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Regional Summer Temperature Reconstruction in the Khibiny Low Mountains (Kola Peninsula, NW Russia) by Means of Tree-ring Width during the Last Four Centuries

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Abstract

This study presents a new pine (*Pinus sylvestris* L.) ring-width chronology and a summer temperature reconstruction for the last 400 years from the Khibiny Low Mountains (Kola Peninsula, NW Russia). Pine trees from sites at the altitudinal timberline of Khibiny Mountains show pronounced climatic signals in tree-ring width. We found a strong positive correlation with summer temperature of July–August ($r = 0.58$). The reconstruction shows lower summer temperatures from A.D. 1630 to 1840, a subsequent warming up to the mid-20th century and a cooling trend afterwards. According to our data, a temperature increase is observed during the past decade. The good coherence of multi-decadal to secular trends of our reconstruction and series of observed solar activity indicate that solar activity may have been one major driving factor of past climate on Kola Peninsula.

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Introduction

According to numerous studies involving interpretation of various climatic proxies such as historical records, ice cores, lake sediments, and tree-ring data, the Late Holocene was characterized by several periods of natural global warming and cooling (Lamb, 1977). In Europe the climate during the last millennium includes the Medieval Warm Period (MWP; e.g. Bradley et al., 2003) and the cooler period of the Little Ice Age (LIA; e.g. Bradley and Jones, 1993). Even if both the MWP and LIA can be seen as global climatic features, they have occurred in various regions with different local features of magnitude, rate, and time frame (Hughes and Diaz, 1994; Solomina, 1999). After the middle of the 19th century a warming is observed in the northern hemisphere, particularly enhanced during the second part of the 20th century. This widely recognized warming (e.g. Jones et al., 1998; Mann et al., 1999, 2008; Bradley, 2001, Esper et al., 2002) is considered to be the result of anthropogenic influence (IPCC–Synthesis Report, 2007).

However, the magnitude and rate of the current warming within a multi-centennial time scale remains debatable. A number of global high-resolution paleoclimatic reconstructions for the northern hemisphere are based mainly on data from tree-ring width and late-wood density measurements. Some data show that the abrupt and intensive 20th-century warming is truly exceptional at least throughout the last millennium (Jones et al., 1998; Mann et al., 1999). Other reconstructions demonstrate that present warming is comparable in magnitude and rate with previous climate oscillations, i.e. Medieval Warm Period (e.g. Briffa et al., 2001; Esper et al., 2002; Moberg et al., 2005).

To understand observed modern climate variability it is necessary to characterize natural climate variability over the past few centuries and improve the understanding of the links between large-scale climate forcing and regional climate. Tree-ring records allow, with the development of quantitative and validated paleoclimate reconstructions, understanding of high-resolution climate variability beyond instrumental data (e.g. Touchan et al., 2008). But the question of how well high-frequency climate variability is expressed by tree-ring proxies including the error estimation still requires special consideration (von Storch et al., 2004). Additionally, in order to study spatiotemporal patterns of climate variability and to calculate valid global means of climate variables, there is a need of a network of data from different regions (Widmann and Tett, 2003). However, there is still a lack of tree-ring chronologies for many climate-sensitive regions. In this respect, northern Europe, particularly the geographic region between Scandinavia, mainly affected by the North Atlantic and the Eurasian continent, is of interest.

In this paper we report on a new regional temperature reconstruction of the last 400 years based on a Scots pine (*Pinus sylvestris* L.) tree ring-width chronology from the Khibiny Low Mountains on the Kola Peninsula in northwestern Russia. This 400 year period covers the time from the pre-industrial LIA to the modern "global warming" period and is of particular importance for the investigation of modern climate change.

Study Area

The Khibiny Low Mountains (67°41′N, 033°15′E) of northwestern Russia are located between northern Scandinavia—which has been the subject of a number of dendroclimatological investigations (e.g. Briffa et al., 1990; Kirchhefer, 2001; Eronen et al., 2002; Grudd et al., 2002)—and the eastern polar region of Russia, which has been so far only sporadically studied

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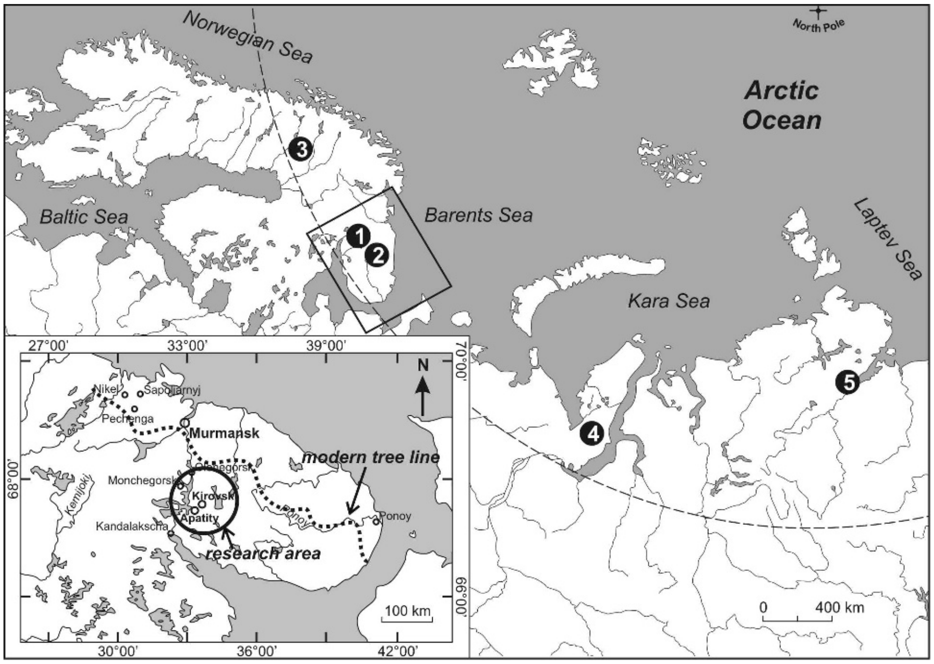

FIGURE 1. Map of geographical locations for the following tree-ring chronologies: 1—Khibiny Low Mountains (this paper); 2—Kola (Gervais and MacDonald, 2000); 3—northern Swedish Lapland (Grudd et al., 2002); 4—Yamal, northwestern Siberia (Hantemirov and Shiyatov, 2002); 5—Taimyr, north-central Siberia (Naurzbaev et al., 2002).

(Hantemirov and Shiyatov, 2002; Naurzbaev et al., 2002). The climate of the Kola Peninsula is strongly affected by the North Atlantic Current and the variations in the strength of the zonal atmospheric circulation over the North Atlantic, i.e. by the North Atlantic Oscillation, and the Eurasian continental climate. This geographic position of the Kola Peninsula between the North Atlantic and the Eurasian continent makes this region particularly suitable to study variations of the zonal circulation. As sites at the altitudinal (alpine) timberline show a steep temperature gradient we expected pronounced climatic effects on the annual wood increment in trees (Fritts, 1976) of the Khibiny Mountains.

The Khibiny Mountains are a compact low-elevation system in the central part of the Kola Peninsula, c. 150 km north of the Arctic Circle (Fig. 1), and reach 1100–1200 m a.s.l. The geology of the region is represented mainly by Precambrian crystalline rocks related to the Fennoscandian crystalline massif. The Khibiny Mountain ranges have flat plateau-like tops and steep slopes. The mountain range is bracketed by two great lakes: Imandra from the west and Umbosero from the east. Major river valleys follow the line of long faults. The topography of Khibiny was transformed by Quaternary glacial activity, and glacial landforms are typical (Perov, 1983).

The climate of Kola is cold-temperate, with long and moderately cold winters and cool humid summers. Within the Khibiny Mountains the climate is colder due to orographic effects. Mean January temperature at the southern/southwestern margin of the Khibiny is about −12 °C, while the mean July temperature is in the range of +13 °C. The growing season of 60–80 days lasts from May to September and sporadic frost may occur at any time during this period. The annual precipitation in the Khibiny foothills (stations Apatity and Khibiny) amounts to 450 mm, 75–120 mm of it falling during winter (Jakovlev, 1961).

The high inter-annual and inter-decadal variability of the temperature regime is a characteristic local climate feature of the Khibiny Mountains. For the period of instrumental observations of 80 years, air summer temperature variation was 4.8 °C in Kandalaksha (southern Kola), 5.7 °C in Murmansk (northern Kola), and 6.8 °C in the center of the mountain range.

The Khibiny foothills are covered by northern taiga vegetation which is dominated by spruce (*Picea abies* L.), pine (*Pinus sylvestris* L.), and birch (*Betula pubescens* Ehrl.). Pine trees are close to their northern latitudinal limit and are exposed to strong altitudinal constraints in the Khibiny Mountains. The vegetation of the mountains shows three pronounced belts: (1) Forests grow up to 300–450 m a.s.l., depending on slope and exposure. Norway spruce is the dominant species in the Khibiny forests, usually mixed with birch, mountain ash (*Sorbus glabrata* Hedl), and gray alder (*Alnus incana* (L.) Moench). Shrubs, such as willows (*Salix* sp.), redcurrant (*Ribes rubrum* L.), and honeysuckle (*Lonicera pallasii* Ledeb.) are common. Pine forests grow mainly in the western and northern part of the mountain system and also along river valleys on sandy soils in the eastern part. Pine can also be a component of the spruce forests. (2) A narrow mountain birch belt (with *Betula tortuosa* Ledeb.) occurs between 450 and 600 m a.s.l. (3) Tundra with shrub birches and polar willows, moss-lichen communities, and stone fields occupy the upper level of the mountains (Ramenskaya, 1983; Kremenetski et al., 2004).

Material and Methods

For this study we used a collection of 69 tree samples (discs and cores) of Scots pine (*Pinus sylvestris* L.). Samples were taken from living and dead pines from three sites of the mountain massif where pine forests grow (Fig. 2, Table 1). The site "Khibiny W" is located in the western part of Khibiny on the southern slopes of the valley of the Malaya-Belaya River, flowing into the Imandra Lake. The site "Khibiny E" is on the eastern part of the Khibiny Mountains at the Tuljok River valley, a tributary of Lake Umbosero. The site "Khibiny N" is located in the northern part of Khibiny on the eastern slopes of the valley of the Kunijok River.

Core samples from living trees were obtained with an increment borer; a minimum of two cores were taken from each tree. In total 106 cores from 45 living trees and 24 disks of dead trees were taken. Sampling sites were chosen mostly at the upper tree-line. Ten to fifteen trees were investigated at each plot. To get

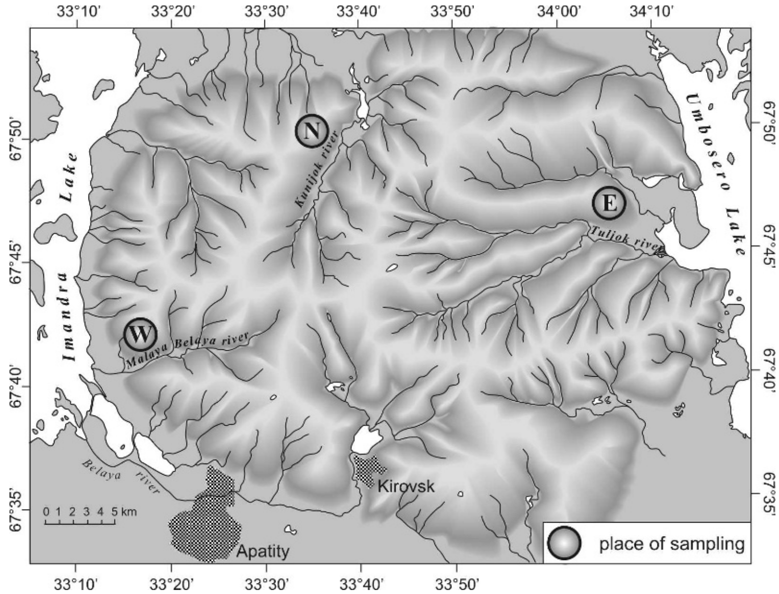

FIGURE 2. Map of the Khibiny Low Mountains, central Kola Peninsula, showing the sampling sites.

a homogeneous age structure in the chronology we also cored young pines at the same sites. The mean individual age of living trees is 200 years; the oldest pine had 420 annual rings. Living trees were sampled in June 2005, thus, the last total tree ring corresponds to A.D. 2004. Samples from dead trees were taken as discs. They were sampled mainly near the forest line from 250 to 450 m a.s.l. Trunks of dead trees at the uppermost forest belt were well preserved; some of them even kept vertical position.

All samples underwent standard laboratory preparation. Increment cores from living trees and sections from dead trees were surfaced using razor blades. On discs we surfaced several radii and avoided segments of reaction wood. For a better optical contrast on the surface we used chalk. This standard procedure allows clear identification of all cellular structures of tree rings, which is the prerequisite to avoid problems related to extremely narrow rings, which consist of 1–2 rows of cells only. It also helps to identify partly absent rings, which are very common in pine wood from sensitive sites. Tree-ring widths were measured with the accuracy of 0.01 mm on the Hohenheim measurement device. Data management and cross dating was carried out using TSAP software. Tree-ring curves of the different radii were compared visually to check for missing rings. Annual ring-width values of the corrected and synchronized radii were averaged to produce an individual mean curve for each sample. Comparisons and synchronization of tree-ring curves with existing data from living trees with known ages allow us to date dead trees and to combine those data series with local and regional chronologies. External comparisons with existing pine chronologies from Finnish Lapland (Eronen et al., 2002) confirmed our chronology for the entire period.

TABLE 1

The sites of pines sampled for Khibiny tree-ring chronology.

Site	Latitude (N)	Longitude (E)	Number of samples (trees) Living	Dead	Total
Khibiny W	67°42′	033°15′	14	10	24
Khibiny E	67°47′	034°03′	18	10	28
Khibiny N	67°50′	033°38′	13	4	17
Total			**45**	**24**	**69**

Although tree-ring growth is strongly controlled by climate factors in this region, the climatic signal in tree-ring width is often masked by various non-climatic factors. In this respect the biological age trend is of great importance. Trees form wider rings in the juvenile period (inner rings) and smaller rings in the adult phase (outer rings). The magnitude of this negative growth trend depends on local growth conditions such as light, nutrition, water supply, and concurrence with other trees. Consequently, it is very crucial to remove the age trend relevant to cambial age and retain the climatic signal. A number of methods and techniques has been developed to fit the age trend (Cook and Kairiukstis, 1990) and to remove the individual age trends of trees. In our study we used two different methods.

First, we used the "regional curve standardization method" (RCS), which is based on the assumption that the biological growth trends of the same species at a homogeneous site are similar and independent of time. On homogeneous sites the age function of trees can be determined by the calculation of the mean individual trend of a representative group of trees. This common, site-specific trend can then be used to de-trend the single series. Its advantage is the preservation of low-frequency signals and trends on time scales longer than a few decades (Briffa et al., 1992, 1996; Esper et al., 2003). For our trees (1) the cambial age from samples with preserved pith was determined. (2) Then the common age function was calculated and used to standardize the single tree-ring width series (Fig. 3).

The RCS methods very much rely on homogeneity of the site. In our case the sampling sites are located in some distance from each other and may differ in site quality. Therefore, the RCS method might not be applicable. To account for that we also used a more conservative standardization method, where a negative exponential curve (NEC) is fitted to the individual ring-width series and each series is detrended one by one (Fritts, 1976). This is one of the widely used standardization methods.

The signal strength of the chronology was evaluated over time using the expressed population signal or EPS statistic. We used a 50-year window with 25-year overlaps between adjacent windows. The overlapped EPS cutoff point is 1970.

To identify climate-growth relationships for Scots pine in the Khibiny Mountains, we calculated simple correlations between tree-ring width chronology and monthly mean temperature records from three meteorological stations: "Khibiny" and

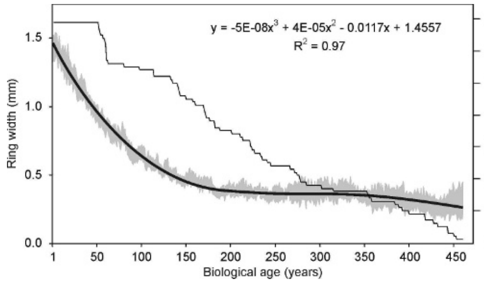

FIGURE 3. General growth-trend curve from the Khibiny Mountains. The equation shown (plotted as smooth bold line) is based on third-order polynomial fits to the mean values of all series after realigning according to biological (i.e., tree) age (x). The shaded area represents one standard error around the average values. The thin line represents the sample size for each year.

"Apatity" in the vicinity of the study region, and "Kola" at a distance of about 100 km. The climate stations Khibiny and Apatity are located next to each other and near to site Khibiny W (Fig. 2) in the Khibiny Mountains foothills. The Khibiny station provided meteorological observations from 1923 to 1978. At Apatity climate data were recorded during 1933–1964 and 1979 to present. Comparison of the common period of observations (1933–1964) has revealed strong correlation between both station records. The Kola station has the longest period of instrumental observation (from 1878 to present). The average correlation coefficient for the months series of air temperatures between stations is $r = 0.990 \pm 0.005$. High correlations and long common observation periods yielded a regression equation representing the relationship of monthly temperatures at Khibiny weather station (nearest to the study area) with data from nearby stations Apatity and Kola. Using these equations, missing data of Khibiny station were calculated and complemented, thus temperature series were extended back to 1878. The result was a continuous series of monthly air temperatures for a period of 127 years, which we used for our analyses.

Split-sampling calibration and verification tests were used to evaluate the quality and temporal stability of the reconstruction model (Fritts, 1976; Cook and Kairiukstis, 1990). The period of temperature records (1878–2004) was divided into two parts (1878–1941 and 1942–2004). The verification statistical methods used were Pearson's correlation coefficient *r*, the reduction of error (RE) statistic, the coefficient of efficiency (CE), and the sign test (Fritts, 1976; Cook et al., 1994).

Results and Discussion

The resulting RCS and NEC chronologies are shown in Figure 4a and the relevant statistics in Table 2. As shown, both chronologies are quite similar, although the RCS reconstruction shows higher amplitudes in the low frequency and more positive overall trend compared to the NEC. An EPS of 0.85 suggests the sample size is adequate (Wigley et al., 1984; Cook and Kairiukstis, 1990). The EPS of both chronologies exceeds this value for the entire reconstructed period (Fig. 4b). The highest correlation for tree-ring width index was found with summer air temperature. That indicates that the strongest impact on tree growth is caused by the temperature regime of July and August (Fig. 5). The correlation is slightly higher for the RCS chronology. We therefore chose RCS standardization for our reconstructions (Fig. 6) and used linear regression over a common 127-year calibration period (Table 3) to develop a regression model to

TABLE 2

RCS and NEC chronology statistics.

	RCS	NEC
Chronology length (yr)	400	400
Mean sensitivity	0.168	0.163
Standard deviation	0.317	0.239
First-order autocorrelation	0.632	0.585

RCS = regional curve standardization method.
NEC = negative exponential curve.

reconstruct summer (July/August) temperatures back to A.D. 1600 (Fig. 7). The results of calibration and verification tests (Table 3), which include positive RE and CE values, reveal that we can have faith in our model over the full length of the record. The lower frequency course of the temperatures is very well picked up by our model, even though the inter-annual variability and the extremes seem to be damped to some extent. The latter may be explained by the interference of various physiological influences in common signals of tree growth (Boettger and Friedrich, 2009).

Overall, the reconstructed course of summer (July/August) air temperatures for the Khibiny Mountains (Fig. 7) shows pronounced fluctuations for the last 400 years. Since A.D. 1600, the reconstructed July/August temperature has varied between 10.4 °C (1709) and 14.7 °C (1957), with a mean of 12.2 °C. During the meteorological observation period in the 20th century, the mean summer temperature was 12.8 °C.

The longest period when temperatures were continuously below the long-term mean lasted from about A.D. 1630 to 1750. During that period, the coldest year was 1709 when the mean air temperature for July–August was 10.4 °C only, which is 1.8 °C lower than the average mean temperature for the last 400 years and almost 2.5 °C lower than the mean for the 20th century. Between A.D. 1730 and 1759 the summer temperatures increased

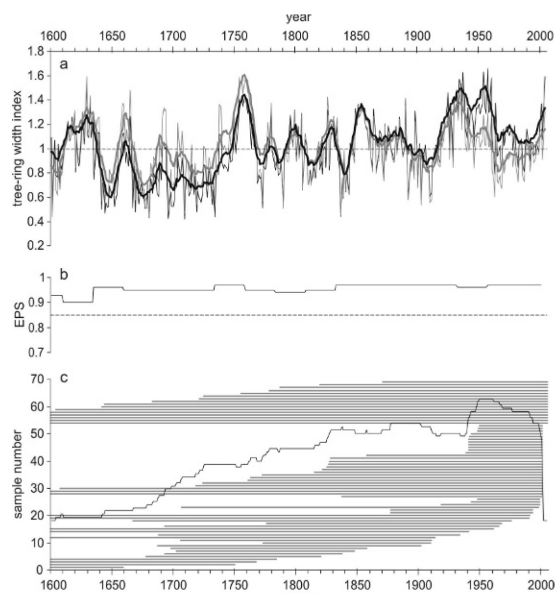

FIGURE 4. Scots pine ring-width chronology of the Khibiny Mountains: (a) regional curve standardization (black line) and negative exponential curve (gray line) standardized data series, (b) expressed population signal with the significance limit of 0.85 marked by dotted line, (c) sample depth and age profile of cross-matched tree-ring series (horizontal lines).

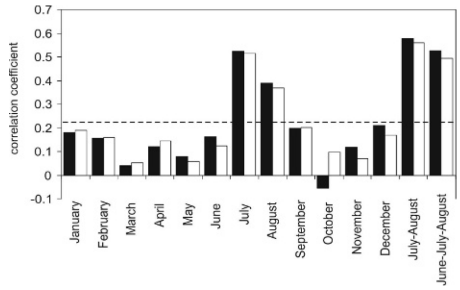

FIGURE 5. Relationship between mean monthly air temperature and regional curve standardization method (RCS) (black bars) and negative exponential curve (NEC) (light bars) tree-ring width index of the period 1878–2004. The horizontal dotted line indicates the level of significance ($p < 0.05$).

sharply by 3.5 °C and reached 13.5 °C. However, up to the year 1748 summer temperatures remained below the present level.

Between 1760 and 1899 summer temperatures show high variability both on annual and decadal scales with amplitudes up to 2.5 °C. The mean summer temperature increased during the first half of the 20th century from the minimum value of 10.9 °C to a maximum of 14.7 °C, which is also mirrored in the instrumental record. This warm period lasted up to the end of the 1950s, followed by a cooling and by a warming during the past decade.

The early part of the reconstructed period (1600–1750) in our study most certainly represents one of the coldest phases of the LIA. The mean summer temperature from c. A.D. 1630 to 1840 was 0.4 °C lower than its mean value for the whole investigated period. After 1840 the subsequent warming lasted with considerable oscillations up to recent times.

Comparison with other tree-ring data from Kola Peninsula revealed similarities, but also differences. Pine tree-ring width data from a 278-year pine chronology from Murmashi (68°N, 32°E), close to the latitudinal (northern) timberline (Schweingruber, International Tree-Ring Data Bank, NCDC) are highly correlated ($r = 0.7$) with the Khibiny pine chronology. Furthermore, the tree-ring–based reconstruction of July temperatures from pine trees at a site southeast of Murmansk (68°N, 35°E) on Kola Peninsula (Gervais and MacDonald, 2000) for the same period (1595–1995) revealed good convergence (resemblance) with our reconstruction on the inter-annual variability ($r = 0.6$)

In contrast, the inter-decadal variability differs significantly. These differences may be explained by the different standardization methods, the different reconstructed season, and the different geographical location. Possibly, the latter is of special importance. The temperature reconstruction of Gervais and MacDonald (2000) is derived from trees growing near the latitudinal (northern)

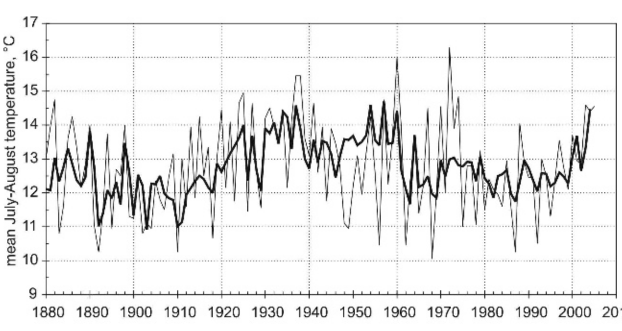

FIGURE 6. Comparison of recorded instrumental (thin line) data and reconstructed (bold line) summer (July–August) air temperature.

timberline, whereas the reconstruction presented here refers to altitudinal (alpine) timberline sites in the Khibiny mountains, about 100 km south of the present day latitudinal timberline. The temperature gradients at the altitudinal timberline and particularly near the latitudinal timberline are clearly stronger, with steeper slopes, compared to those at the latitudinal timberline. Furthermore, the altitudinal range of sites with strong temperature influences on growth at the distinct altitudinal timberline in the mountains is narrow and well definable (Fritts, 1976). At the latitudinal timberline small-scale differences in site qualities such as high groundwater table may be of greater importance for tree growth. The high climate sensitivity of trees growing at altitudinal timberlines on Kola is also documented by pronounced timberline fluctuations during the Holocene. Boettger et al. (2003) showed that pine forests expanded between 7000 and 3500 yr B.P. on the northwestern sections of the peninsula to about 50 km north of their present-day limit. According to MacDonald et al. (2000) and Gervais et al. (2002), the modern latitudinal (northern) timberline of pine on the Kola was established about 2500 years ago. Significant fluctuations of this timberline have not occurred since then. The subsequent climatic change during the last 2500 years seems to be of little influence on the spread of Scots pines at the latitudinal timberline on Kola Peninsula. However, the altitudinal timberline in the Khibiny Mountains near the latitudinal timberline has varied significantly during the past c. 1000 years. Hiller et al. (2001) showed that 1000 years ago the tree line in the Khibiny Mountains was located at least 100–140 m above its current position. Accordingly, pine tree growth at the altitudinal timberline seems to have been influenced more strongly by climate fluctuations during the past c. 1000 years than those at the latitudinal timberline. Pines at the altitudinal timberline in the North therefore promise to record climatic variations with special sensitivity.

For the comparison between climate fluctuation in the central part of the Kola Peninsula and in other regions of the Eurasian Arctic along the latitudinal (northern) timberline, reconstructions based on tree-ring chronologies for northern Swedish Lapland (Grudd et al., 2002), Yamal, northwestern Siberia (Hantemirov and Shiyatov, 2002) and Taimyr, north-central Siberia (Naurzbaev et al., 2002) were used. These regional dendroclimate reconstructions are widely used for global climate interpretations of the past (i.e. Juckes et al., 2007; Osborn and Briffa, 2006; Overpeck et al., 1997). The changes of summer temperature (June–July–August) calculated on the base of those chronologies are shown in Figure 8. Data of these chronologies (data source: International Tree-Ring Data Bank) were transformed by the same standardization methods (RCS) and reconstruction was done for the same season as it was done by Osborn and Briffa (2006). For reliable comparison we have transformed our reconstruction from Khibiny Mountains according to Osborn and Briffa (2006). The regression model was converted for the summer period (June–July–August). Correlation between the width of annual rings and mean temperatures of the three summer months is lower than for July–August, but it remains significant. Overall these reconstructions correlate among themselves differently with correlation coefficients varying between $r = 0.35$ and $r = 0.72$ (Table 4). Interestingly, the correlation coefficients do not depend on the distance between the investigated regions only. The temperature course in Khibiny correlates better with the Taimyr region in northern central Siberia than with those from Yamal in northwestern Siberia, situated much closer to the Kola Peninsula (Fig. 1). Presumably this can be caused by a different combination of global and regional effects on the local climate.

TABLE 3

Calibration and verification statistics for July–August temperature reconstruction.

	Calibration			Verification				
Model	period	*r*	aR^2	period	*r*	RE	CE	ST (±)
Early	1878–1941	0.67	0.44	1942-2004	0.49	0.175	0.163	44/19
Late	1942–2004	0.49	0.23	1878-1941	0.67	0.392	0.385	46/18
Full	1878–2004	0.58	0.32					
Transfer function models								
Early	JAt = 3.8313 × TRW + 8.7091							
Late	JAt = 3.2933 × TRW + 8.9623							
Full	JAt = 3.5013 × TRW + 8.895							

r = Pearson correlation coefficient.

aR^2 = square of the multiple correlation coefficient following adjustment for loss of degrees of freedom.

RE = reduction of error statistic (positive values are considered to pass).

CE = coefficient of efficiency statistic (positive values are considered to pass).

ST = sign test.

JAt = July–August temperature.

TRW = tree-ring width.

To test the representativity of our temperature reconstruction we compared data from the entire Arctic. A number of studies are related to modern climate variations in the Arctic and in particular to analyses of temperature trends (e.g. Alekseev et al., 2001; Polyakov et al., 2002a, 2002b; Makshtas and Walsh, 2003). Polyakov et al. (2002a) presented the single record of mean annual Arctic temperature based on data from 75 weather stations. Using the same data and methods of data treatment we obtained the variations in mean summer temperature (mean temperature for the 3 summer months: June–July–August) as means for the whole Arctic.

Figure 9 shows that fluctuations of reconstructed mean summer temperature at the Khibiny Mountains correlate with the fluctuations of summer temperature from instrumental data of the Arctic. Inter-annual amplitudes of both time series are different, because the Arctic time series represents an average over a vast territory. However, a significant correlation could be shown between the Arctic and both instrumental (r = 0.67) and reconstructed mean summer temperatures (r = 0.49) from Khibiny. Hence, there is a good probability that the climatic system of the central Kola Peninsula mirrors to some extent the climate state of the Arctic.

The suggestion that the regional climate is an indicator of climatic features of the Arctic can be tested by comparing relevant meteorological and reconstructed data with variations of global climate forcing such as solar activity (e.g. Beer et al., 2000; Scafetta and West, 2006). For these comparisons we used solar irradiance data for the last 400 years obtained from historical records of sunspots (Lean et al., 1995; Lean, 2000). We found that over the whole investigated period fluctuations of summer air temperature reconstructed for the Khibiny Mountains in the central part of the Kola Peninsula have a good consistency (r = 0.50) with changes of solar radiation (Fig. 10), especially for the low-frequency signal.

For the last 400 years there have been three well-known phases of low solar activity. The lowest and longest phase was the

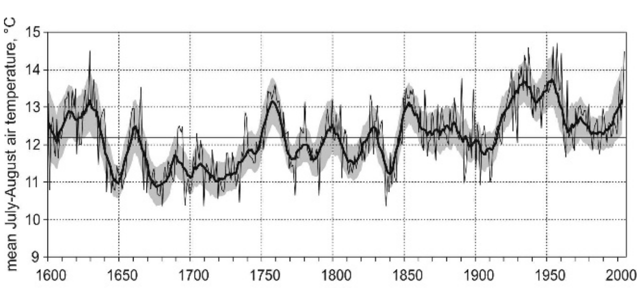

FIGURE 7. Reconstructed July–August mean temperature variations for the past 400 years based on the Scots pine ring widths from Khibiny. The horizontal line indicates the mean temperature (12.2 °C) for the period 1600–2004. The thin line represents annual and bold line 11-year running means variations. The shaded area represents corresponding 95% confidence limits.

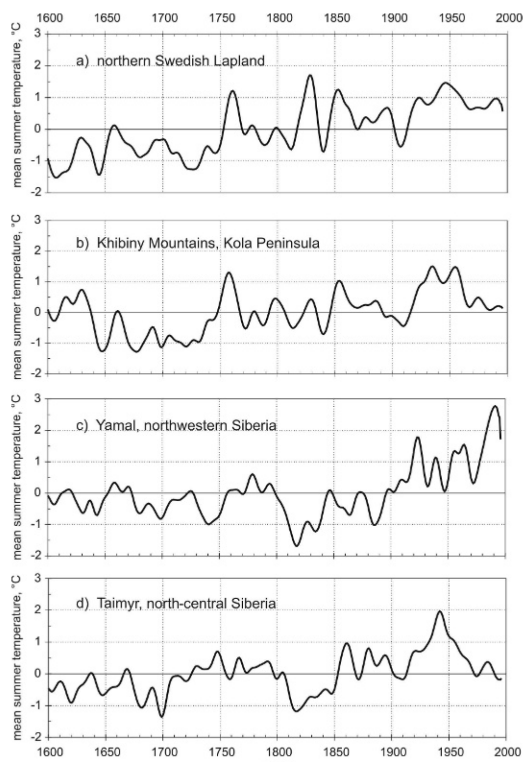

FIGURE 8. Reconstructed mean summer temperatures for (a) northern Swedish Lapland (Grudd et al., 2002); (b) Khibiny Mountains (presented chronology); (c) Yamal, northwestern Siberia (Hantemirov and Shiyatov, 2002); (d) Taimyr, north-central Siberia (Naurzbaev et al., 2002).

TABLE 4

Correlation matrix of climatic reconstructions.

	Swedish Lapland	Khibiny	Yamal
Khibiny	0.72	—	—
Yamal	0.39	0.35	—
Taimyr	0.48	0.58	0.45

so-called Maunder minimum from A.D. 1645 to 1715 (Maunder, 1922). The Dalton minimum and the 1900 minimum are two subsequent phases of low solar activity which took place from A.D. 1795 to 1825 and from A.D. 1880 to 1900 (Scafetta and West, 2006). All these minima of solar activity coincide with periods of low summer temperature in the Khibiny Mountains, expressed by the low-frequency signal of our reconstruction. An especially good agreement can be found during the Maunder minimum. During this phase the summer air temperature in the Khibiny region was 0.9 °C lower than the mean over the 400 years. The time from c. A.D. 1660 up to c. 1720 is a period of extreme cold summers at central Kola Peninsula. Analog to that during the Dalton and the 1900 minima the summer temperatures stayed below the 400 yr mean value, even though the temperature differences from the mean were less significant at −0.2 °C and −0.1 °C. However, there are shorter cold periods in the tree-ring data around 1770–1790 and 1890–1910 in the same amplitude compared to the periods of solar minima. In addition, after 1970 the coherence between solar activity and tree-ring growth vanish, which may be explained by the dominance of regional climate forcing over the global ones during the last decades. This is in agreement to Lockwood and Froehlich (2007) who report the lack of agreement between global mean temperatures and solar variability after 1985. Therefore, solar activity is maybe one of the major driving factors on summer temperatures at Kola Peninsula and is probably most evident on multi-decadal fluctuations.

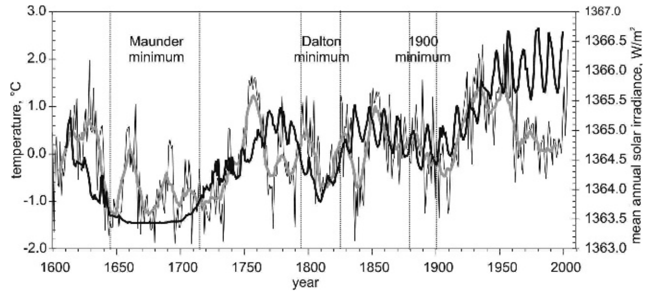

FIGURE 10. Comparisons of mean summer temperature reconstructed for the Khibiny Mountains (thin line represents annual and gray bold line 11-year running means) with solar irradiance (black bold line).

chronology from Khibiny shows significant summer temperature signals: $r = 0.58$ for two months (July–August) and $r = 0.53$ for three summer months (June–July–August), respectively.

The reconstruction shows colder summer temperatures from 1630 to 1840, which corresponds to part of the Little Ice Age (LIA) at the Khibiny Mountains, a subsequent warming up to the middle of 20th century, and then a cooling trend. During the past decade a new temperature increase can be observed.

The Khibiny summer temperature reconstruction corresponds well to results of other studies from the Kola Peninsula. The pattern of reconstructed summer temperatures in the Khibiny Mountains is strongly correlated with that from northern Sweden and is even significantly correlated with those from the Taimyr Peninsula situated c. 2500 km away from Kola. The supraregional teleconnection may be explained by the influence of solar activity on summer temperatures. The broad similarity between this temperature reconstruction and solar radiation indicates that solar activity is an important driver of centennial to multi-decadal trends in summer temperatures of the Kola Peninsula.

Conclusions

We present a reconstruction of summer temperatures for the last 400 years from a pine (*Pinus sylvestris* L.) ring-width chronology from the Khibiny Low Mountains (Kola Peninsula, NW Russia). Due to its geographical position this region is related both to the atmospheric circulation over the North Atlantic and to the Arctic. Additionally, carefully selected trees from sites at the altitudinal timberline ensure strong climatic sensitivity of the tree growth, which is recorded in ring width. The ring-width

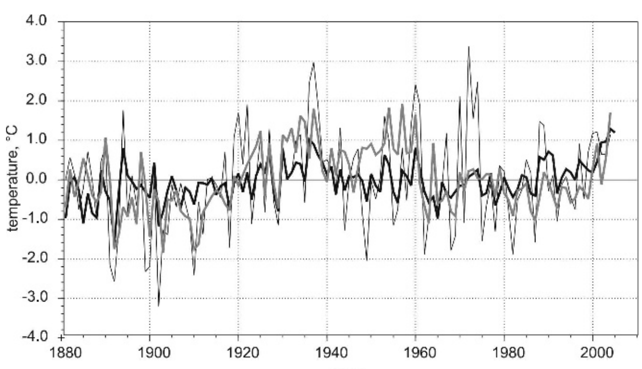

FIGURE 9. Comparison of instrumental data of Arctic (bold line), Khibiny (thin line), and Khibiny reconstructed (gray line) summer air temperature variations.

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