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Droughts and rainfall in south-eastern Finland since AD 874, inferred from Scots pine ring-widths

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Early summer (May–June) precipitation variability was reconstructed for south-eastern Finland using a millennia-long (from 874 to present day) ring-width chronology of Scots pine (*Pinus sylvestris* L.). A regression-based calibration model using tree-ring widths captured 31% of the variance in the observed precipitation record. The time stability of the reconstruction equations was studied by cross-calibration/verification. Additional verification was provided by a neighbouring weather station. Interannual variability as well as periods of abundant rainfall and drought are presented. The three most humid early summers occurred in 1090, 1094 and 1924, and the driest in 939, 943 and 1116. Prolonged periods of severe drought took place during 1173–1191, 1664–1680 and 1388–1402, and wet spells during 1081–1095, 1433–1447 and 1752–1765. Fast Fourier transform showed the most dominant cyclic behaviour on interdecadal time scales.

Introduction

Tree-rings of Scots pine (*Pinus sylvestris* L.) from northern Fennoscandia have frequently been used for climatic reconstructions, expanding existing instrumental records backwards in time. Growth and temperature relations have been studied in the forest-limit region, producing long-term temperature proxies (Erlandsson 1936, Siren 1961, Briffa *et al*. 1988, Lindholm 1996, Lindholm *et al*. 1996, Gervais and MacDonald 2000, Lindholm and Eronen 2000, Kirchhefer 2001). Forest-limit pines are known to have a strong summer temperature signal. However, the northern pines also respond significantly to variation in early-summer (May) precipitation, although this is considered secondary to the temperature forcing (Lindholm 1996). A temperature- and precipitation-related reconstruction model for North Atlantic Oscillation was recently produced in the region by Lindholm *et al*. (2001). Furthermore, Lindholm *et al*. (1997) showed that a network of Scots pine chronologies in south-east Finland was sensitive to summertime rainfall. The work is continued here by a 1250-year pine chronology in a first experimental attempt to reconstruct annual variability in rainfall and droughts in Finland.

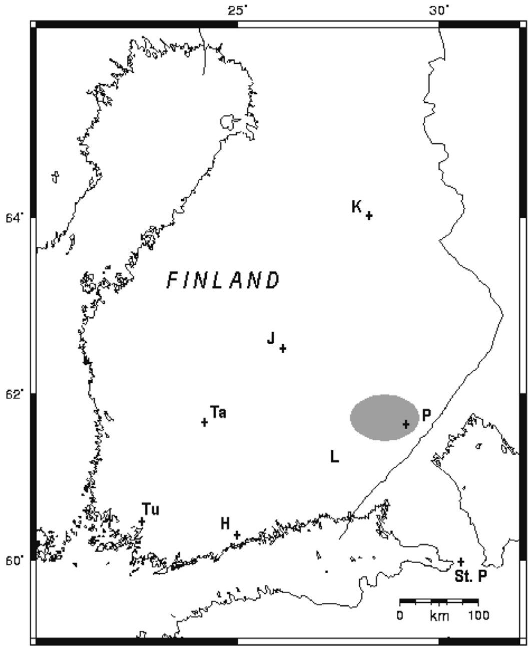

Fig. 1. Shaded oval indicates the approximate limits of the study area. The weather stations at Punkaharju, Lappeenranta, Kajaani, Jyväskylä, Tampere, Turku, Helsinki and St. Petersburg are shown as crosses with corresponding initials.

Scots pines have been used previously in drought and rainfall reconstructions. Jacoby *et al*. (1999) reconstructed summer and annual variation in precipitation in the eastern part of Central Mongolia, Oberhuber and Kofler (2002) reconstructed spring precipitation in the Alpine valley in Austria and Thomsen (2001) winter precipitation in the north-western Siberian Plain in Russia. Scots pine has the widest geographical distribution of all pines (Mirov 1967), and different forcing mechanisms control its growth in climatically different regions. Thus, the species should provide opportunities for reconstruction of various climatic phenomena.

Virtually no studies in Finland focus on annual rainfall variation prior to the period of modern meteorological observations. Vesajoki and Tornberg (1994) collected historical writings on climatological conditions in south-western Finland. These data also include some extreme annual rainfall and drought events. In addition, some more or less discontinuous precipitation measurements were carried out in Turku, along the south-eastern coast of Finland, during the late 18th and early 19th centuries (Wild 1887). Dendroclimatological evidence can further our knowledge on annual and decadal scale fluctuations of rainfall and droughts, which are important for a variety of human activities, such as agriculture, water management, forest fire research and monitoring long-term environmental changes. This is the main purpose of the work at hand.

Materials and methods

Study area

The study area covers a region surrounding the central parts of the Lake Saimaa Basin, between 61°–62°N and 29°–30°E, in the province of South Savo, in south-eastern Finland (Fig. 1). The region lies within the south boreal forest zone (Ahti *et al*. 1968). This region is part of the Vuoksi lake and river system, and the landscape is dominated by the Saimaa Lake Complex and thousands of small lakes that drain into this large basin. The Vuoksi outlet channel allows the waters to drain into Lake Ladoga and further into the Gulf of Finland.

Ring-width and climate data

Ring-width samples were collected from standing (living) trees, construction timber and subfossil natural wood (Fig. 2: upper panel). Lindholm *et al*. (1997) have earlier described the collection of samples from standing trees and the building of six site chronologies in the region (Fig. 1). Dead wood material comes from structures of numerous historical buildings in the study area as well as from logs found at the bottom of small lakes in the central parts of the Lake Saimaa Basin. The millennial master chronology, from 48 standing and 91 dead trees, was briefly reported by Lindholm *et al*. (1998–1999).

Climate data, i.e. mean monthly temperatures and total precipitation sums, came from two local weather stations. These stations (Fig. 1) are located at Punkaharju (61°48´N and 29°20´E) and at Lappeenranta (61°30´N,

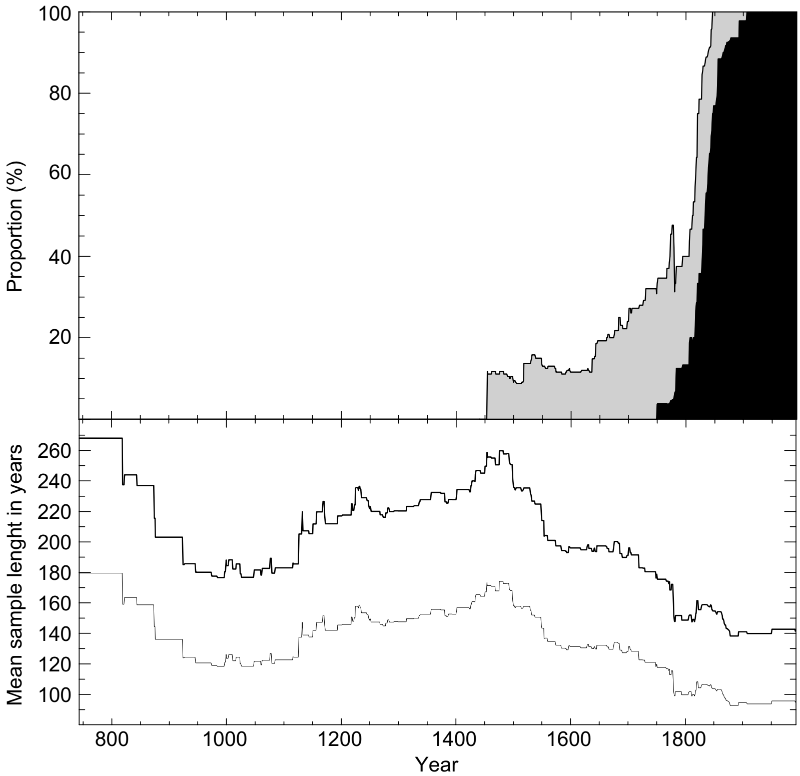

Fig. 2. Chronological material shown in upper part of the figure as proportions of living trees (black area), historical construction wood (grey area) and subfossil wood collected from small lakes (white area). In the lower part, the thick line represents the temporal evolution of the mean sample length. The thin line represents a value two-thirds of the former, indicating the expected maximum wavelength of climatic variations with no more than half of the amplitude preserved in the chronology after standardization.

28°11´E). The earliest available measurements at these stations were made in 1905 at Punkaharju and in 1886 at Lappeenranta. In addition, monthly total precipitation sums from Helsinki (60°10´N and 24°57´E), Tampere (61°30´N and 23°46´E), Jyväskylä (62°14´N and 25°44´E) and Kajaani (64°13´N and 27°46´E) weather stations (Fig. 1) were used for spatial comparison and verification. Early meteorological observation series from Turku and St. Petersburg, covering the latter part of the 18th century (Wild 1887), were used for early validation.

Building the chronology and measuring its reliability

Cores from living trees and old buildings were extracted by an increment borer. Samples taken from tree trunks from lake bottoms were sawn into discs after lifting the trunks to the surface. The ring-widths were measured to the nearest 0.01 mm, and a mean tree series was estimated from 2–4 cores/radii for each tree.

The ring-width series were cross-dated, which is one of the basic principles of dendrochronology (e.g. Fritts 1976, Schweingruber 1988). Cross-dating is based on the general year-to-year agreement (synchrony, association, correlation) between variations in tree-ring series taken from different sides of a tree, different trees or different site chronologies. According to Fritts (1976), this synchrony is evidence of the limiting effect of climatic variation on tree growth. Several numerical procedures (Holmes 1983, van Deusen 1992, Aniol 1989) were applied in addition to visual comparison of ring-widths on the light table.

By definition, a tree-ring chronology is the average of cross-dated indices, i.e. standardized measurement series (e.g. Fritts 1976, Cook *et al*. 1990). We have applied a standardization procedure which has frequently proven successful in North European pine forests (Briffa *et al.* 1990, Lindholm *et al.* 2000, 2001). Ring-width variability in measurement series is generally considered to be a reflection of the impact of a variety of environmental factors. According to Cook (1985, 1990), this variability includes an age-size related trend, the disturbance pulses caused either by a local endogenous disturbances or by a standwise exogenous disturbances. There exists also a largely unexplained component of variability collectively referred to as error, which includes measurement errors. Since the tree-ring material of this work was sampled from southern, closed boreal canopies, it is reasonable to expect a multitude of disturbance pulses (factors) to be more or less present in the series. In order to remove these factors, and thereby to strengthen the common signal in the resultant chronology, a spline function (Cook and Peters 1981) was fit to the original ring-width measurement series of each tree, which were divided by the values of these functions. The rigidity of the spline was determined to be 67% of the length of each individual time series (50% frequency response cut-off) as suggested by Cook (1985). This criterion ensures that large amounts of low-frequency variance will not be lost in growth trend removal. Consequently, no more than one half of the amplitude of the variations with wavelength two thirds of the measurement series length can be expected to be preserved in the resulting series or in the averaged chronology (Fig. 2: lower panel).

The 1250-year chronology was built by averaging annual index values by biweight robust estimation (Cook 1985). The tree-ring data from closed-canopy forests are expected to contain a higher level of outlier contamination than tree-rings from tree limits. The use of the biweight robust mean admits the likelihood of contamination of not normally distributed properties such as endogenous disturbances (Cook *et al*. 1990). According to Cook *et al*. (1990), the biweight mean iteration of tree-ring width index (TRWI) in the year t is a sum of products of symmetric weight function and TRWI.

Mean interseries correlation (r_{bt}) was used as a measure of the strength of the common signal in a chronology, and Expressed Population Signal (EPS) as a measure of chronology confidence (Wigley *et al*. 1984, Briffa and Jones 1990). The EPS is calculated as a function of r_{bt} and the series replication, according to an equation derived by Wigley *et al*. (1984).

To adjust variance to sample size, each annual value was scaled by the procedure presented by Osborn *et al*. (1997). That is simple scaling of the average time series ($TRWI_t$), expressed as a departure from its long-term mean, by the effective number (n') of independent samples available in each year (*see* Osborne *et al*. 1997 for a detailed description of n').

Climatic calibration

The relationship between tree growth and climate was studied by means of response and transfer functions, a procedure commonly called calibration (Fritts *et al*. 1971, Fritts 1976, Guiot *et al*. 1982, Guiot 1990). Growth responses of pines to climatic factors were quantified by Pearson's product moment correlation, which was calculated between the tree-ring width chronology and monthly mean temperatures and total precipitations. Prior growth values (at positions $t-1$, $t-2$ and $t-3$) were included in the analysis to quantify the strength of biological preconditioning (Fritts *et al*. 1971).

Linear transfer functions were derived by ordinary least squares and step-wise multiple regression to reconstruct climate from tree-rings (Fritts 1976, Guiot 1990). Generally, they rely on the most significant relationship between climatic factors and tree-ring indices. The modern (20th century) part of the master chronology was used to model the most important precipitation seasons and individual months using model structure $t-2$, $t-1$, t, $t+1$, and $t+2$. Thus, in addition to the concurrent growth in year t, two succeeding (lagging) and preceding (leading) growth variables were simultaneously used. Entry and removal criteria of the step-wise multiple regression were the predetermined probability of F as 0.05 for the former and 0.10 for the latter (e.g. Lindholm 1996). This procedure was repeated for the various seasons and months to study their reconstruction ability and then to study the time stability of the equation. The initial models were built using climate data from Punkaharju for calibration and climate data from Lappeenranta for verification. The later models were built using only Punkaharju data for both calibration and verification.

A cross-calibration/verification exercise (e.g. Briffa *et al*. 1990, 1995, Lindholm and Eronen

2000, Lindholm *et al*. 2001) was carried out to test the general form of the regression equations. Calibration was done using weather data from Punkaharju station from 1918 to 1985. Both the dependent and independent variables, tree-rings and precipitation series from Punkaharju weather station were divided into two groups of roughly equal length (1918–1951 and 1952–1985). Models were built separately for these subperiods. When satisfied with the submodels, the entire calibration period, 68 years between 1918 and 1985, was utilized for building the final model. Additional verification was achieved for the period 1887–1917 using independent data from Lappeenranta station. The verification statistics applied here, i.e. reduction of error (RE), coefficient of error (CE) and first difference sign test, are described by Fritts (1976), Briffa *et al*. (1988) and Fritts *et al*. (1990).

Spatial coverage of reconstruction was studied in terms of verification, that is, the model retained in transfer function model was additionally validated against instrumental precipitation data of four different weather stations ca. 200–300 km from the study area (Fig. 1).

Spectral analysis

Fast Fourier transform using the Blackman and Tukey (1958) method was carried out to estimate the power spectrum of a given reconstruction. Estimation deals with the choice of window shape and width (M). Barlett window of width M = 110 was exploited here. The confidence levels of spectral estimates were provided applying a chi-square test. The procedure has been widely used in all fields of paleoclimatology. For a detailed description of the method and comparison with other spectral approaches, *see* e.g. Ghil *et al*. (2002).

Results

Correlation between growth and climate

Early summer rainfall was a major factor in pine growth (Table 1). Rainfall during concurrent growing seasons had significant values in March, May and June. The only significant monthly temperature variable was the previous year's August. Growing season temperatures had virtually no impact on the radial growth of pine. Prior growth ($t - n$, $n = 1…3$) had a statistically significant impact on growth in year t.

Transfer functions

May, May–June and April–June seasons yielded significant ($p < 0.01$) reconstruction models (Table 2, upper part). All of these also passed the first difference sign test at a 0.95 level of significance and had positive values for RE and CE. This is generally taken as an indication of

Table 1. Correlations between the tree-ring index and regional temperature and precipitation values of previous (lower case letters) and concurrent (upper case letter) over the calibration period. Significant correlations at the 1% level are denoted as (**) and at the 5% level as (*). A1, A2 and A3 are the autocorrelations in tree-ring widths of order from one to three.

	Previous year								
1918–1985	a	s	o	n	d	A1	A2	A3	
Temperature	–0.29*	0.01	0.03	0.07	0.16	0.56**	0.32**	0.25*	
Precipitation	0.09	–0.06	0.17	–0.01	0.12	0.12			
	Concurrent year								
1918–1985	J	F	M	A	M	J	J	A	S
Temperature	0.21	0.18	0.23	0.22	0.01	–0.18	–0.01	0.14	0.22
Precipitation	–0.02	0.17	0.27*	0.09	0.32**	0.50**	0.10	–0.03	0.11

a reasonable reconstruction skill (Fritts 1976, Fritts *et al*. 1990). Of these seasons, May–June had the highest explained variance (R^2 and r^2). The results of the verification of this season showed that 35% of the dependent precipitation was explained over the 31-year early verification period by tree-rings.

The first half of the formerly applied calibration period showed better reconstruction skill in terms of R^2 but poorer verification statistics (Table 2: lower panel); RE yielded a reasonable model, but CE had a slightly negative value and the sign test was not statistically significant. The second half gave a poorer ability for reconstruction but better results in verification; RE and CE yielded a reasonable model and the result of sign test was statistically significant ($p < 0.01$). Both models correlated significantly ($p < 0.01$) over the independent instrumental data.

Although the cross-calibration/verification was not entirely satisfactory (Table 2: lower part), the results justified the calibration of a final transfer function using all available data. The final transfer function was formulated as:

$$P(t) = 94.6 + 65.8 \times \mathrm{TRWI}(t) \quad (1)$$

where $P(t)$ is the estimated early-summer (May and June) precipitation sum in millimetres in year t, and TRWI(t) is the tree-ring width index value for the year t. The model accounted for 31% of the observed variation in precipitation. Standard error of the estimate was 30.4 mm. The Durbin-Watson (1951) d-test showed that no statistically significant serial correlation was present (0.01 level) in the residuals from this regression.

The first reconstructed year was AD 874, when the sample size of the chronology was five trees and EPS values were more than 0.85 (Fig. 3: lower plot), both of which are generally considered satisfactory for dendroclimatic work (Wigley *et al*. 1984, Briffa and Jones 1990). Since the year 874, the EPS values stayed above 0.85 rather well, except for a short period between 1111 and 1157. This slight drop in chronology confidence was a consequence of both relatively lower r_{bt} and n. The long-term mean between 874 and 1993 was 93.1 mm with a standard deviation of ±17.5 mm.

Table 2. Calibration and verification statistics for selected months and seasons (upper part). Because the May–June season is superior in calibration performance, it is calibrated and verified over the two periods of equal length in order to examine the time stability of the equation (lower part). Climate data from two stations are used: Punkaharju data for calibration and Lappeenranta data for early verification. Coefficient of determination (R^2), correlation (r), reduction of error (RE) and coefficient of error (CE) statistics are described in the text. Sign test is calculated as a ratio of correct (C) and incorrect (I) first differences. Statistically significant results at the 1% level are denoted as (**) and at the 5% level as (*).

Season/ month	Model retained	R^2	r	r^2	RE	CE	Sign Test C/I
Calibration period: 1918–1985			Verification period: 1887–1917				
May	(t)	0.10	0.53**	0.28	0.14	0.14	22/8*
Jun	(t – 1, t)	0.30	0.34	0.12	0.05	0.03	20/10
May–Jun	(t)	0.31	0.59**	0.35	0.16	0.14	22/8*
May–Jul	(t, t + 1)	0.29	0.38*	0.15	0.04	0.02	19/11
Apr–Jun	(t)	0.25	0.51**	0.26	0.11	0.08	21/9*
Apr–Jul	(t)	0.22	0.41*	0.17	0.07	0.05	21/9*
Mar–Jun	(t)	0.31	0.41*	0.17	–0.01	–0.17	19/11
Mar–Jul	(t)	0.26	0.34	0.11	–0.02	–0.13	18/12
Calibration period: 1918–1951			Verification period: 1952–1985				
May–June	(t)	0.36	0.44**	0.19	0.23	–0.02	19/14
Calibration period: 1952–1985			Verification period: 1918–1951				
May–June	(t)	0.19	0.60**	0.36	0.36	0.22	25/8**

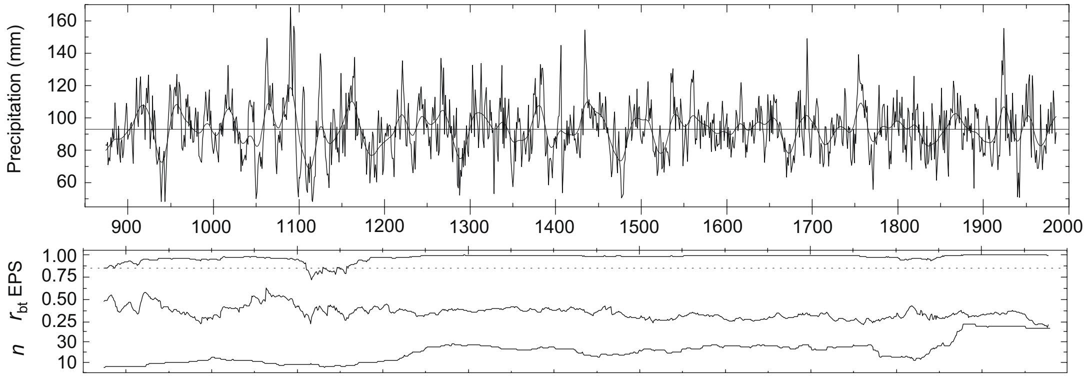

Fig. 3. Annually resolved reconstruction of early-summer rainfall and droughts between 874 and 1993 (upper plot). A low-pass filter, i.e. a 28-year cubic spline (thick line), emphasizes long-term variations at wavelengths of roughly ten years or longer. The horizontal line represents the long-term mean of the reconstruction. In the lower plot, Expressed Population Signal (EPS), correlation between trees (r_{bt}) and sample size (n) express chronology reliability. The dashed horizontal line represents the 0.85 level of EPS.

Early-summer rainfall and drought in south-eastern Finland since AD 874

The three wettest early summers in the region as recorded by pine ring-widths, occurred in 1090, 1094 and 1924 (Table 3). Each of these was clearly graphically visible (the upper plot of Fig. 3). Years 1090 and 1094 were also included in the period between 1081 and 1095 in the list of prolonged rainy periods (Table 4). In 1924, the reconstructed May–June precipitation was 155 mm, which should be compared with the 180 mm recorded in the instrumental data. The latter value was also the highest recorded value at the Punkaharju weather station.

The driest early summers reconstructed were in 939, 943 and 1116 (Table 3). The first two occurred during a spell when precipitation was diminished for more than ten years (Fig. 3, upper plot), as can also be observed in the list of prolonged rainless periods (Table 4). The third driest year, 1116, was preceded by the fourth driest. However, these years belonged to the period of weak chronology reliability indicated by EPS (asterisks in Tables 3 and 4), as mentioned above. Two of the driest years listed (Table 3), 1940 and 1942, occurred during the calibration period.

Episodes of prolonged wet and dry conditions were evident and superimposed on interannual fluctuations in humidity conditions (Fig. 3: upper plot). The most prolonged wet periods occurred in 1081–1095, 1433–1447 and 1752–1765 (Table 4). The first period (1081–1095) included five of the wettest individual early summers. This was also reflected in the standard deviation (Table 4) of that period, which was relatively high.

Table 3. The years with the wettest and driest early summers (874–1985), presented with corresponding estimated rainfall totals. Events modelled from chronology having an Expressed Population Signal (EPS) value below 0.85 are denoted as (*).

Wettest years	Rainfall (mm)	Driest years	Rainfall (mm)
1090	168.3	939	48.2
1094	156.7	943	48.3
1924	155.4	1116*	48.3
1434	154.4	1115*	49.3
1095	152.2	1050	50.1
1063	149.3	1477	50.5
1694	149.0	1942	50.8
1406	144.8	1099	51.1
1091	143.7	1940	51.2
1062	140.3	1478	51.6
1125	139.7	1288	52.2
1754	139.2	1479	53.0
1165	137.5	1328	53.2
1435	137.4	1408	53.6
1266	137.0	1117	53.9
1089	136.4	1110	53.9
1925	135.6	944	54.3
1922	135.4	1051	54.4
1221	135.3	1771	55.8
1313	133.7	1109	56.0

Table 4. Prolonged periods of humidity and drought. The number of years (n) in each period as well as standard deviation of annual precipitation totals are shown. Events modelled from chronology having an Expressed Population Signal (EPS) value below 0.85 are denoted as (*).

Wettest periods			Driest periods		
Period	*n*	SD	Period	*n*	SD
1081–1095	15	22.3	1173–1191	19	10.8
1433–1447	15	16.7	1664–1680	17	8.3
1752–1765	14	11.5	1388–1402	15	10.1
1374–1387	14	13.8	933–946	14	11.5
1060–1072	13	17.2	1107–1119*	13	9.4
908–919	12	10.2	1048–1059	12	12.9
1155–1165	11	12.1	1470–1481	12	13.3
1012–1022	11	9.5	1029–1040	12	7.9
1945–1955	11	11.5	1285–1295	11	11.7
953–962	10	8.6	1766–1776	11	10.6

The prolonged droughts were slightly longer in duration and less variable in terms of standard deviation than those of prolonged wet spells. The longest droughts were experienced during 1173–1191, 1664–1680 and 1388–1402. The period between 1173–1191 initially occurred as a rapid drop in rainfall and then as a gradual rise back to the long-term average level of precipitation (*see* Fig. 3: upper plot).

Interestingly, the period between 1752 and 1765, the third in the list of prolonged wet spells, was immediately followed by a period in 1766–1776 (Table 4). The latter was tenth in the list of prolonged dry spells.

A couple of periods in which the variation decreased and stabilized around the long-term mean were present. From the shortest to the longest, these periods were 1780–1830 and 1540–1650 (Fig. 3: upper plot). The period 1540–1650 was rather exceptional in its length and lack of extreme rainfall events. Perhaps expectedly, none of these relatively even periods showed up among the most extreme events (*see* Tables 3 and 4).

Table 5. Statistics for spatial verification. The approximate distance (*D*) from the study area as well as verification statistics (*see* Table 2) are included. Significant correlations at the 1% level are denoted as (**) and at the 5% level as (*).

Location	*D* (km)	*r*	RE	CE	Sign test
Jyväskylä	200	0.44*	0.04	–0.01	19/11
Tampere	300	0.41*	0.05	–0.002	17/13
Helsinki	300	0.36*	0.12	0.12	21/9*
Kajaani	300	0.01	–0.13	–0.15	dnc

Spatial verification

The precipitation time series from Jyväskylä, Tampere and Helsinki (Fig. 1) showed significant correlations with the reconstruction, and reasonable skill of reconstruction in terms of RE (Table 5). However, the statistic CE was positive only for the Helsinki data. Verification against Helsinki data yielded the only significant result in the sign test. However, verification against precipitation in Kajaani had almost no correlation with negative (failed) RE and CE, and therefore, the sign test was not performed.

Spectral properties

There was an indication that the power spectrum of the early-summer rainfall reconstruction (Fig. 4) may have contained concentrations of cyclic behaviour on timescales of about 0.043, 0.033 and 0.018 cycles per year. These cycles corresponded to periods of approximately 23, 30 and 57 years, respectively. Peaks of oscillations at somewhat weaker power were also observed on timescales of about 0.137 and 0.100 cycles per year, corresponding to periods of 7 and 10 years, respectively.

Discussion

Spatial and temporal representativeness

One way to validate the results is to study how widely representative the reconstruction is geographically. According to Heino (1994), spatial correlations of precipitation are considerably lower than for temperature in Finland. An $r = 0.5$ value was reached at a distance of 300–400 km to the north and the south between the years 1961 and 1990 when using various instrumental datasets (Heino 1994). The spatial verification exploited here (Table 5) yields results consistent with those of Heino (1994). He explained the poor correlation for this part of the country (Kajaani in Table 5) and south-eastern Finland as being due to topography. The routes of topographic depressions bringing precipitation to Finland are most often from the south-west to the north-east. The same direction was found to bear the greatest spatial rainfall correlations by Heino (1994).

The reconstruction models developed in this work retrieved 19%–36% of the independent climate variance. The temporal stability of the regression equations requires further experiments. However, we consider these initial results to be encouraging for future research. Compared with earlier precipitation reconstruction models employing Scots pine ring-widths as predictors, our models show an average performance (Table 6).

Reconstruction was compared with early meteorological observations (precipitation sums of May and June) from Turku (1750–1794) and St. Petersburg (1758–1767) provided by Wild (1887). Correlation between the early-summer precipitation reconstruction and the Turku precipitation record was 0.317 ($p < 0.05$). Correlation between reconstruction and the St. Petersburg precipitation series was 0.681 ($p < 0.05$). During the time of these historical precipitation observations, chronology was constructed mainly from dead wood material (*see* Fig. 2: upper panel), that is, samples which were not used to model the tree growth climate relationship in Eq. 1. Bearing in mind the geographical distance between the actual study site and locations of these two meteorological observations, these early observations can be thought of as strong supporting evidence for the reliability of our precipitation estimates.

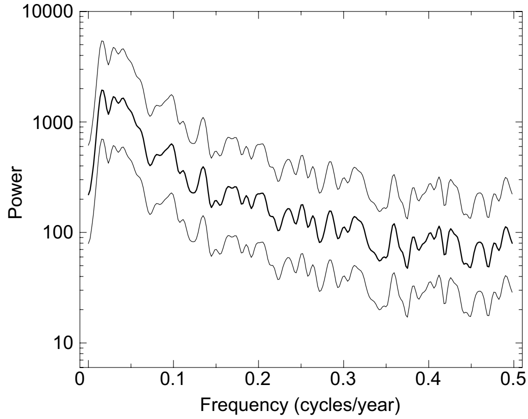

Fig. 4. The power spectrum (Blackman-Tukey) shows peak power between frequencies of zero and 0.05 cycles per years (thick line), with corresponding error bars at the 0.95 uncertainty range for spectral estimates (thin lines).

Documentary events of extremes

Vesajoki and Tornberg (1994) examined annual events from various historical sources which were recorded as favourable or unfavourable for

Table 6. Description of various precipitation-related reconstructions and model performance from different parts of the northern hemisphere (collected from the corresponding literature sources). All of the studies employ tree-ring widths of Scots pine.

Region	Season	R^2	Reference
Tyrol, Austria	April–June	0.30	Oberhuber and Kofler 2002
Ural Mountains, Russia	October–May	0.48	Thomsen 2001
Mongolia	Annual	0.54	Jacoby *et al*. 1999
Mongolia	June–August	0.42	Jacoby *et al*. 1999

agricultural activities in south-west Finland. The great majority of these events occurred during the 17th century, and only the year 1694 appeared as a dry early summer here (Table 3). However, the summer of 1693 has also been known dry, while the summer of 1695 as very rainy (Vesajoki and Tornberg 1994). While the period between 1664 and 1680 appeared in our data as the second longest period of drought based on south-eastern pines (Table 4), the cultivated vegetation in south-western Finland suffered from growing season drought during the late 1670s and the 1680s (Vesajoki and Tornberg 1994). Furthermore, this prolonged rainless period, as recorded by south-eastern pines, seems to precede the great famine years of the 1690s, which were, however, rainy (Neumann and Lindgren 1979).

Various difficulties are to be expected when comparing historical data of any kind with proxy records (*see* e.g. Bradley 1985, Vesajoki *et al*. 1996) such as tree rings. Harvest failures or very successful harvests may be affected by many different factors depending on the climatic response of different species under cultivation. Prolonged rains or droughts during the growing season are considered as most harmful for the crop (and thereby recorded in agricultural diaries) when they occur during late summer. However, variations in precipitation during late summer are not supposed to be recorded by the tree-rings of the present study due to the strongest response of pines to rainfall occurring in May and June (*see* Table 1). Moreover, the geographical distance between the two areas (south-western *vs*. south-eastern Finland) is another factor biasing comparison (*see* Table 5).

Periodicity

Climate variability may be divided into interannual, interdecadal and century-scale oscillations, the latter two being roughly 15–35 and 50–150 years, respectively. They may also be divided by being either externally forced or intrinsic to the natural climate system. The former includes the signals of solar variability, among others, and the latter, atmospheric or oceanic circulation signals. The solar signal is commonly represented by the sunspot cycle of 11 years, the Hale cycle of 22 years and the Gleissberg cycle of ca. 80 years. North Atlantic Oscillation (NAO) is known to bear concentrations of spectral power around periods of 7.3–8.0 and 20 years during the secular period (Rogers 1984). Most of the above-mentioned periodic features, except the Gleissberg cycle, could be considered as potential forcing behind the variation of the reconstruction (Fig. 4) if judging by the periodicity of variance. Further investigations are recommended on the features of spectral evolution through the reconstructed variations of precipitation.

Some limitations of the methods applied

The present work is based on the assumption that the uniformitarian principle (for dendrochronological applications, *see* Fritts (1976), Fritts and Swetnam (1989)) holds. All of the samples included in the chronology are expected to come from a population responsive to the May–June precipitation. This assumption is supported by the consistent strength of the common growth signal in a chronology (Fig. 3: lower plot). In addition, comparison of reconstruction with early weather observations from Turku and St. Petersburg further illustrated the temporal stability of the model during the earlier spell (18th century).

Precipitation alone may be an insufficient indicator of the amount of water available to plants, as the effect of rainfall is determined by the ambient temperature and other factors affecting evaporation and transpiration. Precipitation is not in every case the best variable to maximize the efficiency of a model. Such measures as number of precipitation days (e.g. Sato *et al*. 1989, Woodhouse and Meko 1997) or different humidity and drought indices (e.g. Cook and Jacoby 1977) were not tested in the present study but remain to be studied later.

The results of climatic response on radial growth of Scots pine represented here are mostly parallel to those of earlier literature. According to Mikola (1950), reduced early-summer precipitation can have a negative impact on growth in southern Finland, especially on trees growing on dry lands. However, Mikola (1950) did not employ actual correlations between growth and precipitation. Henttonen (1984) examined the radial growth of Scots pine at several sites in southern Finland. She found that the effect of precipitation sum (May–July) was significant in every studied site in this area. Based on her correlation analysis, the precipitation sum seemed to be more important for the radial growth of Scots pine in southern Finland than the second important factor, the effective temperature sum of the latter part of the summer. The negative effect of high effective temperature sums during the latter part of the previous summer in two of the studied sites of Henttonen (1984) is a parallel result to the significant, negative response to the previous August of the pines of the present study. However, results shown here are in contradiction to those of Laitakari (1920) in southern Finland, who found that temperature in April had a significant effect on radial growth of pines. The present work further points out the importance of deriving response functions from data originating from nearby weather stations. The growth response to different precipitation variables rapidly decreases with increased geographical distance between study site and weather station (Tables 2 and 5). We associate this with a lower spatial correlation in precipitation variables compared with spatial correlation in temperature (cf. Heino 1994).

It should be borne in mind that moving from the northern forest-limit zone towards the south, factors other than climate become more determinant on pine growth (e.g. Lindholm *et al.* 2000). Due to this fact alone, the coefficient of determination (R^2) over the calibration period in the present study is expected to not be as high as in some previous studies in the forest-limit zone (e.g. Lindholm 1996, Lindholm and Eronen 2000). The effect of non-climatic factors, however, should be partly eliminated by the standardization method exploited in this paper. Another factor affecting the relative deterioration of the coefficient of determination, as discussed earlier, is the more intricate nature of climatic factors affecting pine growth in southern, as compared with northern Finland, particularly in the forest-limit.

According to Wigley *et al.* (1984), EPS values greater than 0.85 may be deemed satisfactory for dendroclimatological purposes. The present chronology expresses EPS well above this over the majority of observations, the mean value of EPS being 0.97.

Conclusions

Ring-widths of Scots pine explained 31% of the variation in independent early-summer rainfall record. Reconstruction expanded spatially over several hundred of kilometres to the west and the south. Interdecadal variation, superimposed by considerable annual variation, was present through the early-summer precipitation reconstruction. However, there is an implication of exceptional periods 1780–1830 and 1540–1650, when the variance was diminished. A prominent shift from prolonged wet spells to a relatively rainless period occurred in the middle of the 1760s. Comparison with historical documents yielded somewhat consistent results and suggested that prolonged dry early-summers preceded the great famine years of the 1690s.

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