Climatic Influence on Scots Pine Growth on Dry and Wet Soils in the Central Scandinavian Mountains, Interpreted from Tree-Ring Widths

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Tree rings are one of the most important proxy data sources for reconstructing past climate variability. In order to understand climate variability, it is necessary to get a spatial and temporal coverage of climate information. Summer temperatures mainly influence tree growth at the altitudinal tree line, while at lower altitudes additional factors affect growth. In addition, the nature of soil where trees grow may affect growth response to climate. To decide climate as well as growth-substrate influences on Scots pine (*Pinus sylvestris* L.) growing below the tree line, two tree-ring width chronologies, sampled at dry mineral soil and wet peat soil in a mountain valley in the central Scandinavian Mountains, were analysed for climate responses and spectral signals. Temperatures during growth season (May–August) showed the strongest influence on tree growth at both sites. Influence of precipitation in the growing season was low, indicating sufficient amounts of available water during growth. However, at the dry-soil site the influence of late winter/early spring precipitation was significant. Strength of the climate–tree–growth relationship at the dry site was similar to that of trees growing at the present tree line, while weaker at the wet site. Both site chronologies exhibited common spectral peaks at c. 3.5 and 13 years indicating a common growth forcing at those time scales. The wet-site chronology displayed low-frequency variations with a 19-year periodicity, where growth peaks coincided with the lunar tidal maxima indicating a possible influence of lunar forcing. At the dry-site, multi-decadal fluctuations displayed a periodicity of 66 years. Both 13- and 66-year periods can be linked to variations in sea surface temperatures of the North Atlantic Ocean, pointing to a maritime influence, on decadal scales, of pine growth in the area. These results suggest that Scots pine in this environment may be regarded as proxies of North Atlantic Ocean coupled climatic variability.

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1 Introduction

In order to assess human impact on increased global temperatures during the 20th century, knowledge of natural changes and variability in climate is essential (LaMarche 1974, 1978, Jacoby and D'Arrigo 1989, Bradley and Jones 1995). Northern Scandinavian climate is sensitive to changes in the North Atlantic Current, which is believed to be of importance for global climate (e.g. Karlén 1998). However, most meteorological records in Scandinavia cover only short periods, usually less than 100 years, and such short records cannot be expected to represent the full range of climate variability (D'Arrigo and Jacoby 1993). Therefore, an extension of climatic data in time is needed in order to understand natural variations (e.g. Bradley and Jones 1995).

In Sweden, dendroclimatological investigations have mainly been conducted at the tree line in the northern parts of the country, where a multi-millennial dendrochronology has been constructed in Torneträsk (e.g. Bartholin and Karlén 1983, Briffa et al. 1990, 1992, Grudd et al. submitted 2000). As the yearly growth of trees at high latitude or high elevation is chiefly dependent on local temperature variability (Jacoby and Cook, 1981, Briffa et al. 1990, D'Arrigo and Jacoby 1993), these tree-ring series are suitable for making temperature reconstructions with inter-annual to decadal and century scale resolution. Few studies have been made on trees growing in central and southern Sweden; Johnsson (1969) studied the climatological effects on growth of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) at several localities in Sweden, and a new multi-millennial dendrochronology is under construction in west central Sweden (Gunnarson 2001, Gunnarson and Linderholm submitted 2001). Furthermore, Linderholm (1999) discussed the climatological and anthropological influence on the growth of Scots pine at a peat bog in south central Sweden.

The aim of this paper is to determine the climatic influence on tree growth of Scots pine (*Pinus sylvestris* L.) growing on dry and wet soils in a mountain valley in west central Sweden. Here glacial mineral soil is defined as dry and organic soil at a peatland defined as wet. Dendroclimatic analyses were made on pine growing approximately 200 m below the present tree limit. In addition to determining climate sensitivity of Scots pine below the tree line in the mountains, it is important to know if Scots pine growing on wet soils can be useful in dendroclimatology since large areas of Sweden are covered by peat where you frequently find scattered pine stands. Previous research has shown that climatic influence on the yearly growth of bog pines at lower latitudes is weak (Läänelaid 1982, Vaganov and Kachaev 1992, Linderholm 1999). However, no evaluations of use of pine, growing on peat surfaces in mountain environments, in dendroclimatological investigations have yet been published.

Remains of trees, subfossil wood, are occasionally encountered in peat bogs (Lundqvist 1969, McNally and Doyle 1984, Ward et al. 1987, Bridge et al. 1990, Pilcher et al. 1995, Grudd et al. 2000). Subfossil pine was found in several peat bogs in the studied area. Pine remains are often restricted to distinct layers, recurrence surfaces (e.g. Barber 1982), which have been attributed to changes in the degree of peat humification caused by climatic changes (Aaby 1976, Barber 1982, Frenzel 1983). At the Klockamyren peat bog, near Lake Ånn, pine remains from the basal layer of the peat have been ^{14}C dated to 6330 BC (Lundqvist 1969). If bog pines contain climatic information, studies of subfossil pine combined with studies of the peat stratigraphy and pollen analysis could be a useful source of paleoclimatic information spanning most of the Holocene.

2 Study Area

The investigated area is located in the westernmost part of central Sweden (Fig. 1). Sample localities are located in the Lake Ånn basin (63°15', 12°30', 526 m a.s.l.), just east of the main divide of the Scandinavian Mountains. Mountains surrounding the basin are rounded, reaching elevations of 800–1000 m a.s.l., except in the south where more alpine massifs rise to –1700 m a.s.l. The Lake Ånn basin is characterised by widespread glacial lake deposits and eskers (Borgström 1979). Both continental and

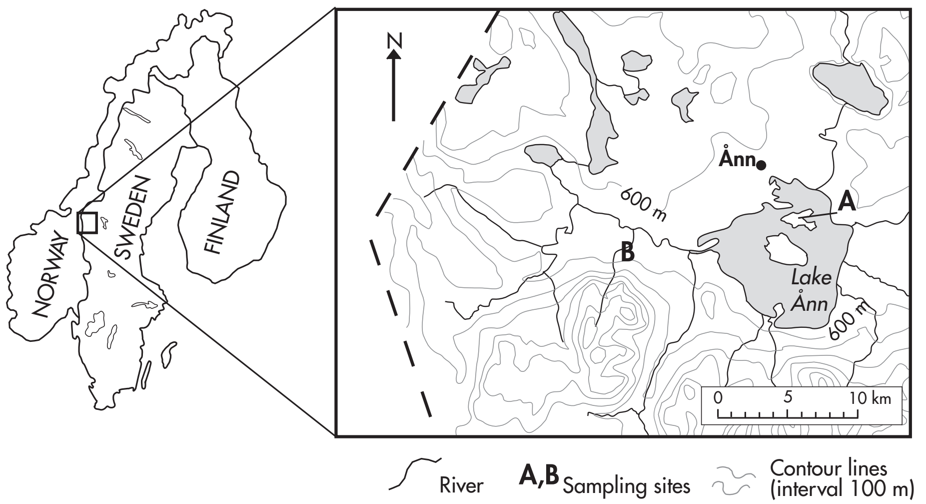

Fig. 1. Map showing the locations of the sampled sites in the Lake Ånn basin (63°15', 12°30'), western Jämtland, Sweden. Samples of Scots pine (*Pinus sylvestris* L.) for dendroclimatological analyses were collected at a wet-soil site, a peat bog, on the island Årsön (A), and a dry-soil site west of Lake Ånn (B).

maritime west coast climates, due to the proximity to the Norwegian Sea, influence the climate regime of the area. The area is located within the Northern Boreal zone with a pine tree-limit at about 700 m a.s.l (Kullman 1981). Monthly temperature and precipitation data were obtained from SMHI (Swedish Meteorological and Hydrological Institute) for Duved (1911–1979, 400 m a.s.l., 63°23', 12°56', Fig. 2).

2.1 Sampling Sites

Dry soil site. Pines growing on glacial lake sediments were sampled west of Lake Ånn at an elevation of 530 m a.s.l. (Fig. 1). Tree height ranged from 6 to 15 meters depending on site conditions; finer sediments tend to inhibit tree growth. Old and dominant trees were sampled in order to extend the chronology as far back in time as possible. At the dry site, 23 trees (46 cores) were sampled.

Wet soil site. Årsön (528 m a.s.l.), a small island in Lake Ånn (Fig. 1), where glacial sediments are partly covered by peat, was chosen as the wet site. Pines grow at the edges of the bog, leaving the wetter central part of the bog free from trees.

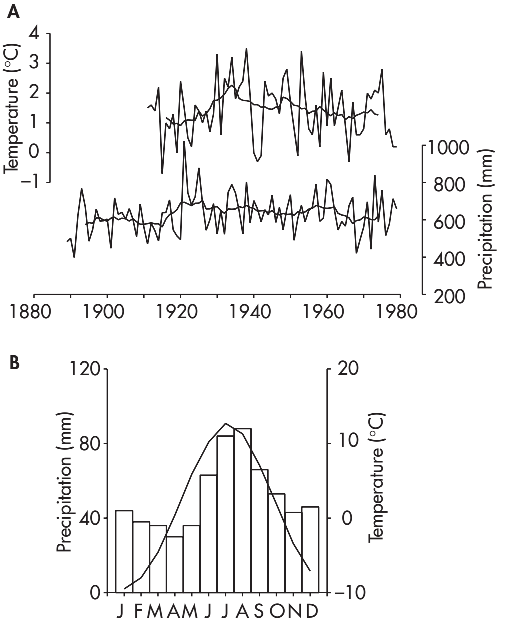

Fig. 2. Meteorological records from Duved. A) Mean annual temperature (1911–1979) and total annual precipitation (1889–1979). B) Mean monthly temperature and precipitation.

Samples were taken from 26 trees (52 cores). Trees growing at the edge of the open area on peat exceeding 1 m in depth were selected in order to ensure a wet environment.

3 Methods

3.1 Chronology Building

Cores were mounted and prepared according to methods described by Stokes and Smiley (1968). Annual tree ring widths of each core were measured on an Aniol tree-ring-measuring device with a precision of 1/100 mm, and, if synchronous, averaged into one tree-ring curve for each tree. All curves were checked with COFECHA (Holmes et al. 1986), a software that analyses the quality of a set of tree-ring measurements, verifies cross dating among tree-ring series and indicates possible dating or measurement problems. The ring-width series were standardised to remove age-associated trends and maximise high frequency variations (Fritts 1976). This was done by fitting a negative exponential curve, or regression line, to each series and then dividing the widths by the fitted curve. When no age trend was present, a straight line was used. The remaining, dimensionless, indices were then averaged into a single chronology for each site. Standardisation was performed with ARSTAN software (Holmes et al. 1986). Residual chronologies, computed by averaging residuals from autoregressive modelling of detrended measurement series, were used in the analysis of climate growth response as they contain a strong common signal (Lindholm 1996).

3.2 Growth–Climate Relationship

Response functions are widely used in dendroclimatology to describe the climate tree-growth relationship (Fritts 1976, Guiot et al. 1982, Heikkinen 1987). In this investigation, indices of residual chronologies were compared to mean monthly temperature and total monthly precipitation. A 12-month period extending from previous September to August of the growth year was analysed. The analysed period was 1911–1979 for which climate data was available from Duved. Response of tree growth to temperature and precipitation was computed with software RESPO (Lough and Holmes 1994), where climatic parameters are transformed into principal components (PCs, Briffa and Cook 1990) and then entered into a regression where the tree ring chronology is the dependent variable and PCs are independent variables. The result is a response function for each chronology, expressing the independent relationship between tree growth and climate.

3.3 Spectral Analysis

To detect any periodicities present in the data sets, multi-taper spectral analysis, using five tapers with the time-bandwidth product 3 (Thomson 1982), was performed on the standardised tree-ring chronologies. The multi-taper method provides a better tradeoff between spectral resolution and statistical variance than conventional single-taper methods and, in addition, allows for local statistical F-tests for presence of sinusoidal signals against a varying, locally white, spectrum background. One F-test value was calculated for each single frequency from zero up to the Nyqvist frequency 0.5 yr^{-1}. If there is a consistent periodic climate (or environmental) signal with frequency f represented in the data, this signal should appear as a spectral peak accompanied by a F-test value above the critical level (here 99.9% significance level) at the frequency f in both tree-ring spectra.

4 Results

4.1 Ring-Width Chronologies

At the dry site, 22 tree curves and at the wet site, 25 tree curves were averaged into two master chronologies, spanning 220 years (dry site) and 171 years (wet site) (Table 1). Standardised chronologies, as well as sample depths are shown in Fig. 3. Wet-site chronology displays regular fluctuations of c. 20 years, a feature not seen in the dry-site chronology. Both chronologies exhibit growth depressions in the 1840s, early 1900s and from the 1980s to the present. In addi-

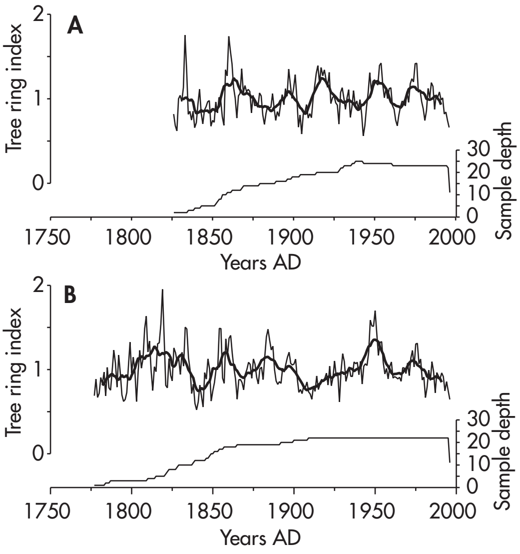

Fig. 3. Standardised tree-ring width chronologies from the Lake Ånn Basin: A) wet site, and B) dry site. Thick line represents an 11-year running average. Sample depths (i.e. number of trees per year) of each chronology are indicated in the lower part of each diagram.

Table 1. Chronology statistics for tree-ring width chronologies in western Jämtland.

Chronology	Wet site	Dry site
Time span	1826–1996	1777–1996
Average tree age	115 yrs	158 yrs
Average ring width (mm/year)	0.76	1.05
Residual chronology:		
Mean sensitivity	0.190	0.213
Standard deviation	0.167	0.182
Standardised chronology:		
Mean sensitivity	0.148	0.160
Standard deviation	0.214	0.236
First order autocorrelation	0.63	0.63
Variance due to auto-regression (%)	41.6	43.9
Signal-to-noise ratio	8.68	16.73

tion, there are periods of below average growth at the wet site in the 1880s, 1940s and 1960s. Periods of above average growth are in 1800–1830 (dry site), 1850–60s (both sites), 1880s (dry site), 1910s (wet site), 1950s and 1970s (both sites).

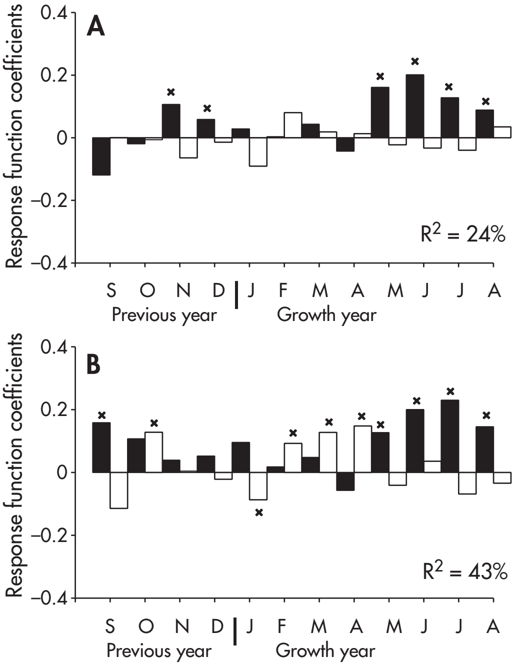

Fig. 4. Response function coefficients (A wet site, and B dry site) for mean monthly temperature (white bars) and total monthly precipitation (shaded bars) from September of the previous year to August of the growth year. Meteorological data are from Duved (1911–1979). * = significant at the 0.05 level. R^2-values indicate the variance in tree growth explained by climate.

4.2 Growth Responses to Climatic Factors

Response function coefficients of the climate–tree growth analyses are shown in Fig. 4. Variance in tree-ring widths explained by climate (R^2) was higher at the dry site (43 %) than at the wet site (24%). Temperature was by far the most important growth-influencing factor. At both sites temperatures of the growing season (May through August) were significant. In addition temperatures in mid-winter (November and December) at the wet site and previous September at the dry site were significant. Response to precipitation was lower than to temperature at both sites, being positive and significant in late winter/early spring (February through April) at the wet site. There

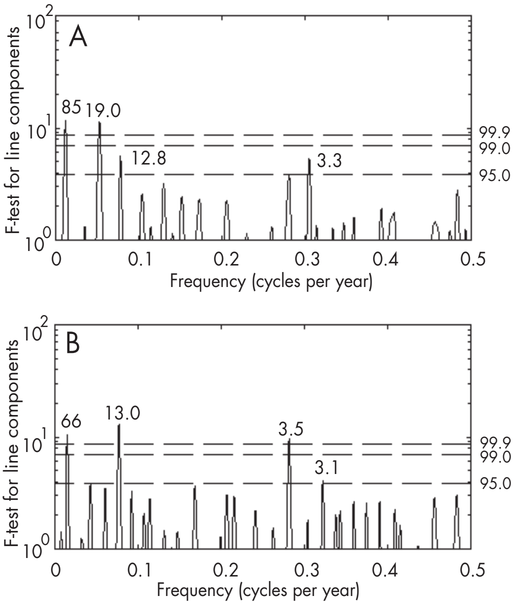

Fig. 5. Power spectra of the standardised tree-ring chronologies from A) wet site and B) dry site. Horizontal lines indicate significance at 95% level (lower line), 99% level (middle line) and 99.9% level (upper line). Numbers indicate significant spectral peaks.

was a strong and significant correlation between previous years growth and present year in both standardised chronologies (0.6 at both sites), indicating a high autocorrelation.

4.3 Periodicity

Multi taper spectral analysis of the standardised wet and dry site chronologies revealed a number of peaks, but few were significant (Fig. 5). Both chronologies have common peaks at around 3 and 13 years, while longer periods of 19, 66 and 85 years are site specific. Although the 85-year period at the wet site is significant, its reliability is questionable since only two cycles fit into the length of the chronology.

5 Discussion

Temperatures during the growing season are most important for Scots pine growth in the Lake Ånn basin at both dry and wet sites. This is in line with results previously obtained for tree growth at high latitudes (Jacoby and Cook, 1981, Briffa et al. 1990, D'Arrigo and Jacoby 1993, Luckman et al. 1997). Response to temperature was positive for most of the analysed months, except April at both sites. If tree growth starts before the actual vegetation period (May in west central Sweden, Jonsson 1969), e.g. in a warm spell in April, trees may be subjected to frost events that can cause injuries. Low growth response to precipitation during the growing season suggests that there is sufficient water available. Notable is the positive and significant influence of precipitation at the dry site prior to the growing season. However, precipitation in winter and early spring will fall as snow, which will act as an insulator of the tree–root system and reduction of frost depth. Also snow melt will provide additional water for trees at the dry site at the beginning of the growing season, which might prevent water deficit in dry summers (e.g. Kirchhefer 1999).

The climate response of the dry site trees was almost equal to that of trees growing close to the tree line 50 km E of Ånn (Gunnarson and Linderholm submitted 2001), indicating that trees 200 m below the tree line can be used for climate interpretation back in time. The low climate–tree growth relationship at the wet-site trees indicates that factors other than precipitation and temperature are of importance, although temperature is by far the most growth-limiting factor at the site. Trees growing on natural peatlands are highly dependent on depth and fluctuations of the water table (Boggie 1972). Both precipitation and temperature regulates the depth of the water table (Freeze and Cherry 1979, Mannerkoski 1991), and in addition there might be a lag in the response of the water table to changing climate conditions (Kilian et al. 1995). This combination of direct effect of temperature and precipitation on tree growth in combination with the delayed effect of climate on water table variations and decomposition of peat most likely dilutes the annually resolved climate information in tree rings.

Spectral analyses indicate that both chronologies share climate information at high frequencies, while differing at lower frequencies. Periods of 3–3.5 years and ~13 years found in both chronologies suggests a common forcing at those time scales. When analysing a multi-century chronology from northern Fennoscandia, Briffa et al. (1992) found that few peaks in the spectra were consistently significant over a number of subperiods. However, peaks at around 3.1 and 3.6 years were stable in time. The ~3 year periodicity may be due to autocorrelation in tree growth. Sutton and Allen (1997) found a spectral peak at 12–14 years in the power spectrum of sea surface temperatures (SSTs) along the Gulf stream/North Atlantic Current. They identified the 12–14-year timescale as a coupled ocean-atmosphere mode. Although the SST record presented by Sutton and Allen (1997) is short (late 1940s to 1990), there are similar features between winter-time SSTs and both tree-ring records, emphasising the possible effect of North Atlantic SSTs on tree growth in western Scandinavia. In addition, Schlesinger and Ramankutty (1994) found an oscillation in the global climate system of 65–70 years, interpreted as an internal oscillation in the atmosphere-ocean system, where a peak is evident around 1950, coinciding with the high growth at the dry site. A significant peak at 66.7 years was also found in Fennoscandia (Briffa et al. 1992). The proximity of Ånn to the Norwegian Sea, where maritime air can easily penetrate the basin from the west, could account for sensitivity in tree growth to variations in the North Atlantic Ocean.

The 19-year period in the wet site chronology was also found in a pine chronology from a wet site in south central Sweden, 550 km SE of Ånn (Linderholm 1995). Lunar tidal maxima, or lunar nodal tide (M_n), which is a function of the declination of the moon, exhibit a periodicity of ~19 years (Lamb 1972, O'Brien and Currie 1993, Currie 1995). Mitra et al. (1991) identified a ~19-year period in rainfall in India, and Currie (1995) found the same periodicity in Chinese dryness-wetness indices. Dutilleul and Till (1992) assigned a periodicity of ~19 years in Atlas cedar (*Cedrus atlantica*) in Moorocco to M_n, and Woodhouse et al. (1998) found indications of a connection between drought in the U.S. and lunar tidal maxima. Recent maxima of lunar declination were in about 1876, 1894, 1913, 1931, 1950 and 1968 (Lamb 1972), which corresponds very well to periods of high growth at the wet site in Ånn. As this period was not seen in tree-ring records from dry-soil sites, it is probable that it is related to a lowering of the water table in the peat, which improves tree growth conditions as the roots can draw nutrients from a larger volume of aerated soil (e.g. Penttilä 1991, Trottier 1991). The peak at 85 years in the wet site chronology, close to 85.7 found by Briffa et al. (1992) might be connected to the Euroasian temperature oscillation of 84 years found by Schlesinger and Ramankutty (1994), but since the time series are short this period should be interpreted with caution.

6 Conclusion

The climatic influence on Scots pine growth in dry and wet environments in a mountain valley in western Jämtland can be summarised as follows:

- Temperatures of the growth season (May–August) were most important for pine growth at both sites. In addition, precipitation in late winter/early spring (February–May) had a positive influence on pine growth at the dry site.
- Variance in tree-ring widths explained by temperature and precipitation at the dry site equalled that of trees growing at the present tree line. At the wet site, climate–tree growth relationship was weaker, most likely due to additional effects of water table variations on tree growth.
- Spectral peaks at c. 3.5 and 13 years at both sites indicate a common forcing at those timescales. While the 3.5 yr period probably is a function of autocorrelation in tree growth, the 13 yr period could be associated to spectral peaks in sea surface temperature in the North Atlantic Current. In addition, the 66 yr peak in the dry site chronology, also found in northern Scandinavian tree-rings, could be a function of oscillations in the atmosphere-ocean system, indicating a maritime influence on tree growth in Ånn on decadal scales.
- In the wet-site chronology a statistically significant period of 19 years, also found in a peatland pine

chronology 550 km SE of Lake Ånn, could possibly be linked to the lunar tidal maxima, which has an effect on variations in precipitation patterns. Times of lunar tidal maxima coincide with growth peaks at the wet site.
- The nature of the spectral signals suggests that Scots pines in this environment may be regarded as proxies of climate variations coupled to the North Atlantic Ocean.

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