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A 7400-year tree-ring chronology in northern Swedish Lapland: natural climatic variability expressed on annual to millennial timescales

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Abstract: Tree-ring widths from 880 living, dry dead, and subfossil northern Swedish pines (*Pinus sylvestris* L.) have been assembled into a continuous and precisely dated chronology (the Torneträsk chronology) covering the period 5407 BC to AD 1997. Biological trends in the data were removed with autoregressive standardization (ARS) to emphasize year-to-year variability, and with regional curve standardization (RCS) to emphasize variability on timescales from decades to centuries. The strong association with summer mean temperature (June–August) has enabled the production of a temperature reconstruction for the last 7400 years, providing information on natural summer-temperature variability on timescales from years to centuries. Numerous cold episodes, comparable in severity and duration to the severe summers of the seventeenth century, are shown throughout the last seven millennia. Particularly severe conditions suggested between 600 and 1 BC correspond to a known period of glacier expansion. The relatively warm conditions of the late twentieth century do not exceed those reconstructed for several earlier time intervals, although replication is relatively poor and confidence in the reconstructions is correspondingly reduced in the pre-Christian period, particularly around 3000, 1600 and 330 BC. Despite the use of the RCS approach in chronology construction, the 7400-year chronology does not express the full range of millennial-timescale temperature change in northern Sweden.

Key words: Dendroclimatology, tree rings, climate, summer temperature, *Pinus sylvestris*, northern Scandinavia, Holocene.

Introduction

Climatic change studies generally recognize both a natural and an anthropogenic component influencing the climate in the twentieth century (e.g., Mitchell *et al.*, 2001). However, the relative importance of these two factors is debated and requires a better capability to estimate the role of natural variability in the climate system. Instrumental observations cover only the last 100–200 years and are likely to be affected by anthropogenic greenhouse-gas emissions. Therefore, natural climate variability can be better assessed by combining the instrumental record with other indirect or inferred records of climate in the pre-industrial era. These so-called proxy records should preferably have high resolution and good dating control to allow precise identification of short (i.e., yearly) anomalies as well as multidecadal and longer variability, but also to allow rigorous calibration against recent instrumental records.

Trees growing close to their thermal limit of distribution, such as at high-latitude or high-altitude tree-lines, react to variations in

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the growing-season temperature through its influence on cambial activity (Tranquillini, 1979). In such localities, the widths of the annual tree-rings will tend to be proportional to the overall warmth of the summer. Hence, the interannual pattern of such tree-ring sequences can be used as a tool to reconstruct annually resolved histories of summer-temperature variability in areas where instrumental records are sparse, potentially for periods long before the instrumental observations began. Averaging the data derived from numerous tree-ring samples into mean chronologies, continuously linked to its present day, ensures absolute dating control and an enhanced expansion of common underlying growth forcing by reducing the random 'noise' contained in individual tree series (Fritts, 1976).

Scots pines (*Pinus sylvestris* L.) in northern Fennoscandia commonly reach an age of over 300 years, and may on some rare occasions grow for more than 600 years (Sirén, 1961; Bartholin and Karlén, 1983; Engelmark and Hofgaard, 1985). In northern Sweden, the juxtaposition of such old-living trees and dead trees from even older times, preserved on dry ground and in lake sediments, provides a rare opportunity to construct a temperature-sensitive ring-width chronology representing much of the Holocene. Extensive sampling in the Torneträsk area in northern Swedish Lapland in the 1970s and 1980s (Bartholin and Karlén, 1983; Bartholin, 1987) yielded a 1440-year reconstruction of annually resolved summer temperatures, covering the period AD 540–1980 (Briffa *et al.*, 1990; 1992). The Torneträsk tree-ring-based reconstruction has made an important contribution to the understanding of natural climate variability over the last millennium (Jones *et al.*, 1998; Briffa and Osborn, 1999; Mann *et al.*, 1999) and, in recent years, considerable effort has been made to extend this record into early-Holocene time within the framework of the European Community (the ADVANCE-10K project; see Briffa, 1999; Briffa *et al.*, 1999).

In this paper we present an updated, extended and considerably improved tree-ring-width chronology from the Torneträsk area covering the last 7400 years, from which we are able to deduce new information on natural temperature variability, on annual to millennial timescales, in the climate system of northern Sweden.

Area description

Our study area is located in the northwest of Sweden (Figure 1). Though this is well north of the Arctic Circle, the climate of this area is relatively mild and classed as Subarctic (Sonesson, 1974; Sonesson and Lundberg, 1974) influenced by the ameliorating effect of the Atlantic Ocean circulation, which conveys warm surface waters to the Norwegian Sea. The Scandinavian mountain range forms an effective barrier to the warm and moist air masses originating off the Norwegian coast, giving rise to a strong east/west gradient in continentality, i.e., in seasonal temperature variability and total precipitation.

The geology in this area is characterized by two main bedrock units: the Caledonian mountain range in the west with alpine relief, and the Precambrian basement in the east with rocks of low relief (Lindström, 1987). The majority of our field sites are located within the transition zone between these two main geological units, in particular in the Torneträsk area. The dominating physical feature of our study area is the large Lake Torneträsk at 341 m a.s.l., surrounded by mountains typically 1000–1500 m high. Lake Torneträsk covers an area of 340 km^2 and, although it is only some tens of kilometres from the Atlantic waters in the west, it drains to the Gulf of Bothnia about 300 km to the southeast.

Radiocarbon dated lake sediments in the area show that deglaciation took place at about 10 000 cal. years BP (Sonesson, 1974; Karlén, 1979; Barnekow, 1999). The final stages of the deglaciation were rapid over a wide area in northernmost Swedish Lapland, indicating that the ice sheet over the mountain range was thin when deglaciation started (Melander, 1980). Thus, the high alpine areas may have been ice-free well before the final deglaciation. These ice-free areas probably experienced early colonization of plants and trees while there was still ice in the valley floors (Barnekow, 1999; Kullman, 1999). The margin of the diminishing ice sheet retreated towards the east, thus obstructing water drainage in that direction (Melander, 1977). Therefore, meltwater in the Torneträsk basin had to drain towards the Norwegian fjords in the west through a canyon 80 m above today's lake level. When drainage towards the east eventually started, the lake surface was lowered successively, washing the glacial tills free of fine material and leaving a patchwork of washed tills and accumulations of fine material. The different stages of the proto-Lake Torneträsk are evident today from numerous erosional beach features and deltas located high up on the slopes surrounding the lake (Gretener and Strömquist, 1981).

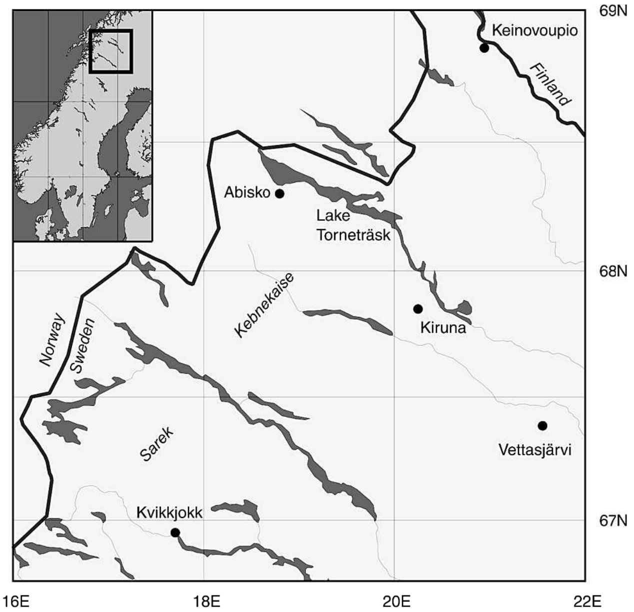

Figure 1 The field area is located close to the tree-limit area on the eastern slopes of the Scandinavian mountain range in the extreme north of Sweden.

The altitudinal tree-line, defined as a line connecting the highest patches of forest within a given slope or series of slopes of similar exposure (for terminology conventions, see Körner, 1998), consists of mountain birch (*Betula pubescens* ssp. *tortuosa*) at 600–800 m a.s.l. The present-day continuous boreal forest extends to the eastern end of Lake Torneträsk, where a distinct pine tree-line can be identified at 440 m a.s.l., while the pine distribution further to the west is of a disjunct relic type.

During the twentieth century there has been a major establishment of young trees in the tree-line forests and, presently, new pine germination is extensive throughout the region; for example, about 50% of the pine population at Abisko is less than 20 years old and about 75% is less than 50 years old (Stöcklin *et al.*, 1996). However, few pine trees have established above the mid-twentieth century tree-line and, thus, the recent expansion has been in tree density rather than in altitude.

Chronology construction

Material

The sampled pine trees that constitute the basis of the current chronology number 880 and can be divided into three distinct groups. We use the following terminology: living trees, dry dead trees (i.e., preserved on dry ground) and 'subfossil' trees found in lakewaters and lake sediments.

We have sampled living trees from sites around Lake Torneträsk. Two of these sites are situated at the limit of the present-day boreal zone at the eastern end of Lake Torneträsk, while three sites outside (i.e., west of) the boreal zone represent pine stands of a relic type. In sampling, we avoided coring close to branches, wounds or wedging at the base of the stem. We also avoided taking samples from the upslope or downslope side of trees growing on sloping ground where reaction wood may form. It is common dendrochronological practice to sample trees at breast height (e.g., Schweingruber, 1988). However, in many trees at the tree-line, the lowest branches grow at about, or even below, 1 m above the ground and sampling was therefore done at a variable height between 0.4 and 1.4 m up the stem. Two cores were sampled from each living tree using a standard increment borer.

Pines growing in this environment commonly produce large amounts of resin, which preserves the wood by inhibiting the growth of fungi for a long time after a tree has died. In recent decades, it has been possible to find dry dead wood on the ground over a wide area in northern Sweden. Unfortunately, this wood has also been collected for firewood, so that this source of wood has virtually disappeared from all but a few remote areas. This material has a wide age range, including trees that died more than 1000 years ago. The oldest dry dead wood remains we have found were from a tree that germinated a few years before AD 447, i.e., about 1560 years ago. This sample contains 365 rings and the tree must therefore have been preserved on dry ground for about 1200 years. This source of wood was sampled near to, or inside, present-day pine forests in the Torneträsk area by cutting stem disks with a chainsaw.

Trees that grow on or close to, lake shorelines may at some point fall into the water, where they can be preserved under near anaerobic conditions for thousands of years. Many small lakes, i.e., with an area less than about 0.1 km^2, have clearly visible tree remnants lying on top of, or in the surface layers of, the sediments. This source of subfossil wood in small northern Swedish lakes in the tree-line zone has been known to exist since the late nineteenth century (Gavelin, 1909) and it is this material that has served as one of the most important assets for reconstructing changes in Holocene tree-lines (Karlén, 1976; Kullman, 1995; Karlén and Kuylenstierna, 1996).

On clear calm days, subfossil logs may be easily identified from the air. We have undertaken systematic helicopter surveys of lakes over a wide area, from Keinovoupio in the north to Kvikkjokk in the south (Figure 1), and up to an altitude of about 1200 m. We discovered a wealth of subfossil pines in lakes up to a height of about 600 m a.s.l. However, we found no evidence of subfossil trees in lakes above this altitude. Only a limited number of the numerous lakes that contain subfossil logs have been sampled to date, and the majority of these sampled sites are concentrated in the Torneträsk area. In the lakes that have been sampled, we attempted to collect material from all existing, sizable subfossil pines located. With the aid of divers, it is probable that the large majority of trees have been found. The subfossil logs were recovered using manpower or a winch, and from each a stem disc was cut at about 0.5–2 m up the trunk. However, since the trees were in a varying state of disintegration, i.e., in most cases with roots and branches missing, it was not always possible to determine the exact sampling height of the sample. After sampling, the trees were restored to their approximate original position and marked on a detailed map.

Clean and sharp surfaces for measuring were prepared using a razorblade knife and chalk powder. All samples were prepared by this method, which provides very good detail. Tree-ring widths in two cores from each living tree, and a minimum of two radii in most stem discs, were measured to the nearest 0.01 mm and the data were stored on computer files using standard tree-ring measurement systems. Within-tree radii were cross-checked for measurement error and averaged to produce a mean ring-width series for each individual tree.

Cross-dating

The interannual ring-width variability within each mean-tree series was compared against all other series using both statistical and graphical programs, e.g. CATRAS (Aniol, 1983) and TSAP (Rinn, 1996). This procedure is known as 'cross-dating' (a description of 'European style' cross-dating methodology is given in Schweingruber, 1988). In order to identify locally absent rings, eliminate measurement errors and ensure relative and absolute dating accuracy, the quality of the cross-dating was repeatedly checked with program COFECHA (Holmes, 1983). Problematic samples, such as samples with missing rings or a distorted growth pattern, were dismissed from the data set.

The outermost ring in the current sample of living trees was produced during the summer of 1997. By including the dry dead and the subfossil trees, progressively older material could be cross-dated and, thus, the record of precisely dated tree rings could be extended back to 5407 BC. Thus, the data are now continuous over the last 7400 years; incorporating measurements from a total of 880 calendrically aligned individual trees (Figure 2).

Difficulties in finding datable material from the first centuries BC resulted for many years in a persisting 'gap' in the data around 330 BC. Trees from around this period show extremely suppressed growth, often associated with distorted ring patterns and the occurrence of reaction wood. The 'gap' around 330 BC was finally bridged by dendrochronological cross-dating using samples from

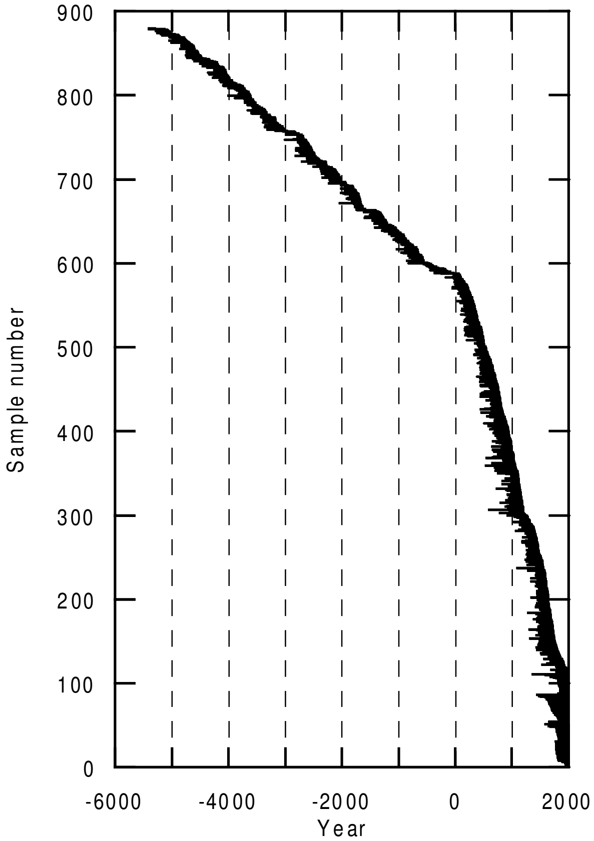

Figure 2 A total of 880 sampled trees was used to construct the 7400-year Torneträsk chronology. Each sample is represented by a horizontal bar, with length equal to the number of annual rings, and position corresponding to the dendrochronological cross-dating.

Table 1 Dendro age and corresponding radiocarbon dates of some subfossil samples

Dendro sample ID	Subsample rings no.	Dendro age (cal. BP)	^{14}C lab. ID	^{14}C age BP	Error (1 sigma)	^{14}C age (cal. BP) (95%)
25045	1–22	6970–6991	Lu2306	6050	70	6720–7160
TB111Z	1–10	6366–6375	–	5648	18	6350–6490
TB111Z	81–90	6286–6295	–	5512	21	6200–6400
TB111Z	111–120	6256–6265	–	5362	18	5990–6280
25075	1–60	6168–6227	Lu2576	5440	60	5990–6400
19006	1–60	5548–5607	Lu2577	4750	70	5310–5610
22117	5–30	4733–4758	Lu2254	4100	60	4440–4830
22038	100–139	4579–4618	Lu2253	4030	60	4300–4850
22137	70–140	3762–3832	Lu2303	3540	60	3640–3990
22028	180–352	3631–3803	Lu2298	3570	60	3690–4080
22176	35–95	3590–3650	Lu2305	3390	60	3470–3830
22095	50–80	3465–3495	Lu2302	3150	50	3250–3480
22029	100–220	2867–2987	Lu2299	2910	50	2880–3220
22040	1–20	2760–2779	Lu2300	2750	50	2760–2950
TE0879	26–29	2164–2166	St13722	2115	15	2000–2150
22072	1–25	1929–1953	Lu2301	2000	50	1820–2110
TE0689	30–32	1862–1864	St14410	1880	15	1730–1880
22089	1–30	1697–1726	Lu2782	1650	50	1410–1700
22173	1–20	1586–1605	Lu2304	1760	50	1550–1820
TD0019	1–232	1266–1497	St14021	1395	55	1180–1410

a subfossil tree located at Vettasjärvi east of the main investigation area (Figure 1), i.e., well inside the present-day boreal zone. The precise dating of this period was later confirmed by independent cross-dating of overlapping tree-ring data from northern Finland (Eronen *et al.*, this issue), and from Jämtland in central Sweden (Gunnarson and Linderholm, this issue).

The precise dendrochronological dating is supported by ^{14}C determinations of a selected set of 20 samples (Table 1). The ^{14}C dates agree with the dendrochronological dating within the uncertainty provided by the radiocarbon method (Figure 3). To minimize the relatively large errors associated with the radiocarbon dating method, we also applied the technique of 'wiggle-matching' a set of high-quality ^{14}C determinations from one individual sample, i.e., with precisely known separation in calendar years (Pearson, 1986). The wiggle-match provided a ^{14}C date with error limits of ±10 years (at 95% probability) (Figure 4) which is precisely consistent with the dendrochronological dating.

Standardization

Tree-ring widths are the expression of a number of environmental and physiological factors interacting in a complex manner to control tree growth. These factors can be conceptually modelled by regarding each individual ring width (*RW*) as a linear aggregate of a restricted number of hypothetical 'signals' (Cook, 1990), the

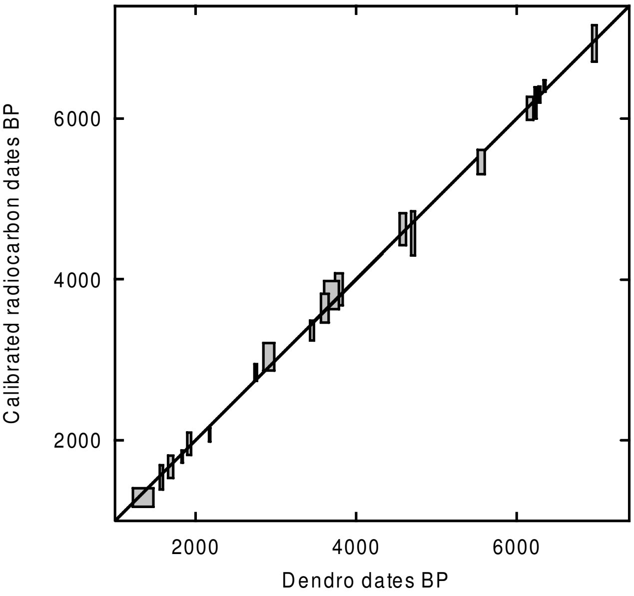

Figure 3 Each box represents one sample, which was dated with both dendrochronology and radiocarbon (data from Table 1, columns 3 and 7). The width represents the number of rings in the sample and the height represents the 95% confidence range of the radiocarbon date. Ideally, all boxes should be centred on the diagonal line.

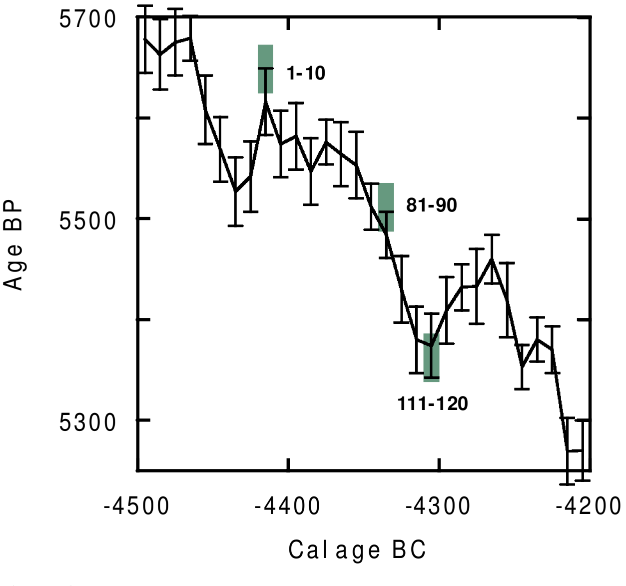

Figure 4 A sequence of three 10-year blocks of wood (rings 1–10, 81–90 and 111–120) from one individual tree (TB111Z; Table 1) was ^{14}C dated and 'wiggle-matched' to fit the decadal radiocarbon calibration curve (Stuiver and Becker, 1993). The sequence happens to fall on a distinct anomaly of the calibration curve. Thus, the 95% probability range of the match is just ± one decade. This date corresponds perfectly with the dendro date of the same sample.

most important ones for our purpose being the product of climatic forcing (*C*) and biological age (*A*). Thus:

$$RW = C + A + \epsilon$$

where ϵ represents growth-controlling factors other than climate and biological age. Our main concern in this study is to isolate the climatic signal (*C*), which we may think of as a regional signal acting similarly on the whole population. The age signal (*A*) is controlled by the ageing process within each individual tree which tends to decrease the thickness of the annual rings as the tree gets older. This decline in ring width is partly due to a decline in vigour and partly due to a geometrical effect, i.e., in each year a new layer of wood is formed circumferentially outside that of the previous year, thus, around an increasingly larger perimeter.

The process of removing the age-related growth (*A*) from the observed tree-ring growth (*RW*) is commonly termed 'standardization' in dendrochronological studies and produces a set of dimensionless index values (*I*). In one specific tree, we may express the index value for year *t* as:

$$I_t = \frac{RW_t}{A_t}$$

In this study we have standardized the data with two principally different methods. (i) The first is autoregressive standardization (ARS), where a smoothing spline function is fitted to each measurement series and regarded as the age function ($arsA_t$) for each individual tree (Cook *et al.*, 1990). This technique removes slowly evolving trends in the data, leaving the high-frequency, i.e., year-to-year, variability in the index series. To adjust for autocorrelation in the series, ARS also involves autoregressive modelling. However, the ARS technique is not capable of distinguishing between low-frequency biological trends and those that result from climate forcing, which leads to a loss of climatic signals on timescales longer than a few decades (Cook *et al.*, 1995; Briffa *et al.*, 1996). Therefore, we also use (ii) an alternative standardization method, originally adopted by Erlandsson (1936) in his early work on dendroclimatology in the Torneträsk region. The method has later been termed regional curve standardisation (RCS), and proposed as a technique to preserve long-timescale variability in tree-ring data (Briffa *et al.*, 1992; 1996). In RCS, the age function ($rcsA_t$) is defined as an empirical time-independent growth function, i.e., controlled by biological age rather than calendar age. Thus, $rcsA_t$ is an approximation of the common age function in the population, regardless of calendar time (Figure 5).

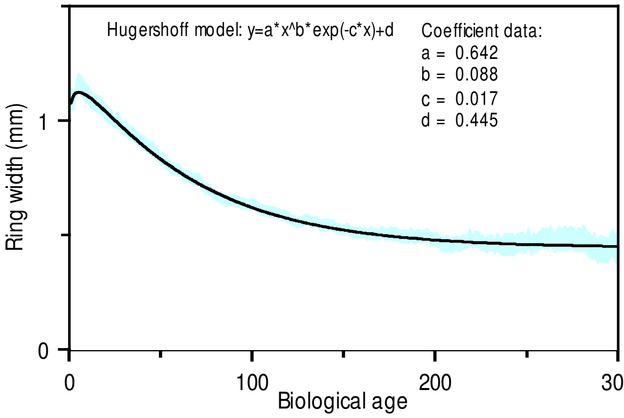

Figure 5 The shape of the age-dependent growth curve was found by, first, averaging the initial ring widths in all 880 samples (biological age = 1), then averaging the widths of the second rings (biological age = 2), etc.The shaded area represents one standard error around the average values. A 'Hugershoff' function (Warren, 1980) was then fitted to the data to find a common age function ($rcsA_t$) for the trees in our sample data set.

Following standardization, each individual index series (I_t) may be regarded as the product of climate forcing (C_t) and an error (ϵ_t):

$$I_t = C_t + \epsilon_t$$

where the error is regarded as largely random. Consequently, averaging overlapping index series into a mean chronology will reduce the error at a proportion that is directly related to the sample size for each year.

The 880 precisely calendar-dated indices series were averaged to produce two site index chronologies for the Torneträsk area: (1) an ARS chronology representing the year-to-year variability, and (2) an RCS chronology representing year-to-year and decadal to century, and possibly longer, timescale variability.

Temperature reconstruction

Meteorological data from Abisko Scientific Research Station (ANS), where daily records of temperature and precipitation extend back to AD 1913, were used to explore the relationship between climate and tree growth. A simple correlation analysis shows that the annual mean tree-ring index is positively correlated with monthly mean temperatures, notably in July (Figure 6a), while there is no apparent correlation with monthly sums of precipitation (Figure 6b). The strong positive influence of July mean temperature on pine growth in the tree-line ecotone in northern Fennoscandia is well known from earlier studies (e.g., Aniol and Eckstein, 1984; Briffa *et al.*, 1990; 1992; Kirchhefer, 2001; Lindholm *et al.*, 1996). Hence, indexed tree-ring-width chronologies from these northern areas are commonly regarded as qualitative proxies of high-summer temperatures. The main vegetation period in the Torneträsk area is June, July and August. Temperatures of these three summer months all show a clear positive correlation against tree growth (Figure 6a). Therefore, we regard the Torneträsk tree-ring indices to be an approximation of the mean summer (Jun–Aug) temperature, but dominated by July.

Complementary data from neighbouring meteorological stations have enabled the record of mean summer (Jun–Aug) temperature at ANS to be extended a further 45 years back in time, i.e., to AD 1869 (Holmgren and Tjus, 1996). Hence, we may use linear regression over a common 129-year calibration period, i.e., from AD 1869 to 1997 (Figure 7). The regression coefficients were then

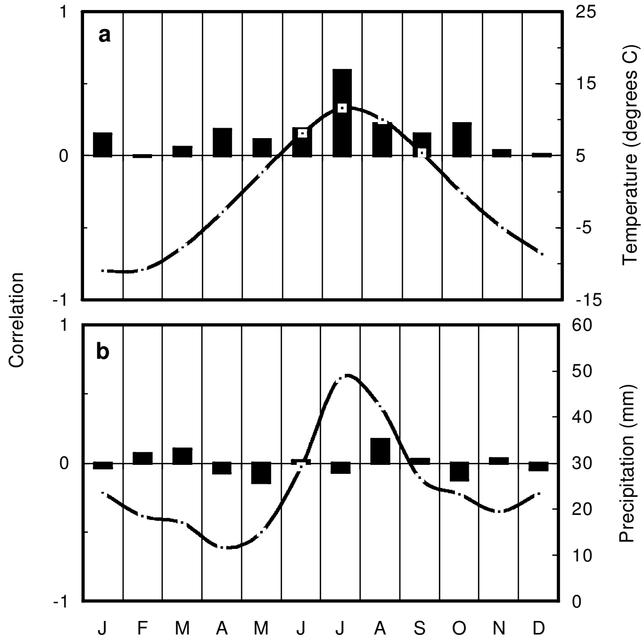

Figure 6 Bars show correlation between RCS tree-ring index and mean monthly temperature (a) and precipitation (b) at Abisko Scientific Research Station over the period 1913–97.

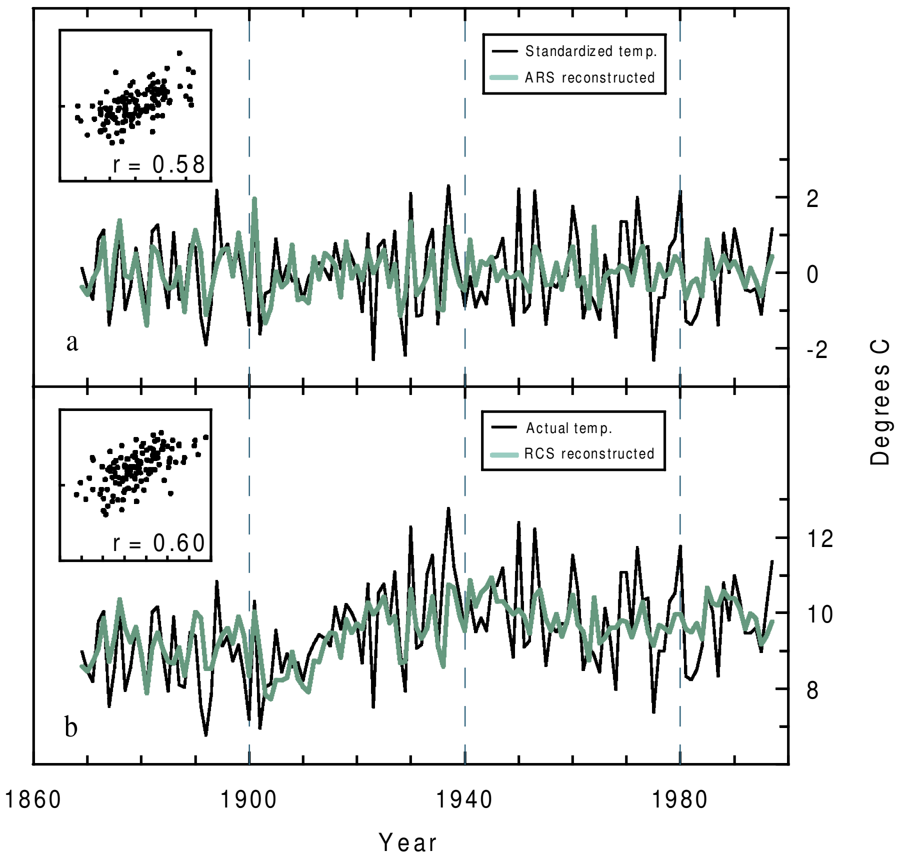

Figure 7 The tree-ring indices were calibrated against summer mean temperature (Jun–Aug) over the common period 1869–1997. The temperature data in (a) have been filtered to be comparable to the high-frequency variation displayed in the ARS-standardized tree-ring data. In (b), actual temperature is compared to the RCS-standardized tree-ring data. Scatter plots show correlation between tree-ring indices and temperature data. Through linear regression, the tree-ring data were transformed into proxies of summer-temperature change on both high-frequency (a) and medium- to low-frequency (b) timescales.

used to reconstruct summer temperature back to 5407 BC. The ARS record (Figure 8a) shows summer temperature variability on a year-to-year timescale over the last 7400 years, while the RCS record (Fig. 8b) is used here to display temperature variability on timescales from decades to several centuries.

Discussion

The positive correlation between summer temperature and tree-ring widths of Scots pine in the Torneträsk area has enabled various reconstructions of past temperature variability as far back as AD 540 (Briffa *et al.*, 1990; 1992). Here, we extend the Torneträsk ring-width chronology back to 5407 BC and update it to AD 1997, allowing temperature inference over a continuous 7400-year period. However, our calibration period (129 years) is less than 2% of the reconstructed period, and we simply have to assume that the environmental processes that force current patterns of tree growth have equally been in operation over the last seven millennia. This is most likely not true. Certainly, the representation of error (ϵ) in our conceptual linear aggregate model will change through time over the 7400-year timespan. Furthermore, it will change on many different timescales. Hence, the quality of the temperature reconstruction may also be related to our choice of calibration period. Since the mid-twentieth century, there has been a documented change in temperature forcing in the growth of northern-latitude boreal forests (e.g., Briffa *et al.*, 1998a; 1998b). This effect is not strongly evident in our data. In this study we utilize the full length of the 129-year period to retain as much low-frequency information as possible in the reconstruction.

Furthermore, the expression of underlying forcing in a chronology is a function of sample replication, i.e., the number of samples making up the mean index in each year. This is often referred to in tree-ring studies as the sample depth. The largest numbers of samples are in the most recent part of our data set, because we have a virtually unlimited capability to sample living trees (Figure 8c). Further back in time, the chronology is dependent on whatever dry dead and subfossil trees can be found and, consequently, the sample depth decreases notably in the pre-Christian period. These changes in sample depth through time undoubtedly affect the strength with which the climatic signal is expressed. The large sample depth for each year in the last 2000 years in conjunction with the strong temperature association translates into narrow confidence limits around the expressed temperature signal (Figure 8b). In the pre-Christian era, the errors are significantly larger. However, while we stress that the potential errors are large at these times, a major part of the temperature signal may still be correctly expressed. Thus, we regard the Torneträsk tree-ring reconstructions as a valid record of summer-temperature variability over the last 7400 years, at least at interannual, decadal and century timescales.

Tree-ring records notoriously lack long-term trends, i.e., the series are usually restricted in the low-frequency domain by the relatively short length of the individual series from which the chronology is constructed (Cook *et al.*, 1995; Briffa *et al.*, 1996). Theoretically, this problem can be solved by using very large numbers of overlapping individual series uniformly spread over time. This is rarely possible in practice, and we usually have to accept that tree-ring chronologies are demonstrably of great value for reconstructing climate variation on short to medium-length timescales, i.e., from interannual to a few hundred years, and that

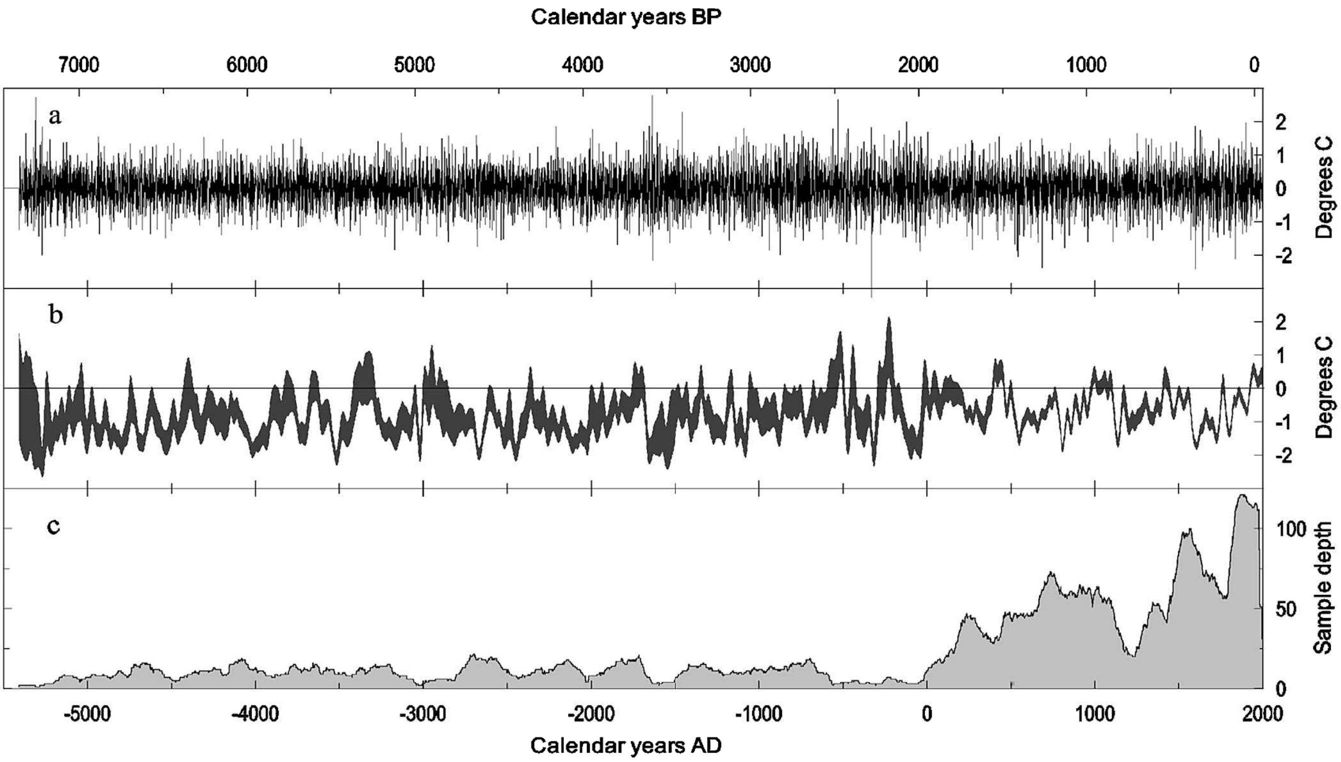

Figure 8 Summer-temperature variability over the last 7400 years in northern Sweden expressed as anomalies from the base period 1869–1997. (a) High-frequency variability, i.e., on a year-to-year timescale. (b) Medium- to low-frequency variability, i.e., on decadal to century timescales, with one standard error banding. (c) The sample size making up the mean index for each year.

the millennium-scale variability is often lost. The RCS technique does have the potential to express century and longer timescale variability to a greater extent than is possible in some earlier approaches (e.g., Briffa *et al.*, 1990), though this method ideally requires large sets of sample data, evenly distributed over a time-span that is substantially longer than the individual series (Briffa *et al.*, 1992; 1996). The Torneträsk data are indeed spread over a very long period, but they are far from evenly distributed through time. Nevertheless, there is some millennial-timescale variation expressed in the RCS record which can be compared to other proxy records of low-frequency Holocene climate variation: pollen and macrofossil records from the Torneträsk area indicate optimal conditions for pine from about 4300 BC to about 2500 BC (Barnekow, 1999), and records of tree-line change in northern Sweden show high tree-lines around 4000 BC (e.g., Karlén and Kuylenstierna, 1996). These data indicate a broad period in early- to mid-Holocene times when summer temperatures were 1.5–2°C higher than present. However, the Torneträsk tree-ring record does not indicate notably high temperatures at this time. Thus, although the RCS record displays some millennial-scale variation, it apparently expresses only a portion of the actual millennial scale trends in Holocene summer temperature.

The fact that dendrochronological cross-dating is possible between Torneträsk and such distant areas as northern Finland and Jämtland in central Sweden indicates a regional representativity of the high-frequency temperature variation displayed in the Torneträsk record. Comparing the record to other independent evidence of low-frequency climatic change in northern Europe indicates that some of the century-timescale variability is representative for a wider area. The Torneträsk data demonstrate particularly severe climatic conditions in the period 600–1 BC, a period that is characterized by low sample replication and high ring-width variability. It includes both the highest and the lowest ring-width values over the last 7400 years, indicating a highly variable but generally cold climate. This period is contemporary with a major glacial expansion in Scandinavia when many glaciers advanced to their Holocene maximum position (Karlén, 1976; 1988). It includes the classic biostratigraphic division between Sub-Boreal and Sub-Atlantic (Berglund, 1986) and, in northern Europe, it also includes the archaeological transition from Bronze Age to Iron Age – a time that brought about major changes to human societies (Burenhult, 1999; van Geel *et al.*, 1996). Especially severe conditions occurred in 330 BC, which is the most extreme year in the Torneträsk data indicating a short-term negative change in mean summer temperature of about 3–4°C (Figure 8a). Around this time, several volcanic eruptions occurred (see Baillie, 1995; 1996; and references therein) that may have played an important role in forcing some of the high variability we see in the Torneträsk chronology. The record of the last 2000 years displays features of century-timescale climatic variation known from other proxy and historical sources, including a warm 'Roman' period in the first centuries AD and a generally cold 'Dark Ages' climate from about AD 500 to about AD 900 (Lamb, 1982; Baillie, 1995). Exceptionally severe summer conditions occurred around AD 540, which resulted in frost-damaged rings and reduced growth, contemporaneous with independent evidence of severe climatic conditions from other parts of the world (Stothers, 1984; Austin, 1985; Baillie, 1994). The warm period around AD 1000 may correspond to a so-called 'Mediaeval Warm Period', known from a variety of historical sources and other proxy records (Hughes and Diaz, 1994). In the Torneträsk region, this period ends at about AD 1100 when a shift to a colder climate occurred. The climatic deterioration in the twelfth century can be regarded as the starting point of a prolonged cold period that continued to the first decade of the twentieth century. This so-called 'Little Ice Age' culminated in the seventeenth century and is known from instrumental, historical and proxy records (Grove, 1988).

Conclusions

(1) The Torneträsk tree-ring chronology is annually resolved and includes continuous data from 5407 BC to AD 1997, providing a precisely dated record of summer-temperature variability.

(2) The strong association with summer temperature in conjunction with the large numbers of samples for each year translates into narrow confidence limits around the expressed temperature signal in the last 2000 years. The errors are significantly larger in the pre-Christian era, mainly due to reduced sample depth.

(3) The record displays significant temperature changes on timescales from years to several centuries, which is representative for a large area in northern Sweden, possibly also for a wider area.

(4) The record does not express the full range of millennial-timescale temperature variation in the Torneträsk area.

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