Trees (2003) 17:173–184
DOI 10.1007/s00468-002-0220-4

ORIGINAL ARTICLE

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Large-scale climatic variability and radial increment variation of *Picea abies* (L.) Karst. in central and northern Europe

Received: 18 March 2002 / Accepted: 2 September 2002 / Published online: 28 September 2002

Abstract High-frequency variation of Norway spruce radial increment [*Picea abies* (L.) Karst.] and its dependence on various climatic variables was compared in stands across latitudinal and altitudinal transects in southwestern and eastern Germany, Norway, and Finland. The tested variables included local temperature and precipitation, northern hemisphere temperature anomalies, and the climatic teleconnection patterns (North Atlantic Oscillation, East Atlantic, East Atlantic Jet, East Atlantic/West Russia, and Scandinavian patterns). Climatic impact on radial increment increased towards minimum and maximum values of the long-term temperature and precipitation regimes, i.e. trees growing under average conditions respond less strongly to climatic variation. Increment variation was clearly correlated with temperature. Warm Mays promoted radial increments in all regions. If the long-term average temperature sum at a stand was below 1,200–1,300 degree days, above average summer temperature increased radial increment. In regions with more temperate climate, water availability was also a growth-limiting factor. However, in those cases where absolute precipitation sum was clearly related to radial increment variation, its effect was dependent on temperature-induced water stress. The estimated dates of initiation and cessation of growing season and growing season length were not clearly related to annual radial increment. Significant correlations were found between radial increment and climatic teleconnection indices, especially with the winter, May and August North Atlantic Oscillation indices, but it is not easy to find a physiological interpretation for these findings.

Keywords North Atlantic Oscillation · *Picea abies* · Precipitation · Radial increment variation · Temperature

Introduction

Radial growth variation of coniferous trees in central and northern Fennoscandia is mainly related to current summer temperatures (Mikola 1950; Mäkinen et al. 2000; Miina 2000). In contrast, growth variation of conifers in central Europe is mainly correlated with precipitation (e.g. Eckstein et al. 1989; Kahle 1994; Kahle and Spiecker 1996). In recent studies, the effect of precipitation on annual radial growth of Norway spruce [*Picea abies* (L.) Karst.] has also been demonstrated in southern and central Finland (Henttonen 1990; Mielikäinen et al. 1996). Mäkinen et al. (2001) observed that low precipitation may even be related to damage and dying off of Norway spruce on drought-sensitive sites in southern Finland. In addition to a latitudinal gradient, a difference in factors controlling tree growth has been observed between low and high altitudes (e.g. Kahle 1994; Dittmar and Elling 1999).

Although the growth response to weather variation differs between geographical regions, a common pattern in growth variation was recently observed for central Europe and Fennoscandia (Mäkinen et al. 2002). This suggests that there are limiting as well as favourable factors for tree growth that are common for the entire area. The common pattern of growth variation could be explained by large-scale weather patterns.

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Large-scale changes in position and dynamics of air masses have caused similar weather patterns in large areas bordering the North Atlantic (Rogers and van Loon 1979; Haas 1992; Hurrell 1995; Klaus et al. 1997; Rodó et al. 1997; Gerstengarbe et al. 1999). A substantial portion of the variability on the climate of the Atlantic sector is associated with the North Atlantic Oscillation (NAO) (Van Loon and Rogers 1978; Greatbatch 2000; Thompson and Wallace 2001). The NAO is defined as an air pressure differential between the subtropical Atlantic and the Icelandic region. During a positive NAO phase low-pressure anomalies occur over Iceland in combination with high-pressure anomalies across the subtropical Atlantic. A positive NAO produces stronger than average westerly winds from the Atlantic Ocean. In winter – which is the period of the strongest pressure gradient – a positive NAO causes warm moist conditions in central and northern Europe. During a negative NAO anomaly, westerly winds are less frequent, which results in colder and drier conditions. Other northern hemisphere teleconnection patterns that dominate the air mass circulation in different seasons have been documented by Wallace and Gutzler (1981) and Barnston and Livezey (1987).

The East Atlantic pattern (EA) is the second and the East Atlantic Jet (EA Jet) the third of the three prominent modes of low-frequency variability over the North Atlantic (Barnston and Livezey 1987). The EA also consists of north-south pressure anomaly centres spanning the entire North Atlantic but the different location of the anomaly centres makes EA distinct from NAO. The EA Jet also consist of a north-south dipole of anomaly centres, one located over the high latitudes of the eastern North Atlantic and Scandinavia, and the other over North Africa and the Mediterranean Sea. Other prominent climatological teleconnection patterns affecting central and northern Europe are East Atlantic/West Russia (EATL/WRUS), and Scandinavian (SCAND) patterns (Barnston and Livezey 1987). The EA appears during all months except May–August, EA Jet between April and August, EATL/WRUS during all months excluding June–August and SCAND throughout the year except June–July. The NAO and EA Jet are, thus, the most prominent patterns during the radial growth period of trees (May–July) in the study area.

Several studies have related ring width variation of Norway spruce to local weather variables (e.g. Henttonen 1990; Kahle 1994; Bednarz et al. 1998–1999). Such studies offer few indications of how tree-growth responds to large-scale weather patterns. Comparison of tree growth time series sampled from several geographical regions may enable one to identify the important environmental driving factors of growth variation and even the underlying mechanisms behind it. Several papers have recently been published on the relationship between NAO patterns and radial growth variation (e.g. D'Arrigo et al. 1993; Cook et al. 1998, 2002; Lindholm et al. 2001). The potential of the NAO to affect the ecology of plants and animals in the northern hemisphere was recently reviewed by Post et al. (1999). However, empirical studies of the effects of other indices describing large-scale weather variability on tree growth are scarce (e.g. Schweingruber et al. 1987; Fritts 1991; Meko et al. 1993; Schweingruber and Briffa1996). The papers mentioned above also suggest that the variation of NAO and other circulation patterns might be useful for extending our understanding of the common patterns of tree growth variation in central and northern Europe.

The study is based on material sampled from stands growing along a transect running from central Europe to northern Fennoscandia, different altitudes being represented in each study region. In the first part of the study, we described medium- and high-frequency changes in radial increment and determined how radial increment varies across the latitudinal and altitudinal gradients (Mäkinen et al. 2002). In addition, simple regional increment-climate relationships were presented. The aim of this second part of the study was to analyse possible causal factors behind the common patterns of Norway spruce radial increment throughout the entire study area. Our starting hypothesis was that radial increment variation is related to changes in precipitation and temperature. In addition, we evaluated relationships between the variations of different air mass circulation patterns, northern hemisphere temperature anomalies and radial increment variation.

Materials and methods

The material was collected across a transect starting from southern Germany and extending to the Arctic spruce timberline in Fennoscandia. The four study regions were located in southwestern Germany, eastern Germany, Norway, and Finland. In addition to the south-north gradient, the sample included maritime and more continental areas at similar latitudes. Within regions, sampling was carried out across elevational gradients from lowlands up to mountains. In Finland, unlike in the other regions, the sampled stands represented similar altitudes, simply because altitudinal differences within the country are small. The study stands were grouped into 'sub-regions' according to their elevation and latitude within each region (Table 1).

Mature dominant trees without visible signs of damage were randomly selected as sample trees. The number of sample trees in a stand ranged from 4 to 15 (Table 1). Increment cores or stem discs were taken at 1.3 m height using the standard sampling procedures of each participating institute, and radial increments were measured to an accuracy of 0.01 mm.

Ring-width series were standardised with the aim of removing variation caused by tree maturation and stand dynamics. Prior to standardisation, the radial increment series were transformed to logarithmic values in order to stabilise the tendency of the variance to increase with increasing radial increment. First, a stiff spline function with a 50% frequency cutoff in 75 years was fitted to the ring-width series in order to remove the low-frequency variation caused by tree ageing (Cook and Peters 1981). Radial increment index chronologies were then calculated as the ratio between the observed and estimated values. In the second phase, a more flexible spline function with a 50% frequency cutoff in 10 years was fitted to the index chronologies, which had been obtained as a result of the first phase of detrending. Values of this flexible spline were considered as medium-term variation. High-frequency indices were calculated as the ratio between the indices calculated in the first phase and the flexible spline. These indices describe short-term radial increment variation, while long-term and medium-term

Table 1 Characteristics of the ring-width chronologies for each region

Region	Sub-region	Latitude	Longitude	Altitude (m.a.s.l.)	No. of plots	No. of trees/plot	Age at breast height
Southwestern Germany	1	47°50'–48°03	7°40'–7°47'	380 (260–490)	3	5 (4–5)	97 (82–114)
	2	47°47'–48°02	7°45'–8°21'	927 (910–930)	3	5 (5–5)	122 (95–151)
	3	47°48'–47°51	7°59'–8°05'	1,275 (1200–1330)	4	5 (5–5)	134 (58–224)
Eastern Germany	1	50°73'–51°11'	13°06'–14°85'	359 (260–420)	14	7 (6–12)	91 (70–119)
	2	50°45'–50°86'	12°55'–14°75'	538 (410–610)	18	6 (5–10)	100 (70–124)
	3	50°46'–50°86'	12°57'–14°73'	733 (640–800)	14	7 (5–10)	98 (78–142)
	4	50°44'–50°76'	12°65'–13°73'	859 (760–1000)	15	8 (5–10)	101 (75–158)
Southern Norway	1	59°26'–59°38'	8°05'–9°08'	131 (40–200)	15	10 (10–12)	97 (67–124)
	2	59°26'–59°43'	8°02'–9°02'	515 (470–550)	19	10 (10–10)	123 (83–186)
	3	59°25'–59°43'	8°02'–9°00'	794 (730–840)	17	10 (10–11)	131 (98–182)
Northern Norway	4	65°32'–66°25'	13°08'–14°26'	77 (20–120)	15	10 (9–11)	130 (76–199)
	5	65°34'–66°31'	13°19'–14°30'	322 (230–420)	15	10 (9–10)	131 (76–164)
Finland	1	60°39'–60°44'	23°41'–23°53'	116 (110–120)	8	10 (10–10)	134 (87–180)
	2	62°49'–62°50'	25°29'–25°29'	167 (162–175)	8	10 (9–10)	127 (93–192)
	3	66°18'–67°10'	25°31'–26°45'	256 (160–315)	14	11 (9–15)	203 (162–267)
	4	67°35'–68°13'	23°59'–27°11'	297 (202–410)	18	10 (6–11)	168 (72–221)

variation is removed. In addition, an autoregressive model was used to remove remaining autocorrelation from the high-frequency chronologies (prewhitening, Box et al. 1994). Mean chronologies were calculated for each sub-region based on the individual stand series. The chronologies were constructed by using the ARSTAN software (Holmes et al. 1986). The material is described in detail in Mäkinen et al. (2002).

Measured monthly mean temperature and precipitation sum data from weather stations in the neighbourhood of the sampled stands were interpolated for each stand (for details see Mäkinen et al. 2002). For each stand, the effective temperature sum (degree days, d.d.), the date of initiation and cessation of growing season, and the length of growing season were estimated from the monthly mean temperatures according to a smoothing spline interpolation as presented by Ojansuu and Henttonen (1983). The effective minimum temperature was defined as 5°C. The initiation and cessation of growing season were defined as the date when accumulation of temperature sum begins and ends. The length of growing season was calculated as the difference between the cessation and initiation dates.

The state of the NAO was quantified by the NAO index, which is based on the mean difference in sea level surface pressures between Gibraltar and Reykjavik, Iceland (Jones et al. 1997).[1] NAO is particularly important in winter. NAO exhibits, however, little variation in its climatological mean structure from month-to-month and it is one of the most prominent climatological teleconnection patterns in all seasons (Rogers 1990).

Relationships between mean temperatures, precipitation sums, teleconnection anomaly indices and high-frequency radial increment chronologies were analysed by correlation and cross-correlation analysis. The northern hemisphere temperature anomalies were also used to characterise large-scale temperature variations (Jones et al. 1999)[2]. The maximum common overlap period 1910–1995 was used in the subsequent analysis for local precipitation and temperature, NAO, and northern hemisphere temperature. Because EA, EA Jet, EATL/WRUS, and SCAND indices were only available after 1950[3], the period of 1950–1995 was used for those variables.

Results

Correlations between the high-frequency radial increment chronologies of individual stands and March and April temperature tend to increase in regions with higher long-term mean March and April temperatures (Fig. 1 A, B). For May temperatures, an equally clear trend was not found (Fig. 1C). In contrast to the spring temperatures, a clearly decreasing trend of the correlations was found with increasing average temperatures of June and July (Fig. 1D, E). In August, the decreasing trend of the correlations virtually disappeared (Fig. 1F).

No such trends were evident in correlations between radial increment chronologies and monthly precipitation sums from March to August (Fig. 2). When the correlations between increment chronologies and monthly precipitation sum were plotted against long-term average temperatures of each month, an increasing trend was, however, found in May and June, i.e. higher than average precipitation was positively related to annual radial increment in regions with higher mean temperature, but negatively in regions with lower temperature (Fig. 3 C, D). An increasing trend in correlations with increasing temperatures was also found in July, but the trend was rather small in August (Fig. 3E, F).

Correlations between radial increment chronologies and cumulative temperature sums in May were small (Fig. 4A). Even though few (14%) correlations were statistically significant ($P<0.05$), almost all of them were positive. For the summer months, the correlations between cumulative temperature sum and increment indices have a clear decreasing trend when plotted against the long-term average cumulative temperature sum (Fig. 4B, C). In regions with lower temperature sum, cumulative temperature sum was clearly positively correlated with radial increment and the correlations were also significant, but in regions with higher temperature sum this was not the case. In regions with annual temperature sum exceeded 1,200–1,300 d.d., radial increment was not related to temperature sum, but below

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[1] URL: http://www.cru.uea.ac.uk/cru/data/nao.htm

[2] URL: http://www.cru.uea.ac.uk/cru/data/temperature/

[3] URL: http://www.met.rdg.ac.uk/cag/NAO/

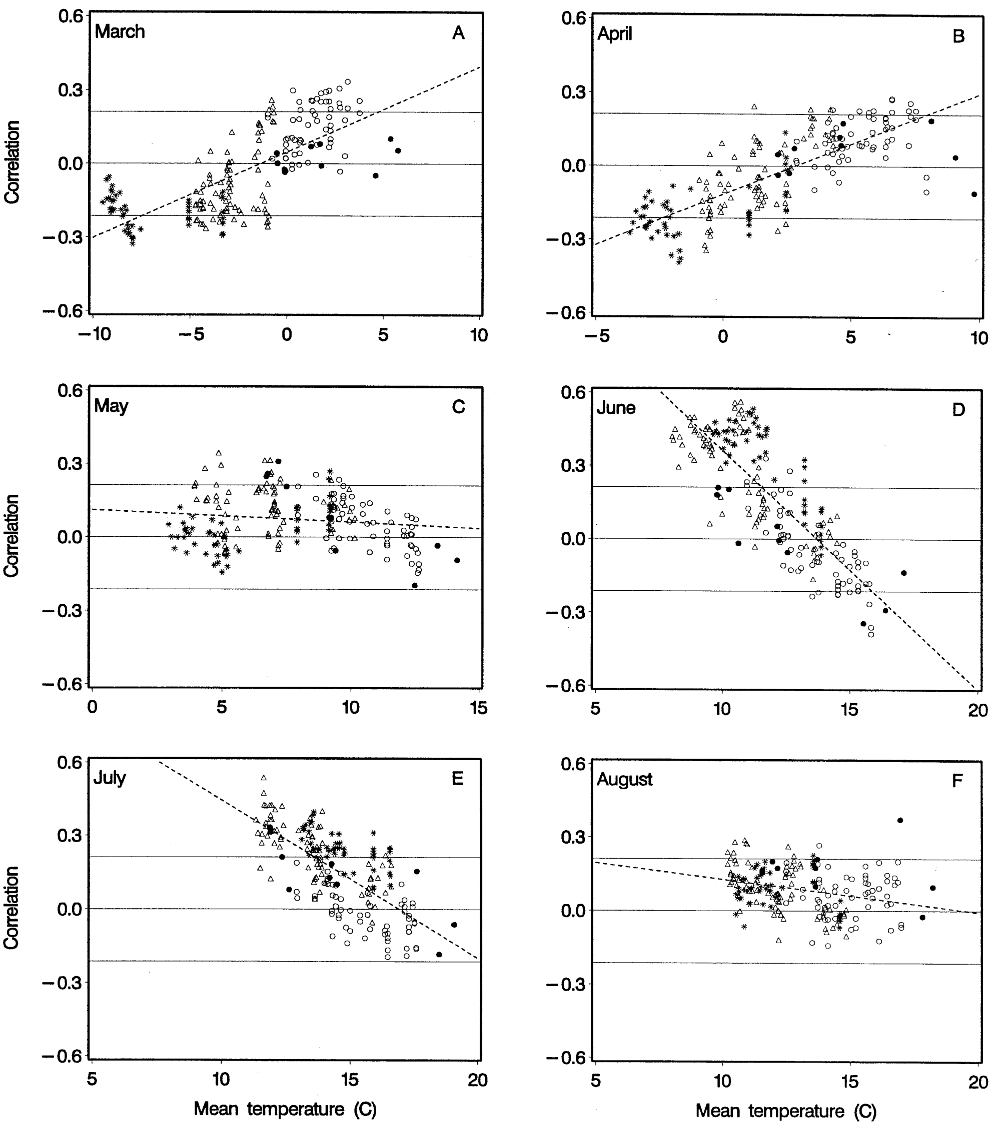


Fig. 1 Correlations between monthly temperatures from March to August and radial increment indices of each stand plotted against the long-term mean temperature of the month in question. *Dots* represent the stands in southwestern Germany, *circles* in eastern Germany, *triangles* in Norway, and *stars* in Finland. *Continuous horizontal lines* and *dashed lines* are 0.05 significance levels and the linear regression line, respectively

this threshold warm summers increased radial growth (Fig. 4D).

Even though the estimated date of the initiation of growing season was only slightly correlated with radial increment chronologies, earlier than average initiation of growing season caused higher radial increment (Fig. 5A). The date of the cessation of growing season and the length of growing season showed almost no relation to radial increment (Fig. 5B, C). Similarly as in Figs. 1, 2, 3, 4, 5, correlation coefficients were also calculated between radial increment chronologies of the current year and weather variables of the previous year (lag 1). The correlations were lower as those with the weather variables of the current year and the trends in relation to weather variables were less evident (results not shown).

In southwestern Germany, the monthly NAO indices were not significantly correlated with radial increment indices (Fig. 6). In contrast, the NAO indices of current and previous May were negatively correlated with radial increment in eastern Germany (Fig. 6). In addition, positive correlation with current August was significant at the lowest altitudes in eastern Germany. Similarly, the correlation with current August was positive and significant in three out of five sub-regions in Norway (Fig. 7). The NAO indices of the winter months were negatively correlated with radial increment at the uppermost altitudes in southern Norway and at both altitudes in northern Norway. Unlike in any other sub-region in Norway, a high positive correlation was found with the NAO indices of previous December at the uppermost altitudes in southern Norway. Similarly as in Norway, the winter NAO indices were also negatively related to radial increment in Finland (Fig. 7). Unlike in eastern Germany, the NAO indices of current May were positively related to radial increment in northern Finland.

The monthly northern hemisphere temperatures were not significantly correlated with increment indices in any sub-region, excluding some individual months at the

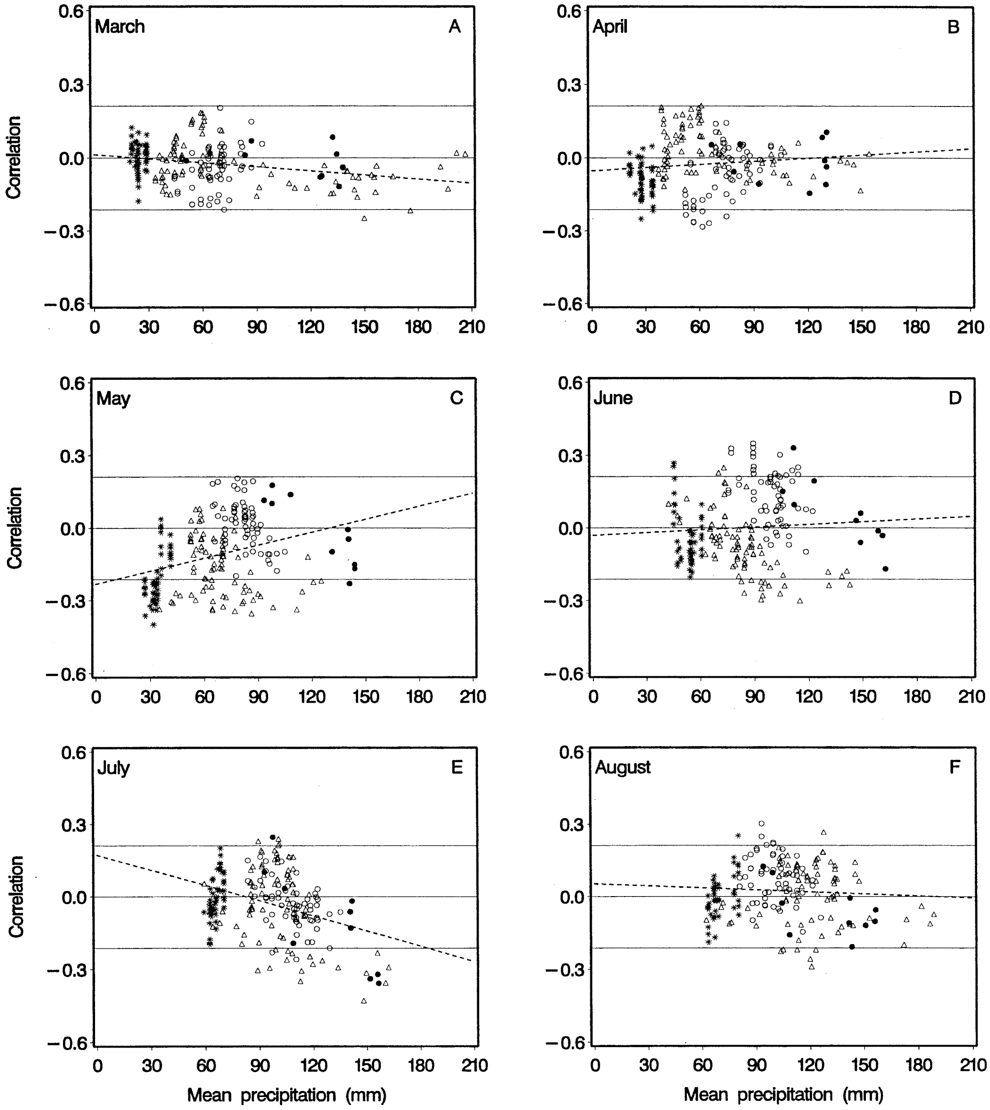


Fig. 2 Correlations between monthly precipitation sum from March to August and radial increment indices of each stand plotted against the long-term mean precipitation sum of the month in question. For symbols refer to Fig. 1

uppermost altitudes in southern Norway, as well as in central Finland (results not shown). Several significant correlations were also found between increment indices and monthly EA, EA Jet, EATL/WRUS, and SCAND indices (results not shown). However, no clear altitudinal, latitudinal, or longitudinal trends were observed in these correlations. In addition, they are difficult to explain logically. In many cases, the correlation of a certain month was significantly negative, but that of the following month significantly positive, or vice versa. Furthermore, the correlation of the current September was in many cases significant at regions, where radial increment invariably ceases by the end of August.

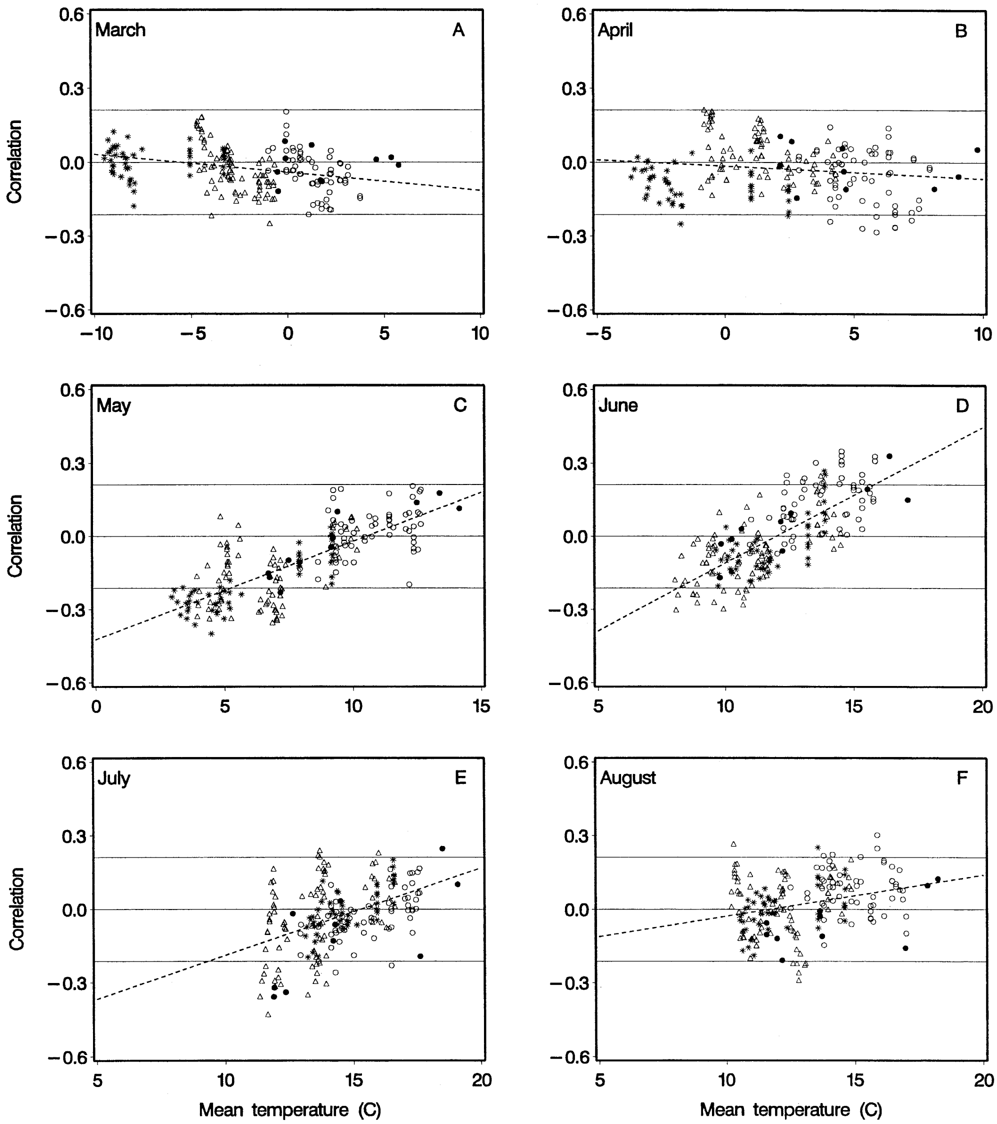
Discussion

Effect of temperature and precipitation

As pointed out by Fritts (1976), trees growing in extreme conditions respond strongly to climatic variation. The results of this study also suggest that climatic control of radial increment increases towards minimum and maximum values of the environmental parameters, i.e. trees growing under average conditions respond less strongly to climatic variation. On the other hand, the relationship between radial increment and climatic variation may be more complex in average conditions, and the factors that affect radial increment may change from year-to-year resulting in low correlations between increment indices and individual weather variables.

Environmental factors controlling radial increment and its variation were rather different in different regions and also at different altitudes within each region. The results of this study are consistent with previous findings

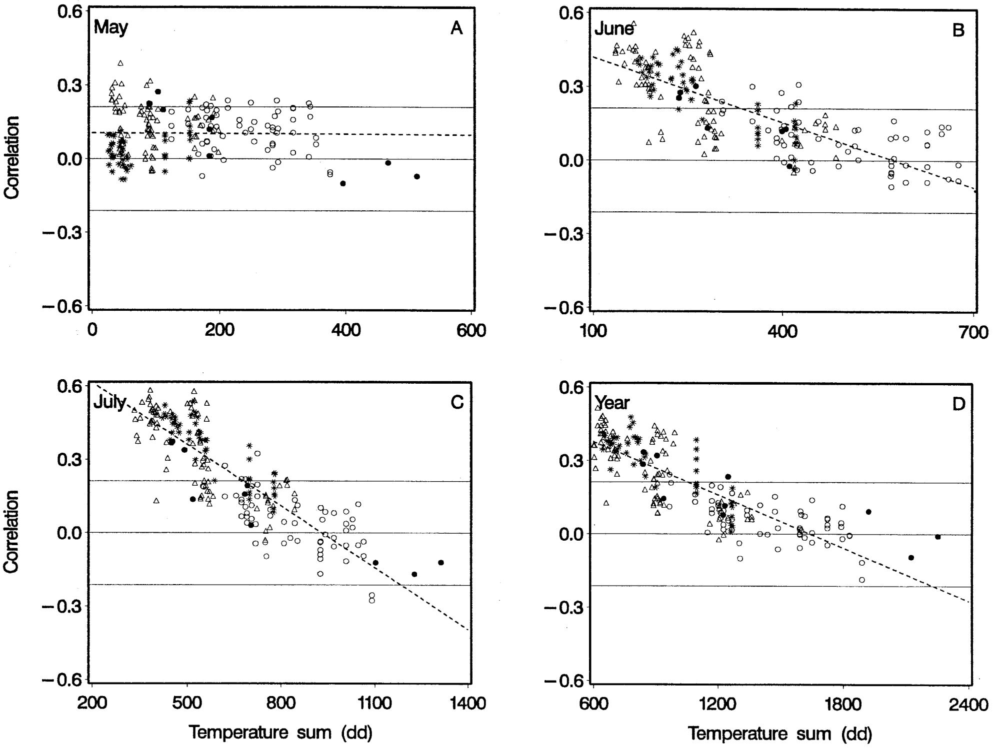
Fig. 3 Correlations between monthly precipitation sum from March to August and radial increment indices of each stand plotted against the long-term mean temperature of the month in question. For symbols refer to Fig. 1



showing that radial increment variation of coniferous trees is related to summer temperature in central and northern Europe (Mikola 1950; Kahle 1994; Bednarz et al. 1998–1999; Meyer and Bräker 2001). In spring, high temperatures favour radial increment in the warmer regions. In contrast, March and April temperatures were negatively correlated with radial increment in the cooler regions, even though most of the correlations were not significant. No self-evident biologically plausible explanation is available for the latter finding. A possible reason for the negative correlation might be that high temperatures in late winter and early spring may increase respiration and evapotranspiration at a time, when the losses cannot be replaced by photosynthesis and water uptake (e.g. Tranquillini 1979). The influence of the late winter and early spring temperatures on increment rate might be worth investigating in more detail in order to gain a better understanding of the relationship between radial increment and weather variation.

Warm May was favourable for radial increment in almost all sub-regions. Thereafter, clearly different increment responses to high temperatures were found (cf. Hofgaard et al. 1999). Above-average June and July temperatures were related to high level of increment in cooler regions, but in warmer regions high temperatures were negatively correlated with increment. An annual temperature sum of about 1,200–1,300 d.d. seems to be the threshold value. At regions with warmer climate, warmer than average summers are unfavourable for Norway spruce radial increment. Accordingly, increment variation of Norway spruce proved to be related to temperature mainly in central and northern Finland where temperature sum varies between 500–1,000 d.d. (Mäkinen et al. 2000; Miina 2000). In the warmest regions in southern Finland the temperature sum rises to 1,300, and previous studies have suggested that increment variation may also be related to precipitation (Henttonen 1990; Mielikäinen et al. 1996). Southern Finland might thus be

Fig. 4 Correlations between cumulative temperature sum in May to July and total annual temperature sum and radial increment indices of each stand plotted against the long-term mean temperature sum of the month in question. For symbols refer to Fig. 1



considered a transition zone, where the effect of precipitation can be significant, but mainly on drought-sensitive sites (Mäkinen et al. 2001).

It was also evident that absolute precipitation sum alone was not the increment-determining factor. High temperature can be considered as a factor promoting drought stress that reduces water availability in the soil because of high evapotranspiration. In the warmer subregions, the limiting effect of low precipitation on radial increment clearly increased with increasing average temperature during the summer months (cf. Jonsson 1969; Tuhkanen 1984; Spiecker 1991). Even though a negative correlation to summer precipitation was found in the cooler regions, a positive increment reaction to drought is less likely to occur. The correlation may well be due to an inverse relationship between precipitation and temperature.

The dates of the initiation and cessation of growing season, as well as the length of growing season, were rather weakly related to annual radial increment (cf. Worrall 1973). Growth rate during the most vigorous growing period is probably a more important factor determining annual radial increment than the length of growing season.

Teleconnection patterns

The NAO indices of current May were negatively correlated with radial increment in eastern Germany and positively correlated in northern Finland. The opposite correlations could be caused by a common NAO-induced weather event that causes different increment reactions in central and northern Europe. Alternatively, the high and low phases of NAO could result in different weather events in different geographical regions. In eastern Germany, the correlations with May precipitation and temperature were, however, considerably lower than the correlations with the May NAO indices (Mäkinen et al. 2002). In northern Finland, the correlation with May temperature was also lower; with May precipitation it was of the same order of magnitude as that with May NAO indices. Similarly, the correlation with current August precipitation and temperature in Norway were lower than the correlation with August NAO indices (Mäkinen et al. 2002). It is not clear whether NAO affects radial increment by some other mechanisms in addition to affecting temperature and precipitation.

Linderholm et al. (unpublished data) found low correlations between Scots pine (*Pinus sylvestris* L.) chronologies sampled from central Norway, central Sweden and central Finland and the May and August NAO indices. In contrast, three chronologies from Norway were negatively correlated with July NAO indices. Their chronologies sampled from Sweden and Finland were not correlated with the summer NAO indices, excluding one chronology from Sweden that correlated positively with the June NAO indices (Linderholm et al., unpublished data). Lindholm et al. (2001) also found that radial increment variation of Scots pine was not related to the summer NAO indices in southern and central Finland and in Russian Karelia. In contrast, their chronologies sampled from northern Finland were positively correlated with the summer NAO indices.

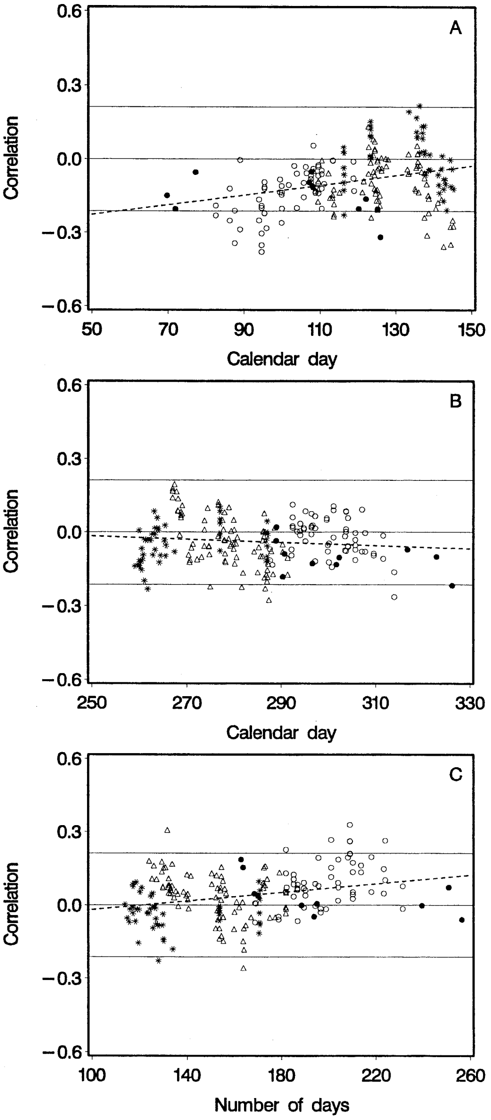


Fig. 5 Correlations between the estimated date of the initiation of growing season (**A**), the date of the cessation of growing season (**B**), and the length of growing season (**C**) and radial increment indices of each stand plotted against the long-term mean values of the parameters in question. For symbols refer to Fig. 1

The contradictory results between this study and the studies cited above may, at least partly, be caused by species-specific reactions of Norway spruce and Scots pine to climatic factors. The correlation between the temperature and the NAO indices also varies from region to region and from season to season (Chen and Hellström 1999). Between September and March, the correlation coefficients between temperature and the NAO indices were highest in southern Sweden, but between May and August they were highest in the northern parts. High and positive correlation coefficient between temperature and the NAO indices existed in autumn, winter and spring, while the correlation was low in summer (Chen and Hellström 1999). This indicates that the NAO indices are not a good measure of the westerly winds in summer, at least not in Sweden.

Even though the climate anomaly pattern associated with the NAO are more pronounced in winter than in summer, there are already studies that have explored the feasibility of reconstructing winter NAO variability based on tree-ring data. D'Arrigo et al. (1993) showed that winter NAO indices (December–February) were related to radial increment data of Scots pine in northern Finland and southern Norway. Their radial increment chronologies showed also positive correlation with winter temperatures in Oslo, southern Norway. When screening 36 radial increment chronologies from western and northern Europe, Cook et al. (1998) observed that some Scots pine chronologies from Fennoscandia were positively, and oak chronologies from the British Isles negatively, correlated with winter NAO indices. The chronologies from France and Spain were not related to the winter NAO indices. Based on the observed relationship, they reconstructed past NAO indices back to AD 1701. Glueck and Stockton (2001) also reconstructed past winter NAO indices mainly based on *Cedrus atlantica* (Endl.) Manetti chronologies from Morocco, but also on one Scots pine chronology from northern Finland. Post and Stenseth (1999) also demonstrated that plant phenology was significantly related to the winter NAO indices in Norway.

In this study, the winter NAO indices were not related to the Norway spruce chronologies from southwestern and eastern Germany. However, the chronologies from northern Norway and Finland were significantly correlated with the January and February NAO indices. It should be noted that the correlations between the tree-ring chronologies of Norway spruce and winter NAO indices were negative, unlike in the studies of D'Arrigo et al. (1993) and Cook et al. (1998), who found positive correlations with tree-ring chronologies of Scots pine sampled from the same geographical region. Lindholm et al. (2001) also found that radial increment variation of Scots pine was positively correlated with the winter NAO indices at the forest limit in northern Finland. Linderholm et al. (unpublished data) found low correlations between Scots pine chronologies and the January and February NAO indices in central Norway, Sweden and Finland. Only one chronology sampled from Finland was significantly correlated with the January NAO. In contrast, they found that three out of ten chronologies were significantly (positively) correlated with the NAO indices of the previous December.

In the previous analysis of this material, negative correlation of the same order of magnitude as those with the January and February NAO indices were found between the radial increment chronologies and winter temperature and precipitation (Mäkinen et al. 2002). In Sweden, Jonsson (1969) also found that low temperature in January and February appeared to be favourable for radial increment. In northern Norway, the mean temperature in January and February varies between –3 and –6°C and in northern Finland between –12 and –14°C. At temperatures as low as these, the metabolic functions of

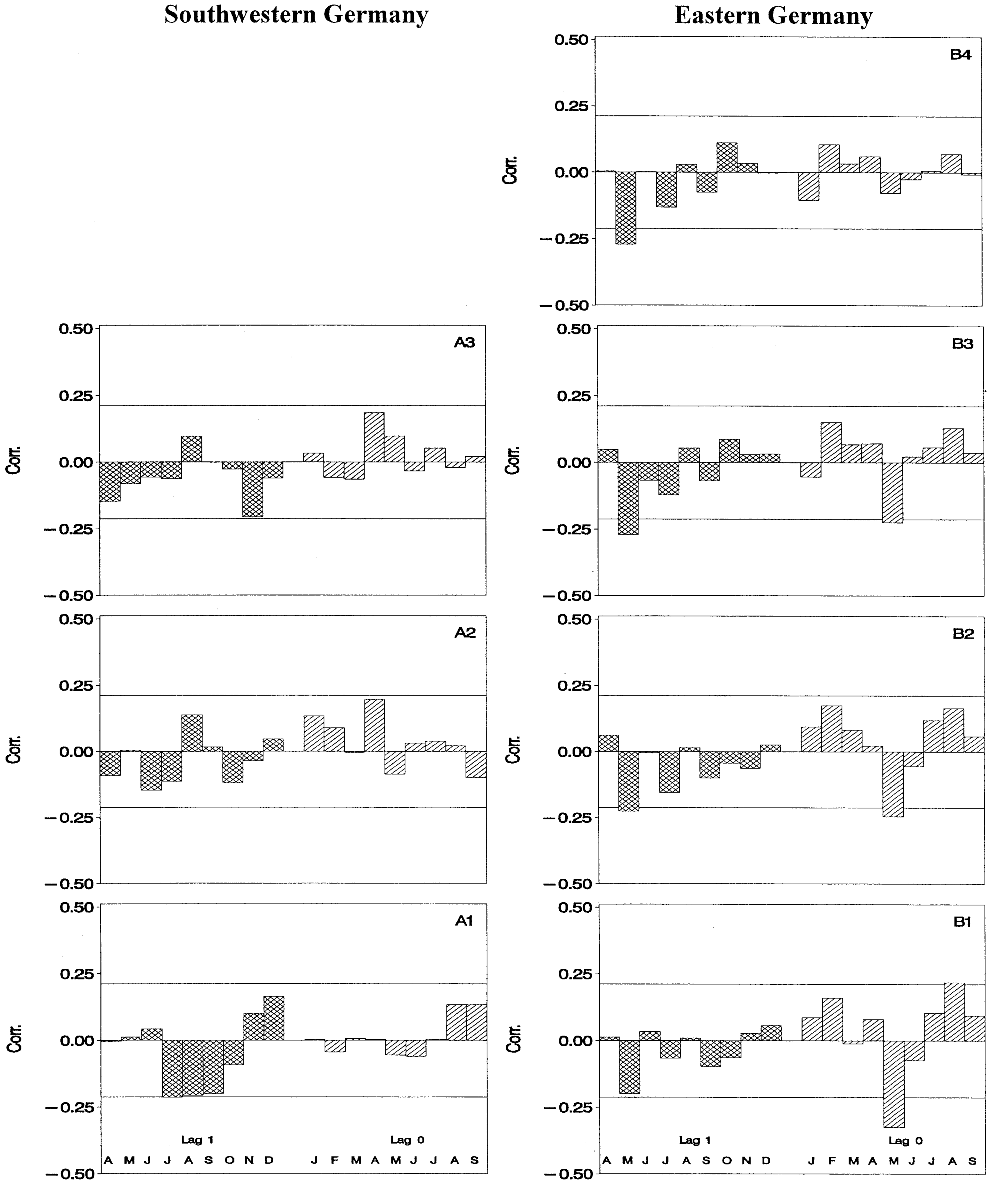


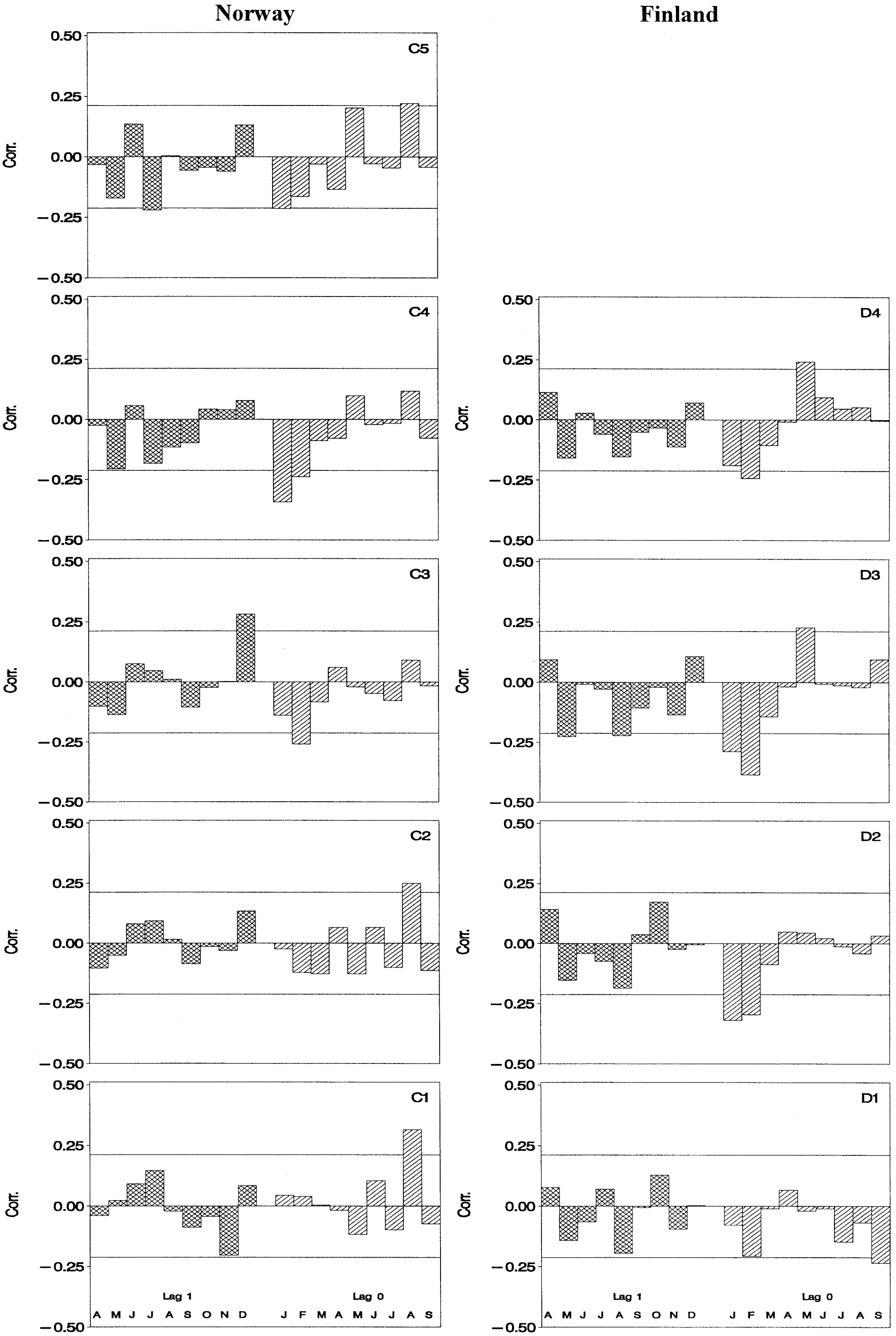
Fig. 6 Cross-correlation analysis between monthly NAO indices from April of previous year to September of current year and radial increment indices from southwestern Germany (*left*) and eastern Germany (*right*). *Horizontal lines* are 0.05 significance levels. Within both regions, the sub-regions are presented from high to low altitudes, from above downwards For the sub-regions refer to Table 1

the trees are likely to be minimal, especially in northern Finland. Even though the relationship between the climatic variability in winter and radial increment near the northern timberline may prove to be a valid interpretation of the data, some caution is still needed. While the results of this study do not necessarily lessen the concern about the detrimental effect of increasing winter temperatures associated with the possible climate change in northern Europe, it would have been more logical to expect negative growth reactions to high winter temperatures in central Europe.

On the other hand, anomalies of climate parameters associated with extreme winter NAO episodes may persist and influence conditions in spring and summer (Rogers and van Loon 1979; Rogers 1990). Warmer periods in winter associated with increased precipitation falling as snow could result in long lasting snow cover in spring. Vaganov et al. (1999) suggested that near the northern timberline in Siberia high winter precipitation could lead to delayed growth initiation. Thomsen (2001) also concluded that in Ural Mountains high winter precipitation may have a negative effect on Scots pine growth during the following summer. In contrast, Jalkanen (1990) and Kullman (1996) suggested that cold winters with thin snow cover result in deep soil frost that may lead to needle loss because of winter desiccation.

Recent intercomparisons reveal little agreement between different proxy-based NAO reconstructions (Schmutz et al. 2000). This was the case for year-to-year as well as for decadal scale variability. It should be stressed that the correlations observed in this study, as well as in the studies cited above, do not describe functional relationships between radial increment and climatic variability. The results should be considered as

Fig. 7 Cross-correlation analysis between monthly NAO indices from April of previous year to September of current year and radial increment indices from Norway (*left*) and Finland (*right*). *Horizontal lines* are 0.05 significance levels. *C5* highest and *C4* lowest altitude in northern Norway, *C3* highest, *C2* intermediate, and *C1* lowest altitude in southern Norway; in Finland from northernmost (*D4*) to southernmost latitude (*D1*)



observational. It is still unclear, whether the significant negative correlation between the winter NAO indices and radial increment variation found in this study was caused by certain wintertime physiological processes of trees, or some climatic events persisting into growing season, or whether it was just a random event. More research is clearly needed to improve our understanding of how the fluctuations of winter conditions and NAO indices may be reflected in increment variation of trees (cf. Cullen et al. 2001).

Difficulties arise when attempting to examine the relationship between radial increment indices and different modes of climate variability. Radial increment does not respond directly to the variability of atmospheric circulation, but instead reacts to its local influence through the effects of temperature, precipitation etc.

Several significant correlations were found between radial increment indices and the other climatic teleconnection patterns. However, these correlations showed no logical geographical or temporal patterns. Furthermore, most of the teleconnection patterns used in this study are not prominent during the active radial growth period in summer. Therefore, their interpretation was even more questionable than the interpretation of the NAO indices. When many correlations are calculated, it is likely that some significant correlations are found by chance. As other studies on the relationship between these teleconnection indices and increment variation are lacking, it was hard to deduce whether the observed correlations were spurious or real.

In conclusion, the results of this study indicate that the radial increment of Norway spruce is strongly related to temperature in central and northern Europe. However, the radial increment reactions to higher than average temperatures differed in different geographical regions. Warm Mays will promote tree growth in all the regions, but high June and July temperatures appear to be detrimental for radial increment in warm regions, where not enough water is available. Some factors synchronising radial increment were common to the entire study area. The common influencing factors may be related to the climatic teleconnection patterns, especially to the NAO. However, our findings on the statistical link between the NAO and radial increment of Norway spruce differ from those reported in previous studies, which concentrated on different tree species. Further studies are needed to produce a more complete understanding of the effects of large-scale climatic oscillations on tree growth in Europe.

Acknowledgements We thank the field and laboratory assistants for their work during the study. The research was supported by the European Union (Fair3-CT96-1310).

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