A DISSERTATION FOR THE DEGREE OF DOCTOR SCIENTIARUM

Dendroclimatology on Scots pine (*Pinus sylvestris* L.) in northern Norway

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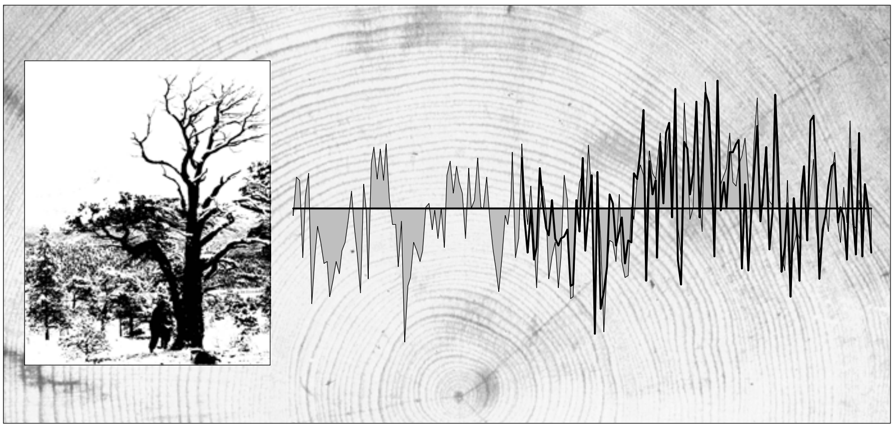

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ABSTRACT

A total of ten tree-ring chronologies of Scots pine, *Pinus sylvestris* L., was constructed between the Vesterålen archipelago and the Finnmarksvidda in order to investigate the regional variability of radial growth and climate response of pine. The longest tree-ring chronology, located in Forfjorddalen in Vesterålen, was highly significant back to AD 1354. The study area was divided into three dendroecological zones; the coast, the inner Scandes and the Finnmarksvidda. In all regions, July temperature was the most important growth-determining factor. At the coast, pine showed a significant positive response also to August temperatures. A partial study in the inner Scandes showed that the radial growth at north-facing slopes was enhanced by high June temperatures, most likely due to the influence of the midnight sun. Evidence of environmental stress due to global warming was seen in reduced growth during periods of warm-moist mid winters at the coast and, particularly in the warm 1930s, in the Scandes. Also, there were indications of drought stress in summer in the intra-alpine valleys of the Scandes and at the edaphically dry coastal site, Stonglandseidet.

On the basis of the tree-ring chronologies, July temperatures were reconstructed back to AD 1800 for northern Norway 69°N and July-August temperatures along the coast back to AD 1358. The 20th century since 1915 was a period of above-average temperatures and growth. In the present reconstruction, a comparable warm period occurred previously only AD 1470-1540. In the 19th century, cool summers prevailed about AD 1810, in the 1830s and from the late 1860s to 1910. The 17th century, the coolest interval of the ‘Little Ice Age’, experienced three intervals of cool summers around AD 1605, 1640 and 1680. There was evidence of a lack of pine regeneration in the first half of the 17th century. Major regional temperature differences were observed around AD 1760 with extraordinarily warm summers east of the Scandes, but average temperatures at the coast, and about AD 1800, when the coast was warm, but the inland cooling. An exploratory reconstruction of June temperatures from growth differences between north- and south-facing slopes demonstrated the potential of site-related growth responses for refined climate reconstructions.

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INTRODUCTION

CLIMATE CHANGE AND PALAEOCLIMATOLOGY

The earth's climate is a dynamic system. In pre-industrial times, climate variations were mainly caused by changes in solar irradiation and by aerosols from explosive volcanic eruptions (Sear *et al.*, 1987; Rind and Overpeck, 1993; Sarachik *et al.*, 1996). However today, by emitting large quantities of greenhouse gases and sulphate aerosols, also man plays an active role in the earth's climate (Schimel *et al.*, 1996; Tett *et al.*, 1999). Since the late 19th century, the global mean temperature has increased by about 0.3°C to 0.6°C (Jones and Briffa, 1992; Parker *et al.*, 1994; Nicholls *et al.*, 1996). Major challenges in climate research are the attribution of causes for this temperature trend (Santer *et al.*, 1996), the prediction of future climate change (Kattenberg *et al.*, 1996), its spatial and temporal variability and its potential impact on the human environment.

The instrumental climate record shows that the northern hemisphere warmed stepwise in the 1920s and since the 1970s, interrupted by a distinct cooling from the 1940s to the late 1960s (Jones and Briffa, 1992). Generally, the warming was strongest in the high latitudes and during winter. However, temperature changes in the regions bordering the North Atlantic Ocean were less representative of the hemisphere mean trends (Briffa and Jones, 1993). For instance, there was no significant warming trend during the 20th century in northern Europe. Spatially and seasonally varying trends also were observed within Norway (Hanssen-Bauer and Nordli, 1998). The months contributing most to the annual warming were June to August in the north and the autumn months, particularly October, in the south. A summer-autumn temperature maximum in the early 1920s was restricted to northern Norway. Furthermore in the late 19th century, the northern coast was colder than the northern inland (Hanssen-Bauer and Nordli, 1998). Such differences are due to the large latitudinal range of the country as well as its topography and proximity to the North Atlantic Ocean which cause steep east-west gradients and local climates. Monitoring these patterns of climate change is of high scientific significance because they are an expression for changes in the atmospheric circulation and sea surface temperatures over the northern North Atlantic which is the area of main heat transfer between low latitudes and the Arctic. Furthermore, the positive temperature anomaly sustained by heat advection by the North Atlantic Drift has large socio-economic implications in northern Europe.

Long series of climate information are necessary to gain insight into the natural variability of climate and their causes. The timescales and amplitudes of regular variations as well as the frequency and severity of extreme weather events such as storms, summer frosts, droughts or catastrophic rain falls can be studied from relatively numerous instrumental records back to the 1870s. Longer series are rare and their geographical distribution is restricted. The world's longest series of temperature measurements from central England reaches back to AD 1659 (Jones and Bradley, 1992). In Scandinavia, the first climate stations were established in AD 1756 in Stockholm and AD 1761 in Trondheim. Further information on climatic or climate-related events may be extracted from historical documents reporting, for instance, crop yields (Fjærvoll, 1961), glacier advances (Eide, 1955), severe winters (Pfister *et al.*, 1998) and ice conditions (Ogilvie, 1992; Vesajoki and Tornberg, 1994).

Other information on past climate must be derived from natural climate proxy data, contained within biological, sedimentological and glaciological 'archives' (Bradley, 1999). Each type of climate proxy has its strengths and weaknesses concerning record length, dating accuracy, time resolution, replication, geographical coverage and the climate signal. Annual resolved proxy-records such as ice layers (Tarussov, 1992; Grootes, 1995; Mosley-Thompson *et al.*, 1996), corals (Cook, 1995), speleothems (Lauritzen and Lundberg, 1999a; 1999b), varves (Wohlfarth *et al.*, 1998; Snowball *et al.*, 1999) and tree rings (Fritts, 1976; Cook and Kairiukstis, 1990; Kalela-Brundin, 1999; Lindholm *et al.*, 1999) are of high value for the extension of the instrumental climate series (Bradley and Jones, 1995a; Jones *et al.*, 1998). The majority of sediments provide climate and environmental information on decade to century timescales which is 'archived' in their sedimentological, mineralogical or chemical properties and their fossil content such as pollen, diatoms, chironomids and macrofossils (Eronen and Huttunen, 1987; Berglund *et al.*, 1996; Hyvärinen and Mäkelä, 1996; Barnekow, 1999; Eronen *et al.*, 1999; Olander *et al.*, 1999). Further climate information on various timescales can be gathered from fluctuations of glaciers (Karlén, 1988; Ballantyne, 1990; Dahl and Nesje, 1994; 1996), lake levels (Eronen *et al.*, 1999) and tree lines (Kullman, 1989; 1996). Limitations of single climate proxies may, at least partly, be overcome by multi-proxy syntheses.

TREE RINGS AND CLIMATE

Tree rings are a unique source of climate information (Fritts, 1976; Cook and Kairiukstis, 1990). Tree-ring analysis offers absolute time resolution on an annual or seasonal timescale and is applicable over a large part of the globe, i.e. in climate regions where woody plants experience a distinct period of dormancy due to a cold or dry season. Tree rings are formed by the vascular cambium, a cell tissue between the wood (xylem) and bark (phloem) (Larson, 1994). In the first part of the vegetation period, the cambium of conifers creates large cells with thin cell walls (earlywood) and, at the end of the growing season, narrow cells with thick cell walls (latewood). The interannual variability of radial increment is predominantly determined by the climate of the vegetation period. Because tree rings to a large degree reflect the annual changes of the regional climate, the tree-ring patterns of trees of the same stand and climate region are similar. Tree-ring series are particularly characterised by the narrow rings which reflect climate events close to the tree's tolerance limit (Fritts, 1976).

Apart from the regional tree-ring signal, each tree shows an individual response to climate events due to subtle differences in their habitat or ecotype. During extremely unfavourable growing conditions, the annual ring may only develop on parts of the stem, which on an increment core or stem disc might appear as a 'missing ring' (Larson, 1994). Such missing rings are detected by comparing the tree-ring patterns of several samples of the same tree and of several trees from the same site (Stokes and Smiley, 1968; Fritts, 1976). This crossdating procedure is the central principle of dendrochronology and ensures that all rings are recognised and assigned to the correct calendar year. In other words, tree ring counts on single trees are not sufficient for use in dendrochronology. Generally, only mean tree-ring series comprising at least ten crossdated individuals are recognised as a tree-ring chronology (Grissino-Mayer and Fritts, 1997), and only its well-replicated part is applicable for dating and applied tree-ring research. Because tree species differ in their climate response, separate chronologies must be established for each species. Also, the correlation between tree-ring series decreases with distance and each climate region requires its own tree-ring chronologies (Bartholin, 1987; Thun, 1987).

In the same way as climate causes synchronous growth of trees and thus enables dendrochronological dating, tree-ring analyses allow the reconstruction of past climate (Fritts, 1976; Cook and Kairiukstis, 1990). Dendroclimatology aims to detect and maximise the climate signal for the purpose of climate reconstruction. In practical dendroclimatological work, the tree may be considered as a 'black box' between the climate parameter measured at a meteorological station and the tree-ring width measured on the sample. However, a number of biological and meteorological factors should be considered when interpreting tree-ring chronologies. In addition to the autocorrelation component, the total variability in tree-ring series might be divided in the age-related growth trend, the regional climate signal, standwide exogenous and local endogenous disturbances, and remaining unexplained 'noise' (Cook, 1990).

The term ‘age trend’ refers to the fact that the ring widths gradually decline from the innermost towards the outermost rings. Typically in solitary trees in undisturbed environments, this trend can be described by a negative exponential or hyperbola function (Bräker, 1981; Cook *et al.*, 1990). This trend is partly a geometrical function of the increasing radius of a stem. Also, the ring width is related to the distance between the location of photosynthesis in the needles and of wood production in the cambial zone. Particularly when considering a sample extracted near the stem base, this distance increases as the tree grows in height and successively changes its crown structure. Also, the needle mass appears to decrease with tree age and causes a reduction of assimilates available for wood production (Jalkanen *et al.*, 1994).

By removing the age trend, differences in the general growth rate of trees also are removed. This is necessary in order to prevent the tree-ring pattern of fast-growing individuals from dominating the interannual variability of the chronology. Differences in the general growth rate are normally related to site conditions such as soil moisture, light and nutrients. Due to the detrending process, most standardised chronologies fail to show low-frequency variations (Cook and Briffa, 1990; Cook *et al.*, 1990; Sheppard, 1991; Briffa *et al.*, 1996). A chronology is composed of tree-ring series from individual trees and radii, each detrended and standardised to the same mean value. Thus, the remaining low-frequency variability cannot exceed the average sequence length of the radius series, a fact known as the ‘segment length curse’ (Cook *et al.*, 1995). In practice, most chronologies do not show climate fluctuations of wavelengths of more than about two to three centuries. Alternative methods that preserve more low-frequency variability such as the ‘regional curve standardisation’ RCS (Briffa *et al.*, 1992; 1996; Cook *et al.*, 1995) depend on a large sample size with all age groups equally represented.

The tree-ring width of a given year is an expression of the energy balance of the whole tree and its functions. In the first instance, the energy budget depends on the climate of the current vegetation period. However, the climate does not only affect the tree ring directly, but also other compartments of the tree such as needles, annual shoots and roots. The state of the photosynthetic apparatus and roots as well as the amount of stored assimilates determine the amount of assimilates available for radial growth of the following year. Apart from potential time lags in the climate system, this is a major reason for autocorrelation between tree rings. In addition, the climate of the previous vegetation period might determine the photosynthesis rate by physiological pre-conditioning (Fritts, 1976; Kozlowski *et al.*, 1991).

In northern Fennoscandia, the temperatures of June to August determine the length, thickness and chlorophyll content of the needles as well as the number of needles per shoot for the next season (Hustich, 1969; Junttila and Heide, 1981). The needles stay on the branch for five to six years (Jalkanen, 1996). Although the needles are capable of assimilation already at the end of June, they contribute little to photosynthesis in their first year. In the second season, the needles reach their maximum assimilation capacity, which then gradually declines. Climate events which cause heavy needle shed reduce the radial growth of pine during several of the subsequent seasons (Jalkanen, 1996). Because Scots pine is a species with fixed growth, its shoot length also is determined by the climate of the previous summer (Hesselmann, 1904; Wallén, 1917; Mikola, 1950; 1962; Junttila and Heide, 1981; Junttila, 1986). Height growth of Scots pine in northernmost Finland proceeds from late May to mid July, which is earlier than radial growth, 20th June to mid August (Hustich, 1956).

Stand-related influences due to gap dynamics after storm-felling of dominant trees or forest fires might be expressed in decadal-scale growth pulses in single trees or groups of trees (Cook, 1990). Also reproductive functions contribute to the error component in dendroclimatic modelling. After the bud is initiated in the previous year, Scots pine flowers from the end of June to early July. The cone swells between the 10th of June and mid August of the following summer (Hustich, 1956). Because a successful seed year requires three consecutive warm summers, this process is very sensitive to climate conditions. The allocation of assimilates to flowering and particularly seed ripening might compete with radial growth (Sirén, 1961).

TREE-RING RESEARCH IN NORWAY

The first tree-ring study on Scots pine, *Pinus sylvestris* L., from Norway was performed by Andrew E. Douglass (1919). On his search for cyclicity in climate and sun spots, he analysed samples from the Oslo region and western Norway as well as one pine from Mo i Rana in Nordland and another from the inner coast at “latitude 68°45'N”. The first Norwegian dendroclimatological investigation was carried out by Erling Eide (1926) on material from a forest inventory in eastern Norway. Already then, he applied correlation analysis on summer temperatures and the ring widths of 1906-1922 of Norway spruce (*Picea abies* Karst.). Eide was interested in the influence of stand density and soil moisture on radial increment, and aimed to estimate the annual wood production on the basis of June-July temperatures. He could refer to earlier Swedish and Finnish investigations on the effect of summer temperature on tree growth (Hesselmann, 1904; Wallén, 1917; Laitakari, 1920; Kolmodin, 1923; Romell, 1925).

In Solør, south-eastern Norway, the botanist Sigurd Aandstad (1934) investigated the influence of climate on Scots pine, *Pinus sylvestris*. He analysed the climate-growth relationship by the method of 'percent parallel variation', later introduced as Gleichläufigkeit (Eckstein and Bauch, 1969). Due to its significance for dating accuracy and prediction of forest yield, Aandstad studied the cyclic variability of tree-ring series and summer temperatures. He also successfully dated timber in wooden buildings and thereby became Norway's first dendrochronologist. Successively, he extended his master-chronologies to the period AD 1350-1930 (Aandstad, 1938; 1960; 1980). He also developed the first multi-centennial northern Norwegian chronology (Aandstad, 1939) comprising samples of 12 Scots pines in Steigen, Nordland, AD 1561-1932.

The forest scientist Asbjørn Ording (1941b) combined Aandstad's Steigen chronology with two new chronologies to the Steigen-Sørfold chronology (AD 1396-1936). This site represented the northernmost locality of Ording's latitudinal transect from northern to eastern Norway. Other pine chronologies in northern Norway were located at Korgen (AD 1661-1937) and Namdalseidet (AD 1621-1937). Ording further developed the data of Aandstad and worked on methodological aspects. He advocated the use of correlation coefficients for confirmation of dates in addition to visual analysis, but rejected the applicability of the skeleton-plot method in Scandinavia (Douglass, 1919). Ording stressed the importance of series length and replication and species choice in dendrochronology, and thereby strongly questioned the dates obtained by Ebba Hult DeGeer from correlation of Norwegian wood with the North American Sequoia chronology (DeGeer, 1938; 1939). The general rising interest in dendrochronology in Norway in the late 1930s is apparent in the articles of Kierulf (1936) and Schulman (1944), the investigation of wood, excavated from Raknehaugen (DeGeer, 1938; Ording, 1941a; Johnsen, 1943), as well as in the foundation of a dendrochronological commission 'Trekronologikommisjonen' in Oslo, November 1939 (Høeg, 1944).

Already before Aandstad's and Ording's work in northern Norway, the forester Tollef Ruden (1935) investigated the regional growth variability of Scots pine 1901-1933 in Porsanger, Finnmark, with references to the tree-ring series from Sølor (Aandstad, 1934) and Sodankylä in Finish Lapland (Boman, 1927). His general aim was the standardisation of tree-ring analysis for the use in forest taxation. He continued Ording's discussion of dendrochronological methodology (Ruden, 1945) and assessed tree-ring parameters such as resin ducts, latewood percent and latewood density and their relation to climate in the Oslofjord region (Ruden, 1955) and in Vesterålen, northern Norway (Ruden, 1987).

Per Eidem (1943) investigated the climate response and periodicity of tree rings of Norway spruce, *Picea abies*, at nine localities in South-Trøndelag, applying hand-drawn curves for tree-ring standardisation and Gleichläufigkeit for the analysis of the climate-growth response. He assessed the regional variability and the growth differences between species on 15 and 11 localities of Norway spruce and Scots pine, respectively, in North- and South-Trøndelag (Eidem, 1953). Eidem worked as a dendrochronologist in the Trondheim region (Eidem, 1943; 1944b; 1944a; 1953), in Valdres (Eidem, 1955) and Numedalen (Eidem, 1956a; 1956b; 1956c; 1959). His pine and spruce master chronologies from Selbu in Trøndelag covered the period AD 1424-1940 (ten trees since AD 1595) and 1461/1523-1937, respectively (Eidem, 1953) and his pine chronology from Numedalen AD 1383/1536-1954 (Eidem, 1959).

Whereas the studies of Aandstad, Johnson and Eidem were initiated by Jens Holmboe, it was Ove Arbo Høeg (1944; 1956a; 1956b; 1958) who became the main promotor of dendrochronological research in Norway in the late 1940s. Holmboe and Høeg were professors of botany at the University of Oslo. Under Høeg's supervision, much of the southern part of Norway was systematically covered by dendrochronological investigations in Hallingdalen (Eiklid, 1952), Setesdalen and along the southern coast (Damsgård, 1952; 1998), Gudbrandsdalen (Slåstad, 1957), near Oslo (Brandt, 1958), in Ryfylke (Sørensen, 1965) and near Bergen (Brandt, 1975). The topics of these studies were related to the regional variability of tree rings, the influence of site conditions, the comparison of Scots pine and Norway spruce, and the development of chronologies for dating purposes. During this period of high dendrochronological research activity, tree-ring analyses also were applied to assess the fertilising effect of nitrogen emissions on spruce (Strand, 1950), the effect of fruiting on radial increment (Ljunes and Nesdal, 1954) and the predictability of sea-fishery yields (Ottestad, 1942; 1960). Elias Mork at the Norwegian Forest Research Institute did important work on wood anatomy (Mork, 1926; 1946) and the relationship of tree growth, climate and reproduction at the upper tree line (Mork, 1941; 1942; 1957; 1960). Mork (1960) and Majda Zumer (1969a; 1969b) also studied cambial activity.

Tree-ring research at the University of Trondheim began in the 1970s, at first on ^{14}C-isotopes in tree-rings of Scots pine at the laboratory of radiological dating in Trondheim (Glad, 1977; Glad and Nydal, 1982). A dendrochronological laboratory was established at the Department of Botany for dating of the large amount of timber excavated from medieval Bergen and Trondheim (Thun, 1980; 1984). Here, Terje Thun developed several 1200-year long chronologies (Thun, 1987), including pine chronologies for

Trøndelag back to AD 552 (Thun, 1998), for south-eastern Norway back to AD 829 and for western Norway back to AD 883 (Storsletten, 1993). In the recent years, the Trondheim laboratory also worked on drift wood of the Arctic and northern Norway (Johansen, 1998; 1999), including a dendroclimatological analysis of Dahurian larch, *Larix gmelinii* (Rupr.) Kuzen. (Johansen, 1995).

In the early 1980s, a renewed interest in dendrochronology arose in northern Norway. The Steigen chronology was updated (Briffa *et al.*, 1986) and Fritz-Hans Schweingruber collected samples for chronologies in Saltdalen, near Narvik, Lødingen and Skibotn (Schweingruber, 1985; Schweingruber *et al.*, 1987; 1991; Briffa *et al.*, 1988b). Presumably due to the discovery of Norway's oldest living Scots pine, Ruden constructed the first pine chronology for Forfjorddalen, Vesterålen, and interpreted the climate of AD 1700-1850 (Ruden, 1987). Thun and Vorren (1992; 1996) produced a second Forfjorddalen chronology as well as short tree-ring series from lower Kirkesdalen in Målselv, Troms, and Hamarøy in Nordland. A third, now well-replicated chronology from Forfjorddalen was developed at the Department of Biology at the University of Tromsø (Kirchhefer and Vorren, 1995). Also in parts based in Tromsø, the present author studied pointer years of pine and birch (*Betula* sp. L.) AD 1871-1990 in Alta, Finnmark, considering climate, soil moisture and slope aspect (Kirchhefer, 1992; 1996; 1998), and another master thesis was carried out on the climate response of Alaskan White spruce, *Picea glauca* (Moench) Voss (Skoglund, 1993; Skoglund and Odasz, 1998).

A tree-ring laboratory also was founded at the Archaeological museum in Stavanger. Here, Maarit Kalela-Brundin (1996; 1999) developed pine chronologies for south-western and eastern Norway. The pine chronology from Femundsmarka, eastern Norway, extends back to AD 1120 and was applied for the reconstruction of July-August temperatures back to AD 1500. Furthermore, historical and tree-ring data were compared (Pedersen and Kalela-Brundin, 1998). Living oak (*Quercus* sp. L.) as well as Viking age and medieval oak timber along the coast of southern and western Norway has been investigated at the National Museum in Copenhagen (Bonde and Christensen, 1993; Christensen, 1993; Bonde, 1994; Hylleberg Eriksen, 1994; Christensen and Havemann, 1998).

Several studies applied tree rings in the context of glaciology (Matthews, 1976; 1977). Planning a significant extension of this work, Innes (1987) established a sampling network of Scots pine from 39 localities, mainly in the Svartisen-Okstindan and Jostedalsbreen-Jotunheimen areas. Ballantyne (1990) applied tree-ring counts in birch in order to date glacier advances in Lyngen, northern Norway. Birch has been the subject of a number of exploratory investigations (Zumer, 1969a; Millar, 1980; Treter, 1982; Staschel, 1989; Kirchhefer, 1996). An example of the application of tree rings in forestry and environmental research is the report on acid precipitation of Strand (1980). The status of dendrochronological research in Norway in the early 1990s is documented by reports from meetings in Oslo 1991 (Storsletten and Thun, 1993) and Stavanger 1993 (Griffin and Selsing, 1998).

DENDROCLIMATOLOGY IN NORTHERN FENNOSCANDIA

Dendroclimatological research in northern Norway should be seen in a Fennoscandian context. Tree-ring research in Sweden and Finland has been an inspiration for work in Norway and Fennoscandian tree-ring chronologies have been used for dating purposes across the national borders. Most important for dendroclimatology is the fact that climate reconstructions in the climatically heterogeneous region of Fennoscandia must be interpreted in the light of climate modifications due to the Scandes and the North Atlantic Ocean.

In Sweden, Henrik Hesselmann (1904) conducted a pioneering study on the influence of climate on tree-rings of Scots pine 1895-1904, with the northernmost site near Gällivarre. Aarne Boman (1927), who mainly was interested in the analysis of periodicity in radial growth, developed five 150-260 year long tree-ring chronologies near Sodankylä, Finland, north of the Polar Circle. Both authors used between four and six trees per locality. Stellan Erlandsson (1936) studied tree rings and climate near Lake Torneträsk (AD 1464-1931), Kiruna (AD 1578-1931) and Karesuando (AD 1772-1931), Sweden, including Boman’s Sodankylä series (AD 1701-1919).

Using the material from the second Finnish forest inventories, intensive comparative studies have been carried out on radial increment, reproduction, and needle growth of pine and spruce along latitudinal, altitudinal and climatic gradients in relation to soil conditions, stand density and age classes (Eklund, 1944; 1954). Partly based on this material, Mikola (1950) studied the climate-growth response of Scots pine and constructed a pine chronology for Lapland AD 1750-1947. Later, he reviewed results on tree growth and climate in northernmost Finland until 1957 and presented tree-ring chronologies for Pallastunturi, Ivalojoki, Lemmenjoki, Inarinjärvi, Naatamojoki and Kevo 1890-1957 (Mikola, 1962). Hustich and Elfving (1944) studied the ring widths of 1890-1939 in Utsjoki/Kevujoki, northernmost Finland. Hustich (1945) assessed the effect of climate, ripening years and autocorrelation on tree-ring width and made regional comparisons. Successively, he developed series of observations on height growth, needle length and female flowering until 1977 (Hustich, 1956; Hustich, 1958; Hustich, 1969; Hustich, 1978). Also in Kevo, Kärenlampi (1972) performed a small-scale dendroclimatic study on pine growth in the 1960s.

Gustav Sirén (1961; 1963; Sirén and Hari, 1971) developed a northern Finnish chronology for AD 1181-1960, assessed the history of summer temperatures and pine regeneration and made predictions of forest yields. Subfossil pine logs were sampled along the northern tree line of Scots pine in Finland (Eronen and Huttunen, 1987). Based on a tree-ring series which continuously extends back to 165 BC (Zetterberg *et al.*, 1994), a standardised chronology has been published back to AD 50 (Lindholm *et al.*, 1999). A floating, radiocarbon-dated chronology from subfossil wood covers the period 5000-500 BC (Zetterberg *et al.*, 1994; Eronen and Zetterberg, 1996; Zetterberg *et al.*, 1996). Based on pine chronologies elaborated by Matti Eronen and Jouko Meriläinen, the regional variability of pine growth and climate-growth response along the northern tree line in Finland has been assessed mainly by Markus Lindholm (Eronen *et al.*, 1994; Lindholm, 1996; Lindholm *et al.*, 1996a).

In Sweden in the late 1970s, Wibjörn Karlén started collecting pine samples for a multi-millennial pine chronology at five sites near Lake Torneträsk, Sweden, which was developed in co-operation with the dendrochronological laboratory in Lund (Bartholin and Karlén, 1983). Already at an early stage of work, the continuous part of the Torneträsk chronology covered the period AD 436-1980. A preliminary dendroclimatological analysis showed the correlation with July temperatures, and the chronology was compared with glacier advances (Bartholin and Karlén, 1983). Climate-growth response functions on four of the Torneträsk sites and a climate reconstruction back to AD 1680 were computed by Aniol and Eckstein (1984). In the following years, the continuous chronology was extended back to AD 402 and a floating, radiocarbon-dated chronology back to 6000 BP (Bartholin, 1987). This material was analysed radiodensitometrically at the Swiss Forest Research Institute, and climate reconstructions were computed at the Climate Research Unit, University of East Anglia (Briffa *et al.*, 1990; 1992).

Apart from the multi-millennial chronologies in northern Finland and Sweden, a number of shorter chronologies have been established in northern Fennoscandia (Figure 1; Schweingruber, 1985; Schweingruber *et al.*, 1987; Briffa *et al.*, 1988a; Lindholm *et al.*, 1996b). Generally, chronology networks are better suited to show the regional mean patterns of tree growth and past (Fritts, 1991; Cook *et al.*, 1994). Advanced analyses aim at reconstructing circulation patterns (Bradley and Jones, 1993; Hirschboeck *et al.*, 1996). In Fennoscandia, Schove (1950; 1954) made the first attempts to reconstruct prevailing circulation patterns from a compilation of information from tree-ring, historical and instrumental data. Today, the chronology network is denser and the opportunities for such research is considerably improved enabling, for instance, reconstructions of July-August temperatures for Finland and Fennoscandia back to AD 1700 (Briffa *et al.*, 1988a), April-August temperature for northern Fennoscandia and Europe back to AD 1750 (Briffa *et al.*, 1988b) as well as maps of annual summer temperatures in Europe for 1750-1975 (Schweingruber *et al.*, 1991).

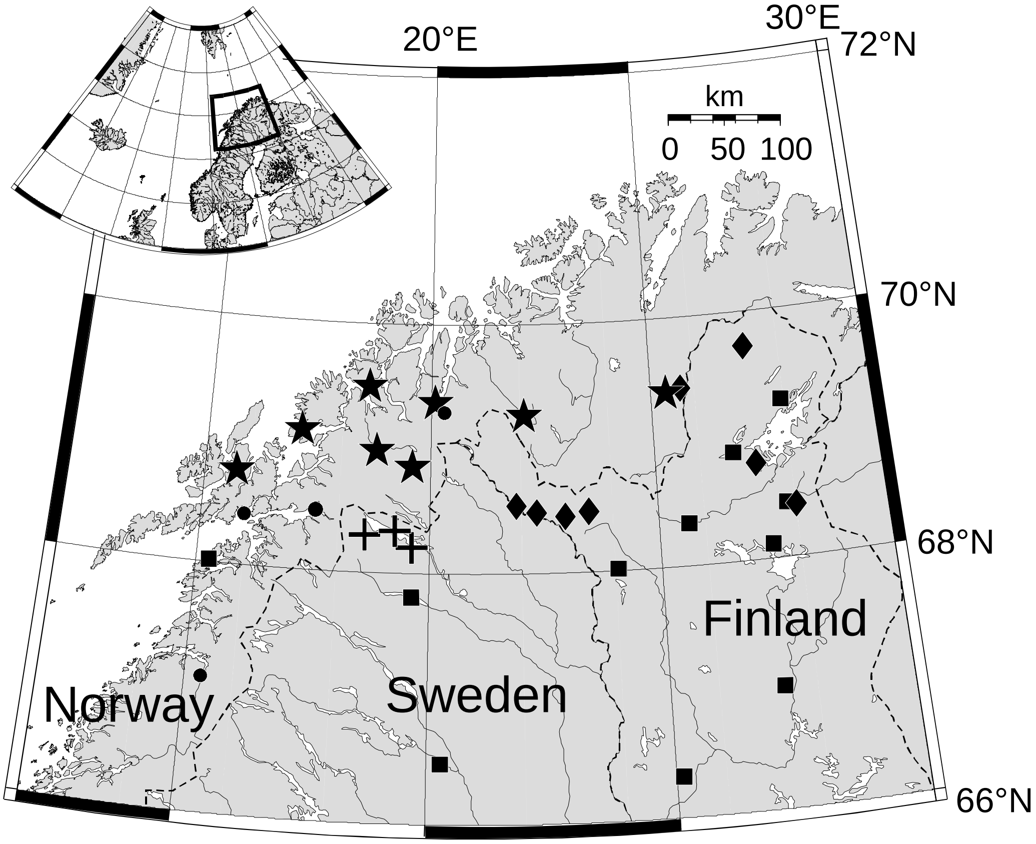

Figure 1: Map of Fennoscandia north of 66°N showing the location of tree-ring chronologies. Crosses: Lake Torneträsk localities (Bartholin and Karlén, 1983), dots: tree-ring density chronologies in northern Norway (Schweingruber, 1985; International Tree-Ring Data Bank), squares: tree-ring network analysed by Briffa *et al.* (1988a), diamonds: chronology network of Lindholm *et al.* (1996b), stars: sites investigated in the present thesis. This map, a polar stereographic projection, was created by GMT-OMC version 4.1 (The General Mapping Tools-Online Map Creation) provided by GEOMAR, Kiel, at the web-site <http://www.aquarius.geomar.de/omc> (Wessel and Smith, 1995).

Recently, Fennoscandian tree-ring chronologies were applied to reconstruct the climate of the Arctic (Overpeck *et al.*, 1997), the North Atlantic Ocean (D'Arrigo *et al.*, 1993; D'Arrigo and Jacoby, 1993) and hemispheric and global temperatures (Briffa *et al.*, 1996; Jones *et al.*, 1998; Mann *et al.*, 1998; 1999). In several of these studies, the Torneträsk chronology has been the only representative for northern Fennoscandia. This reflects the fact that most dendroclimatological efforts have been made in the climatically relatively homogeneous region east of the Scandes, whereas the western slope of the Scandes in Norway was represented by few sites only. Until the early 1980s, the Steigen-Sørfold chronology was the only tree-ring series available in northern Norway for east-west comparisons in northern Fennoscandia. Of Schweingruber's chronologies, only the Narvik and Lofoten/Lödingen series were applied to temperature reconstruction.

Furthermore, although the Lake Torneträsk chronology comprises trees from several sites, it might not be representative for entire northern Fennoscandia. Thus several parallel series must be developed which match the length and quality of the Lake Torneträsk series and the recently published northern Finnish chronology (Lindholm *et al.*, 1999). This is particularly important in the light of the fact that "traditional inferences on global and hemispheric mean temperature change based on regional proxies originating around the margins of the northern North Atlantic must be viewed with some caution" (Briffa and Jones, 1993). The existing coastal chronologies were placed along a south-north axis and did not allow a systematic investigation of pine growth and climate response in relation to the steep gradient of oceanity. Therefore, a more systematic coverage of the western slope of the Scandes and the Norwegian coast seemed to be required.

Reasons for work on dendroclimatology, other than the further development of the chronology network and long chronologies, is the monitoring of boreal forest growth under changing environmental conditions. Several studies have revealed changes in the climate-growth response of conifers in high latitudes (Jacoby and D'Arrigo, 1995; Briffa *et al.,* 1998a; 1998b; Vaganov, 1999). Briffa and Jones (1993) pointed out that "indeed there are potential dangers in assuming that high-latitude (or high-altitude) trees respond exclusively to summer temperatures". On this basis, as well as due to its potential implications for climate reconstruction, the investigation of the importance of site conditions for the climate-growth response of Scots pine in northern Norway is here considered to be a significant aspect of tree-ring research.

THE AIMS OF THE STUDY

Aim 1: Development of tree-ring chronologies from Scots pine along the Atlantic coast of northern Norway and reconstruction of coastal climate.

These series aimed to contribute to the number of coastal chronologies and palaeoclimate records. Ideally, these should be of 500 years length in order to cover the ‘Little Ice Age’. Sampling at the most oceanic pine localities aimed to facilitate the assessment of growth and climate response of pine at sites climatically most different from the localities east of the Scandes and strongly affected by oceanic factors.

Aim 2: Analysis of the spatio-temporal variability of pine growth, climate-growth response and past climate along the gradient of continentality from the coast of northern Norway to the inland east of the Scandes.

From earlier investigations it was known that tree rings of Scots pine along the northern Norwegian coast reflect the temperatures during a longer vegetation period than those pines growing east of the Scandes (Schweingruber *et al.*, 1987; Briffa *et al.*, 1988a). The present thesis aimed at systematically documenting changes of pine growth and its relation to climate on the basis of a denser chronology network than previously available. This network should be homogeneous in terms of site selection and the methods of tree-ring standardisation.

Aim 3: Assessment of the influence of slope aspect on the climate-growth response of Scots pine.

Although summer temperatures are known to be the principal growth-determining factor at the northern and alpine tree line, site conditions modify this general growth response. A single-year analysis in Alta, Finnmark, showed that the slope aspect affects the length of the vegetation period of pine as reflected in the tree rings (Kirchhefer, 1992; 1998). This partial study aims to shed further light on the importance of site selection, and the slope aspect in particular, for dendroclimatological work in northern Fennoscandia.

METHODOLOGY

The present investigation applied standard methods of dendrochronology and dendroclimatology as described by Fritts (1976), Hughes *et al.* (1982) and Cook and Kairiukstis (1990) and software of the International Tree-Ring Data Base Program Library ITRDBproglib, particularly COFECHA for the crossdating and ARSTAN for the tree-ring standardisation and chronology computation (Holmes *et al.*, 1986), and 3Pbase /PPPhalos for the climate-growth response analysis and climate reconstruction (Guiot and Goeury, 1996). Further details are given in Papers 1-3.

THE MAIN RESULTS

The three aims are addressed in separate papers. The main results were as follows:

Paper 1: July-August temperatures at the coast of northern Norway were reconstructed back to AD 1358, based on ring-width chronologies of Scots pine from Forfjorddalen (AD 1354-1994), Stonglandseidet (AD 1544-1995) and Vikran (AD 1699-1992). The 20th century was conspicuous as a long-lasting period of above-average temperatures, only precedented by the period AD 1470-1540. The 17th century, regarded as the coolest interval of the 'Little Ice Age' (Bradley and Jones, 1993), experienced three temperature cycles of approximately 40-year length and minima around AD 1605, 1640 and 1680. In the 19th century, cool summers prevailed about AD 1810, in the 1830s and during the 1860s-1910. In contrast to inner Fennoscandia, coastal summer temperatures were not particularly high around AD 1760, but a warm interval occurred about AD 1800.

Paper 2: At all eight investigated localities between Vesterålen and Finnmarksvidda, July temperature was the most important growth-determining factor of pine growth. Whereas inland pines reacted predominantly to July temperatures, coastal pines responded significantly positively also to August temperatures, but negatively to warm-moist mid winters. During the temperature optimum of the 20th century, the inner Scandes sites represented a separate dendroecological zone with reduced growth due to the oceanic winters of the 1930s and enhanced growth due to high late-winter to spring precipitation ~1950. Three climate reconstructions were obtained back to AD 1800: July temperatures for northern Norway, July temperatures for the inland region and July-August temperatures for the coastal region.

Paper 3: In Målselvdalen and Dividalen in the inner Scandes, a positive growth response to June temperatures was observed at north-facing slopes, in addition to the dominant influence of July temperatures. July temperatures were reconstructed back to AD 1799, based on the regional mean chronology. On an experimental basis, June temperatures were reconstructed back to AD 1776, based on the growth differences between north- and south-facing slopes. The latter reconstruction shows that slope-related differences in radial growth of pine can be used for refining the picture of past summer temperatures. However, firm conclusions require a higher site replication, long local climate series and independent verification.

DISCUSSION

The three papers enclosed in the present thesis were written independently of each other and cross-references were avoided. For practical editorial reasons, each paper refers only to results from the data set under investigation. Therefore several partial results supplemented each other when synthesising the individual papers. Others appeared to be contradictory. Such cases will be discussed in the following section.

TREE-RING CHRONOLOGIES

A major achievement of the present study was the compilation of a northern Norwegian network of tree-ring chronologies at about 69°N. The data set comprised eleven new ring-width chronologies of Scots pine, *Pinus sylvestris*, distributed across eight main localities and covering the gradient of continentality from the Atlantic coast to the Finnmarksvidda. Where previous tree-ring series existed (Forfjorddalen: Ruden, 1987; Thun and Vorren, 1996; Målselvdalen: Thun and Vorren, 1996; Skibotndalen: Schweingruber, 1985; Karasjok: Lindholm *et al.*, 1996b), the presented chronologies are based on entirely new samples[1]. Whereas at Karasjok no significant improvement was gained in relation to Lindholm's chronology, the total length of the tree-ring records of Forfjorddalen, Målselvdalen and Skibotndalen was extended by about 420, 41 and 194 rings back to AD 877, AD 1637 and AD 1579, respectively.

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[1] with the exception of the re-measured ring-width series of the second oldest Scots pine of Norway AD 1275-1979 from Forfjorddalen (Thun and Vorren, 1996)

In the present study, only those chronology sequences comprising at least eight to eleven trees have been applied for the dendroclimatological analyses[2]. All following dates of first years of chronologies refer to this criterion. Therefore, the shortest chronology restricted the common analysis period to the years 1800-1992 (Paper 2). The three coastal chronologies extend back to at least AD 1705 (Forfjorddalen, Stonglandseidet, Vikran; Paper 1) and will potentially contribute to temperature reconstructions such as the northern Finnish reconstruction back to AD 1720 based on four chronologies (Lindholm *et al.*, 1996b) and the reconstruction of Briffa *et al.* (1988a) back to AD 1700 based on 12 northern Fennoscandian chronologies. The chronologies from Forfjorddalen and Stonglandseidet extend back to AD 1358 and 1548, respectively (Paper 1) and thus contribute to knowledge on ‘Little Ice Age’ climate (Bradley and Jones, 1995a; Briffa *et al.*, 1999). The Forfjorddalen chronology FF2 (Paper 1) is the longest single-site chronology in Norway, slightly longer than the recently published pine chronology from Femundsmarka, south-eastern Norway (Kalela-Brundin, 1999). Such tree-ring chronologies of 500 years length or more are in high demand by the palaeoclimatology community (Bradley and Jones, 1995a). The Forfjorddalen chronology is here considered to be particularly high in scientific value because it represents a marginal area at the north-western edge of the Eurasian continent and thus potentially monitors climate changes of the North Atlantic Ocean and the Arctic.

THE GENERAL TREE-RING SIGNAL

Paper 2 showed, that approximately two thirds of the tree-ring variability were in common among the STANDARD and ARSTAN chronologies and as much as three quarters among the RESIDUAL chronologies (Paper 2). This means that the year-to-year variability of ring width was more homogeneous in the region than the low-frequency variability. In accordance with previous knowledge on tree growth in high northern latitudes (Mikola, 1962), the largest portion of the annually resolved tree-ring variability was determined by July mean temperatures at all sites and across the entire study area (Paper 2). This indicates a relatively high thermal and dendroecological homogeneity of northern Fennoscandia. Although the Scandes strongly affect the spatial pattern of precipitation, they do not cause totally different regimes of summer temperature on their oceanic and continental side, respectively. This in turn justified the validity of the reconstruction of July temperatures covering the study area at large which explained 56% variance of the observed July temperatures (Paper 2).

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[2] This refers to the numbers of trees required to reach a level of 85% expressed population signal EPS (Wigley *et al.*, 1984) in STANDARD and ARSTAN chronologies. Only six to seven trees were required for the RESIDUAL chronologies in Paper 3.

REGIONAL VARIABILITY

The present study showed that 25-33% of the tree-ring variability differed between the sites. Nearly 10% of the ring-width variability was related to the west-east gradient (Paper 2). Hypothetically, therefore, if every tenth ring is significantly different between east and west, this might have considerable implications for dating accuracy across the northern Scandes in terms of the regional significance of master chronologies in the east-west direction and the requirements for chronology length. In terms of July temperatures and atmospheric circulation patterns, a more detailed analysis might yield information over the frequency of summers with predominantly cyclonic or anti-cyclonic weather situations over northern Fennoscandia (Paper 2).

The availability of only eight tree-ring localities was too sparse to define regional groups by numerical means. Therefore, the observed climate-growth responses provided the initial subdivision of northern Norway into dendroecological zones, resulting in a coastal zone with a response to July-August temperature and an inland zone with a July-temperature response (Figure 2, Paper 2). This conforms with the results of the principal component analysis which implied that the major variability occurred in the east-west direction. On the other hand, the visual comparison of the chronologies revealed that also other clusters occurred, but that these groups varied in time. The most remarkable

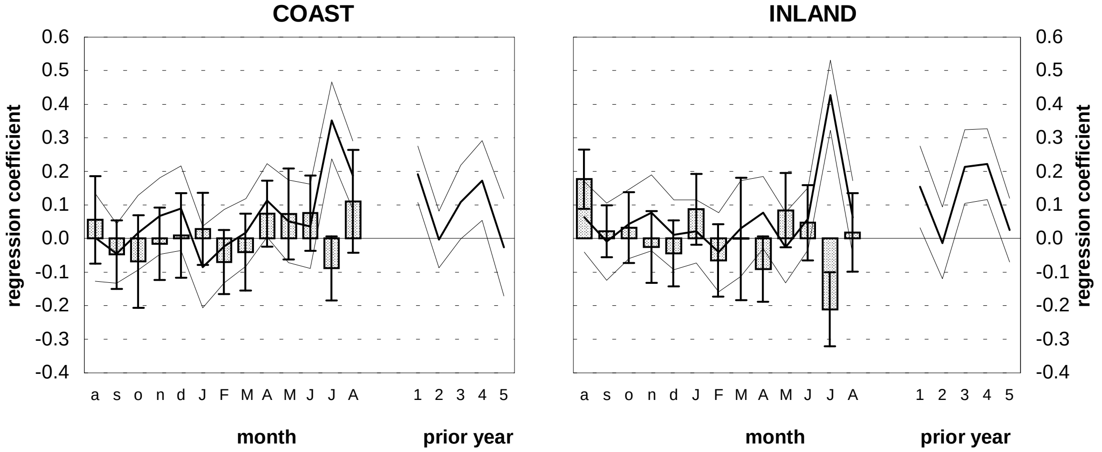

Figure 2: Climate-growth response functions computed from the regional climate series and the first principal components of the ARSTAN tree-ring chronologies for the coastal (Forfjorddalen, Stonglandseidet, Vikran, Målselvdalen) and the inland region (Dividalen, Skibotndalen, Nordreisa National Park, Karasjok) according to Table 6 in Paper 2. Regression coefficients for climate of previous (a) to current August (A) and the ring widths of the five prior years. Lines: response to mean temperatures; bars: response to precipitation. Two standard deviations are indicated.

decadal-scale pattern appeared in the inner Scandes in the 1930s to 1950s (Målselv, Dividalen, Skibotn; Figure 3), which justifies the classification of the inner Scandes as a dendroecological zone of its own, separate from the coast and the Finnmarksvidda east of the Scandes (localities Nordreisa and Karasjok).

The present study showed that the eastern chronologies yielded the strongest tree-ring signal as measured, for instance, by the signal-to-noise ratio, SNR. This is likely to be caused by the short, intensive vegetation period in continental climate of northern Norway. The hypothesis that the northern exposition of the Karasjok site did influence these results (Paper 2), could not be confirmed when directly investigating the effect of slope aspect in the inner Scandes (Paper 3). Another regional trend in statistical parameters was a decreasing low-frequency variability along the coast towards the most oceanic south-west, where also the temperature amplitudes are lowest (Paper 1). On the other hand, the highest ring-width amplitudes were observed in Dividalen in the inner Scandes, where the climate is dry and strongly determined by radiation (Paper 2).

The strongest growth response to July temperatures were obtained at Vikran and Karasjok. Again, Paper 3 could not confirm that the north-facing exposition caused this signal (Papers 1 and 2). Provided that the results from the inner Scandes (Paper 3) are representative also for the coast and the Finnmarksvidda, this supported the hypothesis that the strong July response at Vikran and Karasjok is related to the latitudinal gradient. As a third alternative, the proximity to the long-operative climate stations at Tromsø and Karasjok might affect the results. Karasjok is the only representative of the regional

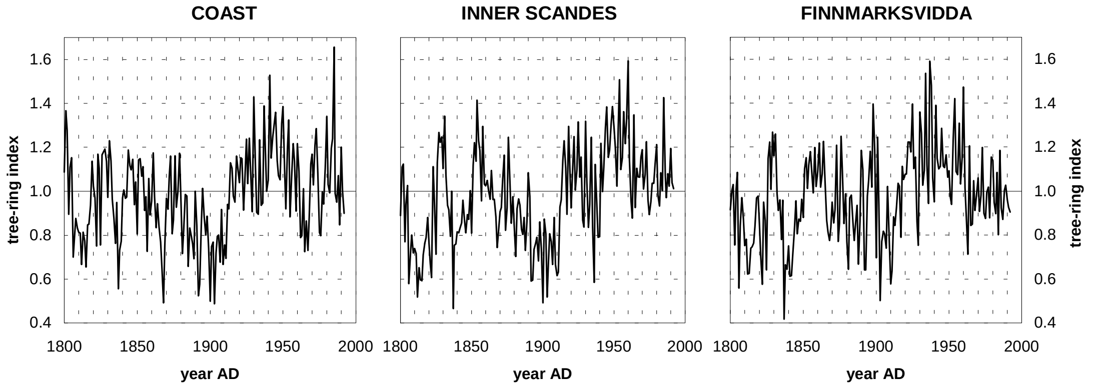

Figure 3: Mean growth AD 1800-1992 of the three dendroecological zones in northern Norway, computed from the ARSTAN chronologies. Coast: Forfjorddalen, Stonglandseidet and Vikran; Inner Scandes: Målselvdalen, Dividalen and Skibotn; Finnmarksvidda: Nordreisa and Karasjok (Paper 2).

inland climate series prior to 1913 (Sihcajavri), and Tromsø represents one of three coastal series prior to 1916 (Røst, Bodø) and one of two series prior to 1890 (Bodø) (Hanssen-Bauer and Nordli, 1998)

At the coast, tree-ring width responded to August temperatures, in addition to July temperatures (Papers 1 and 2). However, this August-temperature signal might be of less regional significance than expressed in Paper 2. Vikran displayed a rather weak August signal (Paper 1) and, in fact, the Målselvdalen chronologies did not show the July-August temperature response when applying local climate data (Paper 3). The results in Paper 2 were biased due to autocorrelation in the coastal temperature data. The correlation coefficients between July and August temperatures at the coast were $r = 0.47$ (Tromsø) to $r = 0.48$ (Skrova fyr), but inland $r = 0.29$ (Karasjok) to $r = 0.24$ (Sihcajavri), only (Førland and Nordli, 1993). This means that the response function reflected the autocorrelation between July and August temperatures rather than a true relation between ring width and local August temperatures.

These findings imply that the dendroecological east-west division of northern Norway with the border along the highest summits of the Scandes is an artefact caused by the application of the regional climate series (Hanssen-Bauer and Nordli, 1998). Instead, the border of the inland region should be moved west of the Målselvdalen sites, i.e. to the sub-oceanic climate region. The dendroecological chronology groups of the inner Scandes and the Finnmarksvidda both display an inland type response function, but the inner Scandes differ in the particular 20th century growth pattern.

However, it should be emphasised that this regional division is mainly a means to describe the spatial patterns of pine growth and climate response observed during the recent 120 years, and the 1930s to 1950s in particular. It might help to select chronologies or new localities for the evaluation of certain dendroecological or dendroclimatological questions such as the reconstruction of past climate and the prediction of global change effects on northern pine forests. It is hoped that in particular syntheses of chronologies and climate reconstructions from different zones contribute to understanding past climate of northern Fennoscandia. The limits of these zones might vary in time due to changing continentality.

SLOPE ASPECT AND JUNE TEMPERATURES

Inland, a June-temperature signal occurred in Målselvdalen, Dividalen, Skibotn and Karasjok in the residual chronologies (Paper 2) and/or at north-facing slopes (Figure 4 and Paper 3). In Paper 2, the slope influence was obscure, because the June response occurred at both north-facing (Karasjok) and south-facing sites (Skibotn). Also the results from Dividalen might appear contradictory, because in Paper 2, the south-west facing slope shows a growth response to June temperatures, but in Paper 3 this is not the case. The reason for this is that Paper 3 is based on a subsample (Devdiselva DEV) of the Dividalen chronology (DIV). Although the general inclination of the sample area is south-west, it receives abundant light from the north-west and north-east in summer, except at Devdiselva (DEV) which receives no direct light from the north-east. This implies that the angle of the horizon is more important than the local slope.

An assessment of the climate-growth responses and light conditions at dendroclimatological sites east of the Scandes investigated earlier (Briffa *et al.*, 1988a; Lindholm *et al.*, 1996b) might answer the question of whether the June response occurs only in the inner Scandes or also on the northern Fennoscandian peneplains north of the Polar Circle and under which slope and light conditions this phenomenon occurs. The sole north-facing locality at the coast, Vikran, does not indicate any June temperature response[3] which might imply that this response is restricted to the inland zones.

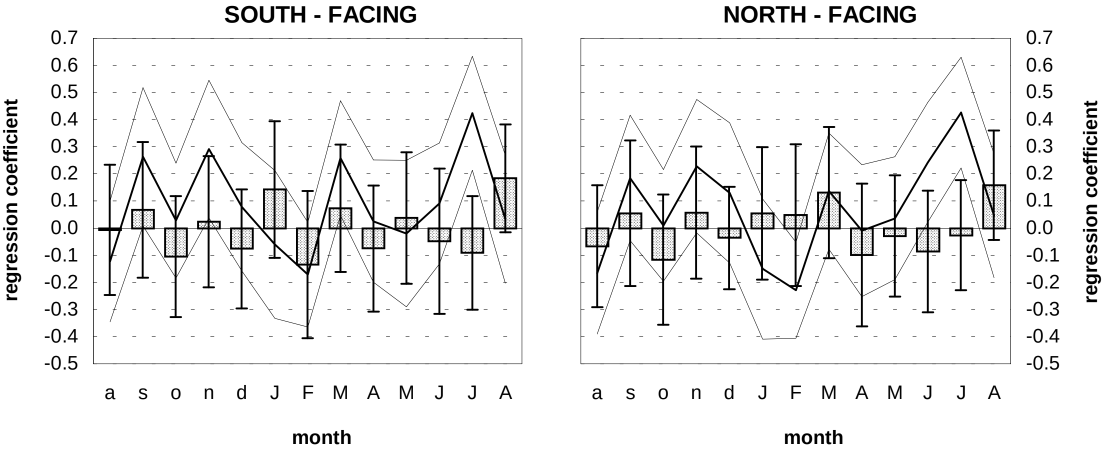

Figure 4: Climate-growth response functions for the south- and north-facing slopes in the inner Scandes, computed from the Bardufoss-Dividalen climate mean 1947-1992 and slope-mean chronologies (Table 3 in Paper 3). Regression coefficients for mean temperature (lines) and precipitation (bars) of previous (a) to current August (A). Two standard deviations are indicated.

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[3] except in the response function for the early calibration period (AD 1875-1915) which, however, is suspicious due to the absence of a significant response to July temperatures

TWENTIETH CENTURY CLIMATE CHANGE

Tree growth was relatively consistent between the study localities in the 19th century (Papers 1-3). This implies that summer temperatures were the main growth-limiting factor during that period. Since AD 1910, however, the growth trends of the individual sites diverged, suggesting responses to additional climate factors during this warm period. One possible factor is drought stress during the vegetation period (Jacoby and D'Arrigo, 1995). Indirect evidence was seen at the steep south-facing site of Stonglandseidet (Paper 1) and in Dividalen (Paper 3), where Scots pine did not show the usually negative response to summer precipitation. In the inner Scandes and the Finnmarksvidda, increasing late winter/early summer precipitation appeared to improve growth on a decadal timescale around 1950 (Papers 2 and 3).

Also, there was evidence for physiological stress due to high December-to-February temperatures and precipitation. This factor apparently modified coastal pine growth constantly (Paper 1) and growth in the inner Scandes particularly in the 1930s (Papers 2 and 3). During this period of exceptionally warm summers (Briffa and Jones, 1993) and weakened influence of western air masses (Tuomenvirta *et al.*, 1998), the assumption of a linear relationship between tree-ring widths and summer temperatures was, to a certain degree, violated. This raises the question of whether such situations occurred also previously and whether such events can be recognised in the tree-ring records. In terms of global warming scenarios, these results implicate that warming summers in combination with increasing winter temperatures do not enhance pine growth in this region. The same will be true if warm summers are associated with a larger risk of drought stress. Thus northern forest may not act as a carbon sink under climate warming.

Other responses to climate outside the vegetation period were observed in the inner Scandes. In Målselvdalen, there were indications that snow-free conditions in early winter (November) caused deeply frozen ground and reduced growth in the following season (Paper 3). In late winter, a positive response to March temperatures occurred at south-facing slopes in the second half of the 20th century and might be interpreted in terms of more frequent south-western air masses and higher cloudiness reducing the risk of needle damage related to frost-drought, extreme diurnal temperature amplitudes and strong insulation during below-zero temperatures (Paper 3). On the other hand, higher cloudiness in June might reduce the vitality of pine at north-facing slopes.

However as seen earlier, not every significant regression coefficient in the response functions may be meaningful in an ecological sense. Statistical artefacts may occur due to autocorrelation between climate parameters, inhomogeneities in the climate series or due to tree-ring standardisation. For this reason, and because these papers primarily aimed at reconstruction of the strongest climate signal, individually occurring responses outside the vegetation period have been ignored in Papers 1 and 2.

CLIMATE-GROWTH CALIBRATION

The most significant climate reconstruction was obtained when calibrating the main growth pattern, i.e. the first principal component of the eight chronologies in the regional network, with the main climate signal as represented by mean July temperatures for northern Norway (Paper 2). This reconstruction explained more than half of the observed temperature variance (R^2_{adj} = 56%). Lower R^2_{adj} values were obtained when integrating chronologies and climate over smaller areas (Paper 2: coastal July-August temperatures R^2_{adj} = 45% and inland July temperatures R^2_{adj} = 48%; Paper 3: inner Scandes July temperatures R^2_{adj} = 38%). Reconstructions based on single chronologies and climate stations along the coast yielded between R^2_{adj} = 29% and R^2_{adj} = 49% (Paper 1). The reconstruction of June temperatures, i.e. a climate parameter that is not the main source of tree-ring variability, accounted for only 26% of the observed climate variability (Paper 3).

Thus, the calibration results clearly depended on the regional integration of ring width and climate data. The more chronologies included and the larger the climate region, the higher the explained variances. Also, the results were inversely related to the distance between climate station and chronology, and positively related to the length of the calibration period. Furthermore, changing climate affected the calibration results. In the cooler period around the turn of the 20th century, tree growth at the coast and in the Scandes depended more on the year-to-year variability of summer temperatures than during the warm period since the 1920s (Papers 2 and 3). Here, one might see an example of the violation of the principal of uniformity in palaeoclimatology. Therefore, climate data from the second half of the 20th century might not be optimal for calibration and reconstruction purposes. Thus, homogenising of the early part of the long climate series deserves continued priority in climate research (Hanssen-Bauer and Førland, 1994; Frich *et al.*, 1996; Nordli, 1997). Correction of the long climate series at the coast of northern Nordland and Troms county is likely to improve the calibration results for the multi-centennial chronologies at Forfjorddalen and Stonglandseidet.

As discussed in Paper 3, the applicability of the slope-related climate signal for climate reconstruction depends on a higher number of sites, long climate records close to the chronology sites, and the possibility of independent verification, for instance, from historical documents.

SUMMER TEMPERATURES OF NORTHERN NORWAY SINCE AD 1358

The present thesis provided several reconstructions of summer temperatures back to AD 1800 (Papers 2 and 3) and for the coastal region back to AD 1358 (Paper 1). Thereby, the northern Norwegian temperature record is extended by minimum 67 and 510 years, respectively, in relation to the longest instrumental temperature measurements from 1867 at the coast (Tromsø, Andenes), and 1871 (Alta) and 1877 in western Finnmark (Karasjok), respectively. In addition, a June temperature reconstruction of experimental character is computed back to AD 1776. Detailed descriptions of these reconstructions are given in Papers 1-3.

All obtained reconstructions of summer temperatures showed above-average temperatures since around AD 1915 and low temperatures for most of the 19th century except around AD 1830, 1850-65 and, at the coast, the 1870s. The variations in summer temperatures during AD 1800-1910 during the late part of the 'Little Ice Age' have been similar on both sides of the Scandes. On the other hand, the coastal temperatures recovered earlier after the extremely cold summers of 1812 and 1815, 1837 and 1868. Synthesising the relatively large number of tree-ring chronologies in northern Fennoscandia covering the period since AD 1800 might enable a more detailed, annually resolved, picture of spatial variability of summer temperatures during the 19th century.

Summer temperatures before AD 1800 were reconstructed only for the coast (Paper 1)[4]. The comparison with the July-August temperature reconstruction for northern Fennoscandia, mainly representing the Torneträsk and Lake Inari regions (Briffa and Schweingruber, 1992) revealed that on both sides of the Scandes, temperatures were close to the long-term average in the second half of the 18th century, but slightly below average during its first half (Figure 5). Major discrepancies were the growth maxima at about AD 1760 and 1800, which were restricted to the inland and the coast, respectively. Paper 1 proposed that these east-west differences were related to certain atmospheric circulation patterns during summer. A final explanation of the two growth maxima of Scots pine re-

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[4] except the June-temperature reconstruction for inner Troms back to AD 1776 (Paper 3)

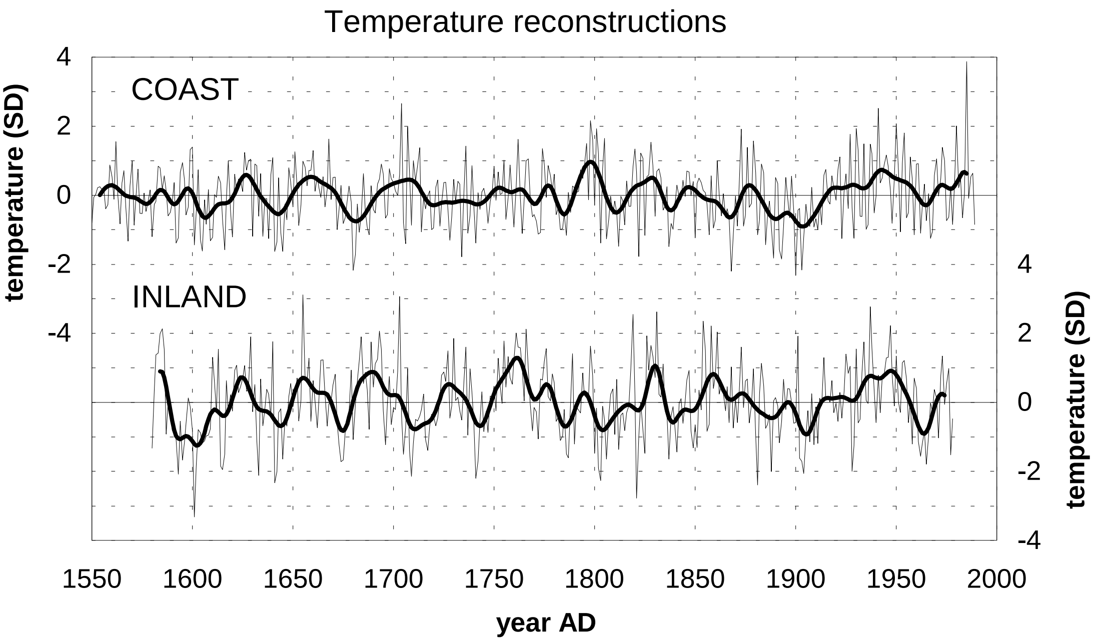

Figure 5: Two reconstructions of northern Fennoscandian July-August temperatures, displayed as standard deviations SD from the mean of AD 1875-1976. Coast: Forfjorddalen-Stonglandseidet mean temperatures AD 1550-1989 (Paper 1); 'inland': northern Fennoscandian temperatures (Briffa and Schweingruber, 1992), predicted by chronologies from Lake Inari, Lake Torneträsk, Muddus, Öst Fröstsjöåsen (62°20'N), Steigen and Lofoten/ Lødingen. The smooth curve represents 10-year low-pass filtered data.

quires a synopsis of the available northern Fennoscandian tree-ring chronologies as well as other palaeoclimate proxies, and remains a challenge for future palaeoclimate studies.

Much of the recent interest in palaeoclimatology has focused on determining the temporal limits of the 'Little Ice Age' and describing its climate character (Bradley and Jones, 1993; 1995a). In the present thesis (Paper 1) the lowest temperatures were reconstructed for the AD 1450s, 1540s, ~1605, ~1640, ~1680, ~1810 and 1880-1910. Thus, the summers of the 17th century, which is regarded as the most severe part of the 'Little Ice Age' (Bradley and Jones, 1993), experienced three strong fluctuations in summer temperatures. At Lake Torneträsk, the onset of low temperatures was earlier at around AD 1570 and the three first decades of the 18th century were cooler than at the coast (Briffa *et al.*, 1992). In part, this might result from differences in the standardisation techniques. The 'regional curve standardisation' (RCS) applied at Torneträsk (Briffa *et al.*, 1992; Briffa *et al.*, 1996) accounted for more low-frequency variability than the fitting of individual curves as applied on the present material. This question must remain open until a sufficient amount of samples has been collected for the early part of the coastal chronologies in order to facilitate the application of the RCS-method.

Also, the trend in the severity of the temperature minima in the 17th century differed between the reconstructions, i.e. ascending in northern Sweden and Forfjorddalen, but descending at Stonglandseidet. Final conclusions about climate severity and interdecadal trends during this period of the ‘Little Ice Age’ must take into account the effect of the proposed logging activity in Forfjorddalen and climate-induced population dynamics. This demonstrates that temperature reconstructions should not be based on single tree-ring chronologies, only.

An amelioration of growth and climate comparable to the 20th century’s occurred from AD 1470-1540 as shown by the Forfjorddalen chronology. This feature is found also in northern Sweden (Briffa *et al.*, 1992), eastern Norway (Kalela-Brundin, 1999) and western Europe (Briffa *et al.*, 1999). Although the Forfjorddalen chronology has no independent replicate at the coast of northern Norway, and in spite of the signs of human impact on pine growth at this locality in later times, this signal may be considered as real and as a European-scale phenomenon. On the other hand, due to the limitations of tree rings regarding the expressed low-frequency variability (Briffa *et al.*, 1996), no conclusions can be made on the absolute temperatures of this period in relation to the 20th century mean. For instance, Bradley and Jones (1995b) offer two alternatives, with the first showing temperatures comparable to the present mean and the second showing the period AD 1470-1540 as an interruption of a general cooling trend towards the 17th century.

FUTURE STUDIES

A major task of palaeoclimatology is to provide long climate-proxy series. Samples presently at hand will yield three additional 500-year long chronologies at Forfjorddalen (FF1), Dividalen and Nordreisa. With only little sampling efforts, it is likely that the coastal chronologies can be extended back to ~ AD 1250 (Forfjorddalen) and ~ AD 1400 (Stonglandseidet), respectively. A continuous 1,500-year chronology comparable with those in northern Finland and Sweden, but exclusively based on pine and pine remains on dry forest ground, appears to be achievable in Dividalen[5]. High priority should be assigned to the construction of multi-millennial chronologies from subfossil pines in lakes of the coastal region.

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[5] In Dividalen, the present sample distribution in time resembles the state of the chronology at Lake Torneträsk in the 1980s (Bartholin and Karlén, 1983), with the oldest ring dating to AD 403, abundant material for AD 700-1000, but only few samples for the period AD 1000-1500.

Because there has been no continuous dendroclimatological research activities in Norway in the recent decades, the list of possible and required tasks is extensive:

1. Synthesis of the recently developed pine chronologies in northern Fennoscandia and detailed study of the regional variability of pine growth and climate;
2. Further search for optimal localities for dendroclimatological research in the present study area, for instance for an improved documentation and characterisation of the dendroecological zones;
3. Extending the network to the northern pine-forest outliers of Nordreisa, Kvænangen, Alta and Porsanger;
4. Systematic investigation of Nordland with its steep gradient of continentality, thereby also bridging the gap to localities in northern Trøndelag presently under investigation (Bård Solberg, University of Trondheim, pers. comm. 1999);
5. Application of more advanced spatial analyses (Fritts, 1991; Cook *et al.*, 1994) on the growing Fennoscandian tree-ring network;
6. Investigation of latewood width (Kalela-Brundin, 1999), maximum latewood density (Schweingruber *et al.*, 1988; Schweingruber, 1990) and stable isotopes (Hemming *et al.*, 1998; McCarroll and Pawellek, 1998) which in most cases are superior over ring width in terms of the chronology and climate signal;
7. Improving the climate data set by homogenising additional long climate series and application of climate data from northern Sweden and Finland;
8. Calibration of pine growth with additional important parameters of climate change such as cloudiness, wind velocity, snow cover and extreme temperatures on various timescales (daily, pentadal, seasonal, annual);
9. Assessing the signal of sea surface temperatures, the North Atlantic Oscillation, NAO (Van Loon and Rogers, 1978; D'Arrigo *et al.*, 1993; Cook *et al.*, 1998), as well as regional air pressure indices such as the zonal Hammerodde-Bodø and the meridional Bergen-Helsinki indices (Tuomenvirta *et al.*, 1998);
10. Synthesising palaeoclimate information from various tree-ring parameters, historical and other high-resolution proxy records;
11. Further analysis of site-related growth responses, in particular slope aspect and soil moisture as well as the climate-growth response of Scots pine at lake shores and in bogs, i.e. candidates for future subfossils;

12. Study on population dynamics and tree-line fluctuations of pine as sources for information about long-term climate trends (Sirén, 1961; Kullman, 1996);
13. field measurements of cambial activity, ecophysiological functions as well as local and microclimate, accompanied by phytotron experiments and phenological observations.

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PAPER 3