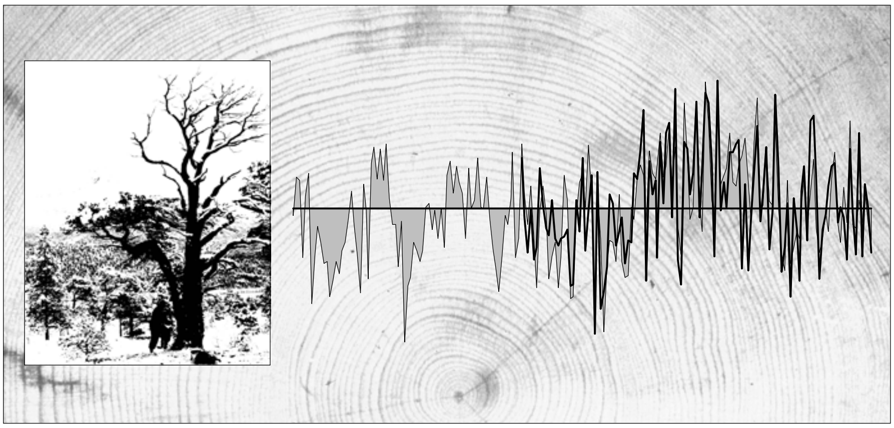
A DISSERTATION FOR THE DEGREE OF DOCTOR SCIENTIARUM

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

Andreas Joachim Kirchhefer

December 1999



Department of Biology, Faculty of Science, University of Tromsø, Norway

TABLE OF CONTENTS

LIST OF PAPERS

Paper 1: Reconstruction of summer temperature from tree rings of Scots pine, *Pinus sylvestris* L., in coastal northern Norway. *The Holocene* in press. 25 pp.

Paper 2: Pine growth and climate AD 1800-1992 along a transect across the Scandes at 69°N. Submitted to *Climatic Change*. 25 pp.

Paper 3: The influence of slope aspect on tree-ring growth of *Pinus sylvestris* L. in northern Norway and its implications for climate reconstruction.
Submitted to *Dendrochronologia*. 20 pp.

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.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, professor Karl-Dag Vorren, for enabling the present thesis by his initiative to establish the tree-ring laboratory at the Department of Biology, University of Tromsø, and supporting my study and research plans in Tromsø and northern Norway. Prof. Dr. Dieter Eckstein, University of Hamburg, willingly became my external supervisor.

The present project has been funded by the Norwegian Research Council under the programme 'Climate and Ozone', project no. 107733/720, during 1995-1998.

Of all those who contributed to the present thesis, I would like to thank in particular:

- Mauri Timonen and Håkan Grudd for generously loaning their chronologies;
- Annette Stavseth Furset and Elisabeth Cooper for field assistance in Dividalen;
- Marianne Iversen and Gunnar Kristiansen for inviting me to Imofossen;
- Victoria Jonsson for precise and reliable measurement work;
- all botany students and staff at the University of Tromsø for creating a pleasant working atmosphere.

Sampling in the Nordreisa National Park was made possible by permission of the State County Governor's Office of Troms, Environmental Department.

Climate data were kindly provided by Eirik J. Førland, Inger Hanssen-Bauer, Stein Kristiansen and Per Øyvind Nordli at the Norwegian Meteorological Institute, Oslo.

The collaboration in the FOREST-project (Forest Response to Environmental Stress at Timberlines), contract no. ENV4-CT95-0063, led to fruitful discussions and, through the dendrochronological workshop at the University of Marseille, strongly influenced the methods and results of the present thesis.

Markus Lindholm, Mauri Timonen, Reinhard Mook and Elisabeth Cooper gave critical and encouraging comments on the three manuscripts.

My warmest thanks to Sabine Cochrane for language consultation and all support during the writing process.

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).

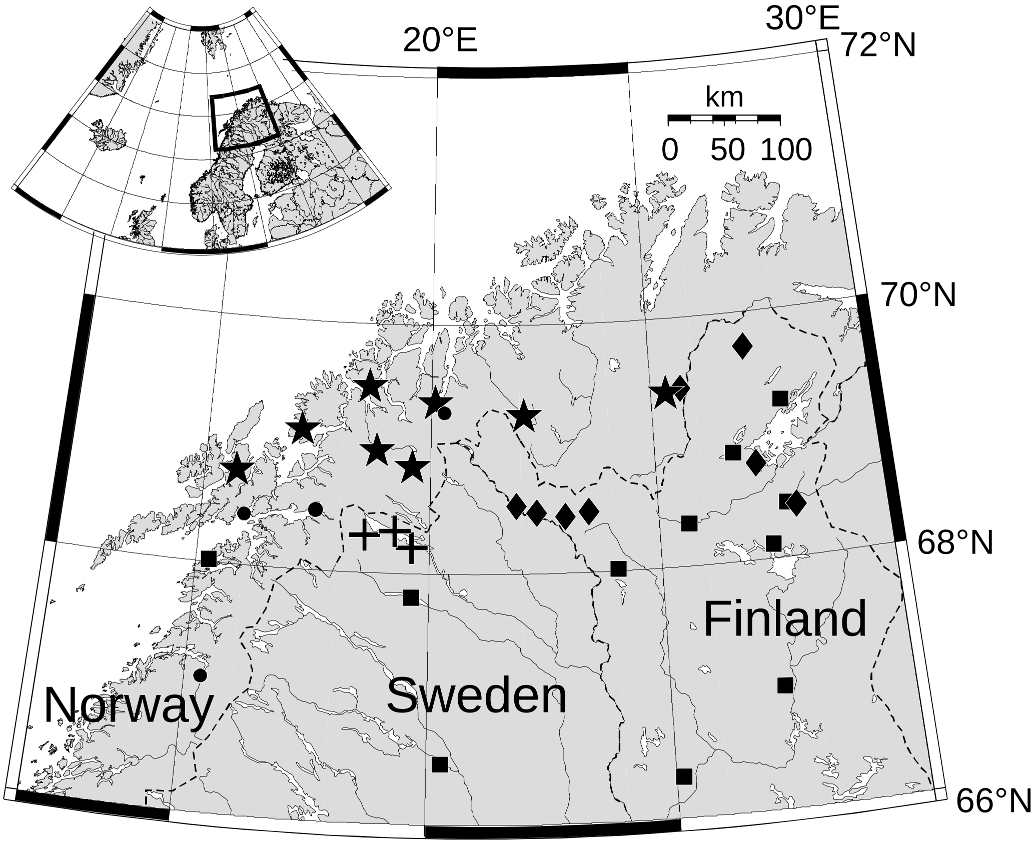


Figure 1: Map of Fennoscandia north of 66°N showing the location of tree-ring chronologies. Crosses: Lake Torneträsk localities (Bartholin and Karlén, 1983), dots: tree-ring density chronologies in northern Norway (Schweingruber, 1985; International Tree-Ring Data Bank), squares: tree-ring network analysed 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.

---

[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).

---

[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

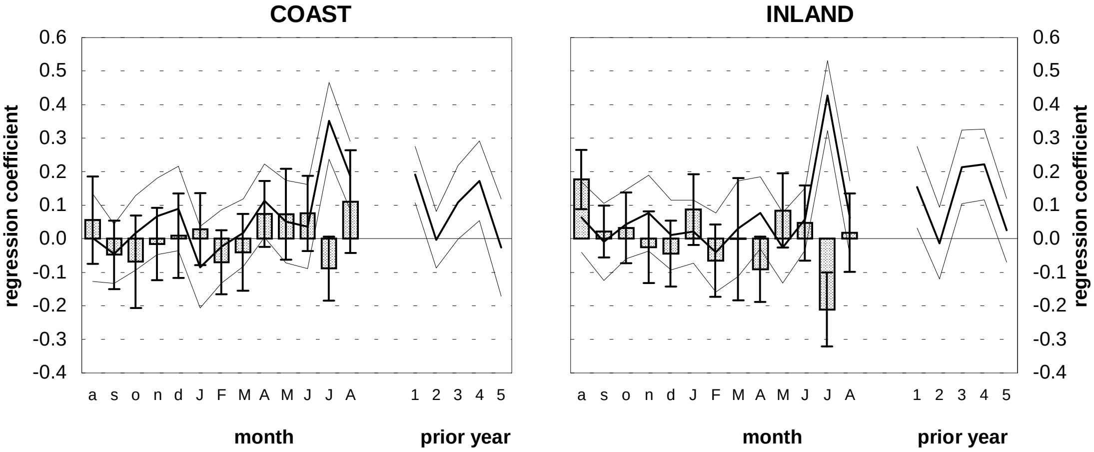


Figure 2: Climate-growth response functions computed from the regional climate series and the first principal components of the ARSTAN tree-ring chronologies for the coastal (Forfjorddalen, Stonglandseidet, Vikran, Målselvdalen) and the inland region (Dividalen, Skibotndalen, Nordreisa National Park, 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

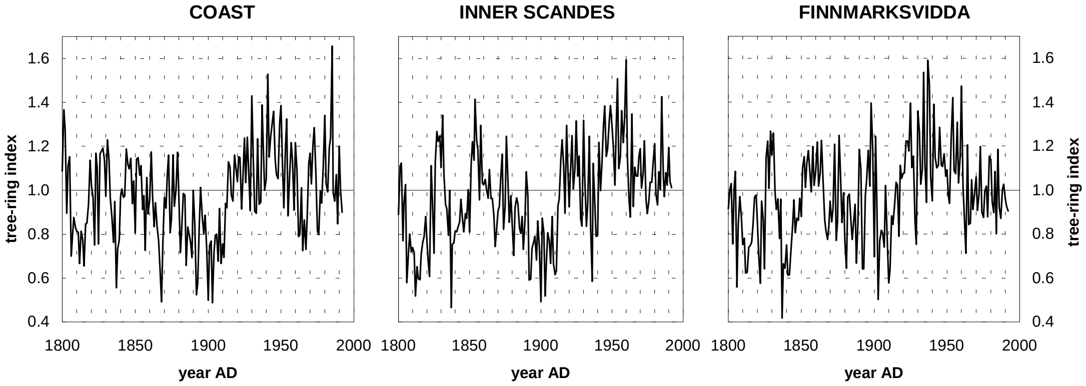


Figure 3: Mean growth AD 1800-1992 of the three dendroecological zones in northern Norway, computed from the ARSTAN chronologies. Coast: Forfjorddalen, Stonglandseidet and Vikran; Inner Scandes: Målselvdalen, Dividalen and Skibotn; Finnmarksvidda: Nordreisa and Karasjok (Paper 2).

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.

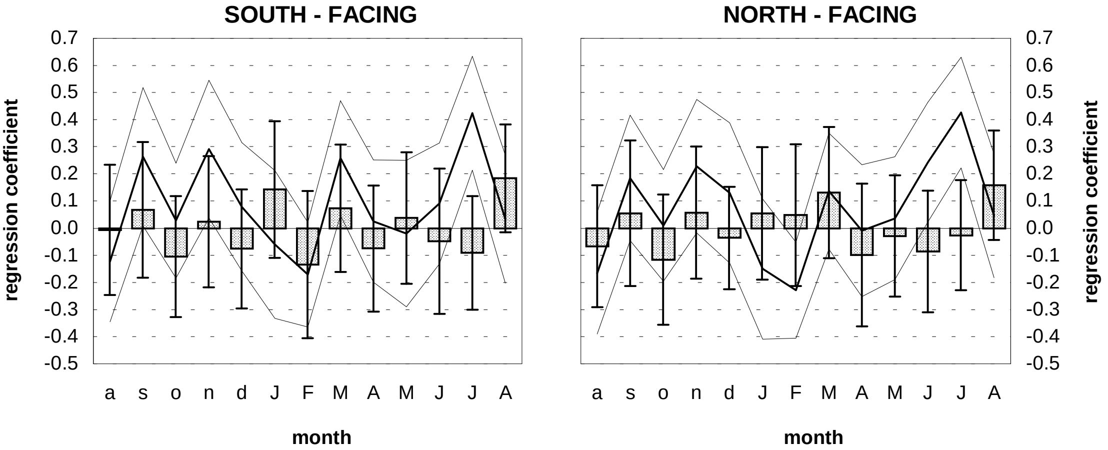


Figure 4: Climate-growth response functions for the south- and north-facing slopes in the inner Scandes, computed from the Bardufoss-Dividalen climate mean 1947-1992 and slope-mean chronologies (Table 3 in Paper 3). Regression coefficients for mean temperature (lines) and precipitation (bars) of previous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

---

[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-

---

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

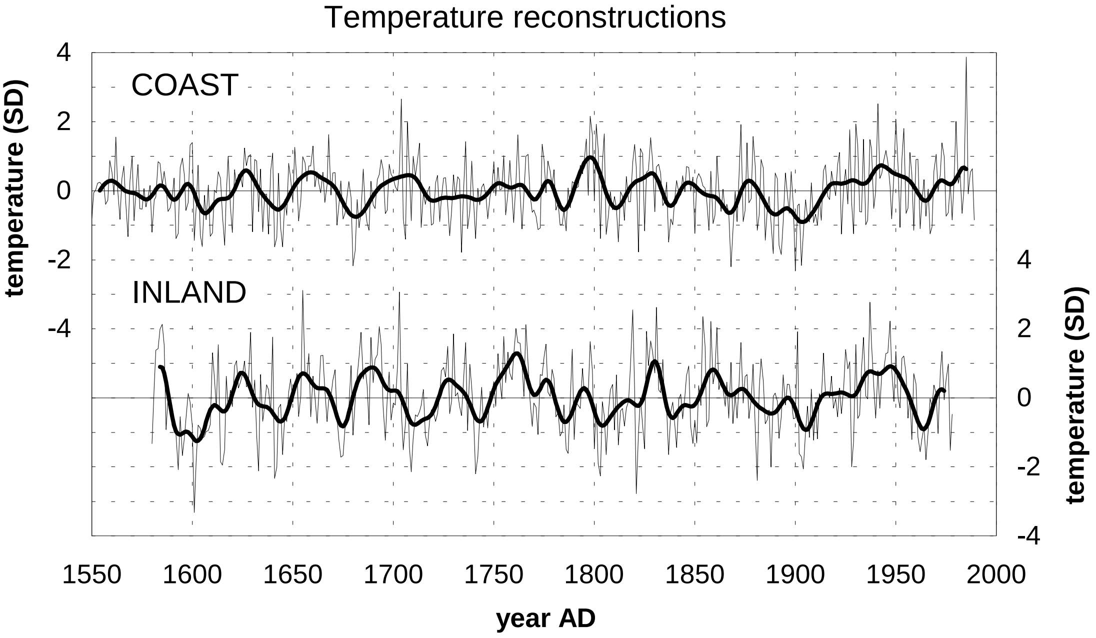


Figure 5: Two reconstructions of northern Fennoscandian July-August temperatures, displayed as standard deviations SD from the mean of AD 1875-1976. Coast: Forfjorddalen-Stonglandseidet mean temperatures AD 1550-1989 (Paper 1); 'inland': northern Fennoscandian temperatures (Briffa and Schweingruber, 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.

---

[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.

REFERENCES

Aandstad, S. 1934: Untersuchungen über das Dickenwachstum der Kiefer in Solør, Norwegen. *Nyt Magazin for Naturvidenskaberne* 74, 121-53.

— 1938: Die Jahresringbreiten der Kiefer und die Zeitbestimmung älterer Gebäude in Solør im östlichen Norwegen. *Nytt Magasin for Naturvitenskapene* 78, 201-26.

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

— 1960: Daterte årringer i furu fra Solør (Dated growth rings in Scots pine in Solør, E. Norway). *Blyttia* 18, 49-67.

— 1980: Dendrokronologisk tidfesting av Gjerdrumsloftet og Stemsrudstua på Glomdals-museet i Elverum. *Blyttia* 38, 23-36.

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

Ballantyne, C.K. 1990: The Holocene glacial history of Lyngshalvøya, northern Norway: chronology and climatic implications. *Boreas* 19, 93-117.

Barnekow, L. 1999: Holocene tree-line dynamics and inferred climatic changes in the Abisko area, northern Sweden, based on macrofossil and pollen records. *The Holocene* 9(3), 253-65.

Bartholin, T.S. 1987: Dendrochronology in Sweden. *Annales Academiae Scientiarum Fennicae A III* 145, 79-88.

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

Berglund, B.E., Barnekow, L., Hammarlund, D., Sandgren, P. and **Snowball, I.F.** 1996: Holocene forest dynamics and climate changes in the Abisko area, northern Sweden - the Sonesson model of vegetation history reconsidered and confirmed. In Karlsson, P.S. and Callaghan, T.V., editors, *Plant ecology in the subarctic Swedish Lapland*. Copenhagen: Munksgaard International Publishers. *Ecological Bulletins* 45, 15-30.

Boman, A. 1927: Tutkimuksia männyn paksuuskasvun monivoitisista vaihteluista Suomen eteläosista kerätyn aineiston perusteella (Über vieljährige Schwankungen im Dickenwachstum der Kiefer, *Pinus sylvestris*). *Acta Forestalia Fennica* 32, 177+54.

Bonde, N. 1994: De norske vikingeskibsgraves alder. Et vellykket norsk-dansk forskningsprosjekt. *Nationalmuseets arbejdsmark* 1994, 128-48.

Bonde, N. and **Christensen, K.** 1993: Dendrochronological dating of the Viking Age ship burials at Oseberg, Gokstad and Tune, Norway. *Antiquity* 67, 575-83.

Bradley, R.S. 1999: *Paleoclimatology: Reconstructing Climates of the Quaternary*. San Diego: Academic Press, 2nd ed. *International geophysics series* 68, 613 pp.

Bradley, R.S. and **Jones, P.D.** 1993: 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* 3(4), 367-76.

— editors 1995a: *Climate Since A.D. 1500.* London: Routledge, 2nd rev. ed., 706 pp.

Bradley, R.S. and **Jones, P.D.** 1995b: Recent developments in studies of climate since A.D. 1500. In Bradley, R.S. and Jones, P.D., editors, *Climate Since A.D. 1500*. London: Routledge, 2nd rev. ed., pp. 666-79.

Brandt, N. 1958: *Årringundersøkelser i Osloområdet*. Master thesis, University of Oslo, 68 pp.

— 1975: Årringundersøkelser på furu (*Pinus silvestris*). Metode og anvendelse. *Reports of the Norwegian Forest Research Institute* 32, 235-335.

Briffa, K.R., Bartholin, T.S., Eckstein, D., Jones, P.D., Karlén, W., Schweingruber, F.H. and **Zetterberg, P.** 1990: A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346, 434-9.

Briffa, K.R. and **Jones, P.D.** 1993: Global surface air temperature variations during the twentieth century: Part 2, implications for large-scale high-frequency palaeoclimatic studies. *The Holocene* 3(1), 77-88.

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

Briffa, K.R., Jones, P.D., Pilcher, J.R. and **Hughes, M.K.** 1988a: Reconstructing summer temperatures in northern Fennoscandia back to A.D. 1700 using tree-ring data from Scots pine. *Arctic and Alpine Research* 20(4), 385-94.

Briffa, K.R., Jones, P.D. and **Schweingruber, F.H.** 1988b: Summer temperature patterns over Europe: A reconstruction from 1750 A.D. based on maximum latewood density indices of conifers. *Quaternary Research* 30, 36-52.

Briffa, K.R., Jones, P.D., Schweingruber, F.H., Karlén, W. and **Shiyatov, S.G.** 1996: Tree-ring variables as proxy-climate indicators: problems with low-frequency signals. In Jones, P.D., Bradley, R.S. and Jouzel, J., editors, *Climate variations and forcing mechanisms of the last 2000 years*. Berlin: Springer-Verlag. *NATO ASI Series* I 41, 9-41.

Briffa, K.R., Jones, P.D., Vogel, R.B., Schweingruber, F.H., Baillie, M.G.L., Shiyatov, S.G. and **Vaganov, E.A.** 1999: European tree rings and climate in the 16th century. *Climatic Change* 43, 151-68.

Briffa, K.R. and **Schweingruber, F.H.** 1992: Recent dendroclimatic evidence of northern and central European summer temperatures. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. London: Routledge, pp. 366-92.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Harris, I.C., Shiyatov, S.G., Vaganov, E.A. and **Grudd, H.** 1998a: Trees tell of past climates: but are they speaking less clearly today? *Philosophical Transactions of the Royal Society of London* B 353, 65-73.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Shiyatov, S.G. and **Vaganov, E.A.** 1998b: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391, 678-82.

Briffa, K.R., Wigley, T.M.L., Jones, P.D., Pilcher, J.R. and **Hughes, M.K.** 1986: *The reconstruction of past circulation patterns over Europe using tree-ring data, Final Report to the Commission of European Communities* Contract No. CL.111.UK(H), 107 pp.

Bräker, O.U. 1981: Der Alterstrend bei Jahrringdichten und Jahrringbreiten von Nadelhölzern und sein Ausgleich. *Mitteilungen der Forstlichen Bundesversuchsanstalt Wien* 142, 75-102.

Christensen, K. 1993: Can oak chronologies from Northern Jutland and Western Sweden be applied to dendrochronological dating of Norwegian oak timber? In Storsletten, O. and Thun, T., editors, *Dendrochronology and the investigation of buildings*. Riksantikvaren, Oslo. *Riksantikvarens Rapporter* 22, 52-8.

Christensen, K. and **Havemann, K.** 1998: Dendrochronology of oak (*Quercus* sp.) in Norway. In Griffin, K. and Selsing, L., editors, *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 59-60.

Cook, E.R. 1990: A conceptual linear aggregate model for tree rings. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 98-104.

— 1995: Temperature histories from tree rings and corals. *Climate Dynamics* 11, 211-22.

Cook, E.R. and **Briffa, K.R.** 1990: A comparison of some tree-ring standardization methods. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 153-62.

Cook, E.R., Briffa, K.R. and **Jones, P.D.** 1994: Spatial regression methods in dendroclimatology: A review and comparison of two techniques. *International Journal of Climatology* 14, 379-402.

Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A. and **Funkhouser, G.** 1995: The 'segment length course' in long tree-ring chronology development for palaeoclimatic studies. *The Holocene* 5(2), 229-37.

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

Cook, E.R., D'Arrigo, R.D. and **Briffa, K.R.** 1998: A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene* 8(1), 9-17.

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

Dahl, S.O. and **Nesje, A.** 1994: Holocene glacier fluctuations at Hardangerjøkulen, central-southern Norway: A high-resolution composite chronology from lacustrine and terrestrial deposits. *The Holocene* 4, 269-77.

— 1996: A new approach to calculating Holocene winter precipitation by combining glacier equilibrium-line altitudes and pine-tree limits: A case study from Hardangerjøkulen, central southern Norway. *The Holocene* 6, 381-98.

Damsgård, H. 1952: *Årringundersøkelser på furu fra Sørlandet og Setesdal*. Master thesis, University of Oslo.

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

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

D'Arrigo, R.D. and **Jacoby, G.C.** 1993: Secular trends in high northern latitude temperature reconstructions based on tree rings. *Climatic Change* 25, 163-77.

DeGeer, E.H. 1938: Raknehaugen. *Universitetes Oldsaksamling Årbok* 1937, 27-54.

— 1939: Kubbestolen från Sauland. II. Biokronologisk datering. *Fataburen* 1939, 123-30.

Douglass, A.E. 1919: *Climatic Cycles and Tree-Growth. A Study of the Annual Rings of Trees in Relation to Climate and Solar Activity*. *Carnegie Institution of Washington Publication* 289, 127 pp.

— 1928: *Climate Cycles and Tree-Growth. Volume II. A Study of the Annual Rings of Trees in Relation to Climate and Solar Activity*. *Carnegie Institution of Washington Publication* 289, Vol. II, 166 pp.

Eckstein, D. and **Bauch, J.** 1969: Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. *Forstwissenschaftliches Centralblatt* 88, 230-50.

Eide, E. 1926: Om sommervarmens innflytelse på årringbredden (Über Sommertemperatur und Dickenwachstum im Fichtenwald). *Meddelelser fra Det Norske Skogforsøksvesen* 7, 87-104.

Eide, T.O. 1955: Breden og bygda (The glacier and the countryside). *Norveg* 5, 1-42.

Eidem, P. 1943: Über Schwankungen im Dickenwachstum der Fichte (*Picea abies*) in Selbu, Norwegen. *Nytt Magasin for Naturvidenskapene* 83, 10-189.

— 1944a: Datering av gammelt bygningstømmer fra Ostbyhaug i Tydal. *Det Kongelige norske videnskabers selskabs forhandlinger* 16(26), 95-8.

— 1944b: En vekstkurve til datering av trevirke fra omegnen av Trondheim. *Det Kongelige norske videnskabers selskabs forhandlinger* 16(32), 115-7.

— 1953: Om svingninger i tykkelsesveksten hos gran (*Picea abies*) og furu (*Pinus sylvestris*) i Trøndelag (On variations in the annual ring widths in Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) in Trøndelag). *Meddelelser fra Det Norske Skogforsøksvesen* 41 (XXI.1), 1-153.

— 1955: Badstua fra Istad i Slidre - en dendrokronologisk tidfesting (Dendrochronological dating of an oust-house from Istad, Slidre, Valdres). *Blyttia* 13, 65-70.

— 1956a: Grønlistua fra Flesberg i Numedal - en dendrokronologisk tidfesting (Dendrochronological dating of Grønlistua from Flesberg, Numedal). *By og Bygd* 10, 149-54.

— 1956b: Tidfesting av gammelt bygningsmateriale fra Flesberg i Numedal (Dendrochronological dating of building material from Flesberg in Numedal, Eastern Norway). *Tidsskrift for Skogbruk* 2, 98-115.

— 1956c: Tidfesting av tømmer fra gammelstua på Søndre Gjellerud i Flesberg (Dendrochronological dating of an old cottage in Flesberg, near Kongberg). *By og Bygd* 10, 143-8.

— 1959: En grunnskala til tidfesting av trevirke fra Flesberg i Numedal (Standard tree-ring series for dating building material in Flesberg, S.E. Norway). *Blyttia* 17, 69-84.

Eiklid, O. 1952: Årring-gransking. Gran (*Picea abies*) fra Halling-Hövreslia i Gol. *Tidsskrift for Skogbruk* 60(1-2), 1-12.

Eklund, B. 1944: Ett försök att numeriskt fastställa klimatets inflytande på tallens och granens radietillväxt vid de båda finska riksskogstaxeringarna. *Norrlands Skogvårdsförbunds Tidskrift*, 193-226.

— 1954: Årringbreddens klimatisk betingade variation hos tall och gran inom norra Sverige åren 1900-1944 (Variations in the width of the annual rings in pine and spruce due to climatic conditions in northern Sweden during the years 1900-1944). *Meddelanden från Statens Skogsforskningsinstitut* 44(8), 1-150.

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

Eronen, M. and **Huttunen, P.** 1987: Radiocarbon-dated subfossil pines from Finnish Lapland. *Geografiska Annaler, Series A, Physical geography* 69A(2), 297-304.

Eronen, M., Hyvärinen, H. and **Zetterberg, P.** 1999: Holocene humidity changes in northern Finnish Lapland inferred from lake sediments and submerged Scots pines dated by tree rings. *The Holocene* 9(5), 569-80.

Eronen, M., Lindholm, M. and **Zetterberg, P.** 1994: Extracting paleoclimatic information from pine tree-rings in Finland. In Frenzel, B., editor, *Climate trends and anomalies in Europe 1675-1715*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 13, 43-50.

Eronen, M. and **Zetterberg, P.** 1996: Expanding megafossil-data on Holocene changes at the polar/alpine pine limit in northern Fennoscandia. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 128-34.

Fjærvoll, K. 1961: *Korndyrkinga i Hålogaland i Gammal Tid, 1500- og 1600-åra*. Tilleggsbok til Håløygminne. Svorkmo Prenteverk. 127 pp.

Frich, P., Alexandersson, H., Ashcroft, J., Dahlström, B., Demarée, G.R., Drebs, A., Engelen, A.F.V.v., Førland, E.J., Hanssen-Bauer, I., Heino, R., Jónsson, T., Jónasson, K., Keegan, L., Nordli, P.Ø., Schmith, T., Steffensen, P., Tuomenvirta, H. and **Tveito, O.E.** 1996: *North Atlantic Climatological Dataset (NACD Version 1) - Final Report*. Danish Meteorological Institute, Copenhagen, *Scientific Report* 96-1, 47 pp.

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

— 1991: *Reconstructing Large-Scale Climatic Patterns From Tree-Ring Data. A Diagnostic Analysis*. Tucson: University of Arizona Press, 286 pp.

Førland, E.J. and **Nordli, P.Ø.** 1993: *Autokorrelasjon i nedbør og temperatur*. Norwegian Meteorological Institute, Oslo. *DNMI report* 11/93 klima, 47 pp.

Glad, T. 1977: *Variasjoner i atmosfærens* ^{14}*C-innhold i dette århundre målt i treprøver*. Master thesis, University of Trondheim, 117 pp.

Glad, T. and **Nydal, R.** 1982: Radial transport of ^{14}C in Norwegian pine. In Hackens, T. and Mejdahl, V., editors, *Second Nordic Conference on the Application of Scientific Methods in Archaeology*. *PACT*, pp. 45-52.

Griffin, K. and **Selsing, L., editors** 1998: *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 108 pp.

Grissino-Mayer, H.D. and **Fritts, H.C.** 1997: The International Tree-Ring Data Bank: an enhanced global database serving the global scientific community. *The Holocene* 7(2), 235-8.

Grootes, P.M. 1995: Ice cores as archives of decade-to-century climate variability. In Martinson, D.G., Bryan, K., Ghil, M., Hall, M.M., Karl, T.R., Sarachik, E.S., Sorooshian, S. and Talley, L.D., editors, *Natural climate variability on decade-to-century timescales*. Washington D.C.: National Academy Press, pp. 544-54.

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

Hanssen-Bauer, I. and **Førland, E.J.** 1994: Homogenizing long Norwegian precipitation series. *Journal of Climate* 7(6), 1001-13.

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

Hemming, D.L., Switsur, V.R., Waterhouse, J.S. and **Heaton, T.H.E.** 1998: Climate variation and the stable carbon isotope composition of tree ring cellulose: an intercomparison of *Quercus robur*, *Fagus sylvatica* and *Pinus sylvestris*. *Tellus* 50B, 25-33.

Hesselmann, H. 1904: Om tallens diametertillväxt under de sista tio åren. *Meddelanden från Statens Skogsförsöksanstalt* 1904(1), 45-53.

Hirschboeck, K.K., Ni, F., Wood, M.L. and **Woodhouse, C.A.** 1996: Synoptic dendroclimatology: overview and outlook. In Dean, J.S., Meko, D.M. and Swetnam, T.W., editors, *Tree rings, environment and humanity*. *Radiocarbon*, Tucson, Arizona, pp. 205-23.

Holmes, R.L., Adams, R.K. and **Fritts, H.C.** 1986: *Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin, with procedures used in the chronology development work, including users manuals for computer programs COFECHA and ARSTAN*. Laboratory of Tree-Ring Research, University of Arizona, Tucson, *Chronology Series* VI, 182 pp.

Hughes, M.K., Kelly, P.M., Pilcher, J.R. and **LaMarche, V.C., Jr., editors** 1982: *Climate from Tree Rings*. Cambridge, London, New York, 223 pp.

Hustich, I. 1945: The radial growth of the pine at the forest limit and its dependence on the climate. *Societas Scientiarum Fennica, Commentationes Biologicae* 9(11), 1-30.

— 1956: Notes on the growth of Scotch pine in Utsjoki in northernmost Finland. *Acta Botanica Fennica* 56, 1-13.

— 1958: On the recent expansion of the Scotch Pine in northern Europe. *Fennia* 82(3), 1-25.

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

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

Hustich, I. and **Elfving, G.** 1944: Die Radialzuwachsvariationen der Waldgrenzkiefer. *Societas Scientiarum Fennica, Commentationes Biologicae* 9(8), 1-18.

Hylleberg Eriksen, O. 1994: *Dendrokronologisk undersøgelse af middelalderlige skibsvrag fra Sørenga, Oslo, Norge*. Nationalmuseets Naturvidenskabelige Undersøgelser, Copenhagen. *NNU rapport* 18/1994.

Hyvärinen, H. and **Mäkelä, E.** 1996: Parallel trends of Holocene tree-line changes and lake and mire development in northwestern Finnish Lapland. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 293-300.

Høeg, O.A. 1944: Dendrokronologi. *Viking* 8, 231-82.

— 1956a: Growth-ring research in Norway. *Tree-ring bulletin* 21, 2-15.

— 1956b: Årringmålinger og dendrokronologi i Norge. *Blyttia* 14, 41-62.

— 1958: Hva årringene forteller. *Forskningsnytt fra Norges almenvitenskapelige forskningsråd* 3, 10-3.

Innes, J.L. 1987: Dendroglaciological investigations in Norway. In Ward, R.G.W., editor, *Applications of tree-ring studies*. *British Archaeological Reports International Series* 333, pp. 107-20.

Jacoby, G.C. and **D'Arrigo, R.D.** 1995: Tree ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles* 9, 227-34.

Jalkanen, R. 1996: Needle retention chronology along a pollution gradient. In Dean, J.S., Meko, D.M. and Swetnam, T.W., editors, *Tree rings, environment and humanity*. *Radiocarbon*, Tucson, Arizona, pp. 419-246.

Jalkanen, R., Aalto, T., Innes, J.L., Kurkela, T. and **Townsend, I.** 1994: Needle retention and needle loss of Scots pine in recent decades at Thetford and Alice Holt, England. *Canadian Journal of Forest Research* 24(3), 863-7.

Johansen, S. 1995: Dendroclimatological study of *Larix gmelinii* at the forest border in the lower Kolyma River region, north-eastern Sibiria. *Gunneria* 69, 1-20.

— 1998: The origin and age of driftwood on Jan Mayen. *Polar Research* 17(2), 125-46.

— 1999: Origin of driftwood in north Norway and its relevance for transport routes of drift ice and pollution to the Barents Sea. *The Science of the Total Environment* 231, 201-25.

Johnsen, J. 1943: *Årringanalyser på trevirke fra Raknehaugen*. Master thesis, University of Oslo, 100 pp.

Jones, P.D. and **Bradley, R.S.** 1992: Climatic variations in the longest instrumental records. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. London: Routledge, pp. 246-68.

Jones, P.D. and **Briffa, K.R.** 1992: Global surface air temperature variations during the twentieth century: Part 1, Spatial, temporal and seasonal details. *The Holocene* 2(2), 165-79.

Jones, P.D., Briffa, K.R., Barnett, T.P. and **Tett, S.F.B.** 1998: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *The Holocene* 8(4), 455-71.

Junttila, O. 1986: Effects of temperature on shoot growth in northern provenances of *Pinus sylvestris* L. *Tree Physiology* 1, 185-92.

Junttila, O. and **Heide, O.M.** 1981: Shoot and needle growth in *Pinus sylvestris* as related to temperature in northern Fennoscandia. *Forest Science* 27(3), 423-30.

Kalela-Brundin, M. 1996: The narrow ring of 1874 in tree-ring series of Scots pine (*Pinus sylvestris* L.) in southwest Norway - a possible result of volcanic eruptions in Iceland. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 107-18.

— 1999: Climatic information from tree-rings of *Pinus sylvestris* L. and a reconstruction of summer temperatures back to AD 1500 in Femundsmarka, eastern Norway using partial least squares regression (PLS) analysis. *The Holocene* 9(1), 59-77.

Karlén, W. 1988: Scandinavian glacial and climatic fluctuations during the Holocene. *Quaternary Science Reviews* 7(2), 199-209.

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

Kierulf, T. 1936: Hvad årringene kan fortelle. *Tidsskrift for Skogbruk* 44(11), 279-84.

Kirchhefer, A.J. 1992: *Der Einfluss des Standorts auf die Jahrringe der Kiefer, Pinus sylvestris L., und Birke, Betula pubescens, in Nordnorwegen*. Master thesis, Westfälische Wilhelms-Universität, Münster, Germany, 134 pp.

— 1996: A dendrochronological study on the effect of climate, site, and insect outbreaks on the growth of *Betula pubescens* coll. in northern Norway. *Palaeoclimate Research* 20, 93-106.

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

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

Kolmodin, G. 1923: Tillväxtundersökningar i Norra Dalarna. *Svenska Skogsvårdsföreningens Tidskrift* 1923, Serien A, 1-35.

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

Kullman, L. 1989: Tree-limit history during the Holocene in the Scandes mountains, Sweden, inferred from subfossil wood. *Review of Palaeobotany and Palynology* 58, 163-71.

— 1996: Structural population dynamics of pine (*Pinus sylvestris* L.) during the past 500 years close to the tree-limit in northern Sweden. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 75-92.

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

Laitakari, E. 1920: Tutkimuksia sääsuhteiden vaikutuksesta männyn pituus- ja paksuuskasvuun (Untersuchungen über die Einwirkung der Witterungsverhältnisse auf den Längen- und Dickenwachstum der Kiefer, *Pinus sylvestris*). *Acta Forestalia Fennica* 17(1), 1-57.

Larson, P.R. 1994: *The Vascular Cambium. Development and Structure*. Berlin: Springer-Verlag. *Springer Series in Wood Science*, 725 pp.

Lauritzen, S.-E. and **Lundberg, J.** 1999a: Calibration of the speleothem delta function: an absolute temperature record for the Holocene in northern Norway. *The Holocene* 9(6), 659-69.

— 1999b: Speleothems and climate: a special issue of *The Holocene*. *The Holocene* 9(6), 643-7.

Lindholm, M. 1996: *Reconstructions of past climate from ring-width chronologies of Scots pine (Pinus sylvestris L.) at the northern forest limit in Fennoscandia*. PhD thesis, University of Joensuu, *Publications in Sciences* 40, 169 pp.

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

Lindholm, M., Meriläinen, J., Eronen, M. and **Zetterberg, P.** 1996a: Summer temperatures reconstructed from tree-rings of pine in northern Lapland. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 84-92.

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

Ljunes, B. and **Nesdal, O.** 1954: Årringstudier i frukttre (Growth ring studies in fruit trees). The Institute of Pomology and Fruit Industry at the Agricultural College of Norway. *Report* 33, 131-69.

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

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

Matthews, J.A. 1976: 'Little Ice Age' palaeotemperatures from high altitude tree growth in S. Norway. *Nature* 264, 243-5.

— 1977: Glacier and climatic fluctuations inferred from tree-growth variations over the last 250 years, central southern Norway. *Boreas* 6, 1-24.

McCarroll, D. and **Pawellek, F.** 1998: Stable carbon isotope ratios of latewood cellulose in *Pinus sylvestris* from northern Finland: variability and signal strength. *The Holocene* 8, 693-702.

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

— 1962: Temperature and tree growth near the northern timberline. In Kozlowski, T.T., editor, *Tree growth*. New York: Ronald Press, pp. 265-74.

Millar, A. 1980: Annual rings of birch (*Betula pubescens* ssp. *tortuosa* Ledeb., Nyman), climate and defoliation. *Merlewood Research and Development Paper* 77, 1-23.

Mork, E. 1926: Våre viktigste skogtrærs anatomiske bygning. *Nytt Magasin for Naturvitenskapene* 64.

Mork, E. 1941: Om sambandet mellom temperatur og vekst. Undersøkelser av de daglige variasjoner i granens høydetilvekst (Über den Zusammenhang zwischen Temperatur und Wachstum. Untersuchungen der täglichen Variationen des Höhenzuwachses). *Meddelelser fra Det Norske Skogforsøksvesen* 27, 1-89.

— 1942: Trærnes frøsetting. *Skogbrukeren* 16(22), 197-8.

— 1946: *Vedantomi*. Oslo: Johan Grundt Tanum, 26 pl., 65 pp.

— 1957: Om frøkvalitet og frøproduksjon hos furu i Hirkjølen (Seed quality and seed production for Scots pine at Hirkjølen). *Meddelelser fra Det Norske Skogforsøksvesen* 14.

— 1960: Om sambandet mellom temperatur, toppskuddtilvekst og årringens vekst og forveding hos gran (*Picea abies* (L.) Karst.) (On the relationship between temperature, lea-ding shoot increment and the growth and lignification of the annual ring in Norway spruce (*Picea abies* (L.) Karst.). *Meddelelser fra Det Norske Skogforsøksvesen* 16(53), 227-61.

Mosley-Thompson, E., Thompson, L.G., Dai, J., Davis, M. and **Lin, P.N.** 1996: Climate of the last 500 years: High resolution ice core records. *Quaternary Science Reviews* 12, 419-30.

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

Nordli, P.Ø. 1997: *Homogenitetstesting av norske temperaturseriar - ajourført 2. utgåve*. Norwegian Meteorological Institute, Oslo. *DNMI report* 29/97 klima, 43 pp.

Ogilvie, A.E.J. 1992: Documentary evidence for changes in the climate of Iceland, A.D. 1500-1800. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. London: Routledge, pp. 92-117.

Olander, H., Birks, H.J.B., Korhola, A. and **Blom, T.** 1999: An expanded calibration model for inferring lakewater and air temperatures from fossil chironomid assemblages in northern Fennoscandia. *The Holocene* 9(3), 279-94.

Ording, A. 1941a: Skoghistoriske analyser fra Raknehaugen (Forest historical analyses from Raknehaugen). *Meddelelser fra Det Norske Skogforsøksvesen* 27, 19-130.

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

Ottestad, P. 1942: On periodical variations in the yield of the great sea fisheries and the possibility of establishing yield prognoses. *Report on Norwegian Fishery and Marine Investigations* VII(5), 1-11.

— 1960: Forecasting the annual yield in sea fisheries. *Nature* 185, 183.

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

Parker, D.E., Jones, P.D., Folland, C.K. and **Bevan, A.** 1994: Interdecadal changes of surface temperature since the late nineteenth century. *Journal of Geophysical Research* 99, 14373-99.

Pedersen, E.S. and **Kalela-Brundin, M.** 1998: Utvalgte år i en årringkurve fra Suldal, Rogaland, korrelert med historiske klimadata. In Griffin, K. and Selsing, L., editors, *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 41-51.

Pfister, C., Luterbach, J., Schwarz-Zanetti, G. and **Wegmann, M.** 1998: Winter air temperature variations in western Europe during the Early and High Middle Ages (AD 750-1300). *The Holocene* 8(5), 535-52.

Rind, D. and **Overpeck, J.** 1993: Hypothesised causes of decadal-to-century scale climate variability: climate model results. *Quaternary Science Reviews* 12, 357-74.

Romell, L.-G. 1925: Växttidsundersökningar på tall och gran. *Meddelanden från Statens Skogsförsöksanstalt* 22, 45-116.

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

— 1945: En vurdering av anvendte arbeidsmetoder innen trekronologi og årringanalyse. *Meddelelser fra Det Norske Skogforsøksvesen* 9(32).

— 1955: Klimapregede detaljer i enkeltårringene. Det norske videnskaps-akademi i Oslo. *Årbok 1954*, 28-29.

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

Santer, B.D., Wigley, T.M.L., Barnett, T.P. and **Anyamba, E.** 1996: Detection of climate change and attribution of causes. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., editors, *Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 407-43.

Sarachik, E.S., Winton, M. and **Yin, F.L.** 1996: Mechanisms for decadal-to-centennial climate variability. In Anderson, D.L.T. and Willebrand, J., editors, *Decadal climate variability: dynamics and predictability*. Berlin: Springer. *NATO ASI series* I 44, 158-210.

Schimel, D., Alves, D., Enting, I., Heimann, M., Joos, F., Raynaud, D., Wigley, T.M.L., Prather, M., Derwent, R., Ehhalt, D., Fraser, P., Sanhueza, E., Zhou, X., Jonas, P., Charlson, R., Rodhe, H., Sadasivan, S., Shine, K.P., Fouquart, Y., Ramaswamy, V., Solomon, S., Srinivasan, J., Albritton, D., Derwent, R., Isaksen, I., Lal, M. and **Wuebbles, D.** 1996: Radiative forcing of climate change. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., editors, *Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 65-131.

Schove, D.J. 1950: Tree rings and summer temperatures, A.D. 1501-1930. *The Scottish Geographical Magazine* 66(1), 37-42.

— 1954: Summer temperatures and tree-rings in North-Scandinavia A.D. 1461-1950. *Geografiska Annaler* 36(1).

Schulman, E. 1944: Tree-ring work in Scandinavia. *Tree-ring bulletin* 11(1), 2-6.

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

— 1990: Radiodensitometry. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 55-63.

Schweingruber, F.H., Bartholin, T.S., Schär, E. and **Briffa, K.R.** 1988: Radiodensitometric-dendoclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). *Boreas* 17, 559-66.

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

Schweingruber, F.H., Briffa, K.R. and **Jones, P.D.** 1991: Yearly maps of summer temperatures in Western Europe from A.D. 1750 to 1975 and Western North America from 1600 to 1982 - results of a radiodensitometrical study on tree rings. *Vegetatio* 92, 5-71.

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

Sear, C.B., Kelly, P.M., Jones, P.D. and **Goodess, C.M.** 1987: Global surface temperature responses to major volcanic eruptions. *Nature* 330, 365-7.

Sheppard, P.R. 1991: Identifying low-frequency tree-ring variation. *Tree-ring bulletin* 51, 29-38.

Sirén, G. 1961: Skogsgränstallen som indikator för klimatfluktuationerna i norra Fenno-skandien under historisk tid. *Communicationes Instituti Forestalis Fenniae* 54(2), 1-66.

— 1963: Tree rings and climate forecasts, *New Scientist*, pp. 18-20.

Sirén, G. and **Hari, P.** 1971: Coinciding periodicity in recent tree rings and glacial clay sediments. *Reports from the Kevo Subarctic Research Station* 8, 155-7.

Skoglund, T. 1993: *Klimarespons hos kvitgran (Picea glauca (Moench) Voss) ved tregrensen i Brooks Range, Alaska*. Master thesis, University of Tromsø, 56 pp.

Skoglund, T. and **Odasz, A.M.** 1998: Klimarespons hos kvitgran, *Picea glauca*, ved subarktisk tregrense i Brooks Range, Alaska. In Griffin, K. and Selsing, L., editors, *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 29-35.

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

Snowball, I.F., Sandgren, P. and **Petterson, G.** 1999: The mineral magnetic properties of an annually laminated Holocene lake-sediment sequence in northern Sweden. *The Holocene* 9(3), 353-62.

Staschel, R. 1989: Die Kartierung von Weiserjahren als Methode der dendroökologischen Differenzierung von Baumstandorten. *Dendrochronologia* 7, 83-95.

Stokes, M.A. and **Smiley, T.L.** 1968: *An Introduction to Tree-Ring Dating*. Chicago: University of Chicago Press, 73 pp.

Storsletten, O. 1993: Dendrochronology in building investigations in Norway. In Storsletten, O. and Thun, T., editors, *Dendrochronology and the investigation of buildings*. Riksantikvaren, Oslo. *Riksantikvarens Rapporter 22*, 29-34.

Storsletten, O. and **Thun, T., editors** 1993: *Dendrochronology and the investigation of buildings*. Oslo: Riksantikvaren. *Riksantikvarens Rapporter* 22, 82 pp.

Strand, L. 1950: Undersøkelse angående den innflytelse som kvelstofftapet ved salpeterfabrikasjonen har på granens diametertilvekst (Investigations in the effect of N loss occurring under saltpetre production on the diameter increment of Norway spruce). *Meddelelser fra Det Norske Skogforsøksvesen* 11(38), 79-127.

— 1980: *Acid precipitation and regional tree ring analyses*, Oslo-Ås, *SNSF-project Internal Report* IR 73/80, 79-127.

Sørensen, Å.M. 1965: *Om årringvariasjon på furu i Ryfylket*. Master thesis, University of Oslo, 78 pp.

Tarussov, A. 1992: The Arctic from Svalbard to Severnaya Zemlya: climatic reconstructions from ice cores. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. London: Routledge, pp. 505-16.

Tett, S.F.B., Scott, P.A., Allen, M.R., Ingram, W.J. and **Mitchell, J.F.B.** 1999: Causes of twentieth-century temperature change near the Earth's surface. *Nature* 399, 569-72.

Thun, T. 1980: *Undersøkelser over anvendelsen av årringkronologier for korrelering av resent materiale fra Trøndelag, samt forsøk på dendrokronologisk korrelering av middelalder-materiale fra Borgundkaupangen i Ålesund, Møre og Romsdal, og Bryggen i Bergen*. Master thesis, University of Trondheim, 178 pp.

— 1984: Dendrochronological dating of a harbour construction in Trondheim. *Norsk geografisk Tidsskrift* 38, 19-26.

— 1987: Comparison of tree-ring chronologies from Southern-Norway. *Annales Academiae Scientiarum Fennicae A III, Geologica, geographica* 145, 89-95.

— 1998: Dendrokronologi i Norge - en historisk oversikt. In Griffin, K. and Selsing, L., editors, *Dendrokronologi i Norge*. Museum of Archaeology, Stavanger. *AmS-Varia* 32, 11-4.

Thun, T. and **Vorren, K.-D.** 1992: Trærnes årringer - klimaets fingeravtrykk. *Polarflokken* 16(1), 163-82.

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

Treter, U. 1982: Fluktuationen der Birkenbaumgrenze in Skandinavien. In Dierschke, H., editor, *Struktur und Dynamik von Wäldern*. Vaduz. *Berichte des Internationalen Symposiums der Internationalen Vereinigung für Vegetationskunde* 25, 417-31.

Tuomenvirta, H., Alexandersson, H., Drebs, A., Frich, P. and **Nordli, P.Ø.** 1998: *Trends in Nordic and Arctic extreme temperatures*. Norwegian Meteorological Institute, Oslo. *DNMI report* 13/98 klima, 37 pp.

Vaganov, E.A. 1999: Influence of snowfall and melt timing on tree growth in subarctic Eurasia. *Nature* 400, 149-51.

Van Loon, H. and **Rogers, J.C.** 1978: The seesaw in the winter temperatures between Greenland and northern Europe: Part I: General description. *Monthly Weather Review* 106, 296-310.

Vesajoki, H. and **Tornberg, M.** 1994: Outlining the climate in Finland during the pre-industrial period on the basis of documentary sources. In Frenzel, B., Pfister, C. and Gläser, B., editors, *Climatic trends and anomalies in Europe 1675-1715*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 13, 52-60.

Wallén, A. 1917: Om temperaturen og nedbördens inverkan på granens och tallens höjd- och radietillväxt å Stamnäs kronopark 1890-1914. In Skogshögskolans lärarråd, editor, *Skogshögskolan 1917: festskrift vid Skoghögskolans invigning 3 maj 1917*. Stockholm, pp. 413-27.

Wessel, P., and **Smith, W. H. F.** 1995: *The Generic Mapping Tools (GMT) version 3.0.* Technical Reference & Cookbook, SOEST/NOAA.

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

Wohlfarth, B., Holmquist, B., Cato, I. and **Linderson, H.** 1998: The climatic significance of clastic varves in the Ångermanälven Estuary, northern Sweden, AD 1860-1950. *The Holocene* 8(5), 521-34.

Zetterberg, P., Eronen, M. and **Briffa, K.R.** 1994: Evidence on climatic variability and prehistoric human activities between 165 B.C. and A.D. 1400 derived from subfossil Scots pines (*Pinus sylvestris* L.) found in a lake in Utsjoki, northernmost Finland. *Bull. Geol. Soc. Finland* 66(2), 107-24.

Zetterberg, P., Eronen, M. and **Lindholm, M.** 1996: The mid-Holocene climatic change around 3800 B.C.: tree-ring evidence from northern Fennoscandia. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 136-46.

Zumer, M. 1969a: Vekstrytme hos noen skogstrær i forskjellige høydelag (Growth rhythm of some forest trees at different altitudes). *Scientific reports from the agricultural college of Norway* 48(5), 1-31.

— 1969b: *Årringdannelse hos gran i fjellskog (Annual ring formation in mountain forest)*. Norwegian Forest Research Institute, Vollebekk. 1969, 163-84.

PAPER 1

RECONSTRUCTION OF SUMMER TEMPERATURE FROM TREE RINGS OF SCOTS PINE, *PINUS SYLVESTRIS* L., IN COASTAL NORTHERN NORWAY

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

Abstract: At the coast of northern Norway, 69°N, tree-ring chronologies from Scots pine (*Pinus sylvestris* L.) were constructed at Forfjorddalen in the Vesterålen archipelago (AD 1358-1992), Stonglandseidet on Senja (AD 1548-1994) and Vikran near Tromsø (AD 1700-1992). All chronologies reflect July-August-temperatures. At the northernmost site, Vikran, the response was more confined to July temperature, resulting in a strong tree-ring and climate signal. The chronology from a steep, south-facing slope at Stonglandseidet showed signs of drought sensitivity. At the most oceanic locality, Forfjorddalen, mild winters appear to suppress tree growth on a decadal scale. Growth variations were consistent between the three sites from AD 1700-1910 but the amount of low-frequency variability decreased towards the most oceanic site. The 17th century, the coldest period of the 'Little Ice Age', experienced three cycles of summer temperatures, with minima around AD 1605, 1640 and 1680. An extended warm period occurred around AD 1470-1540. Temperature reconstruction showed secular trends similar to those observed east of the Scandes, but differed in the magnitude and timing of the extremes. At Forfjorddalen, there was no evidence of pine regeneration from around AD 1575-1650. The latter site is likely to have been affected by logging activity in the 17th century.

Key words: Tree-rings, dendroclimatology, *Pinus sylvestris* L., temperature reconstruction, Norway

INTRODUCTION

Analyses of tree rings provide a means to extend back in time the record of climate information at high latitudes. Climate reconstructions have been obtained from circum-polar chronology networks along the northern boreal timberline (D'Arrigo and Jacoby, 1993; Schweingruber and Briffa, 1996). In Fennoscandia, an interest in forest growth and its dependence on climate arose in the early 20th century (Hesselmann, 1904; Wallén, 1917; Kolmodin, 1923; Eide, 1926). Classical dendroclimatological studies north of the Polar Circle include Erlandsson (1936), Hustich (1945) and Sirén (1961). In recent decades, studies on the climate-growth response of Scots pine have been intensified (Lindholm, 1996; Briffa *et al.*, 1998a; 1998b; Kirchhefer, 1998) and efforts have been made to complete continuous multi-millennial chronologies at the northern timberline (Briffa, 1994; Zetterberg *et al.*, 1996). In addition to being influenced by

Arctic conditions, the northern Fennoscandian climate is characterised by heat advection from the Atlantic Ocean. Fennoscandian pine chronologies recently were used in studies on past changes of North Atlantic sea surface temperatures and the North Atlantic Oscillation, NAO (D'Arrigo *et al.*, 1994; Cook *et al.*, 1998).

By comparison, little attention has been paid to the pine forests along the northern Norwegian coast. After the construction of the Steigen-Sørfold chronology (Aandstad, 1939; Ording, 1941), work did not continue until the 1980s, when five chronologies were established north of the Arctic circle (Schweingruber, 1985). In an analysis of spatial variability of tree-ring growth, those chronologies were treated as a dendro-ecological group independent of northern Finland and Sweden. The chronologies subsequently were included in reconstructions of northern Fennoscandian (Briffa *et al.*, 1988a) and western European summer temperatures (Schweingruber *et al.*, 1987; 1991; Briffa *et al.*, 1988b). It is likely that only the chronologies from Steigen-Sørfold and 'Lofoten' (Schweingruber, 1985) represent oceanic climate, while the other chronologies are obtained from climatically more continental fjord-heads. Subsequent to the discovery of, at that time, Norway's oldest pine at another oceanic locality, Forfjorddalen in the Vesterålen Archipelago, three preliminary chronologies were constructed from that site and interpreted in terms of regional climate and its socio-economic implications (Ruden, 1987; Kirchhefer and Vorren, 1995; Thun and Vorren, 1996).

The principal aims of the present study are to contribute to a more complete picture of past and present variation of tree growth and climate in northern Fennoscandia, by addressing a major gap in paleoclimatic knowledge from the northern Norwegian coast. In addition to an extended Forfjorddalen chronology, two new pine chronologies between the Lofoten-Vesterålen archipelago and Tromsø are presented. The dendroclimatic results aim to allow regional comparisons with northern Sweden (Briffa *et al.*, 1992) and northern Finland (Lindholm, 1996). It is hoped that the present results will be used to supplement existing chronologies from northern Fennoscandia in larger-scale climate reconstructions.

THE STUDY AREA

Close to the coast of Lofoten-Vesterålen and Troms, northern Norway, mountains rise straight from the sea to elevations of 500-1000 m a.s.l. These act as barriers against cool-moist Atlantic air masses, and up to 2500 mm precipitation per year is retained in

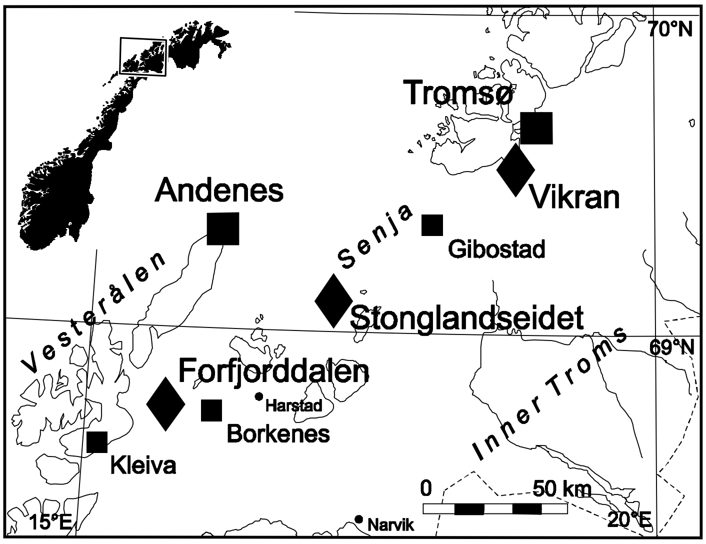


Figure 1: Map of the study area, showing the positions of the investigated sites (♦) and climate stations (■).

the alpine areas of the Lofoten-Vesterålen Archipelago. The coastal pine forests are thought to receive about 1000 mm annual precipitation, while the precipitation regime still is oceanic, with a May minimum and an October maximum (Førland, 1993). As a result of heat advection from the North Atlantic, mean July and August temperatures at the outer coast of Vesterålen and Senja (69°N) during 1961-1990 are 11°C (Aune, 1993). Temperatures near the pine forest localities in the inner part of the archipelago generally reach 12.0-12.5°C at sea level (Figure 1, Table 1). Reflecting the gradient of continentality from Andenes to Tromsø, the annual temperature amplitude is smaller and the extremes occur later at Andenes (Table 1). The westernmost isolated forests of Scots pine (*Pinus sylvestris* L.) occur at 30 km distance from the outer coastline. These forests belong to the middle boreal zone (Moen, 1998). In these areas, Scots pine dominates the canopy where soils are poor and dry, or on mire margins. Many forests are undisturbed by man, and Scots pine often reaches ages of 500 years.

Table 1: Climate parameters for selected months during the normal period 1961-1990, including the temperature difference between the warmest and coldest month (Δ) and the annual precipitation. The positions of the climate stations are given in Figure 1.

	latitude, longitude	m a.s.l.	temperature (°C)					precipitation (mm)				
			July	Aug.	Jan.	Feb.	Δ	May	July	Aug.	Oct.	annual
Andenes	69°18'N, 16°09'E	10	11.0	11.0	-2.1	-2.2	13.2	53	67	77	144	1060
Kleiva	68°39'N, 15°17'E	23	12.5	12.2	-2.1	-1.9	14.6	65	80	89	205	1397
Borkenes	68°46'N, 16°11'E	36	12.6	12.1	-2.8	-2.5	15.4	33	51	56	109	820
Gibostad	69°21'N, 18°04'E	12	12.3	11.6	-4.4	-4.2	16.7	39	62	71	119	900
Tromsø	69°39'N, 18°56'E	100	11.8	10.8	-4.4	-4.2	16.2	48	77	82	131	1031

Table 2: Site characteristics for Vikran (VIK), Stonglandseidet (STO) and Forfjorddalen (FF2): geographical position, elevation, slope aspect and inclination, sampling area and substrate.

	latitude, longitude	m a.s.l.	slope	sampling area	substrate
VIK	69°32'N, 18°44'E	80-120	5° NE	1.5km×0.5km	glacial till between mires
STO	69°05'N, 17°13'E	80-210	25° S	0.5km×0.2km	bare rock, thin cover of glacial till
FF2	68°48'N, 15°44'E	50-170	15° W	1.0km×0.2km	moraine, glacifluvial sediments, talus slope

MATERIAL AND METHODS

CHRONOLOGY BUILDING

Standard techniques were applied for sampling and chronology construction (Fritts, 1976; Cook and Kairiukstis, 1990). Two cores were taken from at least 20 dominant living Scots pines (*Pinus sylvestris*) in open-canopy stands close to the timberline. Samples from dead trees, snags, logs and stumps were collected in order to prolong the tree-ring records. The trees were selected at the driest sites available at each locality. The core surface was cut with a razor blade and polished with white chalk. Tree-ring widths were measured with a resolution of 0.001mm. In order to detect measuring errors and missing rings, the series of each radius, each tree and the mean curve were compared, i.e. cross-dated, by visually examining the cores and tree-ring curves. This process was assisted by correlation analysis (COFECHA; Holmes *et al.*, 1986). Dead wood was dated by the same means.

In order to reduce statistical noise in the chronologies and to enhance the climate signal and long-term trends, sequences containing compression wood were excluded from further analysis. Also periods of reduced growth at the beginning or end of the series were rejected. If major breaks in growth rates occurred in the middle of long series, these were split and subsequently treated as two separate series. Series shorter than ~100 years were discarded. Frequently, samples do not contain the innermost rings of the stem because of wood decay or imperfect coring. If the distance between the innermost present ring and the pith could be estimated realistically from a concentric ring pattern on the core, the number of lacking rings was deduced from the width of the innermost present rings. Knowledge of the cambial age of the tree rings assists tree-ring standardisation and improves the estimation of the tree age and population structure.

When computing the mean growth trend of all radii, it became obvious that fitting negative exponential functions would be the most appropriate way of tree-ring standardisation. Thereby, the age-related growth trend was removed, while a portion of the low-frequency variation and positive growth trends were preserved. In some cases, e.g., samples lacking a large number of innermost rings, horizontal or negative-sloping straight lines were fitted. All chronologies were computed applying bi-weight robust means. For analysis of climate-growth response, RESIDUAL chronologies were constructed after removing autocorrelation from the individual series. Finally, for climate reconstruction, ARSTAN chronologies were produced by reintroducing the pooled auto-correlation into the whitened radius-series before computing the chronologies. ARSTAN chronologies are homogeneous regarding autocorrelation and contain a maximum of low-frequency variability, and therefore are better suited for climate reconstruction than STANDARD chronologies (Cook, 1985; Holmes *et al.*, 1986; Lindholm, 1996). The expressed population signal (EPS), i.e. the number of trees required to satisfactory represent the pine population, was used to define the reliable part of the chronologies (EPS ≥85%; Wigley *et al.*, 1984; Briffa and Jones, 1990).

DENDROCLIMATIC ANALYSIS

Mean monthly temperatures were available from the meteorological stations Tromsø and Andenes back to 1868, and precipitation data back to 1868 and 1911, respectively. The Tromsø data was derived from the homogeneity tested and corrected North Atlantic Climatic Data Set, NACD (Frich *et al.*, 1996). The Andenes record shows an inhomogeneity in the year 1963 due to a relocation of the station. Visual comparison with several neighbouring stations revealed other possible inhomogeneities in the Andenes temperature series in the 1890s, 1914/15 and 1971/72. No corrections were undertaken, as they represent temperature changes far less than the year-to-year variability, and might partly reflect spatio-temporal changes in climate.

Climate-growth response was examined for the sub-periods 1875-1914, 1916-62 and 1964-92, as well as for the main period 1916-1992 and at Vikran 1875-1992. The Vikran chronologies were related to Tromsø climate, and the Stonglandseidet and Forfjorddalen chronologies to Andenes climate. RESIDUAL chronologies were compared with the climate of the previous September through the current August by bootstrap orthogonal regression (PPPbase; Till and Guiot, 1990; Guiot and Goeury, 1996). In the analyses of the ARSTAN chronologies, prior ring widths were added as explanatory variables. The procedure includes principal component analysis (PCA), thereby reducing the number of, and circumventing multi-collinearity between, the explanatory variables. Principal components were chosen by the PVP criterion (Guiot, 1985). The bootstrap routine (Efron, 1979) stabilises the regression results by repeating the analyses on a large number of subsamples of the original data set. In this study, 1000 iterations were performed. The ratio (>2) between mean correlation coefficients from the individual analyses and its standard deviations were used as a guideline for the significance of calibration and verification multiple correlation coefficients, as well as for the regression coefficients. The 90% confidence limit for the regression coefficients were derived from the 5th and 95th percentiles.

In order to determine to which extent autocorrelation has to be considered in the transfer functions, all-subsets multiple regression was performed on July-August mean temperatures as dependent variables and the ring widths of the ARSTAN chronologies as explanatory variables, including one leading ring (t-1) and three lagging rings (t+1 to t+3). Transfer functions were computed by bootstrapped orthogonal regression.

RESULTS AND DISCUSSION

AGE STRUCTURE, FOREST CONTINUITY AND CLIMATE

Tree ages increased towards the south-west of the sampling area (Figure 2, Table 3). The maximum age of Scots pine at Vikran generally did not exceed 400 years, but four individuals were determined to be 600 years old at Stonglandseidet. At Forfjorddalen, a new maximum age for Scots pine in Norway was recorded. The innermost ring extracted from a living pine at 40 cm above ground was dated to AD 1228. Adjusted for sampling height and another 10-15 rings between core and the pith, the age of the tree in 1995 was estimated to be at least 790 years. Also the tree-ring measurements of the former Norwegian ‘record holder’ (705 years, AD 1275-1979) were included in the Forfjorddalen chronology. The observed tree ages might imply that climate fluctuations have been less severe in the south-western, most oceanic part of the study area. In contrast to Vikran, abundant tree remains were available at Stonglandseidet and Forfjorddalen (Figure 2). Wood remains from the latter site are significantly older and contain longer tree-ring sequences than those from Stonglandseidet. Unlike tree age, the presence of dead wood and the number of rings preserved in it are more dependent on soil and air humidity as well as human activity and thus cannot readily be interpreted in terms of climate variability.

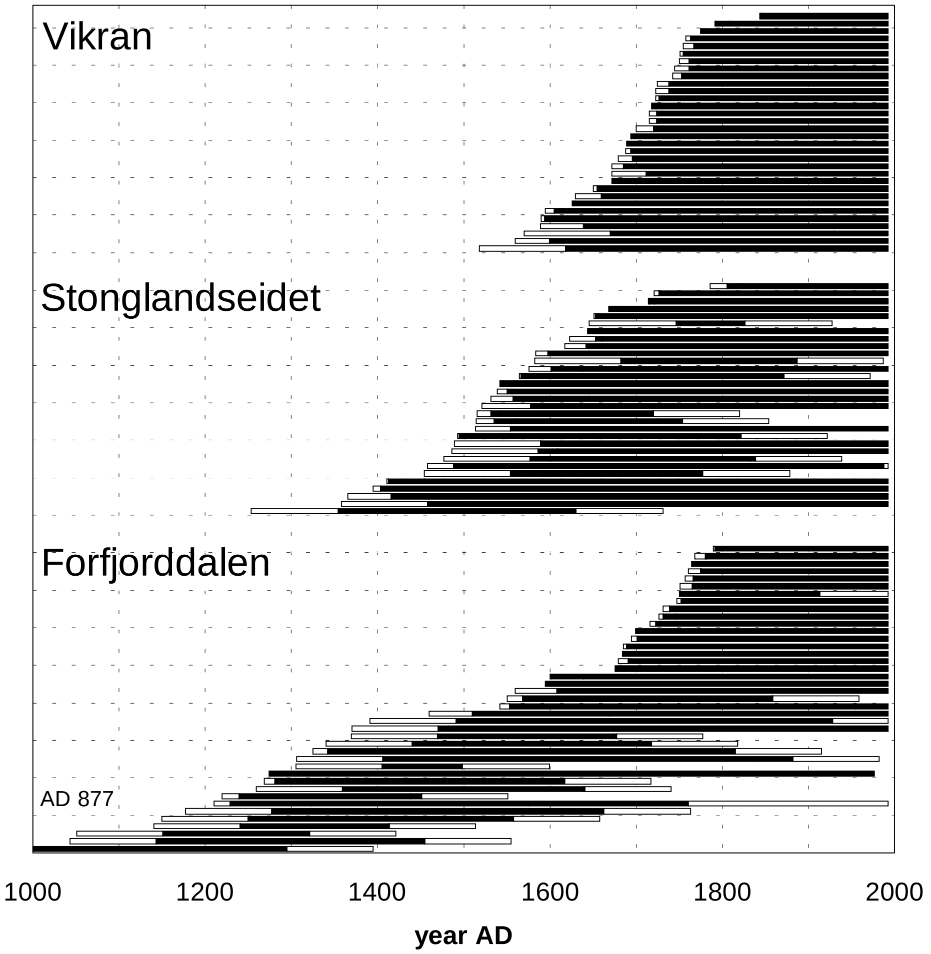


Figure 2: The life span of the trees (bars) sampled between 50 and 100 cm above ground, an estimate of the age structure of the dominant tree layer. Black: sampled rings; white: estimated rings (pith missed, decay, erosion; where no realistic estimate was possible, 100 rings were added).

At Stonglandseidet and Vikran, pine recruitment appears to be relatively even during the observed period, i.e. AD 1300-1700 and 1500-1800, respectively (Figure 2). However, at Forfjorddalen, there is strong evidence for a gap in pine recruitment between AD 1600 and 1675; i.e. ~ AD 1575-1650, when corrected for sampling height. Corresponding gaps are observed in inner Troms (Kirchhefer *in prep.*), northern Sweden (Kullman, 1996) and northern Finland (Sirén, 1961). Also at Forfjorddalen, few pines seem to originate from the years AD 1400-1570, while during the same period at Stonglandseidet, there was strong pine regeneration. This suggests logging activity, because Forfjorddalen is the only local source of timber in Vesterålen and was presumably important during the expansion phase of human settlements after the abandonment of farms during AD 1350-1500. Documents from the 17th century report that Forfjorddalen provided pine logs for construction of the church at Hadsel in AD 1639, and most likely also for the church at

Sortland AD 1675 (Guttormsen, 1990). Extensive logging of pine aged around 150 years would cause such a phenomenon.

Table 3: Chronology characteristics for Vikran (VIK), Stonglandseidet (STO) and Forfjorddalen (FF2): mean sensitivity (MS), standard deviation (SD), first order autocorrelation (r_{AR1}), variance due to autoregression (VAR_{AR}), the autoregressive model (AR n), correlation between trees (r_{TRE}), correlation between radii and chronology (r_{RM}), signal-to-noise ratio (SNR), expressed population ratio (EPS), and variance explained by the first principal component (VAR_{PC1}) (Holmes *et al.*, 1986). The common time period was set to AD 1785-1987 for all chronologies.

		FF2	STO	VIK
total time span AD		877-1994	1403-1997	1599-1992
n trees (radii)		36 (71)	29 (55)	23 (44)
mean series length (yr)		264	257	246
min./max. series length (yr)		119 / 543	94 / 539	95 / 394
ring-width median (mm)		.49	.42	.51
STANDARD chron.:	MS	.189	.169	.171
	SD	.248	.229	.255
	r_{AR1}	.533	.580	.678
	VAR_{AR}	28.2 %	38.5 %	50.9 %
RESIDUAL chron.:	AR model	AR 3	AR 3	AR 5
	MS	.205	.189	.194
	SD	.181	.163	.173
ARSTAN chron.:	MS	.188	.167	.166
	SD	.265	.234	.239
	r_{AR1}	.602	.612	.641
	VAR_{AR}	27.0 %	44.5 %	46.5 %
AD 1785-1987	n	18 (33)	17 (26)	18 (32)
detrended series:	r_{TRE}	.400	.406	.422
	r_{RM}	.647	.648	.665
	SNR	12.0	11.6	13.1
	EPS	.923	.921	.929
	VAR_{PC1}	43.0 %	45.0 %	45.6 %
	SD	.239	.243	.253
	EPS 85% since AD	1358	1548	1700
	EPS 90% since AD	1692	1563	1730
	n trees EPS 85 (90)%	9 (14)	9 (14)	8 (13)
RESIDUAL series:	r_{TRE}	.495	.434	.482
	r_{RM}	.708	.664	.690
	SNR	17.7	13.0	16.8
	EPS	.946	.929	.944
	VAR_{PC1}	52.0 %	46.3 %	50.4 %
	SD	.196	.173	.175

CHRONOLOGY CHARACTERISTICS

In accordance with the occurrence of old trees and tree remains, the longest chronology was obtained from Forfjorddalen, with one sample dating back to AD 877 (Figure 2). Both at that site and at Stonglandseidet, tree-ring series from nine trees were required for a chronology reliable at 85% expressed population signal (EPS; Table 3). The more homogeneous Vikran material required only eight trees. Assuming homogeneous statistical properties over the entire chronologies, the well-replicated series extended back to AD 1700 at Vikran, AD 1548 at Stonglandseidet, and AD 1358 at Forfjorddalen. Only these parts are presented (Figure 3), because the amplitude of the earlier, less-replicated tree-ring sequences are higher and carry the risk of misinterpretation. Due to relatively low replication in its first half, the Forfjorddalen chronology did not reach 90% EPS until 1692 (n = 14 trees; Figure 3).

The shortest series, Vikran, is the most homogeneous, with the highest correlation between trees, signal-to-noise ratio, EPS and variance in the first eigenvector (Table 3). The high amount of low-frequency variability in the Vikran chronology was expressed by the strong autocorrelation statistics. In contrast, the Forfjorddalen chronology contained the most year-to-year variability, as indicated by mean sensitivity.

The mean correlation between the STANDARD chronologies was r = 0.63 for AD 1700-1992, with the maximum value between Stonglandseidet and Vikran (r = 0.70); the mean Gleichläufigkeit, Glk (Eckstein and Bauch, 1969), AD 1700-1992 was 80.2%. The highest value was found between Forfjorddalen and Stonglandseidet (82.0%) and the lowest between Forfjorddalen and Vikran (77.7%). The figures were higher than those reported by Schweingruber (1985) for a group of three chronologies from northern Norway (Glk = 68.8%), and indicate a high climatic homogeneity of the study area, with a common dominant growth-limiting factor.

GROWTH VARIATIONS

All chronologies show above-average growth during major parts of the 20th century after 1910 (Figure 3), though there was more between-site variation than in earlier centuries. Maximum growth at Forfjorddalen and Vikran occurred during the period 1910-55. Stonglandseidet reached maximum growth somewhat later, between 1940-92. Comparably high growth rates also occurred during the 10 years from AD 1793 to 1802, and during a long, stable period AD 1475-1540. The year 1985 is conspicuous with the broadest ring since AD 1535.

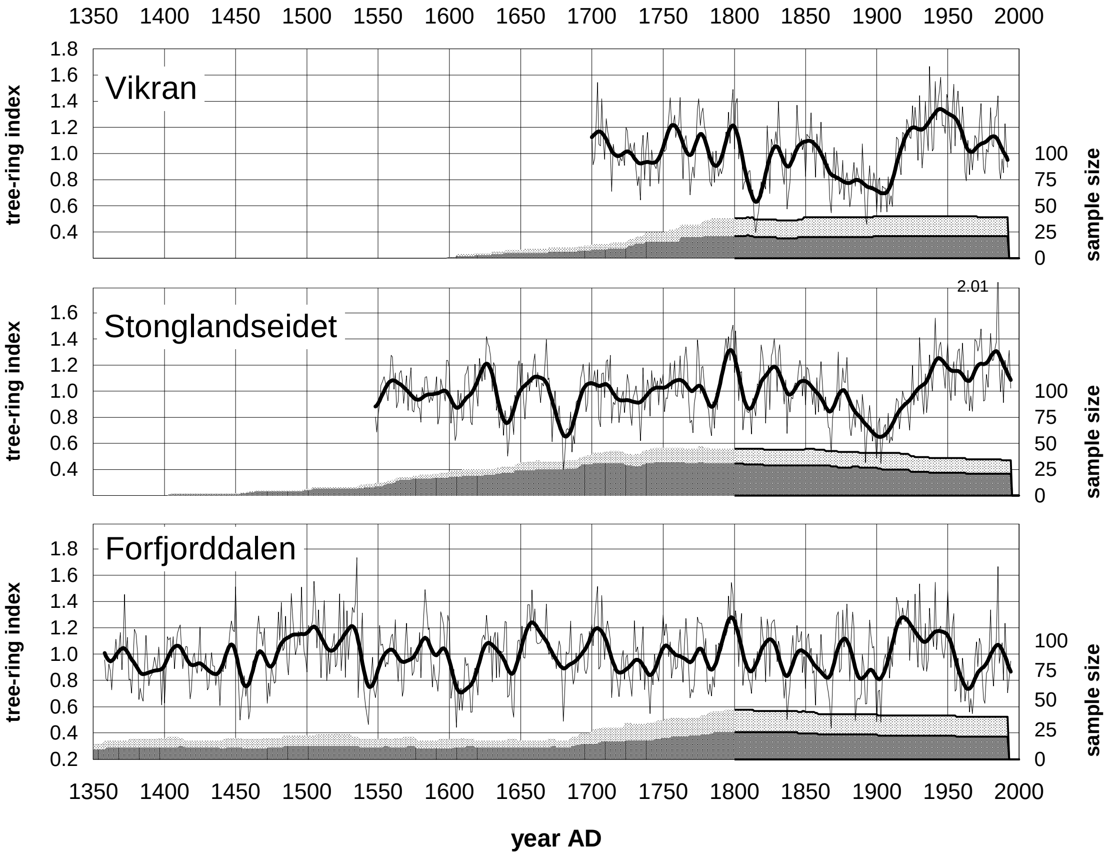


Figure 3: The STANDARD chronologies. Only those sequences comprising a minimum of eight (Vikran) or nine trees (Forfjorddalen, Stonglandseidet) are shown, thus expressing more than 85% of the population signal (EPS). The number of radii and trees included in the chronology are displayed below the chronologies. The low-frequency tree-ring variability is represented by a cubic smoothing spline with a cut-off level at 50% variability per 20 years (bold line).

In contrast to the high growth rates seen from the 1920s, during the years 1881-1910, all sites suffered from heavy growth depressions. At Vikran, growth already declined in the late 1860s, and here poor growth occurred also between AD 1805-1820. Before the relatively stable 18th century, growth depressions occurred in the AD 1450s, the 1540s and 1601-1620 in Forfjorddalen. The Stonglandseidet chronology displayed additional negative anomalies around AD 1640 and 1680. Kirchhefer and Vorren (1995) observed a lower level of tree-ring indices during the second half of the 17th century in Forfjorddalen. That chronology consisted of nine trees dated back to at least AD 1500, but included solitary-growing pines from the damp, east-facing slope. Thus the positive growth trend in the present chronology is considered to be a site-specific signal, related to site-specific climate response, age distribution of the sample trees, or the proposed disturbance logging activity.

In agreement to the long-term variability in growth rates, the narrowest tree rings occur in the 17th and 19th centuries and in the AD 1450s and 1540s (1453/59/60, 1542/43, 1605, 1641, 1680, 1837, 1868, 1892/93, 1900/03). The ten broadest rings occurred around AD 1500 (1450, 1489, 1496, 1505, 1523, 1535), in 1799 and in the 20th century (1930, 1941, 1985).

CLIMATE-GROWTH RESPONSE OF SCOTS PINE

In the present study, the most significant growth-limiting factor was July temperature (Tables 4 and 5). At Stonglandseidet and Forfjorddalen, the sensitive period was longer, and temperatures in August were also found to influence growth considerably. July precipitation was negatively correlated with growth at Vikran and Forfjorddalen, most likely due to reduced insolation and, especially at Vikran, soil cooling. The positive response to May precipitation is best interpreted as rain causing early snow-melt and soil-warming, thus enabling an early start of the vegetation period. Such precipitation effects were not seen at Stonglandseidet. This locality has a low water capacity and is likely to profit from moisture supply from late-melting snow and rainfall during June through August, while the steep south-facing slope gives relatively high temperatures.

RESIDUAL and ARSTAN chronologies displayed similar climate responses. When applying the ARSTAN versions of the Forfjorddalen and Vikran chronologies, ring widths of the lagging rings (t+1), (t+3) and (t+4) were significantly positively correlated with radial growth of the current year. At Stonglandseidet, only the rings (t+1) and (t+2) were significantly positively correlated. The length of the calibration period had a profound effect on the stability of the response functions. The shortest period, 1964-1992 (29 years), was considerably over-calibrated, as shown in the non-significance of the verification coefficients (Table 4). By extending the calibration period, the coefficients for calibration and verification approach each other and stabilise.

Previously, a predominant response to July-August temperatures was found in Forfjorddalen (Kirchhefer and Vorren, 1995; Thun and Vorren, 1996), and at Torneträsk at the eastern slope of the Scandes (Briffa *et al.*, 1990; 1992). In contrast, a short season affecting radial growth, comprising July only, is reported from inner Troms (Thun and Vorren, 1996), in earlier studies at Lake Torneträsk (Erlandsson, 1936; Bartholin and Karlén, 1983; Aniol and Eckstein, 1984; Eckstein *et al.*, 1991), and in northern Finland(Hustich and Elfving, 1944; Briffa *et al.*, 1988a). In a recent investigation, the growth response was mainly related to June-July temperatures in eight out of nine northern Finnish pine chronologies (Lindholm, 1996). These results imply that the

Table 4: Response functions based on bootstrap orthogonal regression on RESIDUAL chronologies and monthly climate data from previous September to current August. Mean bootstrap multiple correlation coefficients (×100) and their standard deviations (×100) are shown for the calibration (cal) and verification procedure (ver) (Till and Guiot, 1990). When significant at the 90% confidence level, mean bootstrap regression coefficients (plain text) and the ratio mean:standard deviation (italics) are shown for individual months. The last three columns (r temp.) show the simple correlation coefficients between tree-rings and July, August and mean July-August (JA) temperatures. Missing data is shown as (-).

	mean r		temperature								precipitation										r temp.		
	cal	ver	Sep	Oct	Dec	Jan	Mar	Jun	Jul	Aug	Sep	Oct	Dec	Jan	Feb	Mar	Apr	May	Jul	Aug	Jul	Aug	JA
VIK																							
1964 -1992	96 *±3*	25 *±28*				22 *1.9*			39 *3.2*											22 *1.6*	56	37	57
1916 -1962	89 *±4*	46 *±18*					22 *2.0*		21 *2.5*		-18 *-1.8*		26 *2.3*					20 *2.1*	-23 *-2.4*		52	36	53
1875 -1914	91 *±4*	40 *±18*			34 *3.2*			22 *2.0*		18 *1.9*						-25 *-2.4*	20 *1.9*		-18 *-1.8*		41	34	49
1916 -1992	79 *±5*	44 *±13*		-18 *-2.1*					31 *4.1*		-14 *-1.8*		17 *2.0*					20 *2.4*	-22 *-2.9*		54	35	54
1875 -1992	74 *±4*	50 *±10*		-11 *-1.8*					29 *4.3*		-11 *-2.0*	-15 *-1.9*						20 *3.6*	-20 *-3.2*		54	37	55
STO																							
1964 -1992	95 *±4*	20 *±30*							30 *2.0*												55	46	58
1916 -1962	83 *±5*	24 *±20*	-22 *-2.0*						20 *1.7*	17 *2.0*											39	41	45
1916 -1992	74 *±5*	33 *±16*							31 *4.2*	23 *3.0*		-17 *-1.8*			-15 *-1.7*					26 *2.8*	45	39	48
1875 -1992	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	48	41	51
FF2																							
1964 -1992	95 *±5*	8 *±29*												-33 *-2.0*							51	48	57
1916 -1962	85 *±5*	29 *±20*							34 *3.1*	23 *2.7*								28 *2.3*	-23 *-2.0*		55	48	58
1916 -1992	77 *±4*	42 *±13*							36 *4.7*	22 *2.7*		-20 *-2.1*						21 *2.5*	-16 *-1.8*	18 *2.1*	53	47	57
1875 -1992	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	49	46	55

western chronologies reflect a later and broader time-window (July-August) than the eastern chronologies (July, June-July). However, the dendroclimatological investigations in northern Fennoscandia cannot be directly compared, because they are based on different time periods and statistical techniques. These effects are demonstrated in the present study (Tables 4 and 5).

Table 5: Response functions for the ARSTAN chronologies. The functions include four prior rings as explanatory variables. For further explanations see Table 4.

	mean r		temperature				precipitation				prior rings				r temperature		
	cal	ver	Dec	Apr	Jul	Aug	May	Jun	Jul	Aug	t-1	t-2	t-3	t-4	Jul	Aug	JA
VIK																	
1920-1992	84	54	12	16	28				-24		14		13	18	58	32	54
	±4	*±13*	*1.8*	*2.2*	*4.4*				*-3.3*		*2.2*		*1.8*	*2.3*			
1879-1992	89	76			27	10	13		-11		21		11	25	60	35	58
	±2	*±7*			*5.6*	*1.8*	*3.8*		*-2.4*		*5.8*		*2.4*	*4.7*			
STO																	
1920-1992	81	51	18		27	19		12		22	33	12			41	25	37
	±4	*±13*	*2.0*		*3.4*	*2.7*		*1.6*		*2.2*	*4.9*	*1.6*					
1879-1992	-	-	-	-	-	-	-	-	-	-	-	-	-	-	51	40	53
FF2																	
1920-1992	84	53		12	28	18	18		-16		28		17	14	47	39	49
	±4	*±14*		*1.7*	*3.2*	*2.6*	*2.3*		*-1.8*		*3.2*		*2.3*	*2.4*			
1879-1992	-	-	-	-	-	-	-	-	-	-	-	-	-	-	47	41	51

CALIBRATION OF TRANSFER FUNCTIONS

Based on the response-function analyses, July-August temperatures were selected for climate reconstruction. Transfer functions were computed which explained July-August mean temperatures by ring-width indices. Mean bootstrapped correlation coefficients were obtained of r = 0.71 to r = 0.60 for the calibration procedure (Table 6). At Stonglandseidet, the function includes four tree rings (t, t+1, t+2, t+3). At Vikran, the first lagged ring (t+1) was not significant, and the model thus contains the rings (t), (t+2) and (t+3). At Forfjorddalen, the model (t-1, t, t+1) proved superior over other alternative models. In all cases, negative weights were assigned to the prior (t-1) and the lagging rings (t+1) and (t+2), while positive weights to the third lag (t+3). Thus, the Forfjorddalen model (t-1, t, t+1) works as a high-pass filter. Therefore an alternative model FF2 (t, t+1,t+2) accounting for more low-frequency variability was chosen (Table 6). All models contain more lags than the transfer functions (t, t+1) which were applied in previous northern Fennoscandian studies (Briffa *et al.*, 1988a; 1992; Lindholm, 1996).

The temperatures reconstructed from the Vikran-chronology closely followed the decadal trend of the instrumental record (Figure 4). This is at least partially attributed to the high quality instrumental climate record at Tromsø, the short distance between climate station and pine locality and a short, well-defined growing season due to the north-facing slope. The strength of the models and amount of the expressed temperature amplitude decreased from Vikran to Forfjorddalen (Figures 4 and 5, Table 6). For the time interval AD 1700-1989, the standard deviation of the annual reconstructed

Table 6: Calibration and verification statistics for the temperature reconstructions 1875-1989: mean bootstrap correlation coefficient (mean r) and standard deviations (SD) for the calibration (cal) and the verification procedure (ver), explained variance adjusted for degrees of freedom (R^2_{adj}), product-mean test (t), sign test (sign), and number of negative sign-products of the first differences (diff.) (Fritts, 1976). For the low-frequency variability (10-year low-pass filter), simple correlation coefficients (r), R^2_{adj}, the results of the product-mean test and the ratio between the observed and estimated standard deviations are indicated ($ratio_{SD}$).

		mean r ± SD		reconstruction				low frequency			
		cal	ver	R^2_{adj}	t	sign	diff.	r	R^2_{adj}	t	$ratio_{SD}$
VIK	(t,t+2,t+3)	.71 ± .04	.69 ± .08	.49	5.8	43	38	.91	.82	11.9	1.07
STO	(t,t+1,t+2,t+3)	.60 ± .04	.56 ± .09	.33	5.4	32	32	.77	.58	8.5	1.30
FF2	(t-1,t,t+1)	.60 ± .04	.56 ± .10	.34	5.3	36	30	.23	.03	2.8	3.09
FF2	(t,t+1,t+2)	.56 ± .05	.50 ± .11	.29	5.2	40	30	.28	.05	3.8	2.39

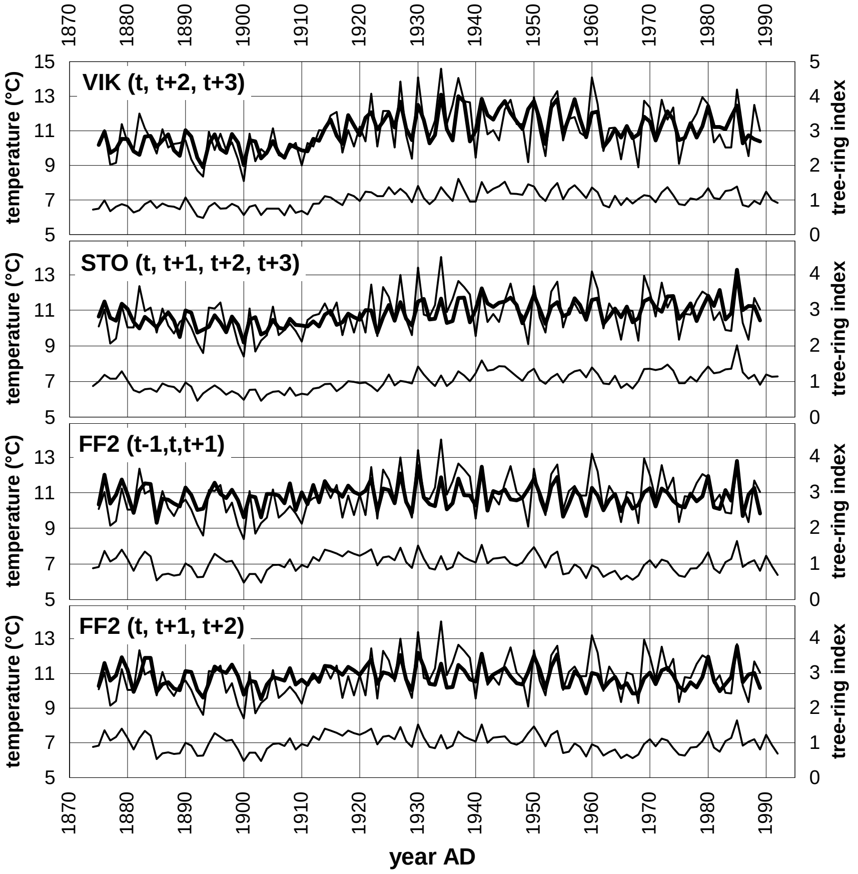


Figure 4: Visual comparison of the ARSTAN tree-ring series (thin, lower), observed (thin, upper) and reconstructed July-August-temperatures (bold, upper), AD 1874-1992. The Vikran chronology (VIK) is compared with the Tromsø climate series, the chronologies from Stonglandseidet (STO) and Forfjorddalen (FF2) with Andenes climate.

temperatures ranged from 0.90°C at Vikran to 0.56°C at Forfjorddalen (t, t+1, t+2). The amplitudes of the low-pass filtered series is highest at Vikran (2.31°C), while only reaching a maximum of 0.9°C at Forfjorddalen (model t, t+1, t+2).

Part of the trend in the amount of expressed low-frequency variability may be due to a more oceanic climate at the south-western sites. The standard deviation of July-August temperatures between 1875-1989 at Tromsø was 1.4°C and the amplitude 6.5°C, while the corresponding values for Andenes are 1.1°C and 5.6°C (Figure 4). Because the Forfjorddalen and Stonglandseidet chronologies were both related to Andenes climate, these two reconstructions are expected to behave similarly. It is most likely that site-specific signals related to local climate and site conditions caused the differences in reconstruction quality. In contrast to Vikran, tree rings from Forfjorddalen are more likely to integrate climate events outside the July-August temperature window. The starting point for improving the long Forfjorddalen reconstruction, will be to explain the growth deviations at Forfjorddalen about 1920 (positive) and 1960 (negative), in relation to the observed summer temperatures. At the oceanic limit of pine, high winter temperatures represent a stress factor. Indeed, the steep rise in growth observed around 1920 coincided with low winter temperatures, while during the decades of maximum summer temperatures and during the 1960s, winter temperatures were high. Also the winter index of the North Atlantic Oscillation is high about 1920 and low in the 1960s (Van Loon and Rogers, 1978), indicating stable winters in the former period and high cyclonic activity in coastal northern Norway during the 1960s. However, no statistical proof for the effect of winter temperatures was found in the response functions; winter conditions appear to influence the low-frequency variability of pine growth, while the year-to-year variability is determined by summer temperatures.

CLIMATE SINCE AD 1358

The reconstruction for AD 1358-1550 was based exclusively on the Forfjorddalen chronology (Figure 5). Summer temperatures were predominantly low AD 1375-1440 and then fluctuated strongly until the onset of an extraordinary long period of high temperatures between AD 1475-1540 which ended with a severely cold phase in the AD 1540s. In terms of growth, this anomaly is an analogy to the 20th century, when considerable deviations between growth and summer temperatures occurred at Forfjorddalen. Though warm summers certainly must have prevailed between AD 1475-1540, additional independent palaeoclimatic information is required to describe in more detail the climatic characteristics of the 15th and 16th century at the coast of northern Norway.

The climate during the period AD 1550-1700 is documented by the chronologies from Forfjorddalen and Stonglandseidet. In the mean reconstruction, summer temperatures were stable and close to average during AD 1550-1600 (Figure 6). The period AD 1600-1715 was dominated by three temperature cycles of about 40 year length, with minima at around AD 1605 (–1.6 standard deviations from 1874-1989 mean; 10-year low-pass filter: –0.67 SD), 1645 (–1.6 and –0.56 SD) and 1680 (–2.2 and –0.77 SD), and the three maxima appeared to be as warm as the 20th century mean. In the mean reconstruction, the cycles had nearly equal amplitudes. However, the individual reconstructions display opposite trends (Figure 5). At Stonglandseidet, the trend for July-August temperatures was negative and the later minima were more severe (AD 1641: 9.5°C, AD

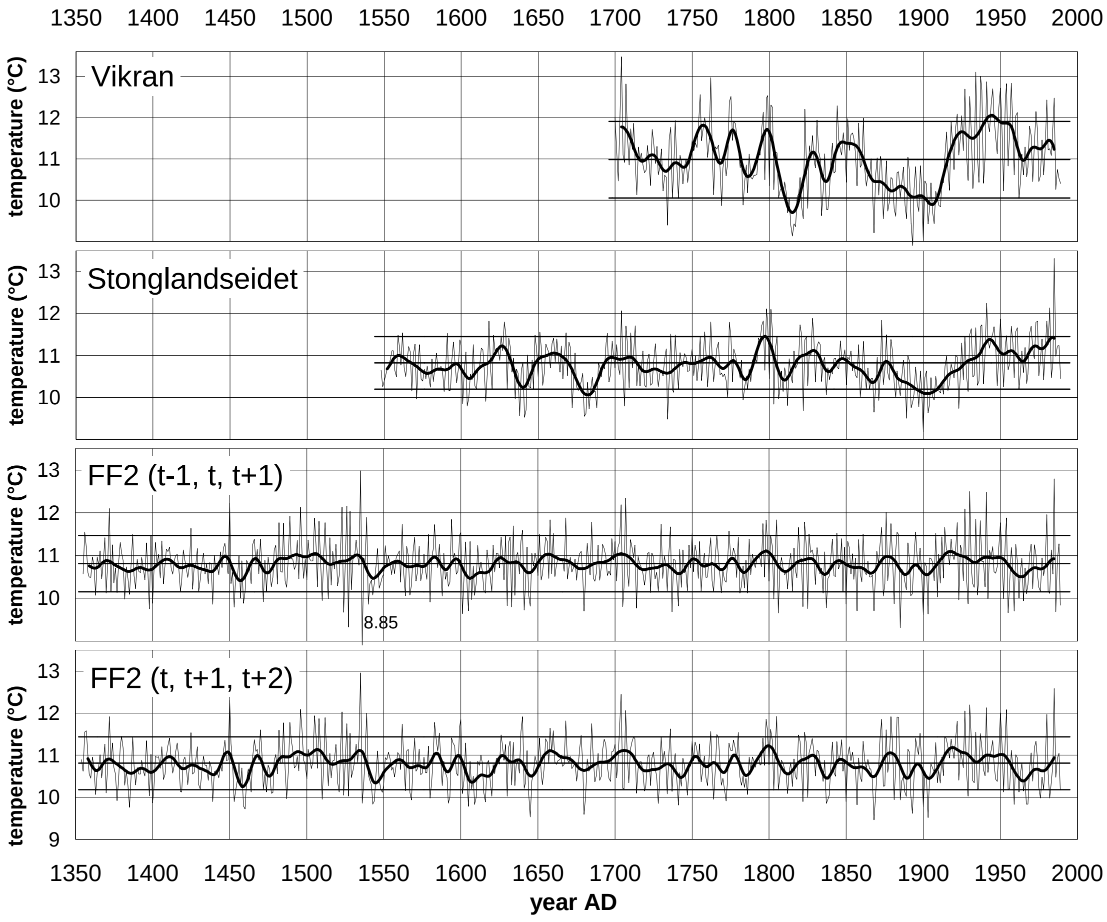


Figure 5: July-August temperatures of Tromsø reconstructed from the Vikran chronology (VIK), and Andenes July-August temperatures reconstructed from the chronologies of Stonglandseidet (STO) and Forfjorddalen (FF2). For Forfjorddalen, two alternative reconstructions are presented. The means and standard deviations for the period AD 1874-1992 are indicated. The decadal variability is shown by a 10-year low-pass filtered series (bold line).

1635-47 mean: 10.3°C; AD 1680: 9.6°C, AD 1672-88 mean: 10.2°C; Andenes AD 1961-90: 11.1°C). In contrast, in Forfjorddalen, only the AD 1601-20 minimum was distinctly developed, while the years AD 1650-1713 apparently experienced rather high summer temperatures. Considering its duration, the AD 1601-20 cold event must be regarded as the most severe of the whole reconstruction, while the third depression of the low-pass filtered series was mostly caused by the extremely cold summer AD 1680. In conclusion, from the observed growth depressions in addition to evidence for a gap in pine recruitment at AD 1575-1650 (Figure 2), the first half of the 17th century appears to have been especially cold and unfavourable for pine growth. The second half of that century can be regarded as slightly warmer, allowing pine recruitment during the warm interval AD 1650-70 and survival of young trees through the AD 1680s. This period of strong temperature fluctuations at the northern Norwegian coast fits well into the period of lowest 'Little Ice Age' temperatures as proposed for the Northern Hemisphere, AD 1570-1730 (Bradley and Jones, 1993). Therefore, further efforts are necessary to increase the chronology length and replication as well as to investigate pine regeneration at Forfjorddalen and Stonglandseidet, in order to obtain a more significant picture of the climate of the 17th century.

The mean reconstruction of July-August-temperature since AD 1710 was based on all three chronologies (Figure 6) and consists of three major phases: I) a stable cool phase AD 1714-1748, 0.23 standard deviations below the 1874-1989 mean, II) a phase of close-to-average temperatures AD 1749-1856, with high decadal variability AD 1780-1815, and III) a strong cooling trend AD 1850-1900, towards a mean at –1 standard deviations. The highest degree of variability is expressed in the Vikran reconstruction (Figure 5). The development of July-August temperatures AD 1700-1910 can be described either by a cooling trend of 0.54°C per century, or by dividing the series at AD 1805/06 into a warm 18th (mean 11.2°C) and a cool 19th century (mean 10.5°C; Tromsø July-August mean temperature 1961-90: 11.3°C). Temperatures in the second half of the 18th century fluctuated strongly with cycle lengths of ~20 years. The low-pass filtered series displayed amplitudes of about 1°C and maxima at about 11.7°C in AD 1757, 1776 and 1798. From AD 1800, temperatures dropped suddenly, culminating in AD 1815 at 9.13°C.

Considering the underestimation of temperature extremes during the calibration period by 1-1.5°C (Figure 4), the real amplitude of this event must have been even greater than the reconstructed 2.0°C (low-pass filtered) and 3.4°C (annual resolution). July-August temperatures remained below 9.5°C for four years, AD 1814-1817, and below 10.1°C for seven years, AD 1812-1818. They rose above 11°C at AD 1823/26 and stayed at this level until AD 1861. During the following 52 years, AD 1862-1913, the reconstructed July-August temperatures, with a few exceptions, stayed below 11°C (mean: 10.2°C). The early instrumental record at Tromsø thus coincided with a long cool phase, and part of the observed warming trend in the instrument record thus reflects a recovery from this negative anomaly.

At Stonglandseidet, summer temperatures during AD 1714-1780 were considerably more stable than at Vikran (Figure 5). At the former site, mean July-August temperatures AD 1714-1741 were 10.6°C, with the century minimum of 9.48°C at AD 1734. Only the last of the late 18th century temperature cycles at Vikran appeared in this reconstruction

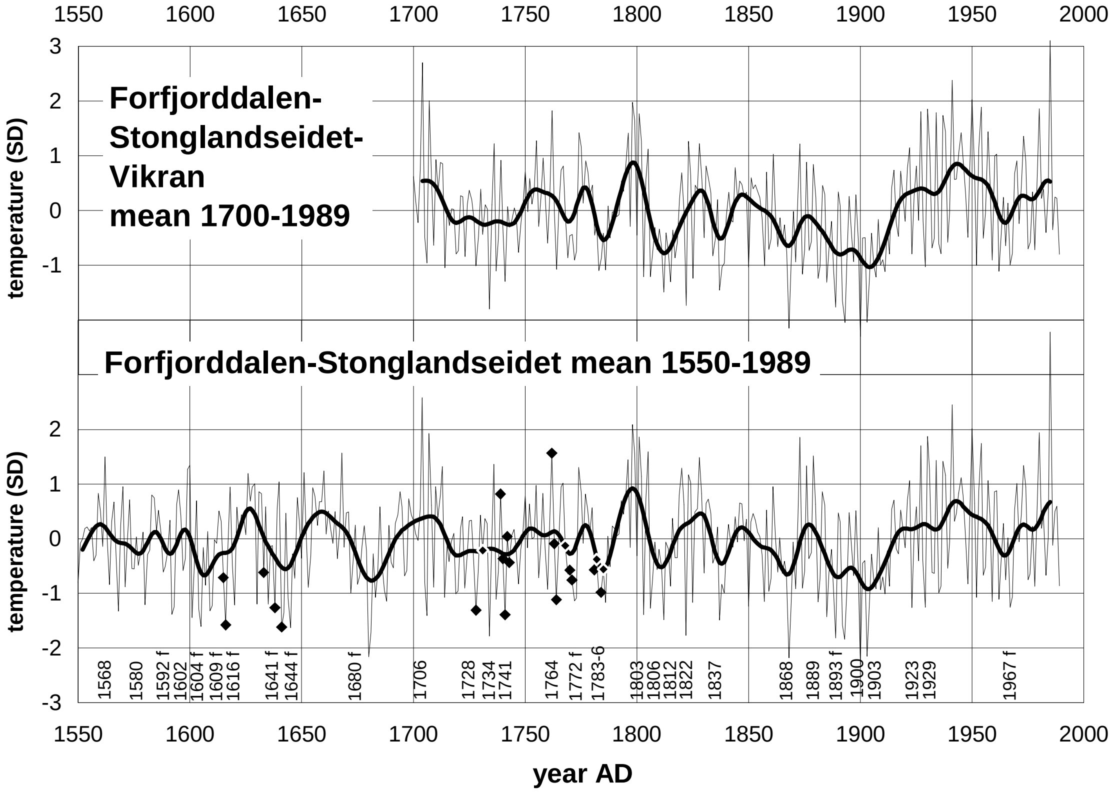


Figure 6: July-August temperatures for the coastal region of southern Troms and Vesterålen back to AD 1700, based on the mean of the reconstructions from Forfjorddalen, Stonglandseidet and Vikran. Also shown are July-August temperatures of Andenes back to AD 1550, based on the mean of the reconstructions from Forfjorddalen and Stonglandseidet. Forfjorddalen is represented by the model FF2 (t, t+1, t+2). Temperatures are expressed in standard deviations from the mean AD 1874-1992. The decadal variability is shown by a 10-year low-pass filtered series (bold line). Dates for selected cold summers are shown below the lower chronology. Years of failed or poor barley harvests (Fjærvoll, 1960; 1964) are indicated (◆).

(mean AD 1793-1802: 11.5°C), and the negative temperature anomaly of AD 1815 was not developed at all. Instead, after the cold summers of AD 1803 (9.8°C), AD 1806 (10.0°C) and AD 1812 (9.8°), the July-August temperature raised to about 11°C until AD 1833, before the onset of the cooling trend towards AD 1900. In the Forfjorddalen reconstruction, the early 19th century temperature depression was even less pronounced, while the temperature amelioration of the 1870s was rather prominent. These might be examples of decadal-scale spatio-temporal variability of summer temperature.

The low-frequency variability of chronologies and reconstructions is limited by the average segment length of the presented chronologies (Cook *et al.*, 1995), in this case about 250 years. Thus, care should be taken when comparing the summer temperatures of AD 1700-1750 or earlier with the 20th century mean. The segment length may have caused both maximum and near-minimum growth to be observed in the time period of the instrumental climate record, which in turn means that the climate reconstructions were unlikely to exceed the temperature band experienced during the recent 130 years.

Independent verification and supplementation of the dendroclimatic reconstruction may be derived from historical records, such as barley harvests (*Hordeum*) documented in tax lists from Vesterålen and Senja (Fjærvoll 1961; 1964). These records are continuous from AD 1611-1641 and AD 1714-1731 and often include comments on summer weather. Harvests were poor in the years 1615/16, good in the 1620s, failed totally in AD 1633 and 1638, and were poor again in 1641. No total failures of crop are reported for the years AD 1714-31, but bad harvests occurred in AD 1728 due to excessive rain and, in 1731, due to rain and frosts. No barley taxes are reported AD 1732-44; AD 1739-43 due to frost. Crop production became more important in the second half of the 18th century and expanded especially towards the 1790s. However, this trend was interrupted by poor barley harvests in the years 1762-64, 1768 (total failure), 1770/71, 1781/82 and 1784/85. Most, though not all, of these years coincide with cool summers in the dendroclimatic reconstruction. However, such historical data is extremely complex and requires care in interpretation. For example, the absence of records in certain years may not reflect regional climate at all, but be caused by external factors such as failure of seed crop import or changes in the taxation routines.

From the Torneträsk-chronology, northern Sweden, and from several additional climate reconstructions of the Northern Hemisphere it was concluded that the summers of AD 1570-1730 were especially cold (Briffa *et al.*, 1992; Bradley and Jones, 1993). The extent of the cold period does not differ much from the present Stonglandseidet reconstruction, where the cold period commences earlier than at Forfjorddalen. At

Torneträsk, the lowest temperatures were recorded in the early part, about AD 1580-1620 and AD 1640, which does agree with the Forfjorddalen reconstruction, but not with the Stonglandseidet reconstruction as discussed earlier in this paper. Warm periods at Torneträsk were reconstructed for AD 1360-1570, AD 1760 and AD 1820 (Briffa *et al.*, 1992; 1998a). At the Atlantic coast, the first of these periods is more restricted and does not commence before AD 1475, which is after the main temperature peaks in the Torneträsk reconstruction, AD 1410 and AD 1430. Also, the coastal warm period appears to end abruptly already in the 1540s. Also in the 18th century, the coastal temperature maximum is delayed: it occurs at about AD 1760 in the inland (Briffa *et al.*, 1992; Lindholm, 1996), but not until the 1790s at the coast.

In conclusion, past summer temperatures show similar long-term trends on both sides of the Scandes, but differ in magnitude and duration as well as in the timing of the extremes. Differences in climate continentality, standardisation techniques, and analysed tree-ring parameters may cause differences in the magnitude of recorded climate anomalies. Spatio-temporal variability in the northern Fennoscandian tree-ring record probably relates to atmospheric circulation patterns. Atlantic and Polar air masses from the western sector cause orographic precipitation at the Norwegian coast, while northern Sweden and Finland lie in the lee of the Scandes. In contrast, when cyclones move from Iceland towards southern Scandinavia, northern Fennoscandia experiences SE-winds, with rain on the eastern slope of the northern Scandes and bright skies along the coast. Whenever such synoptic situations prevail over major parts of the summer, these will be manifested in the tree-ring record. Interpreting contrasting growth rates on both sides of the Scandes in terms of atmospheric circulation patterns, northern Fennoscandia appears to have been influenced by zonal circulation about AD 1760, while dominated by south-eastern winds in the 1790s. Additionally, anomalies of North Atlantic sea surface temperature must be taken into consideration as a cause for regional differences in pine growth, due to changes of the gradient of continentality across the Scandes. A synopsis of northern Fennoscandian chronologies is expected to contribute to reconstructions of oceanographic as well as atmospheric processes in the North Atlantic region on annual to multi-decadal timescales.

CONCLUSIONS & SUMMARY

1. Three tree-ring chronologies from Scots pine, *Pinus sylvestris*, were constructed at the coast of northern Norway between the Lofoten-Vesterålen archipelago and Tromsø (Forfjorddalen AD 1358-1992, Stonglandseidet AD 1548-1994, Vikran AD 1700-1992). The two longest chronologies cover the 'Little Ice Age' (Bradley and Jones. 1993).
2. Bootstrap orthogonal regression revealed a predominant response of ring width to July-August temperatures. Differences in climate response between the localities relate to a shorter growing period at the northernmost, north-facing site (Vikran), drought sensitivity at a steep south-facing site (Stonglandseidet) and stress due to high winter temperature at the most oceanic site (Forfjorddalen).
3. Tree growth was very consistent in the region AD 1700-1910, implying summer temperature as the main growth limiting factor. Since AD 1910, the growth trends of the individual sites differ, suggesting individual responses to summer moisture and winter temperatures during warm periods.
4. The Vikran chronology contained the strongest tree-ring and climate signal. Towards the more oceanic south-west, tree-ages and chronology length increase, while low-frequency variability in tree-rings and climate reconstruction decrease.
5. July-August mean temperatures at the coast of northern Norway were reconstructed back to AD 1358. High temperatures prevailed during the long period AD 1470-1540. The 17th century, along with the 1450s, 1540s and AD 1880-1910, is the coldest period of the reconstruction. Three strong fluctuations in summer temperatures occurred during that century, with minima around AD 1605, 1640 and 1680. Poor evidence for pine regeneration at Forfjorddalen AD 1575-1650 supports the hypothesis of low temperatures in the first half of the 17th century.
6. At Forfjorddalen, further efforts have to be made to explain the climate response in the 20th century, as well as to assess the extent of the proposed logging activity and its implications for the observed growth and climate trend in the 17th century.
7. Reconstructed temperatures showed similar long-term trends on both sides of the Scandes, but differed in the magnitude and timing of the extremes. These differences should be the focus of further studies on past atmospheric circulation patterns and North Atlantic sea surface temperatures.

REFERENCES

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

Aniol, R.W. and **Eckstein, D.** 1984: Dendroclimatological studies at the northern timberline. In Mörner, N.-A. and Karlén, W., editors, *Climatic changes on a yearly to millennial basis*. Dordrecht: D. Reidel Publishing Company, pp. 273-79.

Aune, B. 1993: Air temperature normals, normal period 1961-1990. Norwegian Meteorological Institute, Oslo. *DNMI-report* 02/93 klima, 63 pp.

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

Bradley, R.S. and **Jones, P.D.** 1993: 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* 3(4), 367-76.

Briffa, K.R. 1994: Mid and late Holocene climate change: evidence from tree growth in northern Fennoscandia. In Funnell, B.M. and Kay, R.L.F., editors, *Palaeoclimate of the last glacial/interglacial cycle*. Natural Environment Research Council Special Publications 94(2), 61-65.

Briffa, K.R., Bartholin, T.S., Eckstein, D., Jones, P.D., Karlén, W., Schweingruber, F.H. and **Zetterberg, P.** 1990: A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346, 434-39.

Briffa, K.R. and **Jones, P.D.** 1990: Basic chronology statistics and assessment. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 137-52.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P. and **Eronen, M.** 1992: Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Climate Dynamics*, 111-19.

Briffa, K.R., Jones, P.D., Pilcher, J.R. and **Hughes, M.K.** 1988a: Reconstructing summer temperatures in northern Fennoscandia back to A.D. 1700 using tree-ring data from Scots pine. *Arctic and Alpine Research* 20(4), 385-94.

Briffa, K.R., Jones, P.D. and **Schweingruber, F.H.** 1988b: Summer temperature patterns over Europe: A reconstruction from 1750 A. D. based on maximum latewood density indices of conifers. *Quaternary Research* 30, 36-52.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Harris, I.C., Shiyatov, S.G., Vaganov, E.A. and **Grudd, H.** 1998a: Trees tell of past climates: but are they speaking less clearly today? *Philosophical Transactions of the Royal Society of London* B 353, 65-73.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Shiyatov, S.G. and **Vaganov, E.A.** 1998b: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391, 678-681.

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

Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A. and **Funkhouser, G.** 1995: The 'segment length course' in long tree-ring chronology development for palaeoclimatic studies. *The Holocene* 5(2), 229-37.

Cook, E.R., D'Arrigo, R.D. and **Briffa, K.R.** 1998: A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene* 8(1), 9-17.

Cook, E.R. and **Kairiukstis, L.A.,** editors 1990: *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, 393 pp.

D'Arrigo, R.D., Cook, E.R., Jacoby, G.C., Jr. and **Briffa, K.R.** 1994: NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews* 12, 431-40.

D'Arrigo, R.D. and **Jacoby, G.C.** 1993: Secular trends in high northern latitude temperature reconstructions based on tree rings. *Climatic Change* 25, 163-77.

Eckstein, D. and **Bauch, J.** 1969: Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens zur Analyse seiner Aussagesicherheit. *Forstwissenschaftliches Centralblatt* 88, 230-50.

Eckstein, D., Hoogesteger, J. and **Holmes, R.L.** 1991: Insect-related differences in growth of birch and pine at northern treeline in Swedish Lapland. *Holarctic Ecology* 14, 18-23.

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

Eide, E. 1926: Om sommervarmens innflytelse på årringbredden (Über Sommertemperatur und Dickenwachstum im Fichtenwald). *Meddelelser fra Det Norske Skogforsøksvesen* 7, 87-104.

Erlandsson, S. 1936: Dendro-Chronological studies. Stockholm Högskolas Geokronologiska Institution, *Data* 23, 119 pp.

Fjærvoll, K. 1961: *Korndyrkinga i Hålogaland i gammal tid, 1500- og 1600-åra*. Tilleggsbok til Håløygminne. Svorkmo Prenteverk, 127 pp.

— 1964: *Korndyrkinga i Troms fylke i 1700-åra med tilknytting til nyare tid (Senien og Tromsen Fogderi)*. Bodø: Nordland Boktrykkeri, 110 pp.

Førland, E.J. 1993: Precipitation normals, normal period 1961-1990. Norwegian Meteorological Institute, Oslo. *DNMI-report* 39/93 klima, 63 pp.

Frich, P., Alexandersson, H., Ashcroft, J., Dahlström, B., Demarée, G.R., Drebs, A., Engelen, A.F.V.v., Førland, E.J., Hanssen-Bauer, I., Heino, R., Jónsson, T., Jónasson, K., Keegan, L., Nordli, P.Ø., Schmith, T., Steffensen, P., Tuomenvirta, H. and **Tveito, O.E.** 1996: *North Atlantic Climatological Dataset (NACD Version 1) - Final Report*. Danish Meteorological Institute, Copenhagen. *Scientific Report* 96-1, 47 pp.

Fritts, H.C. 1976: *Tree rings and climate*. London: Academic Press, 567 pp.

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

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

Guttormsen, H. 1990: *Sortlands historie. Bind I - Swartalande*. Sortland Kommune, 280 pp.

Hesselmann, H. 1904: Om tallens diametertillväxt under de sista tio åren. *Meddelanden från Statens Skogsförsöksanst.* 1904(1), 45-53.

Holmes, R.L., Adams, R.K. and **Fritts, H.C.** 1986: Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin, with procedures used in the chronology development work, including users manuals for computer programs COFECHA and ARSTAN. Laboratory of Tree-Ring Research, University of Arizona, Tucson. *Chronology Series* VI, 182 pp.

Hustich, I. 1945: The radial growth of the pine at the forest limit and its dependece on the climate. *Societas Scientiarum Fennica, Commentationes Biologicae* 9(11), 1-30.

Hustich, I. and **Elfving, G.** 1944: Die Radialzuwachsvariationen der Waldgrenzkiefer. *Societas Scientiarum Fennica, Commentationes Biologicae* 9(8), 1-18.

Kirchhefer, A.J. 1998: Climate and site effects on tree-rings of *Pinus sylvestris* L. in northernmost Norway - an exploratory pointer-year study. *AmS-Varia* 32, 15-28.

Kirchhefer, A.J. and **Vorren, K.-D.** 1995: Årringer på furu, *Pinus sylvestris* L., som kilde for klimainformasjon i Vesterålen, Nord-Norge (Tree rings of Scots pine, *Pinus sylvestris* L., a source of climate information in Vesterålen, northern Norway). *AmS-Varia* 24, 79-85.

Kolmodin, G. 1923: Tillväxtundersökningar i Norra Dalarna. *Svenska Skogsvårdsföreningens Tidskrift* 1923, Serien A, 1-35.

Kullman, L. 1996: Structural population dynamics of pine (*Pinus sylvestris* L.) during the past 500 years close to the tree-limit in northern Sweden. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 75-92.

Lindholm, M. 1996: Reconstructions of past climate from ring-width chronologies of Scots pine (*Pinus sylvestris* L.) at the northern forest limit in Fennoscandia. PhD thesis. University of Joensuu. *Publications in Sciences* 40, 169 pp.

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

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

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

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

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

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

Schweingruber, F.H., Briffa, K.R. and **Jones, P.D.** 1991: Yearly maps of summer temperatures in Western Europe from A.D. 1750 to 1975 and Western North America from 1600 to 1982 - results of a radiodensitometrical study on tree rings. *Vegetatio* 92, 5-71.

Sirén, G. 1961: Skogsgränstallen som indikator för klimatfluktuationerna i norra Fennoskandien under historisk tid. *Communicationes Instituti Forestalis Fenniae* 54(2), 1-66.

Thun, T. and **Vorren, K.-D.** 1996: Short dendroseries from northern Norway reflect oceanic and subcontinental climates. In Frenzel, B., Birks, H.H., Alm, T. and Vorren, K.-D., editors, *Holocene treeline oscillations, dendrochronology and palaeoclimate*. Stuttgart: Gustav Fischer Verlag. *Palaeoclimate Research* 20, 120-26.

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

Van Loon, H. and **Rogers, J.C.** 1978: The seesaw in the winter temperatures between Greenland and northern Europe: Part I: General description. *Monthly Weather Review* 106, 296-310.

Wallén, A. 1917: Om temperaturen og nedbördens inverkan på granens och tallens höjd- och radietillväxt å Stamnäs kronopark 1890-1914. *Skogshögskolan 1917: Festskrift vid Skoghögskolans invigning 3 maj 1917*, pp. 413-427.

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

Zetterberg, P., Eronen, M. and **Lindholm, M.** 1996: Construction of a 7500-year tree-ring record for Scots pine (*Pinus sylvestris*, L.) in northern Fennoscandia and its application to growth variation and palaeoclimatic studies. In Spieker, H., Mielikäinen, K., Köhl, M. and Skovsgaard, J.P., editors, *Growth trends in European forests*. Berlin: Springer-Verlag. *European Forest Institute Research Report* 5, 7-18.

Submitted to *The Holocene*, August 7th 1999, in press

PAPER 2

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

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

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

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

INTRODUCTION

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

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

THE STUDY AREA

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

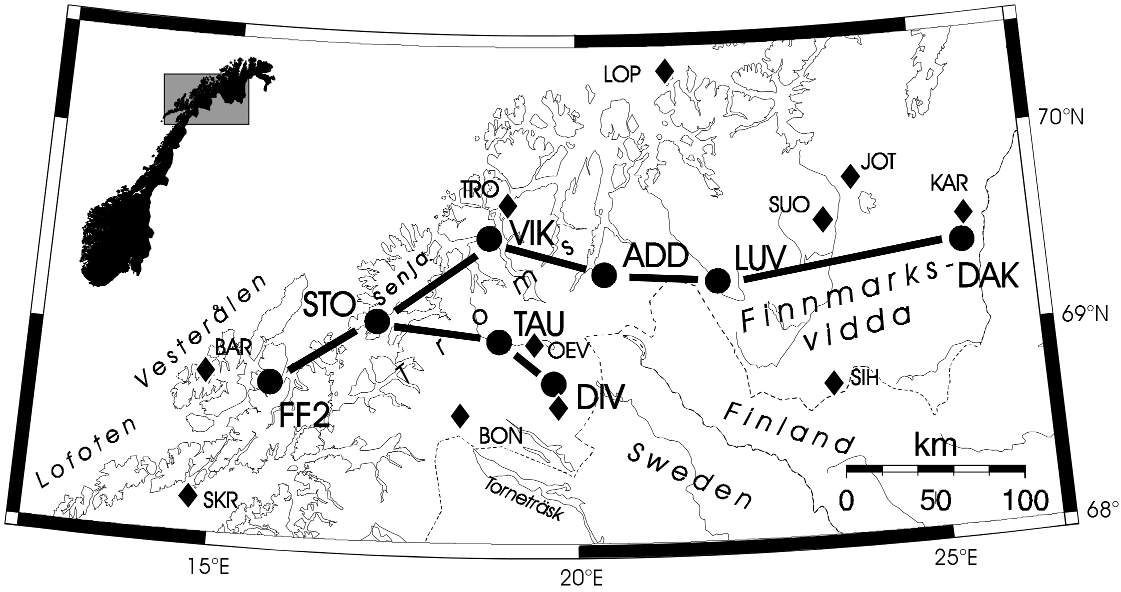


Figure 1: Map of the study area with the locations of the tree-ring chronologies (●) and climate stations (♦). The codes for chronologies and climate stations are explained in Tables 1 and 2, respectively.

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

MATERIAL AND METHODS

DENDROCHRONOLOGY

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

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

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

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

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

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

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

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

DENDROCLIMATOLOGY

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

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

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

RESULTS

TREE-RING CHRONOLOGIES

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

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

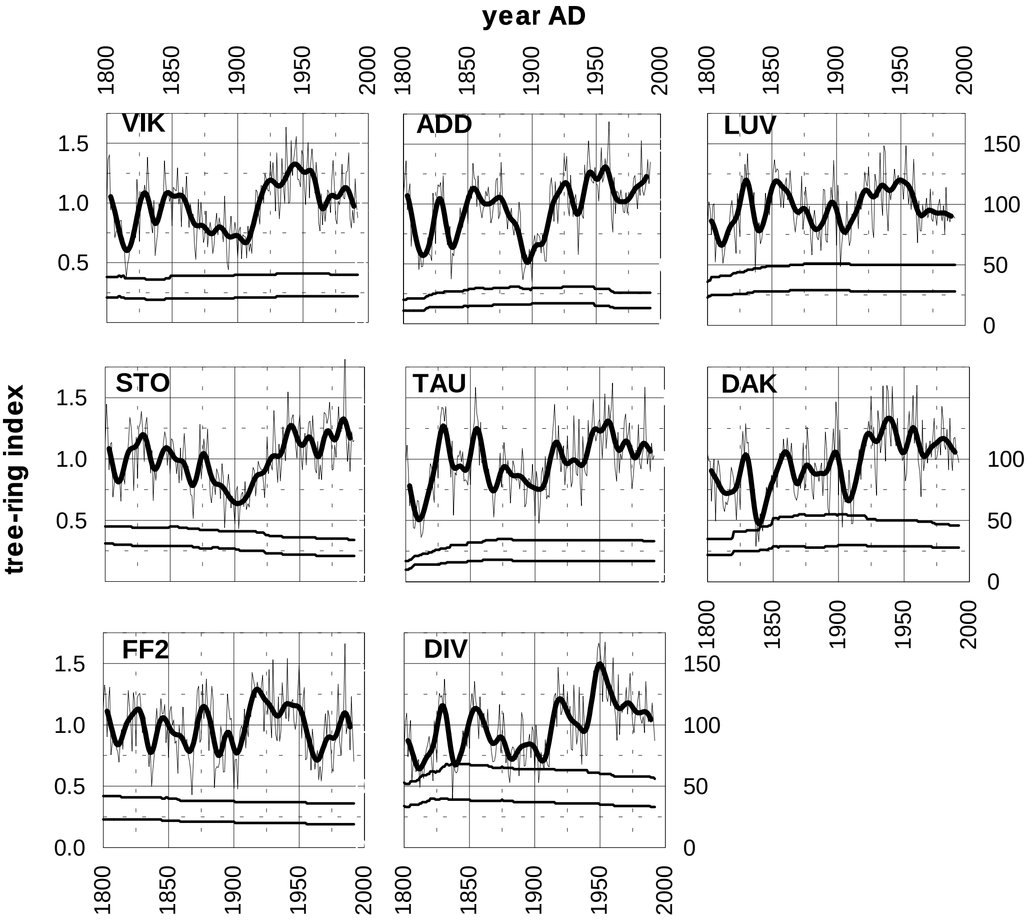


Figure 2: STANDARD tree-ring width chronologies 1800-1992. Left row: the coastal series (VIK Tromsø, STO Senja, FF2 Forfjorddalen); middle row: the inner Scandes (ADD Skibotn, TAU Målselvdalen, DIV Dividalen,); right: Finnmarksvidda (LUV Nordreisa, DAK Karasjok). The bold lines represent the 10-year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

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

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

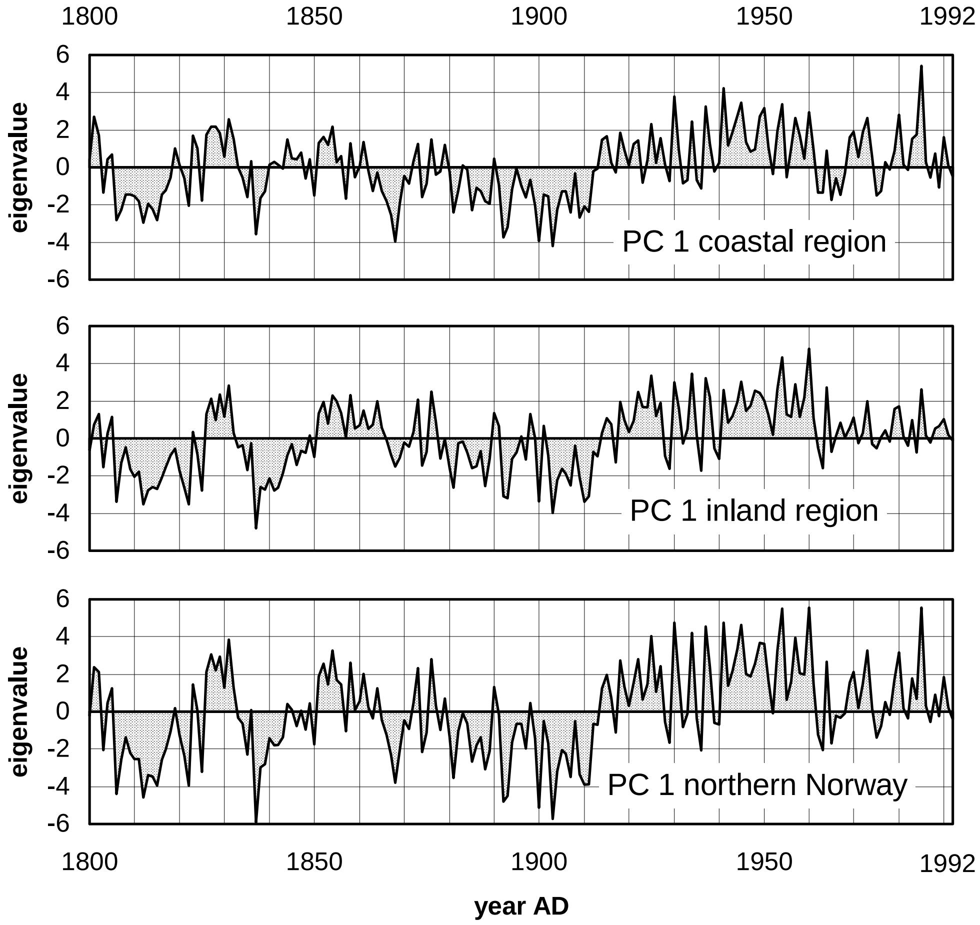


Figure 3: The first principal components derived from the four western (PC 1 coastal region: FF2, STO, VIK, TAU), the four eastern (PC 1 inland region: DIV, ADD, LUV, DAK) and all eight northern Norwegian ARSTAN chronologies (PC 1 northern Norway).

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

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

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

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

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

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

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

CLIMATE-GROWTH RESPONSE OF SCOTS PINE

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

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

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

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

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

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

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

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

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

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

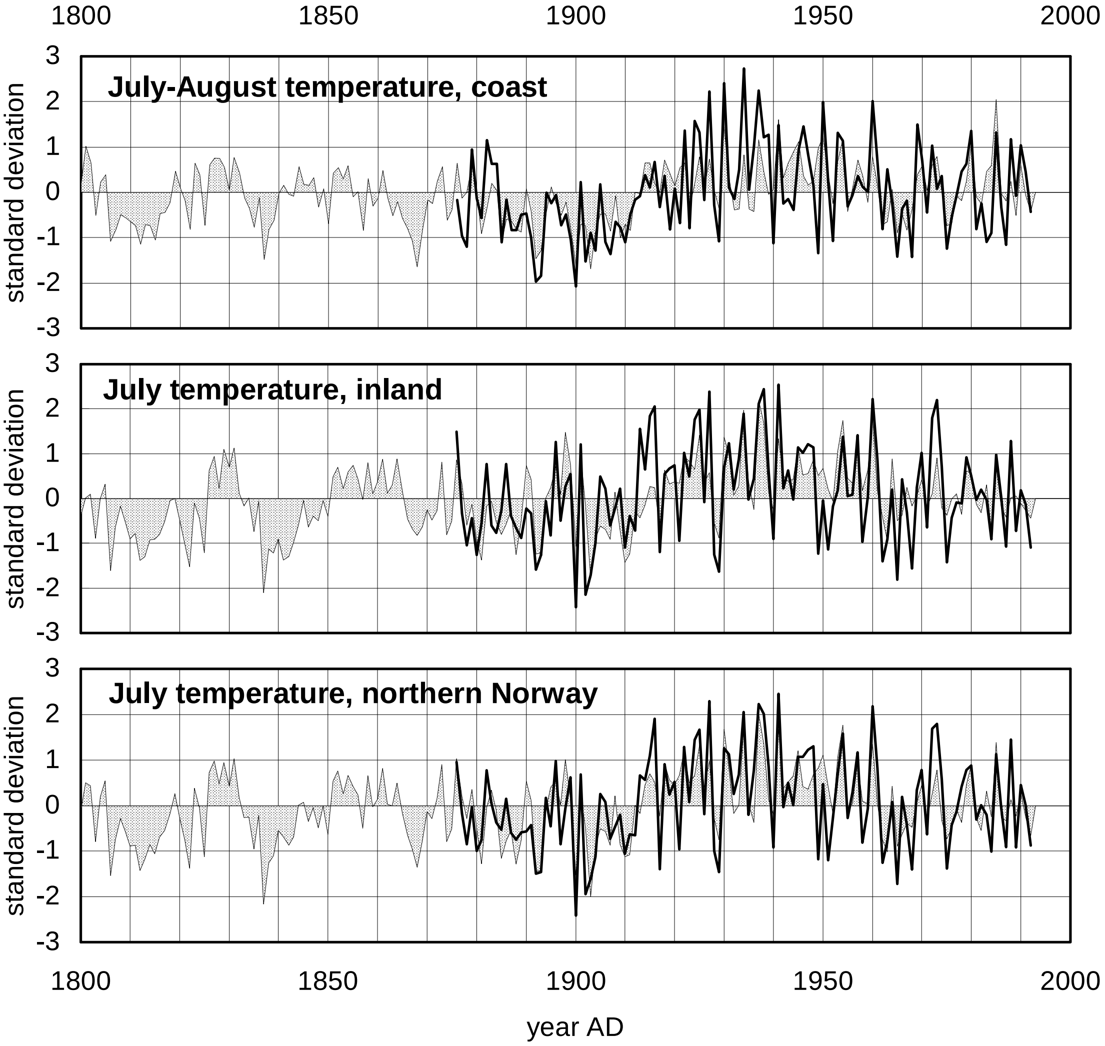


Figure 4: Three climate reconstructions for northern Norway back to 1800 (shaded): July-August temperatures for the coastal region, and July temperatures for the inland region and for northern Norway. Temperatures are expressed as standard deviations from the observed mean 1961-1990 (Table 1). The observed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

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

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

CLIMATE RECONSTRUCTION

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

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

DISCUSSION

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

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

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

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

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

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

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

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

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

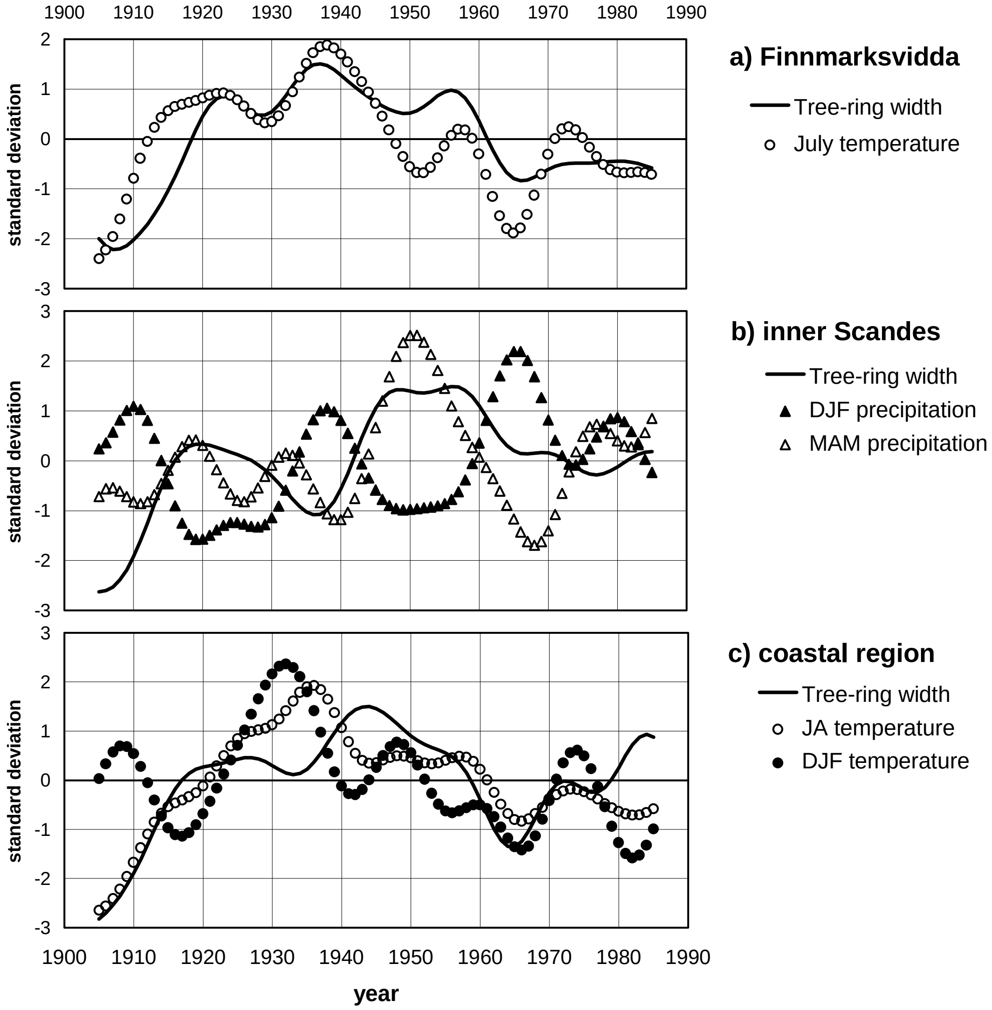


Figure 5: The decadal-scale variability (10-year low-pass filter) of the three regional mean tree-ring chronologies (bold lines) and selected climate parameters. a) The Finnmarksvidda chronology (LUV-DAK mean) is compared with inland July temperatures, b) the Scandes chronology (ADD-DIV-TAU mean) is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

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

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

CONCLUSIONS

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

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

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

REFERENCES

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

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

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

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

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

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

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

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

Briffa, K.R., Bartholin, T.S., Eckstein, D., Jones, P.D., Karlén, W., Schweingruber, F.H. and **Zetterberg, P.** 1990: A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346, 434-9.

Briffa, K.R. and **Jones, P.D.** 1990: Basic chronology statistics and assessment. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 137-52.

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

Briffa, K.R., Jones, P.D., Pilcher, J.R. and **Hughes, M.K.** 1988: Reconstructing summer temperatures in northern Fennoscandia back to A.D. 1700 using tree-ring data from Scots pine. *Arctic and Alpine Research* 20(4), 385-94.

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

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

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

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

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

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

Cook, E.R., D'Arrigo, R.D. and **Briffa, K.R.** 1998: A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene* 8(1), 9-17.

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

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

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

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

D'Arrigo, R.D. and **Jacoby, G.C.** 1993: Secular trends in high northern latitude temperature reconstructions based on tree rings. *Climatic Change* 25, 163-77.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Holmes, R.L., Adams, R.K. and **Fritts, H.C.** 1986: *Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin, with procedures used in the chronology development work, including users manuals for computer programs COFECHA and ARSTAN*. Laboratory of Tree-Ring Research, University of Arizona, Tucson. *Chronology Series* VI, 182 pp.

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

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

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

— 1995: Tree ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles* 9, 227-34.

Jones, P.D., Briffa, K.R., Barnett, T.P. and **Tett, S.F.B.** 1998: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *The Holocene* 8(4), 455-71.

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

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

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

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

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

Lindholm, M. 1996: *Reconstructions of past climate from ring-width chronologies of Scots pine (Pinus sylvestris L.) at the northern forest limit in Fennoscandia*. PhD thesis, University of Joensuu, *Publications in Sciences* 40, 169 pp.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Submitted to *Climatic Change*, January 28th 2000

PAPER 3

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

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

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

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

INTRODUCTION

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

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

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

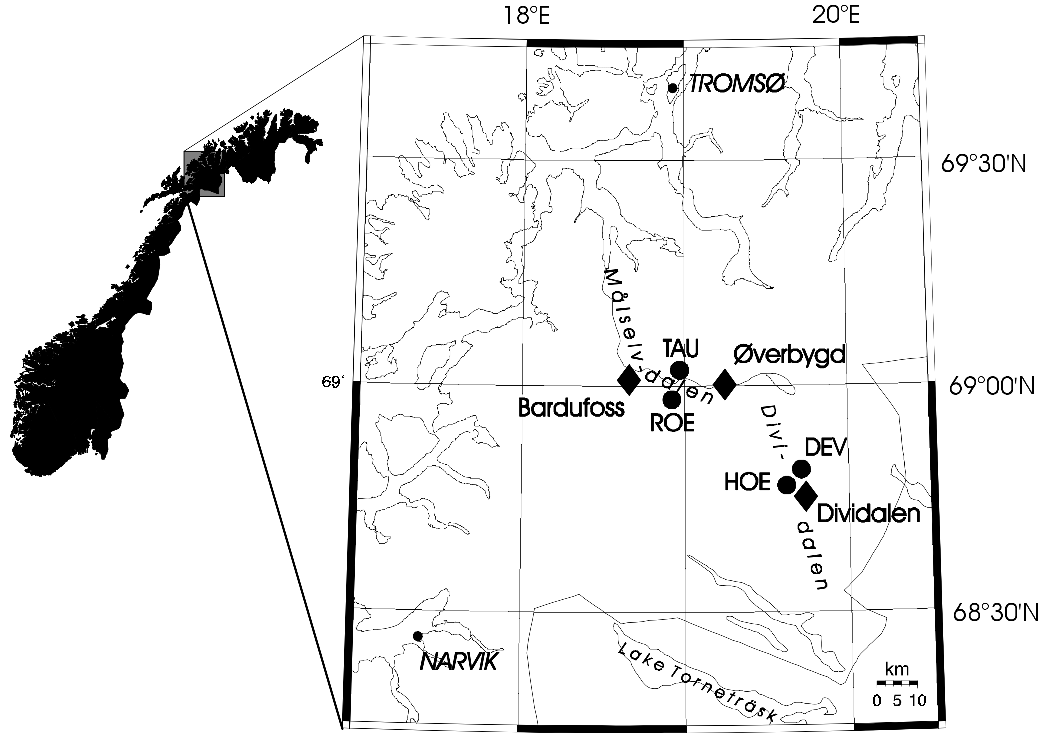


Figure 1: Map of the study area, Målselvdalen and Dividalen in inner Troms, northern Norway, showing the positions of the pine sites Devdiselva DEV, Høgskardet HOE, Tauskjerringa TAU and Rønninglia ROE (●) and the climate stations Bardufoss, Øverbygd and Dividalen (♦).

MATERIAL AND METHODS

THE SITES

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

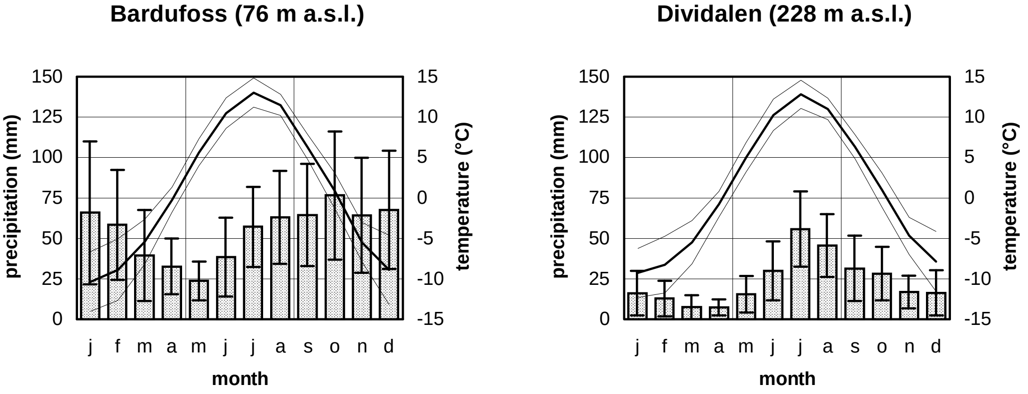


Figure 2: Climate diagrams for Bardufoss and Dividalen showing monthly mean temperatures (lines) and precipitation (bars) for the period 1961-1990 (Aune, 1993; Førland, 1993). Standard deviations are indicated.

TREE-RING ANALYSIS

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

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

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

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

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

RESPONSE-FUNCTION ANALYSIS

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

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

CLIMATE RECONSTRUCTION

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

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

RESULTS AND DISCUSSION

THE CHRONOLOGIES

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

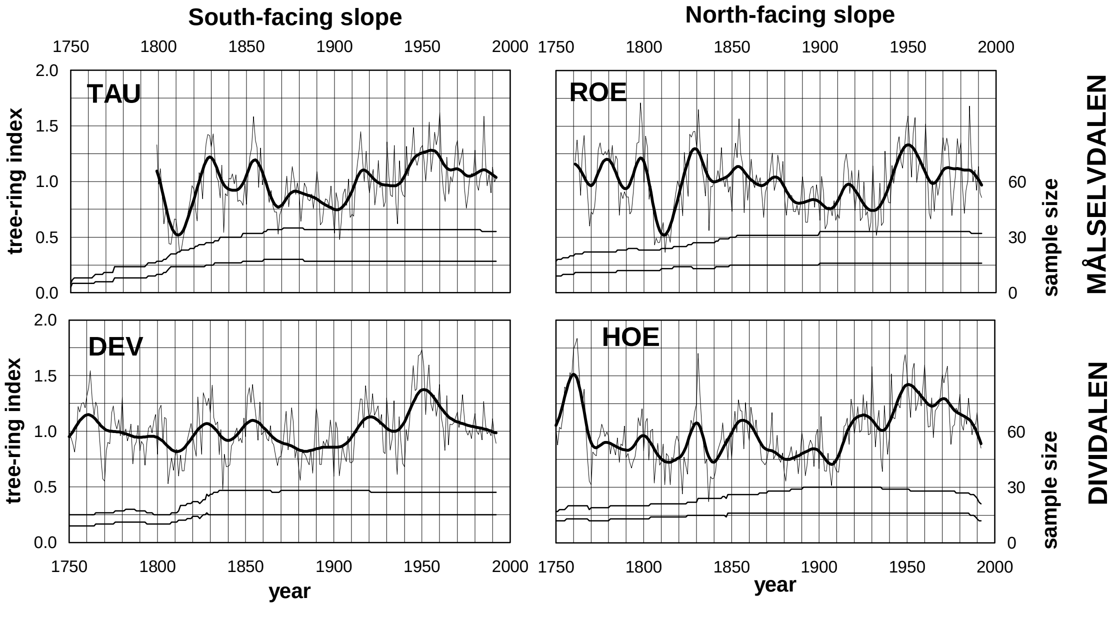


Figure 3: STANDARD ring-width chronologies from Dividalen and Målselvdalen, AD 1650-1992. The low-frequency variability is indicated by a 10-year low-pass filter (bold line). The sample size is shown below the chronologies (upper line: number of radii; lower line: number of trees). The chronologies from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

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

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

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

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

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

CLIMATE RESPONSE

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

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

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

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

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

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

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

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

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

TEMPERATURE RECONSTRUCTION

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

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

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

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

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

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

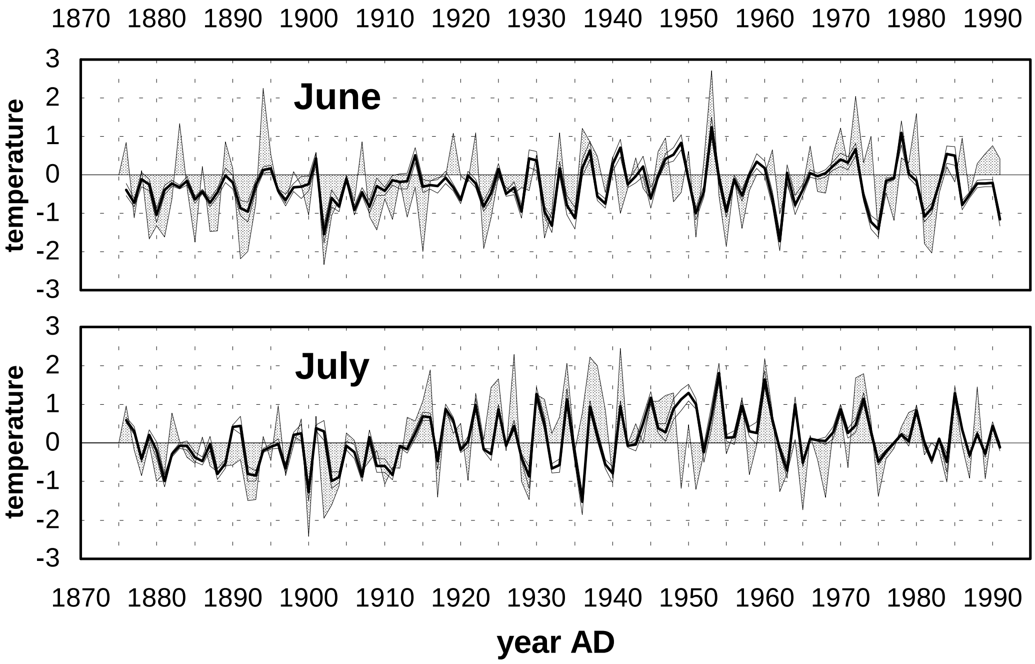


Figure 4: Visual comparison of the observed (shaded) and estimated (bold lines) June and July temperatures of northern Norway (NN), 1876-1991. The observed temperatures are expressed in standard deviations from the mean 1961-1990. The reconstruction represents the median of thousand individual reconstructions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

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

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

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

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

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

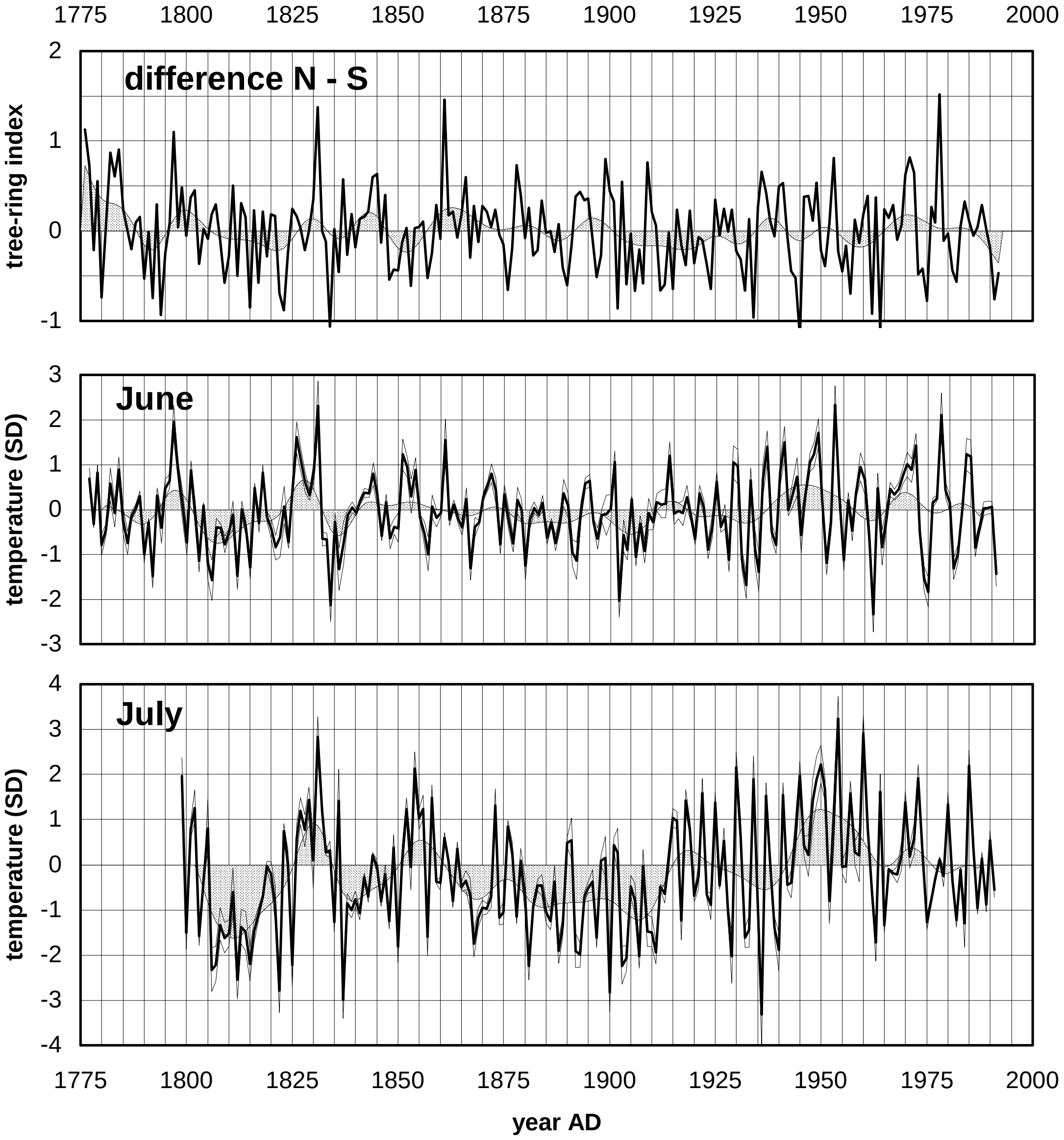


Figure 5: Reconstructed June and July temperatures for northern Norway, expressed in standard deviations from the mean 1961-1990. The reconstruction represents the median of thousand individual reconstructions derived by bootstrap regression; the thin lines show the 5^{th} and 95^{th} percentiles, i.e.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

SUMMARY

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

REFERENCES

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

Aune, B. 1993: *Temperaturnormaler, normalperiode 1961-1990 (Air temperature normals, normal period 1961-1990)*. Norwegian Meteorological Institute, Oslo. *DNMI report* 02/93 klima, 63 pp.

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

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

Briffa, K.R., Bartholin, T.S., Eckstein, D., Jones, P.D., Karlén, W., Schweingruber, F.H. and **Zetterberg, P.** 1990: A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346, 434-9.

Briffa, K.R., Jones, P.D., Pilcher, J.R. and **Hughes, M.K.** 1988: Reconstructing summer temperatures in northern Fennoscandia back to A.D. 1700 using tree-ring data from Scots pine. *Arctic and Alpine Research* 20(4), 385-94.

Briffa, K.R. and **Schweingruber, F.H.** 1992: Recent dendroclimatic evidence of northern and central European summer temperatures. In Bradley, R.S. and Jones, P.D., editors, *Climate since A.D. 1500*. London: Routledge, pp. 366-92.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Shiyatov, S.G. and **Vaganov, E.A.** 1998: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391, 678-82.

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

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

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

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

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

Desplanque, C., Rolland, C. and **Schweingruber, F.H.** 1999: Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). *Trees* 13, 218-27.

Eckstein, D., Hoogesteger, J. and **Holmes, R.L.** 1991: Insect-related differences in growth of birch and pine at northern treeline in Swedish Lapland. *Holarctic Ecology* 14, 18-23.

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

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

Fjærvoll, K. 1964: *Korndyrkinga i Troms fylke i 1700-åra med tilknytting til nyare tid (Senien og Tromsen Fogderi)*. Bodø: Nordland Boktrykkeri, 110 pp.

Frich, P., Alexandersson, H., Ashcroft, J., Dahlström, B., Demarée, G.R., Drebs, A., Engelen, A.F.V.v., Førland, E.J., Hanssen-Bauer, I., Heino, R., Jónsson, T., Jónasson, K., Keegan, L., Nordli, P.Ø., Schmith, T., Steffensen, P., Tuomenvirta, H. and **Tveito, O.E.** 1996: *North Atlantic Climatological Dataset (NACD Version 1) - Final Report*. Danish Meteorological Institute, Copenhagen, *Scientific Report* 96-1, 47 pp.

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

Fritts, H.C., Guiot, J. and **Gordon, G.A.** 1990: Verification. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of Dendrochronology: applications in the environmental science*. Dordrecht: Kluwer Academic Publishers, pp. 178-85.

Førland, E.J. 1993: *Nedbørnormaler, normalperiode 1961-1990 (Precipitation normals, normal period 1961-1990)*. Norwegian Meteorological Institute, Oslo. *DNMI report* 39/93 klima, 63 pp.

Groisman, P.Y., Karl, T.R. and **Knight, R.W.** 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science* 263, 198-200.

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

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

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

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

Hari, P. and **Sirén, G.** 1972: *Influence of some ecological factors and the seasonal stage of development upon the annual ring width and radial growth index*. Department of Reforestation, Royal Collage of Forestry, Stockholm, *Research Notes* 40, 22 pp.

Holmboe, J. 1913: Vaarens utvikling i Tromsø amt. Fænologiske undersøkelser. In Holmboe, J., editor, *Bergens Museums Aarbok 1912. Avhandlinger og Aarsberetning*. Bergen: John Griegs Boktrykkeri, pp. 1-248.

Holmes, R.L., Adams, R.K. and **Fritts, H.C.** 1986: *Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Basin, with procedures used in the chronology development work, including users manuals for computer programs COFECHA and ARSTAN*. Laboratory of Tree-Ring Research, University of Arizona, Tucson, *Chronology Series* VI, 182 pp.

Hughes, M.K., Vaganov, E.A., Shiyatov, S.G., Touchan, R. and **Funkhouser, G.** 1999: Twentieth-century summer warmth in northern Yakutia in a 600-year context. *The Holocene* 9(5), 629-43.

Hustich, I. 1956: Notes on the growth of Scotch pine in Utsjoki in northernmost Finland. *Acta Botanica Fennica* 56, 1-13.

Jacoby, G.C. and **D'Arrigo, R.D.** 1995: Tree ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles* 9, 227-34.

Jalkanen, R. 1993: Abiotic and biotic diseases of the northern boreal forests in Finland. In Jalkanen, R., Aalto, T. and Lahti, M.-L., editors, *Forest pathological research in northern forests with a special reference to abiotic stress factors. Extended SNS meeting in forest pathology in Lapland, 3-7 August 1992*. The Finnish Forest Research Institute. *Research papers* 451, 7-21.

Kienast, F., Schweingruber, F.H., Bräker, O.U. and **Schär, E.** 1987: Tree-ring studies on conifers along ecological gradients and the potential of single-year analyses. *Canadian Journal of Forest Research* 17, 683-96.

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

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

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

Kullman, L. 1991: Cataclysmic response to recent cooling of a natural boreal pine (*Pinus sylvestris* L.) forest in northern Sweden. *New Phytologist* 117, 351-60.

Lindholm, M. 1996: *Reconstructions of past climate from ring-width chronologies of Scots pine (Pinus sylvestris L.) at the northern forest limit in Fennoscandia*. PhD thesis, University of Joensuu, *Publications in Sciences* 40. 169 pp.

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

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

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

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

Pohtila, E. 1980: Climatic fluctuations and forestry in Lapland. *Holarctic Ecology* 3, 91-8.

Romell, L.-G. 1925: Växttidsundersökningar på tall och gran. *Meddelanden från Statens Skogsförsöksanstalt* 22, 45-116.

Schmitt, U., Jalkanen, R. and **Eckstein, D.** 1999: Cambium dynamics. In Hicks, S., Jalkanen, R., Aalto, T., McCarroll, D., Gagen, M. and Pettigrew, E., editors, *FOREST (Forest Response to Environmental Stress at Timberlines). Sensitivity of northern, alpine and mediterranean forest limits to climate - Final Report. EU-contract ENV4-CT95-0063*. Oulu: University of Oulu, pp. 40-3.

Sirén, G. 1961: Skogsgränstallen som indikator för klimatfluktuationerna i norra Fennoskandien under historisk tid. *Communicationes Instituti Forestalis Fenniae* 54(2), 1-66.

StatSoft 1996: *STATISTICA for Windows*. StatSoft Inc., Tulsa, OK, USA.

Stokes, M.A. and **Smiley, T.L.** 1968: *An Introduction to Tree-Ring Dating*. Chicago: University of Chicago Press, 73 pp.

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

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

Tuomenvirta, H., Alexandersson, H., Drebs, A., Frich, P. and **Nordli, P.Ø.** 1998: *Trends in Nordic and Arctic extreme temperatures*. Norwegian Meteorological Institute, Oslo. *DNMI report* 13/98 klima, 37 pp.

Vaganov, E.A. 1999: Influence of snowfall and melt timing on tree growth in subarctic Eurasia. *Nature* 400, 149-51.

Villalba, R., Boninsegna, J.A., Veblen, T.T., Schmelter, A. and **Rubulis, S.** 1997: Recent trends in tree-ring records from high elevation sites in the Andes of northern Patagonia. *Climate Change* 36, 425-54.

Walsh, J.E. 1995: Continental snow ice cover and climate variability. In Martinson, D.G., Bryan, K., Ghil, M., Hall, M.M., Karl, T.R., Sarachik, E.S., Sorooshian, S. and Talley, L.D., editors, *Natural climate variability on decade-to-century timescales*. Washington: National Academy Press, pp. 49-59.

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

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

Submitted to *Dendrochronologia*, January 31st 2000