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Palaeovolcanos, Solar activity and pine tree-rings from the Kola Peninsula (northwestern Russia) over the last 560 years

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ABSTRACT: The paper deals with the analysis of the external factor (solar activity, volcanic eruptions) influence on tree growth at the Kola Peninsula, northwestern Russia. Pinus sylvestris L. (Scots pine) tree-ring chronologies collected nearby the northern timberline (68.63N, 33.25E) include the oldest (1445-2005 AD) living pine tree found up to date in the Kola Peninsula. A total of 18 living trees Pinus sylvestris were sampled taking two cores. Tree rings measured with a precision of 0.01 mm by using an image analysis system (scanner and relevant software). The samples were cross-dated using standard dendrochronological practices and the COFECHA program. A negative exponential curve was used to remove the age trend from individual annual ring series prior to construction of the chronology using the ARSTAN modeling. It was shown that the past climatic variations in the Kola Peninsula were fairly strongly connected to solar variability and volcanic activity. A superposed epoch analysis of 18 large (Volcanic Explosivity Index, VEI>5) volcanic events revealed a significant suppression of tree growth for up to 8 years following volcanic eruptions. The data analysis enabled us to get some conclusions on the past climate variations and to demonstrate the relation of global and regional climatic variations in the European North.

Key words: Volcanic eruptions, Dendrochronology, Climate, Solar cycles

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INTRODUCTION

It is known that prior to the industrialization period during the entire Holocene age global climatic changes took place under the impact of powerful natural factors (solar activity and volcano eruptions) influencing the climate, atmosphere and biosphere of the Earth (Crowley, 2000; Shindell *et al.*, 2003; Soon and Baliunas, 2003; Velasco and Mendoza, 2008). The question of which of these factors is dominating is still a matter of discussion in our days.

During volcano eruptions the emission of enormous amounts of volcano dust, sulphur dioxide and water vapour into the stratosphere reduces the atmosphere transparency and prevents the solar radiation from penetrating to the Earth surface. All these processes, in turn, result in breaking the radiation balance of the atmosphere and, are assumed, in most cases, to lead to reduction of the surface temperature. For example, the recent powerful eruptions of such volcanoes as Tambora (1815), Krakatoa (1883), Santa Maria (1902), Katmai (1912) led to 0.2-0.5°C coolings in the northern hemisphere that continued for several years (Rampino and Self, 1982; Stothers, 1984; Lyons *et al.*, 1990). However, volcano eruptions are neither always nor everywhere the coolings' reason. The results of some studies have shown that volcanic activity, while affecting the radiation balance and changing the circulation conditions of the atmosphere, can trigger regional warmings (Lary *et al.*, 1994; Robock and Mao, 1995; McCormick *et al.*, 1995; Kelly *et al.*, 1996), as it happened, for example, after the eruption of Icelandic volcano of Laki in 1783, when an unusually dry and hot summer was observed over the major part of the European territory (Grattan and Charman, 1994; Thordarson and Self, 2003; Ogle *et al.*, 2007), and of Indonesian volcano of Pinatubo in 1991 (Lary *et al.*, 1994; McCormick *et al.*, 1995).

The period of instrumental observations, on the average, does not exceed 100 years and embraces just a small number of powerful eruptions of that type, therefore, basically, the volcanic activity is studied by paleoclimatic data (the acidity content in ice cores,

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the width of annual growth ring). Quite a number of studies are devoted to investigation of climatic consequences of volcanic eruptions by dendrochronological data (LaMarche and Hirschboek, 1984; Lough and Fritts, 1987; Scuderi, 1990; Briffa *et al.,* 1998; Jacoby *et al.,* 1999; 2000; Gervais and MacDonald, 2001; Hantemirov *et al.,* 2004; Vaganov and Shiyatov, 2005; Salzer and Hughes, 2007). The possible effect in radial growth and even formation of so called "frost rings" in these papers (LaMarche and Hirschboek, 1984; Hantemirov *et al.,* 2004; Vaganov and Shiyatov, 2005) are related to temperature decreases. However, there is also another mechanism, according to which the ingress of a large amount of volcanic gases in the atmosphere subsequently leads to supressed photosynthesis and acid precipitations, which can also result in profound depressions in the radial growth of annual rings (Grattan and Charman, 1994; Thordarson and Self, 2003; Ogle *et al.,* 2007).

The role of the solar activity in the climatic variability is now a subject for discussion of scientists and even politicians. One of the first and brightest experimental confirmations of the solar activity impact on the climate is the very high correlation between length of the 11-year solar cycle and surface temperature of the northern hemisphere (Friis-Christensen, Lassen, 1991). The main heliophysical factors acting on climate are solar radiation (Lean *et al.,* 1995), variability of galactic cosmic rays changing the cloud cover of the atmosphere (Svensmark and Friis-Christensen, 1997; Palle and Butler, 2001; Carslaw *et al.,* 2002) and UVB-radiation (Haigh, 1996). Widely known is, for example, the global cooling ("Little Ice Age") during Maunder minimum of solar activity (1645-1715 AD), and also rather a short-term, but generally speaking, more intensive cooling during and after Dalton minimum of solar activity (1801-1916 AD), temporally coinciding as well with a powerful eruption of Tambora in 1815 (Jacoby *et al.,* 2000; Rind, 2002; Shumilov *et al.,* 2007). The influence of the Sun on the climate during the Holocene was also demonstrated (Karlen and Kuylenstierna, 1996; Keigwin, 1996; Bond *et al.,* 2001). In addition, along with solar radiation and cosmic ray variation in some works other new climate impact factors of extraterrestrial origin have been introduced, for example, stardust (Kasatkina *et al.,* 2007). As a rule, the existence of long-term variations in climatic parameters is attributed to solar activity cycles. The principal periodicities are: 11-year (Schwabe), 22-year (Hale), 30-33-year (Bruckner) and 80-100-year (Gleissberg) cycles.

Data from different meteorological stations and as well as regional palaeoclimatic data demonstrate that the modern climatic changes have got complicated regional structure. The most significant differences in regional climatic variations were observed for the last 30-40 years in the Arctic where the mean annual air temperature anomalies differ not only with respect to their values, but as well in sign (Kahl *et al.,* 1993; Overpeck *et al.,* 1997). For example, at the northeastern part of Canada and at the Western part of Northern Atlantic for the last three decades some temperature decrease (Overpeck *et al.,* 1997) was observed, the temperature changes in Scandinavia were not large (Bradley, Jones, 1993; Helama *et al.,* 2008), and in Siberia and at Alaska a temperature warming (Jacoby *et al.,* 2000) was observed. Tree-ring chronologies of the Arctic represent the major interest for assessment of climatic changes, since, as known, trees, growing near the northern tree-line, possess increased sensitivity to exterior factors impact.

The climate of the Kola Peninsula differs from the other Arctic regions. It is under the influence of both, the warm air masses from North Atlantic (Gulf Stream) and cold air masses from Arctic regions (Barents Sea, Kara Sea, Taymir). Sea-ice extent, sea-surface temperatures and radiation balance have a complex influence on the temperatures of the Peninsula. Meanwhile the problem of how the Kola climate reacts to global climatic changes connected to man-made activity ("global warming") or on natural action (variations of solar activity, volcanic eruptions) is still unsolved. For paleoclimatic studies in the region tree-ring chronologies having got annual resolution seem to be the most acceptable. In northern latitudes the most sensitive to external climatic variations are the trees living close to northern treeline and altitude treeline. Up to date there are only separate studies devoted to paleoclimatic reconstructions of the Kola Peninsula based on regional tree-ring chronologies (MacDonald *et al.,* 2000; Gervais and MacDonald, 2001; Shumilov *et al.,* 2007; Kononov, Friedrich and Boettger, 2009).

The aim of this study is to assess regional climatic response to solar and volcanic activity impacts by analyzing a 561-yr (A.D. 1445-2005) pine tree-ring chronology from a northern treeline location in the Kola Peninsula. This chronology up to date seems to be the longest Kola pine tree-ring chronology based on living trees.

MATERIALS & METHODS

The study area is located near the northern treeline at Loparskaya site, Kola Peninsula (68º37.29´N, 33º14.26´E) (Fig. 1). Tree-ring chronology collected from living pine trees *Pinus sylvestris* L. includes the oldest one (a 561 year old) living pine tree found so far in the Kola Peninsula.

Kola Peninsula can be divided to three climatic zones: sea coast, central part and mountain region. The climate of the Northern sea coast is determined by the Barents Sea influence. The mean July and January temperatures in the region are 12.5ºC and -6ºC:-12ºC, respectively (Arctic Atlas, 1985). From the coast into the heart of the peninsula the mean annual temperatures diminish. The mean January temperature in the continental part of Kola Peninsula, is -13.7ºC (Arctic Atlas, 1985). In the mountain region one meets colder summers and a comparatively mild winters, and a higher precipitation. The maximum mean July temperature is +10ºC , and the minimum of January one is -13ºC (Arctic Atlas, 1985).

The fieldwork was conducted during August 2005. A total of 18 living trees *Pinus sylvestris* were sampled taking two cores. Tree rings measured with a precision of 0.01 mm by using an image analysis system (scanner and relevant software). The samples were cross-dated using standard dendrochronological practices and the COFECHA program (Holmes, 1983; Cook and Kairiukstis, 1990). A negative exponential curve (1) was used to remove the age trend from individual annual ring series prior to construction of the chronology using the ARSTAN modeling (autoregressive standardization) (Cook, Kairiukstis, 1990):

$$Y(t) = aX(t)^{b} e^{-cX(t)} + k \qquad (1)$$

where: *a*, *b*, *c*, and *k* – coefficients. A relative index of tree growth is produced by dividing the ring width value in year *t* by the value of the fitted curve *Y*(*t*) in year *t*. This method of conservative detrending removes age-related growth trends while preserving low-frequency climatic variations (Cook, Kairiukstis, 1990).

Pearsons correlation coefficients were calculated between tree-ring widths and monthly temperature data from Murmansk (68°58’N, 33°03’E), Polyarny (69°12’N, 33°29’E), and Krasnoschelye (67°21’N, 37°03’E). The nearest stations Murmansk and Polyarny are close to the coast and dominated by maritime climate. Krasnoschelye is located in the center of the Kola Peninsula and dominated by continental climate.

To study regional peculiarities of the climatic response to the impact of volcanic activity there have been compared the changes of tree-ring widths in the obtained chronology before and after the most powerful (VEIe≥5, *Volcanic Explosivity Index*) volcanic eruptions (http://www.volcano.si.edu/world/largeeruptions.cfm). The VEI scale considers solid material ejected and the height of the eruption column (Newhall and Self, 1982). At the same time, only those events have been used for the analysis, the time interval between which made at least ten years. As a result, 18 events have been considered for the studied period (1445 – 2005) (see Table 1).

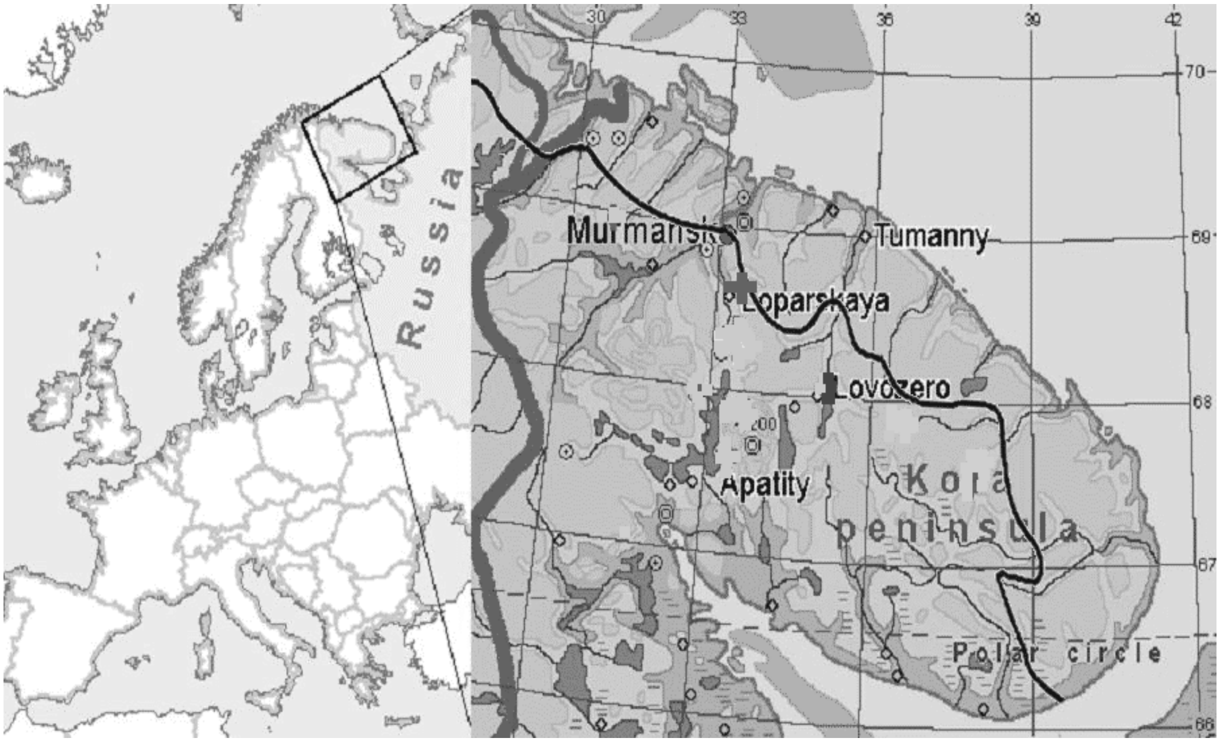

Fig. 1. Map showing location of northern tree-line (after Gervais and MacDonald, 2000) and site where samples of *Pinus sylvestris* were collected

Table 1. Largest explosive volcanic eruptions (VEIe≥5) since AD 1450

Volcano	Eruption date	Lat., long.	VEI
Sakura-Jima, Japan	3 Nov 1471	31.6N, 130.7E	5
Kelut, Indonesia	1586	7.9S, 112.3E	5
Huaynaputina, Peru	19 Feb 1600	16.6S, 70.9W	6
Katla, Iceland	2 Sep 1625	63.5N, 19W	5
Parker, Phillipines	4 Jan 1641	6.1N, 124.9E	5
Usu, Japan	16 Aug 1663	42.5N, 140.8E	5
Fuji, Japan	16 Dec 1707	35.4N, 138.7E	5
Katla, Iceland	11 May 1721	63.5N, 19W	5
Shikotsu, Japan	19 Aug 1739	42.7N, 141.3E	5
Katla, Iceland	17 Oct 1755	63.5N, 19W	5
St Helens, USA	15 Jan 1800	46.2N, 122.2W	5
Tambora, Indonesia	10 Apr 1815	8.3S, 118.0E	7
Cosiguina, Nicaragua	20 Jan 1835	13.0N, 87.6W	5
Shiveluch, Russia	18 Feb 1854	56.7N, 161.4E	5
Askja, Iceland	29 Mar 1875	65N, 17W	5
Azul, Chile	10 Apr 1932	35.7S, 70.8W	5
Bezymianny, Russia	30 Mar 1956	56.0N, 160.6E	5
St Helens, USA	18 May 1980	46.2N, 122.2W	5

To study the presence of periodicity in tree-ring record the pine chronology was spectrally analysed using the Multi-Taper Method (MTM) (Thomson, 1982). To assess the temporal behaviour of different short-term periodicities over the entire time interval covered by the pine chronology from 1445 to 2005 we used a wavelet analysis (Torrence and Compo, 1998). To analyze a tree-ring responce to major volcanic eruptions we used a superposed epoch analysis.

RESULTS & DISCUSSION

The tree-ring chronology (Fig. 2) extends from A.D. 1445 to 2005. The oldest living tree was 561 years old. Correlations were calculated between the ARSTAN residual tree ring chronology (Fig. 2a) and monthly temperature data from Murmansk, Polyarny, and Krasnoschelye. The highest significant correlation (*r*=0.35, *P*<0.01) occurred between the width of tree rings and mean July temperatures recorded at Murmansk. It means that our chronology site seems to be partly influenced by maritime climate. From Fig. 2 it is clearly seen that summer temperatures in intervals 1480-1560 AD, 1730-1790 AD, 1930-1960 AD were higher than at the end of XX century (the supposed era of "global warming"). Fig. 3 shows our tree-ring chronology and mean annual temperature in Europe (Daly, 2003).

The most significant decrease of annual pine tree-ring width (up to 25% relative to previous year) took place in 1601 AD (see Fig. 3). This depression could be caused by Huaynaputina eruption in Peru in 1600 AD (Volcanic Explosive Index, VEI=6), the most powerful eruption for the last 500 years (de Silva, Zielinski, 1998). A similar decrease of tree-ring growth and frost ring creation at the same time was detected in juniper tree-ring record from the Kola Peninsula (Gervais and MacDonald, 2001; Shumilov *et al.*, 2007), Fennoscandia (Helama *et al.*, 2008) and as well as in Polar Ural (Hantemirov *et al.*, 2004). As shown in Fig. 3, the considerable decrease of tree-ring growth in 1780-1830 AD coincided temporally not only with Dalton minimum of solar activity, but as well with two powerful eruptions of Laki (Iceland) in 1783 AD (VEI=4) and Tambora (Indonesia) volcanos in 1815 AD (VEI=7). The last eruption led to significant social and climatic

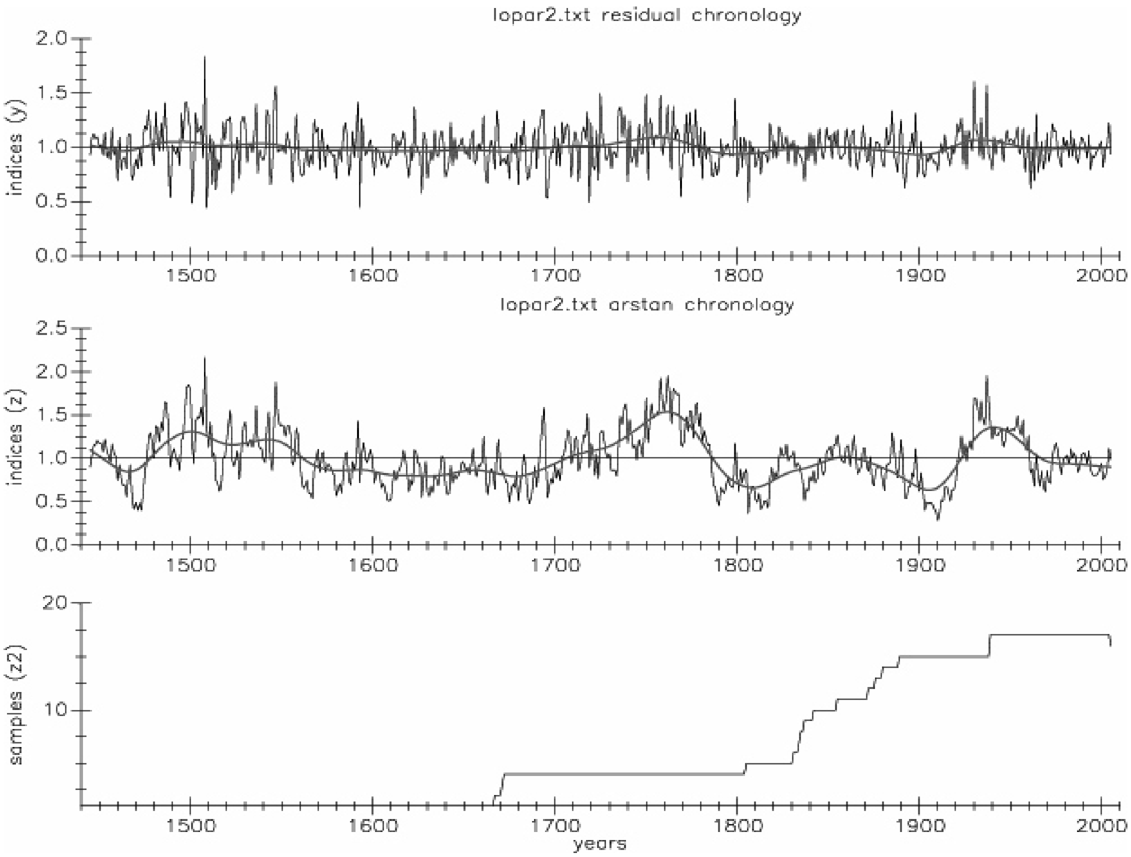

Fig. 2. The ARSTAN tree-ring chronologies of *Pinus sylvestris* and sample depth

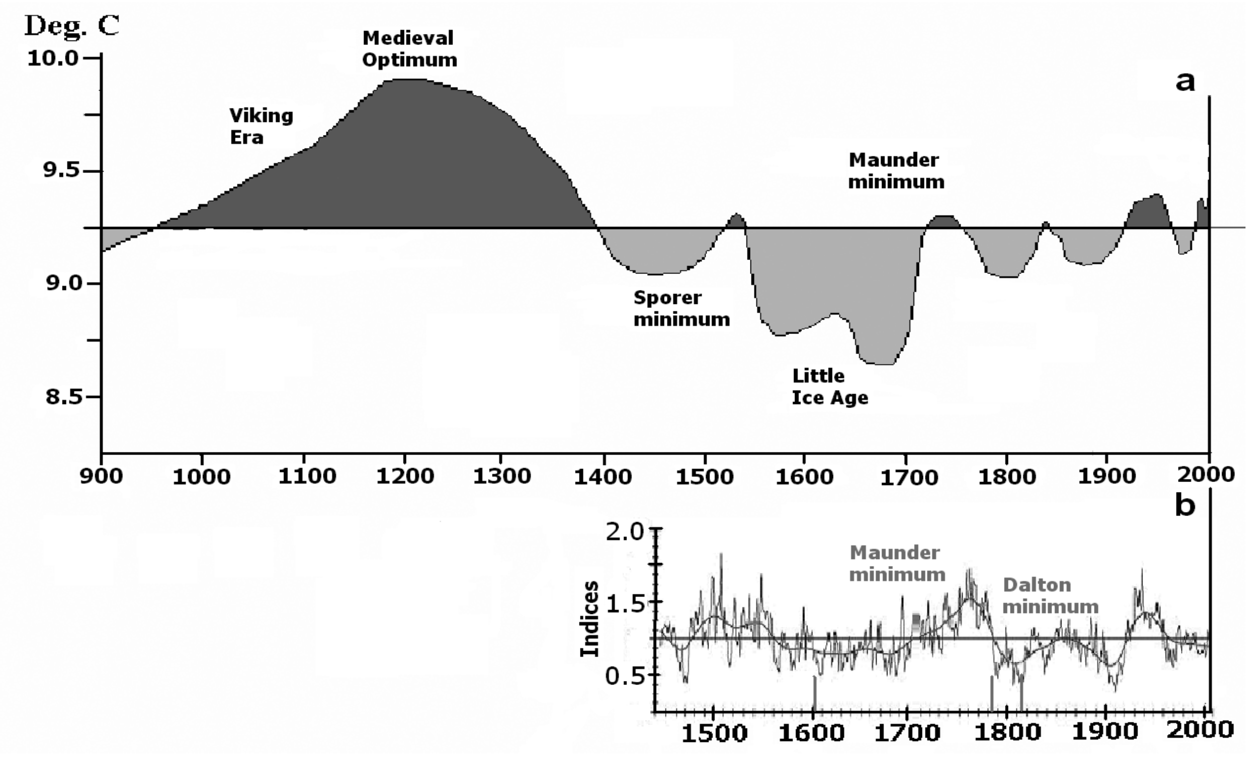

Fig . 3. (a) Long-term climate change in Europe from 900 AD to present (from Daly, 2003); and (b) Kola pine tree-ring chronology (1445-2005 AD). The main volcanic eruptions (1601 AD, 1783 AD, 1815 AD, 1902 AD) are shown by vertical bars

effects (Rampino and Self, 1982; Rampino, 1988; Briffa *et al.*, 1998; Sadler and Grattan, 1999).

A visual comparison between the 20-year smoothed pine tree-ring chronology and a reconstruction of temperature changes in Europe since 900 AD based on proxy data (Fig. 3) reveals a rather good agreement between long-term temperature variation and pine tree-rings (r=0.51, P<0.001). The Little Ice Age is reflected in both records. Sporer (1416-1534 AD), Maunder (1645-1715 AD) and Dalton (1801-1816 AD) minima of solar activity also appear in both records. A pronounced 20th-century (1920-1940 AD) warming evident in our and other Kola records (Gervais and McDonald, 2001; Shumilov *et al.*, 2007; Kononov, Friedrich, and Boettger, 2009) has been observed also in other Arctic regions: Fennoscandia (Briffa *et al.*, 1990); the Polar Urals (Briffa *et al.*, 1995), Siberia (McDonald *et al.*, 1998; Jacoby *et al.*, 2000).

Both the European temperature reconstruction and the pine chronology from Kola Peninsula (Fig. 3) do not demonstrate a significant warming at the end of the last century. The Earth’s climate has experienced even as warm or even warmer temperatures 1000 years ago during the so-called Medieval Climatic Optimum (1000-1300 AD) when greenhouse gases as a consequence of human influence were not present. This conclusion agrees with results of other paleoclimatic studies (Esper *et al.*, 2002; Helama *et al.*, 2008).

Volcanic eruptions injecting large amounts of acidic sulfate aerosols into the Earth’s atmosphere are the major forcing factors of cooling climate on decadal scale (Rampino and Self, 1982; Rampino, 1988; Sadler and Grattan, 1999). As usual in many studies authors pay attention to their potential role in depressing hemispheric temperatures, however the global distribution of the climatic effects of major eruptions is not ambiguously determined so far (Rampino and Self, 1982; Scuderi. 1990; Sadler and Grattan, 1999). Tambora eruption (1815) led to a lowering of average northern hemisphere temperature by a 0.5°C in 1816 (Rampino and Self, 1982) which had been fixed in many tree-ring records from Siberia, Alaska, Fennoscandia (Briffa *et al.*, 1998, Jacoby *et al.*, 2000). Under the eruption of volcano Laki (VEI=4) an ejection of volcanic material into the troposphere was restricted in the northern hemisphere (Sadler and Grattan, 1999; Ogle *et al.*, 2007). The eruption was followed by an anomalous hot summer in 1783 AD and a very cold winter in 1784 AD (Ogle *et al.*, 2007). As one can see from Fig .3 radial depression in 1780-1830 AD coincides with the Dalton minimum of solar activity (1801-1816 AD) and Laki and Tambora volcanic eruptions. Up to date the decrease of tree-ring growth in 1784 AD is possibly connected to Laki eruption that had been detected in Fennoscandia (Kalela-Brundin, 1996) and in Alaska (Jacoby *et al.*, 1999).

As mentioned above, the climatic response to volcanic eruptions is not homogeneous and has some regional peculiarities. Even more, not any volcanic eruption and not everywhere leads to a temperature decrease. To test the influence of large-scale (VEIe ≥ 5) volcanic events on tree growth at the northern timberline two high latitude pine (*Pinus sylvestris*) chronologies were subjected to superposed epoch analysis: the 561-yr Kola Peninsula tree-ring chronology and the ~7500 supra-long chronology from Finnish Lapland (Helama *et al.*, 2008). Fig. 4 shows a composite ringwidth (index) curve obtained using the method of superposed epoch analysis. In the analysis the year of each major volcanic eruption was taken as year zero. Ringwidth indices five years before and ten years after the year zero were superposed and averaged to produce one superposed curve for 18 volcanic eruptions.

Results of analysis revealed a significant (p<0.05) suppression of tree-ring growth at both sites, on the average, during 8 years after eruptions (see Fig. 4). This result does not contradict the previously obtained conclusions concerning tree-ring chronologies of the North of Eurasia (Vaganov and Shiyatov, 2005) and the western part of Northern America (Scuderi, 1990; Salzer and Hughes, 2007). As it had been shown in the paper (Vaganov and Shiyatov, 2005), based on the analysis of the total, over 2000-year, chronology, compiled from tree-ring chronologies of the Arctic zone of Russia (Yamal, the northeast of Taimyr and the lower reaches of Indigirka) using some data from Scandinavian thousand years old chronology, the radial accretion of trees is essentially suppressed, on the average, 5 years after large volcanic eruptions (VEIe≥5) in the Northern hemisphere. Thus, our data confirm the conclusion about the fact that the emission of volcanic dust during powerful eruptions results in the decrease of the summer air temperature and causes the depression of trees’ accretion in the high latitudes. To reveal the impact of solar cycles the pine chronology was spectrally analyzed with help of MTM (Thomson, 1982) and wavelet analysis (Torrence, Compo, 1998). The results of both MTM and wavelet analysis permitted us to select periodicities in our tree-ring record corresponding to solar cycles: 11.7, 22, 50-66, and 80-100-years (see Figs 5 and 6). The similar results have been obtained on juniper chronology collected in Kola Peninsula covering the period from 1328 to 2004 (Shumilov *et al.*, 2007). The 20-22 year periodicity is clearly present in the pine chronology, at

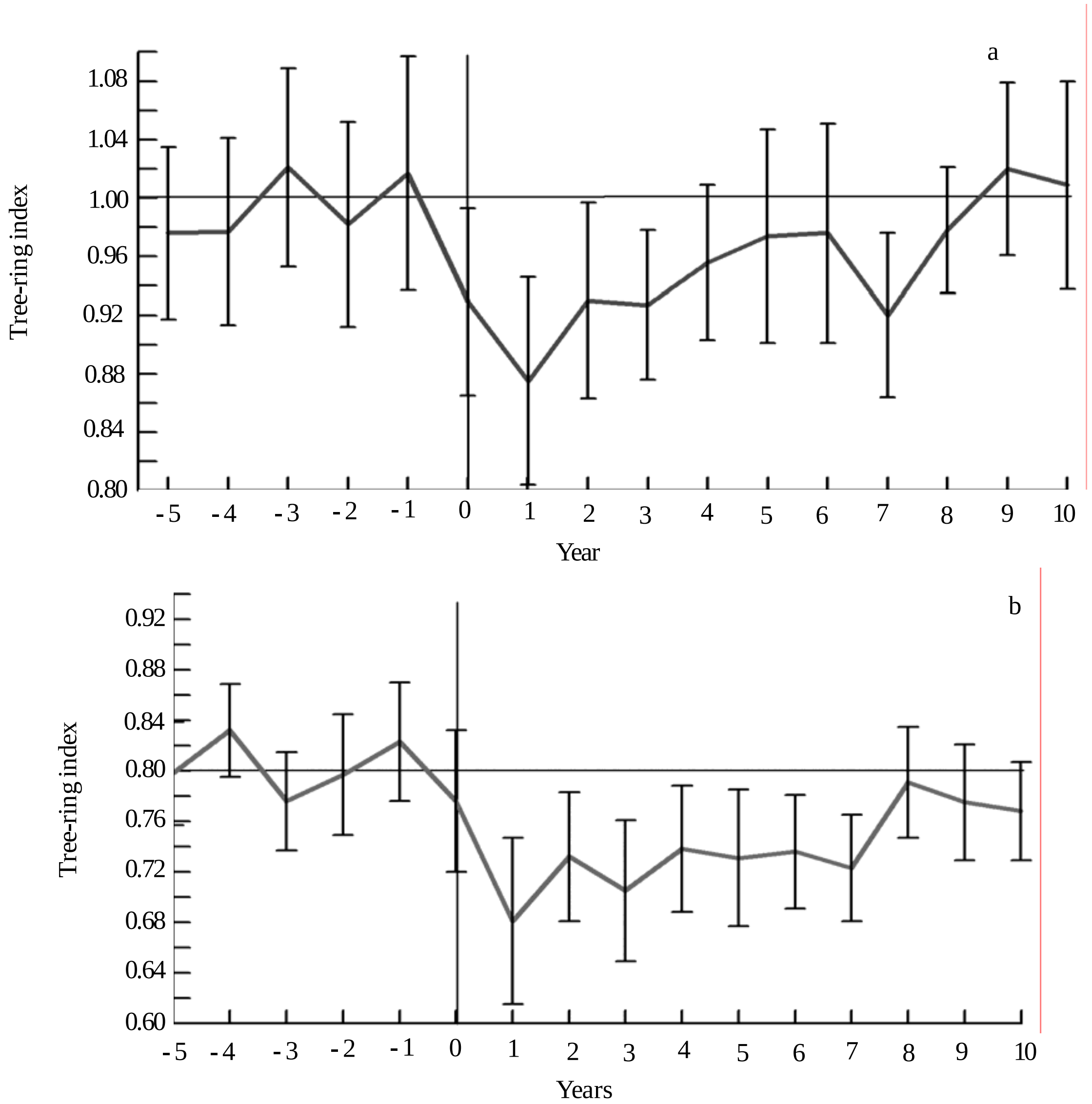

Fig. 4. Superposed epoch analysis for (a) Kola and (b) Finnish super-long (~7500 years) tree-ring chronologies responsed to the most powerful (VEIe≥5) volcanic eruptions for the period 1445 – 2005

the 99% confidence level (Fig. 5). It is known that the 11-year periodicity is not always present in climatic records, and where the signal is apparent it is often preserved with lower amplitudes to those of the 22-year cycle (Molinari *et al.*, 1997; White *et al.*, 1997).

The 11-year and 80-90-year solar cycles are apparent in solar radiation and galactic cosmic ray trends (Lean *et al.*, 1995; Svensmark and Friis-Christensen, 1997; McCracken *et al.*, 2001). As it is seen from fig. 5 the 20-25-year periodicity is not clearly present throughout the entire period but is mainly expressed during the time intervals 1445-1600, 1700-1800 and from 1930 to the present time. At the same time the 22-year solar cycle, related to a reversal of the main solar magnetic field direction is practically absent in either solar radiation (Lean *et al.*, 1995) or galactic cosmic ray variation (Webber and Lockwood, 1988). This frequency is absent in the variation of sunspot numbers. However, a bidecadal periodicity was identified in rather many regional climatic records worldwide (droughts, rainfalls, tree growth) (Cook *et al.*, 1997; Gusev *et al.*, 2004, Shumilov *et al.*, 2007). The appearance of the 22-year cycle in climatic variation could be the result of the influence of other factors of extraterrestrial origin, such as the 18.6-year lunar nodal cycle (Currie, 1984; Cook *et al.*, 1997), or stardust penetration inside the Solar System every 22 years (Kasatkina *et al.*, 2007).

It is important to know that in a number of studies climatic variations with periods from 11 to 90 years are interpreted exclusively in terms of ocean-atmosphere interactions without consideration of the role of solar forcing (Wohlleben and Weaverm, 1995; Latif, 1998).

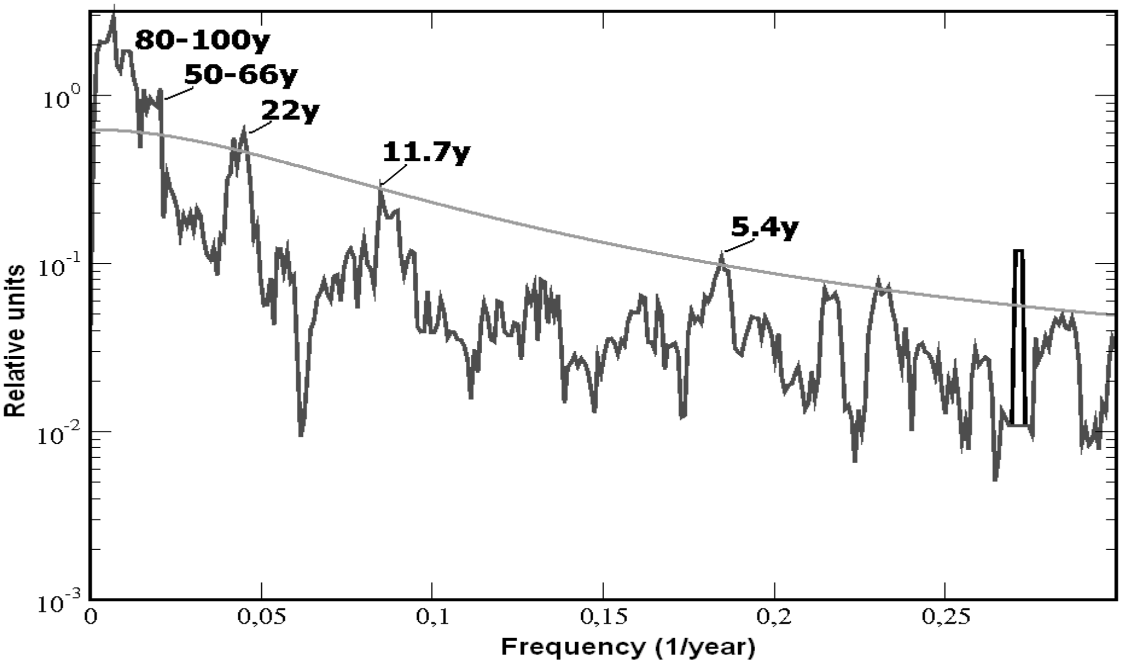

Fig. 5. MTM-spectrum of Kola pine tree-ring chronology (1445-2005 AD). Solid line represents 99% confidence limit

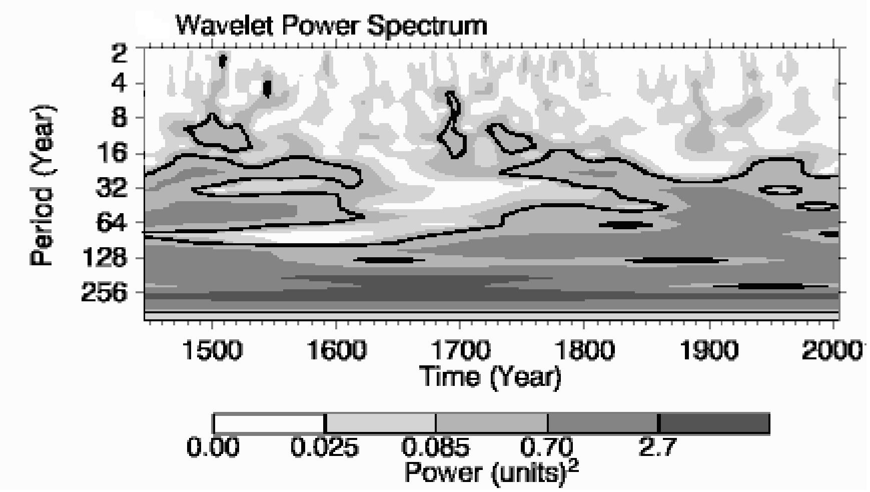

Fig. 6. Wavelet power spectrum of Kola pine tree-ring chronology (1445-2005 AD). Black contour is the 10% significance level, using a white-noise background spectrum

CONCLUSION

A newly constructed 561-yr Kola Peninsula chronology and Finnish ~7500 supra-long chronology demonstrate a depression of tree growth for about 8 years in response to large-scale (VEIe≥5) volcanic eruptions. The Kola reconstruction indicates that the global warming observing from the beginning of the last century is not something extraordinary one. The Earth's climate has experienced as warm or even warmer temperatures in the Past.

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