991	.63±.05	.60±.09	.38	4.1	31	27	116							

Because Scots pine responded to June temperatures only at the north-facing sites, the growth differences between the slopes were tested with regard to their applicability for a reconstruction of June temperatures. The transfer function contained the mean RESIDUAL chronologies from the south-facing (t: positive β; t+1: negative β) and north-facing slopes, respectively (negative β). When applying Dividalen-Bardufoss mean climate for 1947-1991, the mean multiple correlation coefficient was $r_{CAL} = 0.57$ and the explained variance adjusted for degrees of freedom was $R^2_{adj} = 0.28$ (Table 4). The calibration applying NN climate of 1876-1991 yielded $r_{CAL} = 0.53$ and $R^2_{adj} = 0.26$. These figures are slightly lower than those obtained for July temperatures from RESIDUAL chronologies in northern Finland; $R^2_{adj} = 0.31$ (Lindholm, 1996). Despite the relatively low explained variance and the non-satisfactory performance in the high frequencies for the 1947-1991 and 1934-1991 calibrations, the positive reduction of error statistics and the significant results for the long calibration period still suggested some predictive skill of the models (Fritts, 1976).

The visual comparison of both observed and reconstructed temperatures (Figure 4) indicated that the June reconstruction alternated between periods of satisfactory agreement (1885-1908, 1930-1940, 1951-1973) and larger deviations, such as around 1800 and 1920, in the late 1940s and after 1973. In the 1910s, when a strong growth increase occurred at all sites due to the rapid warming in July, little sensitivity was expressed in the June temperature reconstruction. The years 1948-50 were poorly modelled in both reconstructions, implying that in these years, growth was not governed by monthly resolved June and July temperatures. During the 1970s and early 1980s, the June temperature curves were out of phase, but still, the second differences of the reconstruction indicated a certain modifying influence of June temperatures on slope-related pine growth. The temporally variable performance of the June temperature model suggests that additional factors were responsible for the observed growth differences between the slopes (Figure 5) and that these relationships were not stable in time. For instance, March temperature influenced growth at the south-facing slopes during the later part of the analysis period.

Both reconstructions showed a high agreement of the decadal variability during the whole reconstruction period, 1799-1991 (Figure 5). High temperatures in both months, i.e. early commencing warm summers, were reconstructed for the years 1801, 1826,

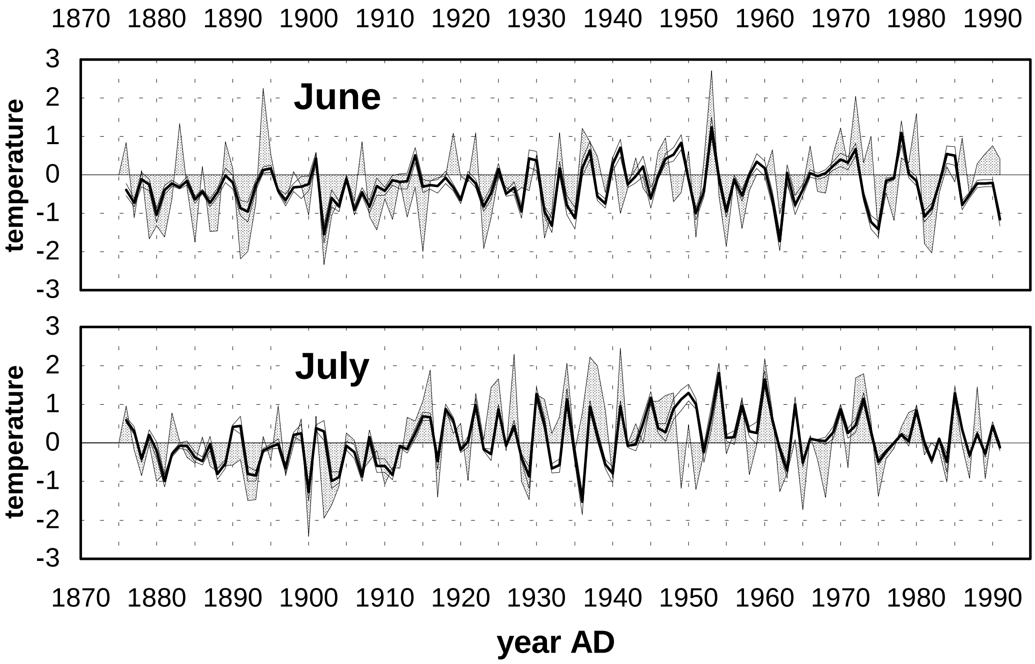

Figure 4: Visual comparison of the observed (shaded) and estimated (bold lines) June and July temperatures of northern Norway (NN), 1876-1991. The observed temperatures are expressed in standard deviations from the mean 1961-1990. The reconstruction represents the median of thousand individual reconstructions computed by bootstrap regression. The 90% confidence band of the reconstruction is indicated (thin lines).

1831, 1852, 1854, 1873, 1901, 1930, 1937, 1941, 1949, 1953, 1960, 1970, and 1985. The underlined figures indicate agreement between reconstructed and observed temperatures 1876-1991. Cool conditions in June and July were reconstructed for the years 1800/03/06, 1812/15, 1822, 1857, 1874, 1892, 1897, 1920/23/24, 1928, 1932/39, 1952/55, 1962, 1975, 1982, and 1991. Warmth in June but cold temperatures in July were correctly estimated for the years 1907, 1953 and 1963. Conversely, cold temperatures in June but warmth in July were correctly estimated for the years 1915, 1931, 1934, 1945, 1954 and 1964, but incorrectly in 1941. Thus, in a number of years the reconstruction of June temperatures gives valuable information about the thermal character of the vegetation period in addition to July temperatures, which would be the subject of a conventional temperature reconstruction, focusing on the most dominant growth-determining climate factor.

The observed response to, as well as the proposed reconstruction of, June temperatures requires further critical assessment. Ideally, assessment of the climate-growth response of Scots pine should be supported by field measurements of eco-physiological functions, cambial activity and local climate. Future dendroclimatic analyses should apply pentade climate data (Hughes *et al.*, 1999; Vaganov, 1999). Both approaches may reveal more detailed knowledge of the differences in the length of the vegetation period on the respective slopes and the contribution of early summers, thereby enabling an improved temperature reconstruction.

An important step in future evaluation of the obtained reconstruction will be a verification by independent data. Potentially applicable historical climate-proxy data reflecting spring and early summer temperatures are the dates of ice-breaking of the rivers Målselva and Torneå as well as data on agricultural activities in northern Fennoscandia (Holmboe, 1913; Erlandsson, 1936; Fjærvoll, 1964). Steps towards a higher reliability of the reconstruction should include a higher site replication, with new pairs of chronologies close to long-established climate stations.

This study showed an example of the site-related variability of pine response to a changing climate. It inferred that a change of the length of the vegetation period caused by a later commencement of summer will particularly affect the north-facing slopes. Forests in these habitats are more marginal, for instance if expressed in equivalent latitudes. Thus, changes in the spring temperatures, but also in the duration of the snow cover and cloudiness must have significant effects at these sites. Both snow cover and cloudiness are climate factors which are considered as important variables of global change (Groisman *et al.*, 1994; Walsh, 1995; Frich *et al.*, 1996; Nicholls *et al.*, 1996;

Tuomenvirta *et al.*, 1998), and addressed in dendroclimatic studies (Pohtila, 1980; Villalba *et al.*, 1997; Vaganov, 1999). Because the temperature response observed in the present study appeared to be triggered by the midnight sun, the conclusions in this case most likely are of limited geographical significance, confined to latitudes north of the Polar Circle.

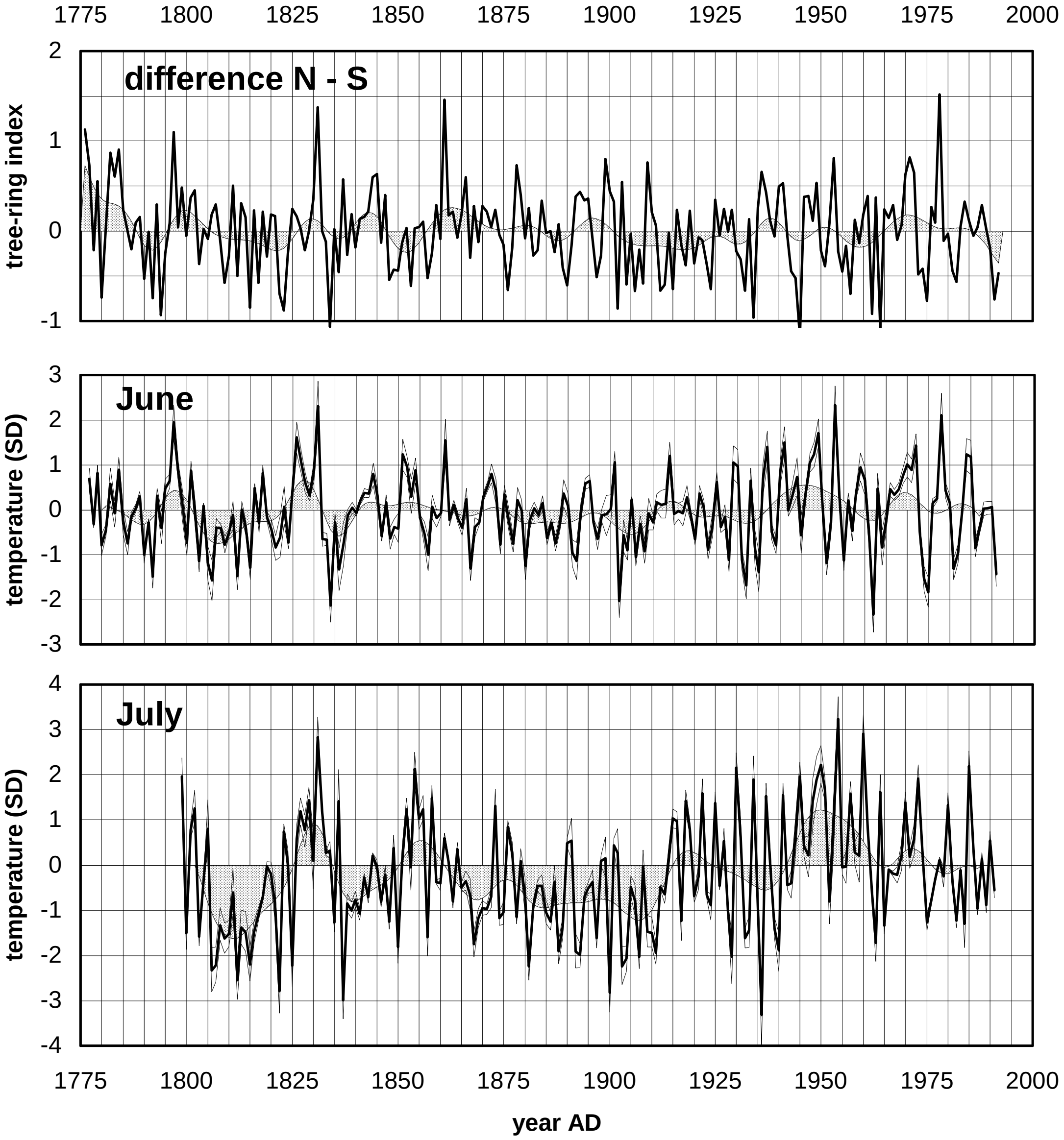

Figure 5: Reconstructed June and July temperatures for northern Norway, expressed in standard deviations from the mean 1961-1990. The reconstruction represents the median of thousand individual reconstructions derived by bootstrap regression; the thin lines show the 5th and 95th percentiles, i.e. the 90% confidence band. The shaded area indicates the low-frequency temperature variability (10-year low-pass filter).

SUMMARY

1. A total of four tree-ring chronologies of Scots pine, *Pinus sylvestris*, were established in Målselvdalen and Dividalen, with one north-facing and one south-facing site in each of the two valleys. The common time period reached back to AD 1799 for the STANDARD chronologies and AD 1776 for RESIDUAL chronologies (expressed population signal EPS 85%).
2. Periods of low growth rates occurred at around AD 1810 and AD 1865-1910. Maximum growth was attained around AD 1950. The growth depression around 1810 was more strongly developed in the more oceanic Målselvdalen than in Dividalen.
3. The two Dividalen chronologies were longer and contained a more homogeneous tree-ring signal. Scots pine from north-facing sites expressed more variability (SD, autocorrelation), whereas south-facing pine stands contained a stronger common tree-ring signal, for example signal to noise ratio (SNR).
4. The largest portion of the year-to-year tree-ring variability was determined by July temperatures at all four sites. However, some systematic slope-related differences in climate-growth response were observed. A positive response to June temperature was seen only at the two north-facing slopes during the entire period analysed (1876-1992) and a positive response to March temperatures occurred at the two south-facing slopes in the second half of the 20th century.
5. The application of local climate data resulted in ecologically more detailed response functions which were interpreted in terms of stress due to summer drought, ground frost and strong insulation at low winter temperatures.
6. The reconstruction of July temperatures, based on the regional ARSTAN chronology back to AD 1799, accounted for 38% of the observed climate variability during 1876-1991. The relatively low explained variance apparently is due to the lack of long local climate series and an assumed non-linear response to summer temperatures during the 20th century temperature optimum.
7. The reconstruction of June temperatures, based on the mean RESIDUAL chronologies for the north- and the south-facing slopes back to AD 1776, accounted for 26% of the observed climate variability during 1876-1991. Further efforts have to be made to verify and optimise this reconstruction.

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