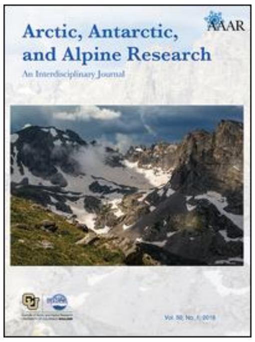

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Abstract

A 403-yr tree-ring chronology (A.D. 1595–1997) was developed from living and dead *Pinus sylvestris* L. (Scots pine) from near treeline on the Kola Peninsula in northwestern Russia. Ring-width is significantly correlated with mean July temperatures. A reconstruction of mean July temperatures generally parallels similar dendroclimatic reconstructions from northern Fennoscandia. The Kola reconstruction indicates that the early- to mid-20th century experienced an exceptional period of warm summer temperatures. Dendrochronological techniques were used to estimate the timing of establishment and mortality of *Pinus sylvestris* at the site. Tree recruitment and mortality appear inversely related and episodic, with pulses of recruitment occurring during the late-17th, 18th, and mid- to late-20th centuries. The mid-20th century pine recruitment episode lags several decades behind the initiation of 20th-century summer warming. Analysis of instrumental climate records and pine recruitment suggests a link between warm fall and early spring conditions in the mid-20th century and increased pine regeneration. The results of this study are similar to findings from northern Fennoscandia and extend this pattern of recent climatic variation and associated treeline response eastward into the Kola Peninsula.

Introduction

Northern treeline dynamics are of considerable interest due to the sensitivity of treeline to temperature changes and the impact that changes in northern treeline position could have on global climate (Kling et al., 1990; Bonan et al., 1992, 1995; Smith et al., 1992; Foley et al., 1994; Oechel and Vourlitis, 1994; Overpeck et al., 1997; MacDonald et al., 1998b). Tree-ring analysis provides a means of reconstructing long records of climate change at treeline and the response of tree populations to past climatic change. A number of such studies are available from Fennoscandia (e.g., Kullman, 1987a, 1987b; Briffa et al., 1990, 1992; Eronen and Zetterberg, 1996), and are being conducted in northern Russia (Shiyatov, 1993, 1996a, 1996b; Earle et al., 1994; Briffa et al., 1996; Vaganov et al., 1996; MacDonald et al., 1998a).

A number of tree-ring and instrumental climate records from Fennoscandia and northern Russia indicate cool summer conditions during the mid-19th century. High rates of tree mortality and low recruitment rates at treeline are reported for the mid-19th century from Fennoscandia, the Polar Urals, and the Lena River regions (Kullman and Engelmark, 1997; MacDonald et al., 1998a). This cooling was followed by pronounced early- to mid-20th-century warming (Vorren et al., 1993; Zetterberg et al., 1996; Overpeck et al., 1997). In some areas of the Arctic and Subarctic, the early- to mid-20th century is the warmest period recorded for the past 400 yr (Overpeck et al., 1997). Circumpolar tree recruitment during this time increased markedly (Kullman, 1987a, 1993; Shiyatov, 1993; Kullman and Engelmark, 1997; MacDonald et al., 1998b). Subsequently, decreases in recruitment or dieback in Fennoscandia in recent decades (post-1960s) has been attributed to a cooling trend in the region (e.g., Kullman, 1993; Vorren et al., 1993). The results presented here are an addition to the small network of published tree recruitment studies from Russia and helps fill the geographic gap between Siberia and Fennoscandia.

In this study we analyze tree rings from living and dead *Pinus sylvestris* L. (Scots pine) from a treeline location on the Kola Peninsula in northwestern Russia (Fig. 1). Our study site lies between Fennoscandian and Siberian regions discussed above, and can be viewed as a gateway through which oceanic and climatic variations in the North Atlantic sector are propagated into the Eurasian Arctic (Aagaard and Carmack, 1994; Rogers and Moseley-Thompson, 1995). The study addresses three questions: (1) How do recent dendroclimatic record from *Pinus sylvestris* on the Kola Peninsula compare with similar records from northern Fennoscandia?; (2) Is *Pinus sylvestris* recruitment at our study site episodic and linked to regional climatic variations?; and (3) How do *Pinus sylvestris* recruitment dynamics compare with similar records from northern Fennoscandia and Siberia?

Study Site and Methods

The study site is located southeast of the northern port city of Murmansk, Russia at 68°24′46″N, 35°16′93″E at an elevation of approximately 150–300 m a.s.l. (Fig. 1) The geology of the region is crystalline bedrock with a Quaternary cover of glacial till, glaciofluvial deposits and peat. Physiography consists of rolling hills, small valleys, and numerous lakes. *Pinus sylvestris* defines the coniferous treeline. *Pinus sylvestris* and *Picea abies* (L.) Karst. (Norway spruce) form coniferous treeline to the west in northern Finland, Sweden and Norway, with south-facing slopes dominated by *Pinus sylvestris* and some north-facing slopes dominated by *Picea abies* (Kullman and Engelmark, 1997). Our study site is in the *Pinus sylvestris*—*Betula pubescens* Ehrh. (mountain birch) forest-tundra zone, some 6 km south

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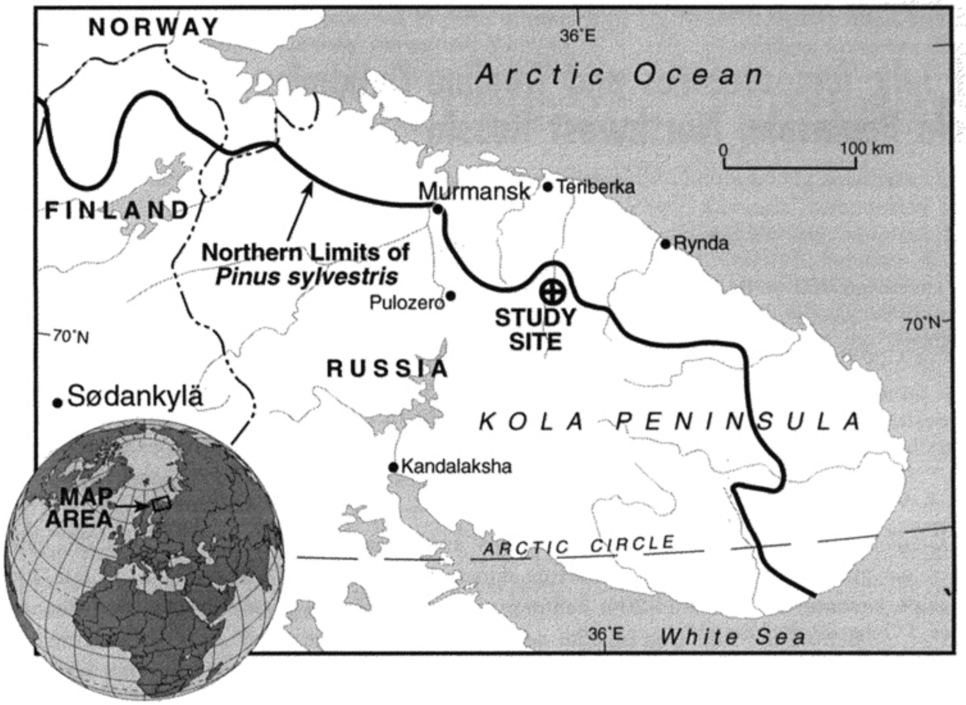

FIGURE 1. The location of the study site in relation to Sødankylä meteorological station and northern Europe.

of the mapped pine treeline. Vegetation on the windswept hilltops consists mostly of *Betula pubescens, Salix* spp., and understorey tundra plants, including Ericaceae, predominantly *Empetrum* and *Vaccinium.* Bare rock and some permafrost patterned ground occur on hilltops. *Pinus sylvestris* is restricted to slower slopes and valleys. The mean July and January temperatures in the region are 14.4°C and −13.5°C, respectively. Mean annual precipitation is on the order of 40 cm and occurs primarily in summer and fall (*Arctic Atlas,* 1985).

The site is far removed from any current permanent human habitation or land transportation corridors. In the past, nomadic Lapp communities of the northern Kola Peninsula primarily inhabited coastal river mouths and inland forested riparian corridors. The Lapps are known to have had a significant but localized impact on treeline in northern Fennoscandia by removing trees for construction and firewood (Rikkinen, 1981). Although we cannot rule out the potential importance of past human disturbance, we assume negligible impact on the age distribution of the treeline stand at our study site (Kullman, 1996; Kullman and Engelmark, 1997). We base this assumption on the remoteness of our site, its hilltop position where Lapp forest impacts were generally not concentrated (Rikkinen, 1981), and the paucity of visible signs of human disturbance (e.g., cut stumps or charred logs). Emissions from metal smelters on the Kola Peninsula have been shown to produce serious growth reductions in *P. sylvestris* through needle defoliation (Jalkanen, 1996). We cannot rule out impact from this, but the closest smelters at Monchagorsk lie some 130 km south and west of our study site.

Field work was conducted in early August 1997. Two stands of *Pinus sylvestris* were chosen for dendroclimatic work. The first was located on a southeast-facing windswept slope just below altitudinal treeline. From this first site we sampled 42 trees, taking two cores from opposing sides of each tree. The second site was located some 30 m lower in elevation and roughly 0.6 km away from the first site, situated in a protected and relatively mesic valley. From this second site 17 trees were cored in the same manner as the first site. Only the oldest-looking and stand-dominant trees in the study area were chosen for coring. Old trees were recognized by irregular crowns dominated by a few upper branches. A total of 29 well-preserved standing and fallen dead trees were found in valleys and on lower hill slopes. Discs were sawed from these at their base to extend the tree-ring chronology using cross-dating techniques. Radii and discs were prepared and tree rings measured using a Nikon stereomicroscope and Velemax table (accuracy of ±0.001 mm) and cross-dated using standard practices (Fritts, 1976). Cross-dating verification was aided using the COFECHA program (Grissino-Mayer et al., 1992). A negative exponential was fitted to most tree-ring series to remove growth trends from individual radii. To remove trends of biological persistence in tree growth autoregressive modeling was carried out using the ARSTAN program to develop the residual chronology (Fig. 2) (Grissino-Mayer et al., 1992).

Pearsons product moment correlation coefficents were calculated between the ARSTAN tree-ring chronology and monthly climate data from Murmansk, Russia (NW), Archangelsk, Russia (SE), and Sødankylä, Finland (67°29′N, 26°32′E), roughly 300 km west of the study site. Correlations between monthly meteorological data from each of the three stations and the tree-ring data shows that Sødankylä correlates best with our study site tree rings (Table 1). Our study site is located well inland from the coast, as is Sødankylä. Both Murmansk and Arkhangelsk, however, are coastal cites dominated by maritime climates. Sødankylä has the additional advantage of a relatively long instrumental climatic record (A.D. 1908 to 1988). A transfer function model using the Sødankylä data was developed and tested according to Fritts (1976) to estimate past July temperatures from the tree-ring chronology (Figs. 3, 4a).

We examined the age structure of our samples to infer the timing of establishment of the oldest stand dominant trees in the study area. Unfortunately, many of the oldest trees (>250 yr) have pith rot, and the timing of establishment could not be determined. Ages of establishment for the living trees were estimated from one core per tree, and only using those radii taken at or below breast height which bisected or crossed in close proximity to the intact pith. In total, dates of establishment were

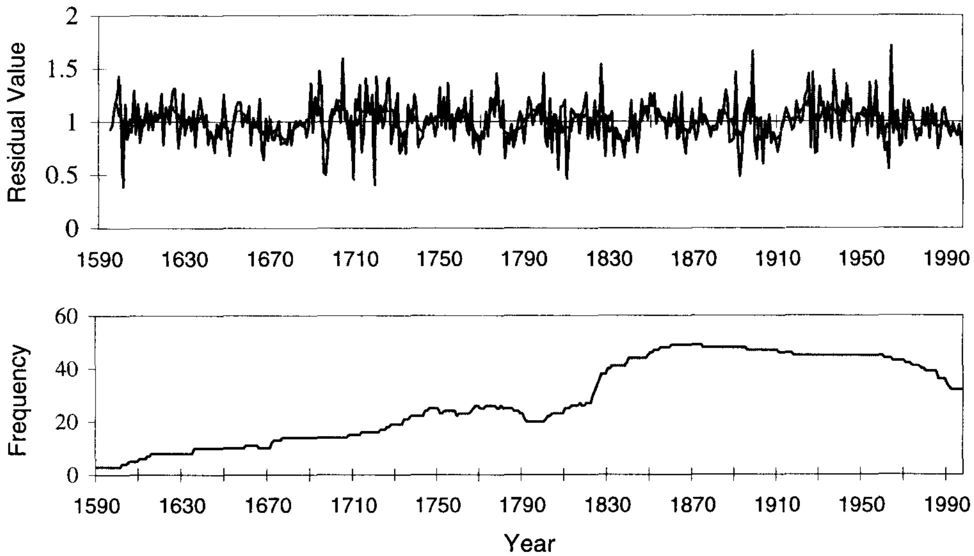

FIGURE 2. The ARSTAN residual tree-ring chronology with a 5-yr running average and sample depth.

obtained from 65 of the 88 living and dead tree cores and discs taken from both study sites (Fig. 4b). In extreme cases northern *Pinus sylvestris* can take as long as 80 yr to reach breast height (Zackrisson et al., 1995). Conservatively, 20 yr were added to pith dates of all radii to account for the time taken to reach coring height. The ages of fallen dead trees were determined by crossdating with the living-tree chronology. One decade was added to the last outer ring of those dead pines which showed evidence of removal of the cambium due to weathering.

Recent recruitment patterns were determined using one 200-m-long by 100-m-wide transect from a treeless hilltop down into a forested valley at the field site. All 44 *Pinus sylvestris* trees and seedlings found within this belt transect were sampled. Discs were taken from the base of seedlings and small trees. A few trees that had a trunk diameter of >30 cm were sampled by coring at the base. Cores and discs were fine-sanded and the tree rings were counted. Because we sampled the trees at ground level along this transect, the age of the pith was assumed to indicate the approximate timing of establishment. Including the belt-transect, in total a total of 109 living and dead trees were successfully crossdated and included in the recruitment analysis (Fig. 4b).

Results

TREE-RING CHRONOLOGY

A total of 42 and 17 trees were cored at the first and second study sites, respectively. Ring widths of trees growing at the sheltered mesic valley at the second site did not correlate with those taken from the exposed first site (roughly 0.6 km away) and were thus not included in the dendroclimatic analysis. Of a total of 42 living trees, 30 could be successfully cross-dated and were used to construct the master chronology. The oldest living tree is 296 yr old. Of the 29 dead trees sampled, 11 were successfully cross-dated and incorporated into the master chronology developed from the living trees. The tree-ring residual chronology spans from A.D. 1595 to 1997 (n = 63; three-radii minimum; Fig. 2, Table 2).

TABLE 1

Correlation coefficient matrix for meteorological stations

Month	Arkhangelsk	Murmansk	Sødankylä
May	0.11 ($P < 0.27$)	−0.02 ($P < 0.93$)	−0.01 ($P < 0.93$)
June	0.16 ($P < 0.11$)	0.27 ($P < 0.13$)	−0.02 ($P < 0.86$)
July	0.39 ($P < 0.001$)	0.50 ($P < 0.003$)	0.63 ($P < 0.001$)
August	0.35 ($P < 0.00$)	0.25 ($P < 0.17$)	0.23 ($P < 0.04$)
September	0.11 ($P < 0.19$)	0.07 ($P < 0.69$)	0.07 ($P < 0.54$)

CLIMATE AND RING WIDTHS

Pinus sylvestris ring-width-derived residual values correlate significantly with mean July temperatures ($r = 0.63$, $P < 0.001$; Table 1). This result is in agreement with other published studies of *Pinus sylvestris* in Fennoscandia which show that ring-width variation correlates best with summer temperatures, particularly June and July temperatures (e.g., Briffa et al., 1990, 1992; Zetterberg et al., 1996; Kullman and Engelmark, 1997). There is a weak but significant correlation between residuals and mean August temperatures ($r = 0.23$, $P < 0.04$; Table 1). Otherwise, no significant correlations were found between the rings and any other monthly, seasonal or annual averages of temperature or precipitation.

DENDROCLIMATIC MODEL

The dendroclimatic model is a simple linear transfer function that estimates July temperature from tree-ring residual values. The calibration and verification steps involved dividing the Sødankylä July temperature record into two periods (1908–1948 and 1949–1988) and building separate transfer function models from each section and then estimating temperatures for the other period. Both models passed the Reduction of Error (RE) and Coefficient of Efficiency (CE) tests with positive scores (Fritts, 1976). There are no statistical tests for determining the significance of the RE and CE scores. The Signs Test was passed with positive scores only for the latter of the two time periods. Failure to pass the signs test indicates that the model is better at capturing low-frequency variation than high-frequency variation (D'Arrigo and Jacoby, 1992). A transfer function model was developed (July temperature = 8.762 + 5.739 [ARSTAN chronology width]) from the full 1908–1988 meteorological record (Tab 3). The r^2 (adj) of the full model is 0.39 ($P < 0.001$), capturing almost 40% of the temperature variability during the period of verification (Fig. 3; Table 3).

Five-year and 10-yr moving averages accentuate the general

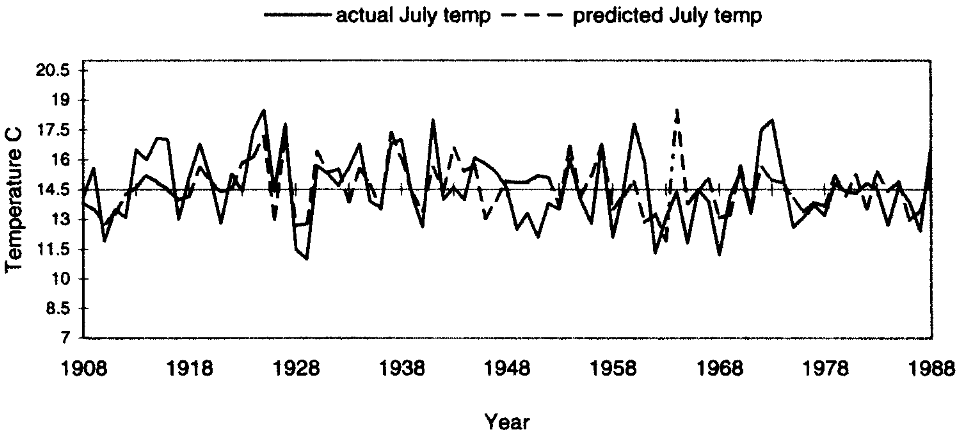

FIGURE 3. Observed mean July temperatures from Sødankylä, Finland, 1908–1988, and predicted July temperatures for the same period using the full (1908–1988) transfer function model derived from Pinus sylvestris *ring widths.*

temperature trends during the reconstruction period, A.D. 1595–1997 (Fig. 4a). Our temperature chronology largely parallels similar studies from adjacent Fennoscandia. Most of the 1600s are marked by below-average temperatures and have some of the most prolonged cooling episodes in the record. In our data, and elsewhere in boreal Fennoscandia, above-average temperatures occurred in the early 1700s, and the second half of that century was marked by average to below-average temperatures. The 19th century experienced oscillations between cool and warm periods, each lasting several decades. Similar results have been reported from Fennoscandia (Briffa et al., 1990; Zackrisson et al., 1995). The 1900s began with several decades of below-average temperatures. These rose to levels considerably above average for the period roughly from A.D. 1920 to 1970. The prolonged middle-1900s warming was reported from a number of sites across Fennoscandia (Kullman, 1985, 1987b; Briffa et al., 1990, 1992; Briffa and Schweingruber, 1992; Vorren et al., 1993; Zetterberg et al., 1996; Eronen and Zetterberg, 1996; Kullman and Engelmark, 1997), Siberia (Briffa et al., 1995; MacDonald et al., 1998a) and much of northern Eurasia (Briffa et

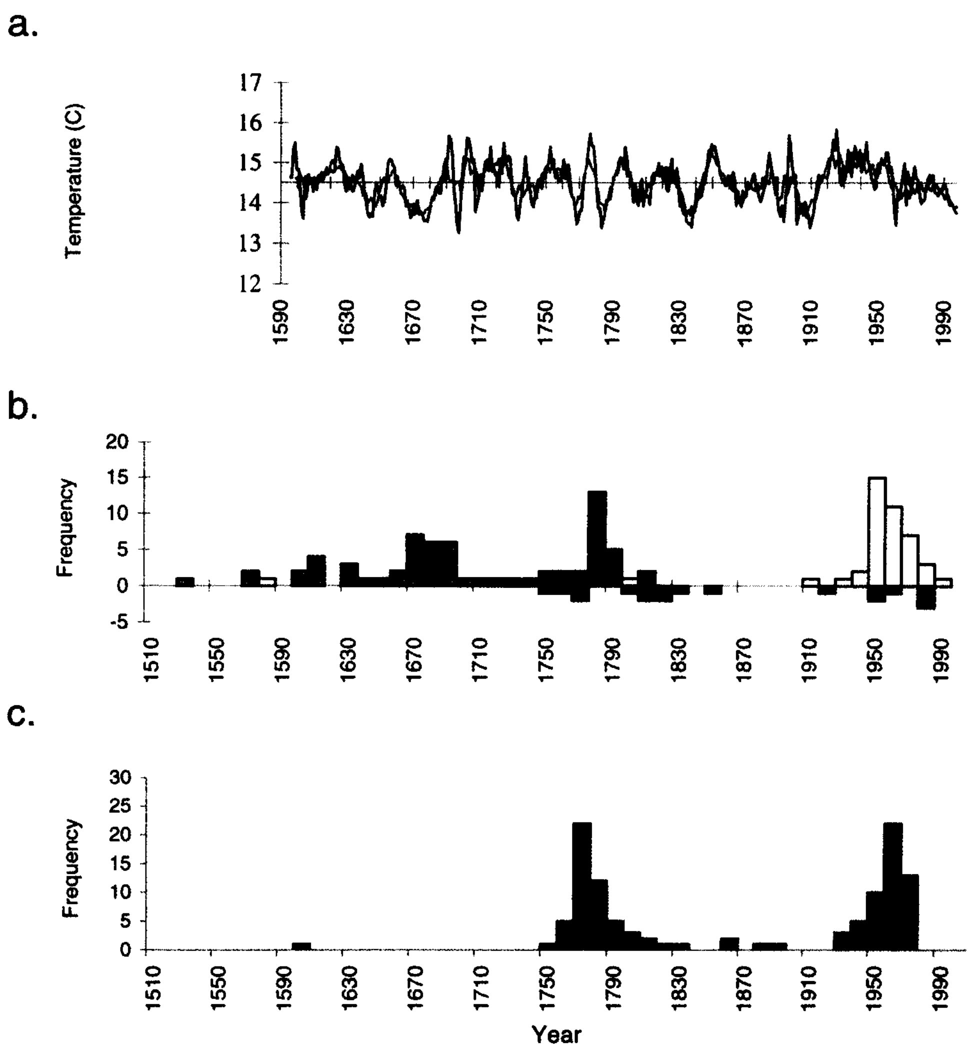

FIGURE 4. (a) Mean July temperatures reconstructed from 1595 to 1997 with a 5- and 10-yr running temperature averages. (b) Pine establishment and mortality histogram from the Kola Peninsula. Light bars are samples from a 200 × 100 m transect, and dark bars are old and stand-dominant trees. Bars with negative values are mortality frequencies (number of trees for decadal classes). (c) Pine establishment histogram from northern Sweden (after Zackrisson et al., 1995).

TABLE 2

ARSTAN chronology statistics

Chronology length (3 radii minimum)	403 yr
Mean sensitivity	0.217
Standard deviation	0.202
First-order autocorrelation	0.007

al., 1996; Vaganov et al., 1996). The post-1950s cooling apparent on the Kola is also similar to cooling trends observed in instrumental and tree-ring records from Fennoscandia and much of northern Eurasia.

TIMING OF RECRUITMENT AND MORTALITY

Core samples from a total of 47 living trees and disc samples from a total of 18 dead trees were used to determine the timing of germination and mortality. Included in this data set are the 44 trees sampled along the 200-m × 100-m belt transect designed to record recent tree recruitment (n = 109) (Fig. 4b). To account for weathering of the outermost rings of the dead trees and inherent difficulty of establishing exact germination timing from trees cored at breast height, these data were placed in decadal age categories. Caution needs to be exercised in interpreting these combined results because the sampling of trees outside of the transect area is biased toward older, stand dominant individuals, while sampling within the belt transect includes all age classes. We compared 5-yr age classes of recent pine establishment at our transect to monthly and annual instrumental temperature and precipitation data from Sødankylä. The timing of maximum recruitment appears related to the timing of highest September and April temperatures.

Discussion

The ARSTAN chronology from the Kola Peninsula correlated with mean July temperatures. This relationship between tree rings and summer temperatures is in agreement with the findings of many other studies for Fennoscandia. Short arctic summers provide a limited time for tree growth and a cool temperatures during the growing season produce decreased rates of photosynthesis and growth (Fritts, 1976; Schweingruber, 1996). However, July temperature variability accounts for roughly 40% of the variation in the ring widths. Other climatic factors, such as short-term, localized events may reduce the correlation between data sets. In addition, the impact of biological factors such as competition with other trees or the effect of pathogens (Jardon et al., 1994) may also be reflected in the unaccounted variation. Indeed, our second, relatively sheltered and mesic coring site was dismissed from the analysis since tree growth response to climate differed from that of the first tree-coring site.

The pattern of cool temperatures during the 1800s and early 1900s and pronounced warming during the middle 1900s evident in the Kola record has been observed in various proxy climate data from a number of arctic and subarctic studies (Overpeck et al., 1997). Instrumental records suggest that between A.D. 1935 and 1955 temperatures in the Arctic were approximately 1.5°C warmer than they were in 1900 (Chapman and Walsh, 1993). Our temperature estimations follow this general pattern. The early to middle 20th century appears to be the longest and most prolonged warming period (ca. 40 yr) to have occurred in the last 400 yr. Similar 20th-century warming has been reported from the Polar Urals (Graybill and Shiyatov, 1993; Briffa et al., 1995) and Siberia (Shiyatov et al., 1996a, 1996b; MacDonald et al., 1998a), the Taimir (Vaganov et al., 1996) and across much of northern Eurasia (Briffa et al., 1996). Temperature reconstructions from northern Fennoscandia provide some evidence of mid-20th century warming, but do not indicate that it is exceptional relative to warming episodes of the past several centuries (Briffa et al., 1990; Briffa and Schweingruber, 1992). The Fennoscandian sites may be more influenced by variations in North Atlantic temperatures due to changes in thermohaline circulation and the impact of Barents Sea deep-water cooling which moderates the temperature trends (Briffa et al., 1990; MacDonald et al., 1998a). Although the absolute magnitude of 20th-century warming, inferred from the Kola Peninsula record, is unexceptional compared to earlier warm periods, the duration of warm July temperatures from approximately 1915 to 1950 is unique for the past 400 yr. Thermal patterns are in general agreement between our study site and northern Fennoscandia and Siberia during the 19th and 20th centuries, and the earlier part of the

TABLE 3

Calibration and verification statistics

Calibration and Verification Statistics

Model*	calibration period	calibration r	r-sq (adj)	verification period	verification r	RE	CE	sign test (+/-)
early	1908-1948	0.69	0.47	1949-1988	0.36	0.09	0.02	24/14 (fail)
late	1949-1988	0.51	0.24	1908-1948	0.70	0.51	0.48	28/12 (pass)
full	1908-1988	0.63	0.39					

r Pearson Product Moment correlation coefficient
RE Reduction of Error statistic (positive values are considered to pass)
CE Coefficient of Efficiency (positive values are considered to pass)
* transfer function models
early: Julyt = 8.894 + 5.876(residual)t
late: Julyt = 9.289 + 4.907(residual)t
full: Julyt = 8.762 + 5.739(residual)t

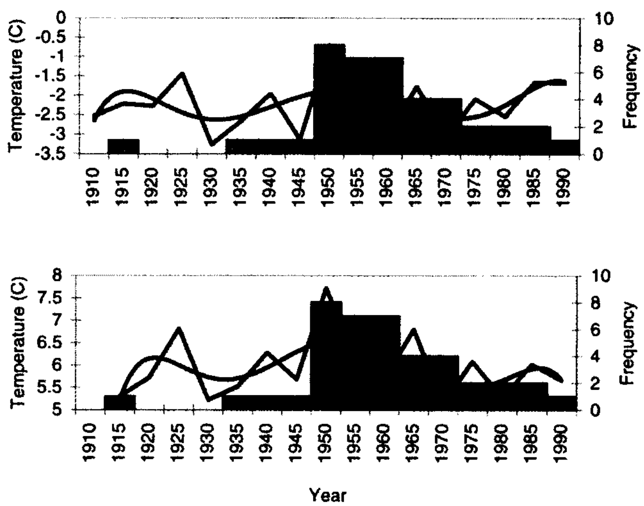

FIGURE 5. Five-year age classes of 20th-century pine establishment (1910 to 1990) and recorded temperature for September (top) and April (bottom) with a 6th-order polynomial smoothed trend line.

record. In general, some site-dependent thermal variability is evident in most circumpolar arctic and subarctic proxy temperature records (Overpeck et al., 1997).

Tree recruitment at our study site is clearly episodic and appears concentrated in the periods A.D. 1650 to 1700, 1770 to 1810, and 1930 to 1980. Pine recruitment pulses on the Kola during the late 17th, 18th, and middle 20th centuries are similar to those observed in northern Fennoscandia (Zackrisson et al., 1995) (Fig. 4c). At our site an earlier recruitment pulse occurred in the late 1600s, which does not occur at other sites to the west. This could be due to either the presence of pith rot in the oldest trees or earlier selective logging operations at the Fennoscandian sites (Kullman, 1987b; Zackrisson et al., 1995). Summer warmth in the 19th century (1840 to 1900) did not result in increased pine recruitment at our study site. High-latitude marginal forest stands at the same latitude in northern Fennoscandia also show greatly reduced *Pinus sylvestris* recruitment during most of the 19th century (Figs. 4b, 4c), while less marginal Fennoscandian sites to the south experienced 19th-century pine recruitment (Kullman, 1985, 1987a; Zackrisson et al., 1995). The phase of recruitment in the 20th century is very typical of the result found for *Pinus sylvestris, Picea abies,* and *Betula* spp. in Fennoscandia (Kullman, 1985, 1987a, 1987b, 1993, 1996; Zackrisson, 1995; Kullman and Engelmark, 1997); for *Larix siberica* in the Polar Urals (Shiyatov, 1993); and for *Larix dahurica* in northeastern Siberia (MacDonald et al., 1998a). Although our mortality data are sparse, tree mortality and establishment timing appear to be inversely related, with tree mortality loosely bracketing the late 18th-century regeneration pulse. The episodic pattern of *Pinus sylvestris* establishment on the Kola Peninsula and similar patterns in northern Fennoscandia (Fig. 4b) are most likely largely the result of climatic influences common to both regions. We would thus expect to find a good correlation between the tree regeneration pattern and the climatic record. Twentieth-century pine recruitment appears related to September and April temperatures (Fig. 5).

It is plausible that low fall and spring temperatures could result in seedling mortality if temperature reductions occur without the protection of an insulating snow bed. However, reproductive biology of northern pines is complex and pine regeneration controls are probably not limited to fall and spring temperatures. Successful high-latitude tree germination is influenced by summer temperatures during cone formation, at germination and during seedling growth up to several decades after germination (Elliott-Fisk, 1983; Szeicz and MacDonald, 1995; Scott et al., 1997). Lack of tree recruitment has been attributed to edaphic factors (Kullman, 1987a; MacDonald et al., 1998a), snow depth (Kullman, 1987a; Hessl and Baker, 1997), competitive exclusion from ground vegetation (Zackrisson et al., 1995) and habitat disturbance (Kullman, 1987a; Payette and Morneau, 1993). The extent to which each of these factors individually and in conjunction has impacted tree regeneration at our study site is unknown. However, the correspondence between recruitment at our site and other areas in northern Fennoscandia suggest climate plays a major role.

Taken as whole, the result of this study indicate that changes in summer temperatures and treeline dynamics over the past two centuries on the Kola Peninsula are in general agreement with those reported from boreal Fennoscandia. This result is not unexpected given the proximity of the Kola Peninsula to northern Fennoscandia and position downstream of atmospheric and oceanic circulation that impacts Fennoscandian climate. There is much scope for comparative studies of *Picea abies* and *Betula* spp. histories between the two regions. In addition, it is likely that longer and more detailed dendroclimatic records from *Pinus sylvestris* can be obtained from the Kola Peninsula. Subfossil *Pinus sylvestris* logs as old as 6500 ^{14}C yr BP have been recovered from lakes on the Kola (MacDonald et al., 2000). These long dendroclimatic records could be compared to the multimillennial records from Fennoscandia (e.g., Briffa et al., 1990; Zetterberg et al., 1996) and used to examine the eastward propagation of climate changes at earlier times.

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