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Medieval climate warming and aridity as indicated by multiproxy evidence from the Kola Peninsula, Russia

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Abstract

Data obtained from the low-elevation Khibiny Mountains (ca. 67–68°N; 33–34°E) on the Kola Peninsula, northwest Russia, indicate a period of exceptionally warm and dry conditions commenced at ca. AD 600 and was most pronounced between ca. AD 1000 and 1200. Warmer summer temperatures during this period (coeval with the 'Medieval Warm Period' observed in other parts of Europe) are evident in a 100–140 m upward shift in the pine (Pinus sylvestris L.) limit in the Khibiny Mountains. On average, the cellulose of pine trees that grew between ca. AD 1000 and 1300 is enriched by $\delta^{13}C$ values of around 1‰ compared to the modern trees from the region, further suggesting warmer summer climate than at present. The Medieval Warm Period was also accompanied by a steady decline in avalanche activity and the resulting formation of soils on the current avalanche cones in the Khibiny Mountains, suggesting lower winter precipitation and thinner snow cover. Lower precipitation is also evident by currently submerged tree stumps dating to the medieval period that indicate lower lake levels on the Kola Peninsula. In the middle of the peninsula at about AD 1000, the level of small closed-basin lakes was $\sim$ 1 m lower than the modern time at some sites. Drier conditions may be attributable to decreased cyclonic activity. The medieval warm and dry episode was followed at ca. AD 1300 by the development of a colder climate with increased precipitation resulting in a decline in the alpine pine limits, increased avalanche activity, and higher lake levels. That phase corresponds to the modern aeolian episode reconstructed in subarctic Finland. Our results indicate that the Medieval Warm Period on the Kola Peninsula

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experienced notably warm and dry conditions. Hence, this period of warming extends to northwestern Russia as well as other parts of Europe.
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1. Introduction

The so-called 'Medieval Warm Period' (ca. AD 700–1300) is of great interest because it is the most recent well-pronounced warming event observed in many climatic records. Although warming during this time is not evident in available records from all parts of the Northern Hemisphere, it is recorded in many parts of continental Europe, Fennoscandia and northern Asia (Briffa et al., 1995; Crowley and Lowery, 2000). In northwestern Russia, an increase in the mean summer temperature during the medieval period is recorded by a radiocarbon dated upward shift of the alpine tree line in the Khibiny Mountains in the central Kola Peninsula (Hiller et al., 2001). Similar evidence is available for the northern Scandinavian mountains (Karlén, 1976; Kullman and Engelmark, 1990). It still remains unclear if the medieval summer warming was accompanied by changes in the precipitation regime.

In order to increase our understanding of the climatic pattern of the medieval warming and elucidate possible hydrologic changes at that time, a multi-proxy study in the Khibiny area was undertaken. In the study, we analyzed and dated a series of subfossil soil profiles buried in avalanche cones. Radiocarbon ages were obtained from pine trees submerged in a small lake located on the plain north of the mountains. In a pilot study, samples from living and subfossil pine trees found in Khibiny Mountains were analyzed for the stable isotopes of ^{13}C, ^{18}O and ^{2}H. These new data are incorporated with the tree line data of Hiller et al. (2001) to provide a multifaceted reconstruction of climatic and environmental conditions during the past 1500 years. Our study addressed two questions: (1) Was the Medieval warming period also a time of deceased humidity? (2) If detected, was the decrease in humidity related with increasing evaporation during warmer summer time only, or it did occur because of lower precipitation?

1.1. Study area

The Khibiny Mountains are located in the central part of the Kola Peninsula between 67–68°N and 33–34°E. The maximum elevation is ~1200 m. The

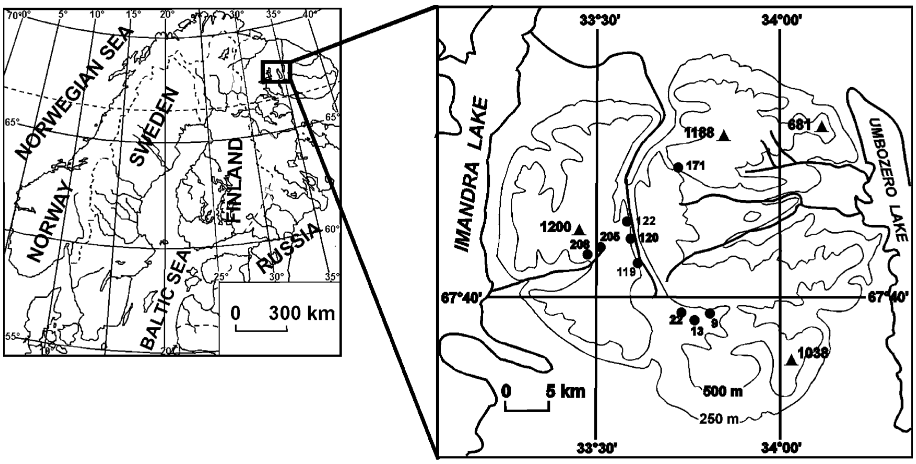

Fig. 1. Location of the Khibiny Mountains. Dots with numbers indicate the positions of studied avalanche fans (see Table 1).

Fig. 2. Avalanche cone # 208. Photograph by T.V. Vaschalova.

Khibiny Mountains are surrounded by rolling lowlands with elevations of 130–170 m (Fig. 1). The Khibiny massif is a great alkaline Caledonian intrusion connected with a regional tectonic fracture. The massif is composed of nepheline syenites, syenites and urtites, to a lesser degree of alkali ultrabasites and carbonatites (Atlas Murmanskoi Oblasti, 1971). Being the highest location on the Kola Peninsula, the Khibiny Mountains receive relatively high amounts of precipitation. The maximum precipitation recorded for the Kola Peninsula occurs at the Yukspor Meteorologic Station (1342 mm, elevation 902 m) (Kremenetski et al., 1999). More than half of this precipitation occurs in the summer–autumn period as rain and the remainder in the winter–spring mainly as snow.

There are three vegetation belts at Khibiny Mountains. Spruce (Picea obovata Ledeb.) and pine-dominated (Pinus sylvestris L.) forests grow at elevations up to ca. 260–380 m depending on the slope exposure and aspect. A narrow dwarf birch forest–tundra belt is

Fig. 3. Avalanche cone # 9 as viewed in 1962 before the development of an open cast mine. Photograph from archive of the Khibiny Moscow State University station.

Table 1
Coordinates of snow avalanche cones in Khibiny Mountains (for location, see Fig. 1)

No. of cone	Location	Latitude, N	Longitude, E	Altitude (m)
205	Malaya Belaya	67°43′	33°32′	580
208	Malaya Belaya	67°42′	33°28′	540
119	Kunyok	67°44′ 30″	33°37′	420
120	Kunyok	67°44′ 32″	33°37′	400
122	Kunyok	67°45′ 20″	33°37′	380
109	Vudyavryok	67°42′	33°39′	500
171	Risyok-1	67°47′	33°40′	580
177	Risyok-2	67°47′	33°40′	580
9	Yuksporyok	67°38′ 50″	33°46′	410
13	Yuksporyok	67°38′ 40″	33°43′	380
22	Saamskaya	67°39′	33°43′	375

located between the forest and upper-elevation tundra belt. Mountain tundra occurs at elevations between 400 and 700 m with alpine desert occupying the uppermost parts of the massif.

2. Materials and methods

2.1. Avalanche cones

Snow avalanche cones are widespread in the Khibiny Mountains (Figs. 2 and 3). They are found at different elevations in modern tundra and forest altitudinal belts. Snow avalanches are the main contributing factor providing clastic material including cobbles and boulders that make up the sediments of these cones. It might be expected that periods of significantly reduced avalanche activity would result in stabilization and soil formation on these features. A number of cones were investigated for the presence of buried fossil soils (Table 1; location is shown on Fig. 1). Avalanche cone # 9 was partly destroyed by an open mine. A good section exposing a well-preserved layer of buried soil can be seen on Figs. 4 and 5. In other cases, trenches were dug to find and uncover buried soils. The stratigraphy of the trench walls was described and the buried soils were sampled for radiocarbon dating. The properties of soils buried in the avalanche profiles are similar to those of corresponding zonal soils. These properties are not so distinct because the time available for the soil processes to develop on the avalanche cone surface was much shorter then in areas not affected by the avalanche activity.

2.2. Submerged wood

On the plain north of the Khibiny Mountains (68°01′ N, 34°32′ E), a small (less then 10 ha) closed-basin lake surrounded by pine forest was

Fig. 4. An exposure of buried soil in a cross section of avalanche cone # 9. Photograph by T.V. Vaschalova.

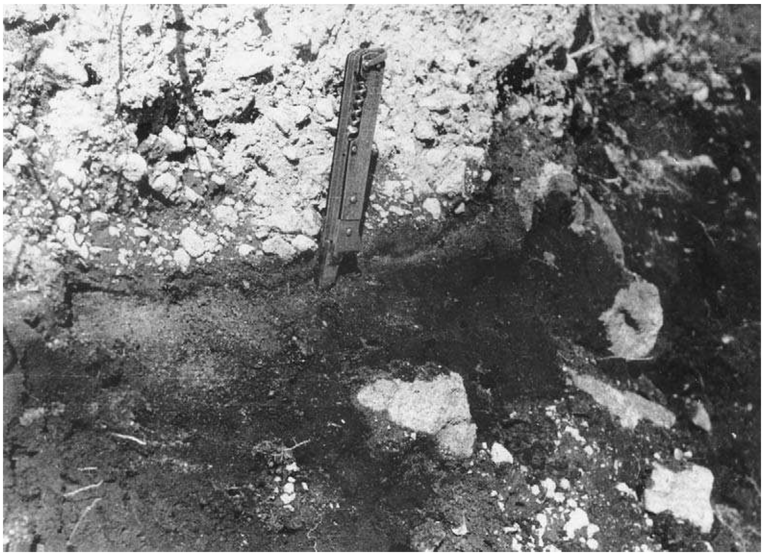

Fig. 5. Buried soil in a cross section of avalanche cone # 9 viewed from closeup. Photograph by T.V. Vaschalova.

studied. Few submerged pines were observed near the shoreline of the lake and sampled. Pine stumps were submerged at the depth of 1 m and were located in situ. This indicates lower lake level during the lifetime of the trees. Four stumps were sampled for radiocarbon dating.

2.3. Alpine subfossil wood

Numerous subfossil pine samples were collected in birch forest–tundra and in tundra belts above the modern limit of pine in the Khibiny Mountains (Fig. 6). Full details on sampling and the ages of the

Fig. 6. A pine log found 80 m above the modern pine limit in Khibiny alpine tundra belt dated to 860 ± 70 cal. BP (Hiller et al., 2001). Photograph by T. Boettger.

samples are provided by Hiller et al. (2001). As tree line appears to be related to summer warmth, the past growth of trees above modern tree line can indicate summer conditions that were warmer than modern times (Hiller et al., 2001).

2.4. Wood isotope analysis and dating

Climatic factors such as air temperature and relative humidity, as well as local factors such as light conditions and soil moisture, affect the fractionation of the isotopes via stomatal resistance (Farquhar et al., 1982). Hot and dry conditions generally lead to a greater $^{13}C/^{12}C$ ratio in the plant tissue, although factors such as soil nutrient content, age of the tree, state of health, etc. and anthropogenic influences (e.g., the increase in the CO_2 concentration and a declining trend in its $\delta^{13}C$ value owing to the combustion of fossil fuels) can exert a major impact on the carboxylation process of photosynthesis—and on the ^{13}C level (Saurer et al., 1995; Robertson et al., 1997; Schleser et al., 1999; Edwards et al., 2000). However, despite such potential complications, the carbon isotope ratios in cellulose of pine tree rings in northern Finland correlate with the average temperatures for the months of July and August, with photon flux (sunshine), air humidity and soil moisture (Sonninen and Jungner, 1995, 1996; McCarrol and Pawellek, 2001).

The δ^2H and $\delta^{18}O$ values in the wood cellulose are determined by the isotope signature of the source water available for tree growth (including groundwater, precipitation and soil water), humidity and the biochemical fractionation processes during photosynthesis. If the source water is mainly meteoric water, the δ^2H and $\delta^{18}O$ values in the tree rings largely depend on regional precipitation. The isotopic effects

Table 2
Results of radiocarbon dating

Location	Material dated	Age, ^{14}C years BP	Age, cal. years BP	Laboratory no.
Avalanche cones in tundra belt				
# 205, trench 1	humic acids	890 ± 80	702–862	GIN-3015a (one residual)
	humic acids	1240 ± 150	1018–1318	GIN-3015b (2 + 3 residuals)
# 205, trench 2	humic acids	810 ± 100	605–805	GIN-3179
# 171	humic acids	1730 ± 150	1510–1810	GIN-3175
# 122	humic acids	4070 ± 120	4411–4651	GIN-3395
	humic acids	3840 ± 150	4084–4384	GIN-4546
# 120	humic acids	1130 ± 70	947–1087	GIN-3394
# 177	charcoals	2840 ± 70	2873–3013	GIN-4552
# 119	humic acids	980 ± 40	882–962	GIN-3393
	humic acids	2160 ± 50	2088–2188	GIN-3385
	humic acids	2430 ± 30	2386–2446	GIN-4545
# 109	humic acids	660 ± 50	598–698	GIN-3399
	humic acids	1110 ± 50	937–1037	GIN-3172
# 208	humic acids	1010 ± 150	780–1080	GIN-3178
	humic acids	1140 ± 100	957–1157	GIN-3177
	humic acids	1530 ± 80	1322–1482	GIN-3176
Avalanche cones in forest belt				
# 9	humic acids	870 ± 50	705–805	GIN-3390
	humic acids	1500 ± 100	1252–1452	GIN-3391
# 22 trench 1	humic acids	790 ± 40	647–727	GIN-3392
# 22 trench 2	fulvic acids	1380 ± 60	1230–1350	GIN-3383
# 22 trench 2	humic acids	1590 ± 60	1445–1565	GIN-3383
# 13	humic acids	2330 ± 80	2262–2422	GIN-3384a (two residuals)
	humic acids	2190 ± 40	2108–2188	GIN-3384b (one residual)
Small lake	wood	370 ± 55	409–519	LZ-1649
	wood	1000 ± 50	900–1000	LZ-1451
	wood	130 ± 50	modern	LZ-1650
	wood	1030 ± 65	855–985	LZ-1651

observed in the precipitation, which are climatically controlled and depend on the location's temperature and relative humidity (Dansgaard, 1964; Yurtsever and Gat, 1981), can also be observed in the wood components (Edwards and Fritz, 1986; Lipp et al., 1993; Feng and Epstein, 1995; Buhay and Edwards, 1995; Pendal, 2000). Higher temperatures and/or reduced humidity frequently result in the relative enrichment of the heavy isotopes ^{2}H and ^{18}O in the tree ring cellulose owing to the increasing evapotranspiration fractionation in the source water and in plant sap prior to cellulose synthesis.

Given the potential climatic sensitivity of wood cellulose, a pilot study was conducted to examine samples from both living and subfossil trees. Increment cores were obtained from living pines at the modern upper limit of pine. Cellulose from the approximately 20 external rings of ^{14}C dated wood samples and from living trees was used for stable isotope measurements.

The annual isotope analyses on increment cores of the three living pine trees were carried out on the cellulose of the late wood. The late wood from tree rings was cut under the microscope. Limited quantities of material available from individual tree rings allowed measurements of only the carbon and oxygen stable isotope ratios.

The stable isotope analyses of fossil and living pine samples were carried out on the cellulose (δ^{13}C and δ^{18}O) or the cellulose nitrate (δ^2H of nonexchangeable carbon-bound hydrogen). The cellulose was extracted and nitrated using the methods of Gray and Song (1984). To measure δ^{13}C and δ^{18}O values, the samples were pyrolysed and measured online using the XLplus Mass Spectrometer (Finnigan MAT). The combustion of cellulose nitrate was conducted offline in ampoules with CuO (30 h, 690 °C), followed by the cryogenic separation of CO_2 and H_2O, and the chromium reduction (800 °C) of the H_2O to H_2, before measurement was carried out with a Delta S Mass Spectrometer (Finnigan MAT). The results are shown using the conventional notation ($\delta = R_{sample}/R_{standard} \times 1000$ [‰]; $R = {}^2H/{}^1H$, $^{13}C/^{12}C$, $^{18}O/^{16}O$) with respect to the VPDB and VSMOW standards. The overall precision of the replicate samples analyses is estimated to be better than 0.1‰ for δ^{13}C, 0.1‰ for δ^{18}O, and 2‰ for δ^2H.

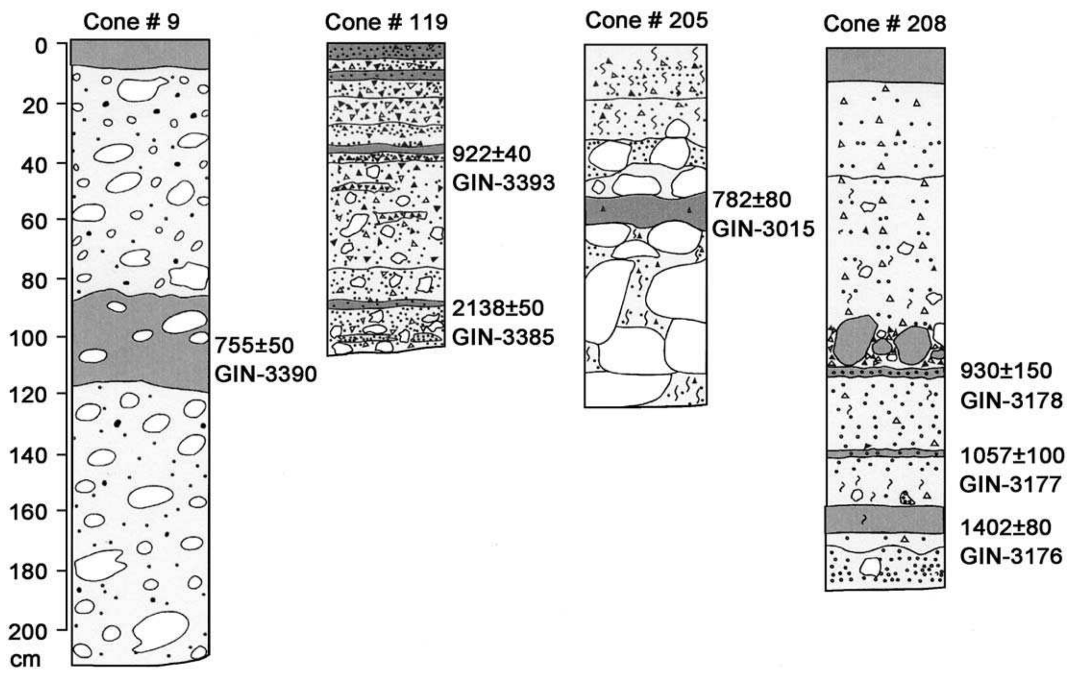

Fig. 7. Cross-sections of selected avalanche cones in Khibiny Mountains and the age of buried soils.

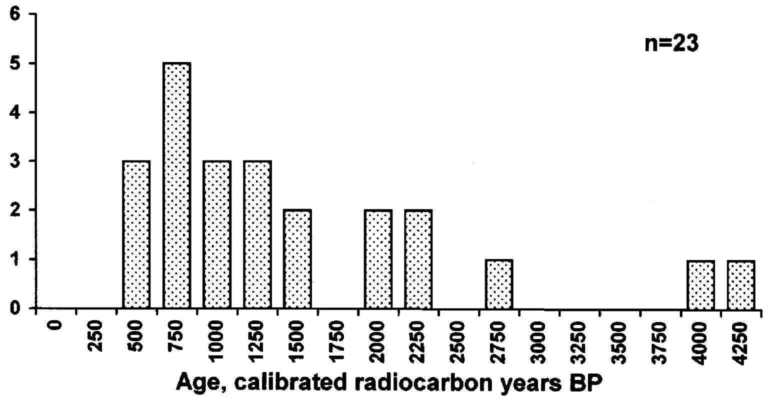

Fig. 8. Distribution of radiocarbon dates of buried soils in avalanche cones in Khibiny.

Conventional radiocarbon methods were used for dating samples. Dates were calibrated with the INTCAL 98 calibration program (Stuiver et al., 1998) (Table 2). Calibrated chronology is used throughout the paper.

3. Results

3.1. Age of buried soils in the snow avalanche cones

The stratigraphy of avalanche cones is somewhat variable, but the common occurrence of buried soil horizons in a number of cones suggested past periods of decreased avalanche activity. The number, thickness and age of buried soils in the avalanche cone sediments differed from site to site (Fig. 7). Although scattered dates from some cones indicate earlier periods of soil formation, the most numerous radiocarbon dates from buried soils range between AD 1200 and 800 (Fig. 8 and Table 2). That period represents the most distinct period of decreased avalanche activity throughout the Khibiny Mountains (cf. Table 1 and Fig. 1).

3.2. Submerged wood

Radiocarbon dating of subfossil pinewood submerged in the small lake on the plain north of the

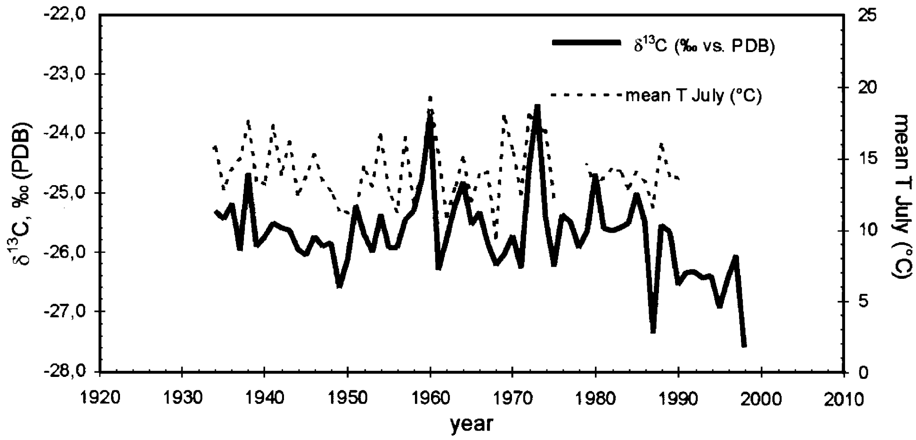

Fig. 9. Time series of mean $\delta^{13}C$ values (not corrected via anthropogenic trend in atmospheric $\delta^{13}C$ values) from late wood cellulose of three living pine trees and monthly mean temperatures of July at Khibiny Mountains.

Khibiny Mountains provides evidence of a distinct episode of low lake level at around 950 BP. One age is younger, thus suggesting that a drop in the lake level also occurred at around 450 BP and the last date is modern, perhaps representing a dating error.

3.3. Stable isotope analysis

The $\delta^{13}C$ and $\delta^{18}O$ values of late wood cellulose from increment cores of three young pine tree correlate significantly with each other ($r_{mean} = 0.46$; $n = 63$). These data were compared with the meteorological

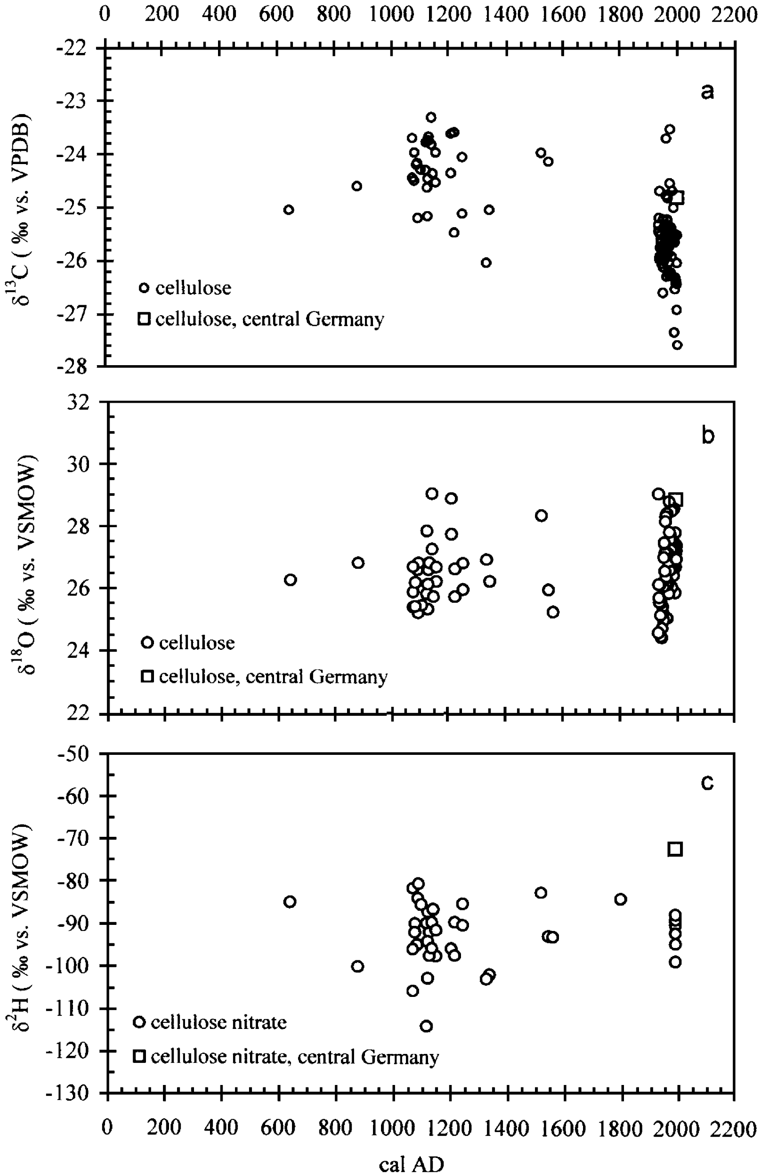

Fig. 10. Original $\delta^{13}C$ (a); $\delta^{18}O$ (b) and $\delta^{2}H$ (c) values for the cellulose nitrate, whole wood and cellulose of living and dead Pinus sylvestris L. tree samples from the Khibiny Mountains.

data (temperature and precipitation) recorded at a weather station near the study area (67°43′ N, 33°15′ E; H = 134 m). A significant correlation was found between the $\delta^{13}C$ values and the average temperatures for July and August ($r_{July/August} = 0.49$; $n = 44$) and July precipitation amounts ($r_{July} = -0.35$) (Fig. 9).

The carbon isotope values of the cellulose of all samples from Khibiny region vary between −23.4‰ and −27.5‰ (Fig. 10a). The $\delta^{13}C$ values of the samples from the period from c. 1000–1300 AD have an average of about −24.5‰ and are clearly more positive (by about 1‰) than the mean $\delta^{13}C$ values of living pines in this region, which have an average of about −25.6‰ (Fig. 10a).

The oxygen isotope values of all the fossil samples (Fig. 10b) fluctuate widely between about 24.9‰ and 29.1‰ around an average of 26.4‰ vs. VSMOW. The living trees from the Khibiny region indicate similar scattering ranges and average $\delta^{18}O$ value of 26.1‰. The $\delta^{2}H$ values calculated throughout the period investigated are also scattered widely between about −80‰ and −120‰ vs. VSMOW around an average of −92‰ (Fig. 10c) and a mean $\delta^{2}H$ value of about −89‰. By comparison, our laboratory standard, homogenized wood dust from several living pine trees (Pinus sylvestris L.) from central Germany has a $\delta^{13}C$ value of −24.60 ± 0.04‰, $\delta^{18}O$ value of 28.93 ±0.07‰ and a $\delta^{2}H$ value of −72.0 ± 1.5‰.

4. Discussion

Radiocarbon-dated pine wood found at an elevation 40–120 m above the modern upper pine limit (at ca. 260–380 m) in the Khibiny Mountains suggests higher summer temperatures occurred in the central part of the Kola Peninsula during the Medieval Warm Period (Hiller et al., 2001). Applying a simple environmental lapse rate of 0.7 °C/100 m, this warming can be estimated as being on the order of at least 1 °C compared to the modern summer temperature.

Buried soils found in the stratigraphy of numerous avalanche cones indicate a widespread and significant decease in the intensity of avalanche activity. As avalanche activity depends upon the amount of snowfall, the decrease in the avalanche activity represents a decrease in the amount of winter/spring precipitation. Thus, periods of soil formation in avalanche cones are equivalent to periods of lower snowfall in the Khibiny Mountains.

Ages of fossil pines found above the modern tree limit and the ages of soils buried in the avalanche cones profiles show the same distribution (Fig. 11). As both lines of evidence happened during the Medieval Warm Period, we can conclude that the Medieval Warm Period was accompanied by a decrease in snowfall in the Khibiny Mountains. At this time, there was also a period of low lake level as recorded by dating of submerged pines from north of the mountains (Table 2). Another episode of lower lake levels at

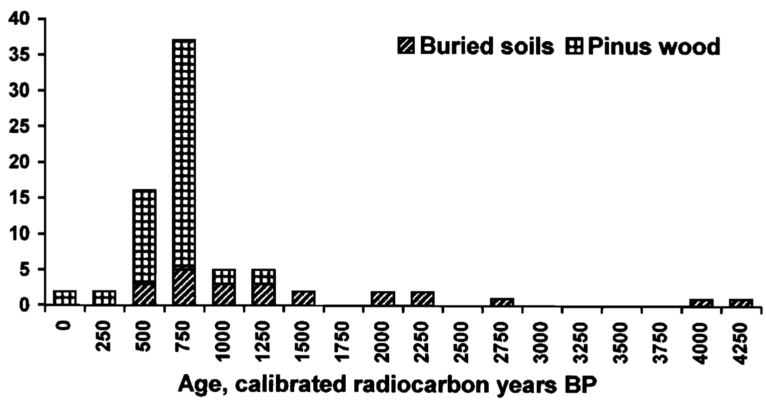

Fig. 11. Age correlation of fossil pines found above the modern pine upper limit and soils buried in snow avalanche cones in Khibiny.

around 450 radiocarbon years BP may correspond to a period of warmer climate before the Little Ice Age. It correlates with a few of the youngest dates of fossil pines found above the modern pine limit (Fig. 11). Although the inherently poor precision in radiocarbon dating during this time interval and the low number of dates do not allow direct comparison, tree ring records from an upper pine limit site located in low hills north of the Khibiny region suggest that there were periods of increased pine establishment centered at ca. AD 1600, 1670 and 1780 (Gervais and MacDonald, 2000).

The oldest radiocarbon ages from soils buried in the snow avalanche cones on the Khibiny Mountains range from 4200 to 4500 BP (Table 2 and Fig. 8). This period of low snowfall in the Khibiny region corresponds to the final stage of mid-Holocene pine tree line advance on the northern Kola Peninsula (MacDonald et al., 2000) and of low lake level recorded in Finnish Lapland and generally drier climate on the northern Kola Peninsula (Eronen et al., 1999; Snyder et al., 2000). This suggests that the lower lake level during the Medieval Warm Period and during parts of the mid-Holocene may have been at least partly due to the lower snowfall level. This evidence correlates well with the chronology of snow avalanche activity and neoglacial stages in western Norway (Nesje and Kvamme, 1991; Blikra et al., 1997).

The conclusions regarding warm and dry conditions during the Medieval period are further supported by the stable isotope results. Preliminary results from the tree ring carbon and oxygen isotope measurements on the cellulose from living trees show a positive relationship exists between the $\delta^{13}C$ values and the average temperatures for the summer months of July and August. These results are similar to studies from northern Finland (Sonninen and Jungner, 1995). Unfortunately, the fact that elevation exerts a strong control on precipitation and the meteorological stations near the study site are located either 200 m above or 600 m above the pine samplings areas (300–400 m) makes comparison of the annual isotope variations with available precipitation records unreliable.

The isotope analyses of carbon show an enrichment of the heavy carbon isotope $\delta^{13}C$ by about 1‰ in the cellulose of medieval subfossil pines compared to the living trees from this region. We attribute the higher $\delta^{13}C$ values during the Medieval Warm Period to temperature increases in July and August. An additional cause may be reduced water availability and/or air humidity during the growing season. The oxygen and hydrogen isotope values are subject to wide scatter in both the modern and fossil samples. However, the magnitude of scatter is similar to, or lower than, for pine samples obtained from central Germany (Fig. 10b and c). The $\delta^{18}O$ and $\delta^{2}H$ values might reflect the isotopic composition of air masses responsible for precipitation as they move across the region and/or changes in the seasonal distribution of precipitation. The similarity in the oxygen and hydrogen isotope ratios together with the increasing of carbon isotope ratios hint at reduced precipitation in summer in relation to that in winter during the Medieval Warm Period.

The precipitation source for the Kola Peninsula is in the North Atlantic. Most precipitation is related to cyclone activity, and the precipitation is almost evenly distributed during the year with summer–autumn precipitation being slightly more abundant than winter–spring. Together with the avalanche results, we can suggest that a decrease in the precipitation during the Medieval Warm Period may have occurred both in the cold and warm periods of the year. This may reflect a weakening of cyclonic activity over the Kola Peninsula at this time. However, further research on stable isotopic records from wood cellulose from the Kola is required to confirm this hypothesis.

After AD 1100, the summer temperature began to decrease, and summer and winter precipitation increased. Lake levels increased and vigorous avalanche activity recommenced. The timing of these changes in the Khibiny region correlate well with data provided by aeolian studies from subarctic Finland (Käyhkö et al., 1999). There, at ca. AD 1100, a recent phase of increased aeolian activity as indicated by ISRL dating of dunes suggest the development of more intense cyclonic activity over Fennoscandia.

In conclusion, evidence from several different sources suggests that during the Medieval Warm Period, summer temperature increased and precipitation in both the winter and summer decreased. Summer warming was reflected in an increase in the elevation of pine limits. There was also a stabilization of slopes on avalanche cones and formation of soils on them. Lake levels were lower than today, and this may be attributed both to an increase in evaporation due to higher summer temperatures and to a decline of precipitation. These results provide further evidence of a medieval warming on the Kola Peninsula and demonstrate a coincidental decrease in moisture, likely due to decreased cyclonic activity.

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