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Climate signal strength in tree-ring width of spruce growing in the Solovetsky Islands (Russia)

Ekaterina A. Dolgova[a,*], Olga N. Solomina[a,b,1], Vladimir V. Matskovsky[a], Elena A. Cherenkova[a], Nadejda S. Semenyak[a]

[a] Laboratory of tree-ring research, Institute of Geography, Russian Academy of Sciences, Staromonetniy Lane, 29, 119017 Moscow, Russia
[b] National Research University, Higher School of Economics, Faculty of Geography and Geoinformation Technologies, Pokrovsky Boulevard-11, L212, Russia

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ABSTRACT

In this study we used 14 spruce tree-ring width local chronologies from sites that are located in different landscape conditions. The climatic response function for the entire period (116 years) shows that all local chronologies without exception have a positive relationship with June temperature (from 0.196 to 0.408) despite quite different local environmental conditions. This finding allowed us to combine all tree-ring width local chronologies into a composite spruce chronology covering the period of 1676–2016 CE with EPS exceeding the 0.85 threshold. The composite chronology was scaled against June air temperatures (CRU TS 4.01) in order to reconstruct it. Monthly air temperature records from the Arkhangelsk weather station were used as an additional source to validate tree-ring based June temperature reconstruction. It is quite remarkable that our reconstruction matches the Archangelsk records not only in the 20th-early 21st centuries but also in the 19th century, confirming the reliability of the reconstruction over more than two centuries. We also used daily records from the nearest Kem'-Port station to identify a more precise target-window. Current research shows that the spruce response to daily temperature is not limited by June, but also extends up to almost half of July. The warmest reconstructed year occurred in 1856 as confirmed by the data published in the local chronicle. The cooling recorded in the historical evidences (describing extremely severe ice conditions in the Arctic seas during the Great Northern Expedition (1733–1743)) was not corroborated by our reconstruction. In the study, we discuss the reasons of the discrepancies found between Solovki June temperature reconstructions and other data such as different seasonality of the compared records, real local climate warming in Solovki, the applied standardization technique, and low of chronologies' replication. The most reliable part of the reconstruction part lasting from the early 19th to the early 21st centuries is also discussed in terms of its properties like wavelength analyses, and the assessment of influence of volcanic eruptions.

1. Introduction

The warming rate in the Arctic observed in the recent decades is significantly higher compared to the global or hemispheric rates of temperature changes (Stocker et al., 2013). However, it is still unclear whether this warming is exceptional in the context of past centuries nor whether modern temperatures exceed the natural temperature variability. Several high resolution summer temperature reconstructions in the Arctic regions (D'Arrigo et al., 2008; Cohen et al., 2014) were built in order to answer this specific question and, in general, to better understand climatic processes at high latitudes.

Among other sources the reconstructions mentioned above included temperature sensitive chronologies from Northern European Russia (Schweingruber and Briffa, 1996; Briffa et al., 2002), however, this region is still more poorly represented than the nearby areas, such as Fennoscandia (Linderholm et al., 2015; Konter et al., 2016), Central Europe (Briffa et al., 1999; Frank and Esper, 2005; Werner et al., 2013) or the Ural mountains (Hantemirov et al., 2004; Shiyatov et al., 2007). Moreover, most of the chronologies of Northern European Russia were constructed in the 1990s and the two last decades when the strong

* Correspondence to: Staromonetniy Lane, 29, 119017 Moscow, Russia.
E-mail addresses: dolgova@igras.ru (E.A. Dolgova), solomina@igras.ru (O.N. Solomina), matskovsky@igras.ru (V.V. Matskovsky), cherenkova@igras.ru (E.A. Cherenkova), semenyak@igras.ru (N.S. Semenyak).
[1] Mailing address: Staromonetniy Lane, 29, 119017 Moscow, Russia.

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warming, which was instrumentally recorded in the Arctic regions, is missing in these data sets. The extension of the chronologies toward the present-day time is critical in order to cover this most recent period. This would allow us to use significantly longer meteorological records for the calibration of the reconstructions. Thus, it would be possible to assess the stability of the temperature signal recorded by tree rings in this region over time, and this information is also important in scrutinizing the fundamental problem of the "divergence" of tree growth parameters from climatic trends that was identified in several northern regions for the late 20th century (D'Arrigo et al., 2008).

As this territory is covered by several weather stations with long instrumental temperature records up to 100–120 years long, these records could be used to provide reconstruction and to analyze temporal stability of the climatic signal in trees growing in the Solovetsky Archipelago.

The Solovketsky Archipelago (Solovki) located in the White Sea is one of the critical points to be added to high latitude temperature reconstructions. The climate of the islands is different from the neighboring regions - with Scandinavia on one side and the Russian mainland on the other - due to its location in the rather isolated Onega Bay and the exposure of the archipelago to the intensive cyclonic activity originating from the Atlantic Ocean. The archipelago is located in the vicinity of the northern tree limit and supports mature and undisturbed spruce and pine forests. Wooden architectural monuments of the Solovetsky Monastery, dating back to the 16th Century, can provide material for the prolongation of the tree-ring chronologies back in time.

Tree-ring samples for this study were collected in 2009, 2012, and 2017. Part of this material has been described earlier (Solomina et al., 2011). In the first paper we identified the potential for extending the chronologies of living trees with architectural wood, and traced the opportunities to create tree-ring based climate reconstructions in this region (Solomina et al., 2011; Matskovsky et al., 2013). The results of

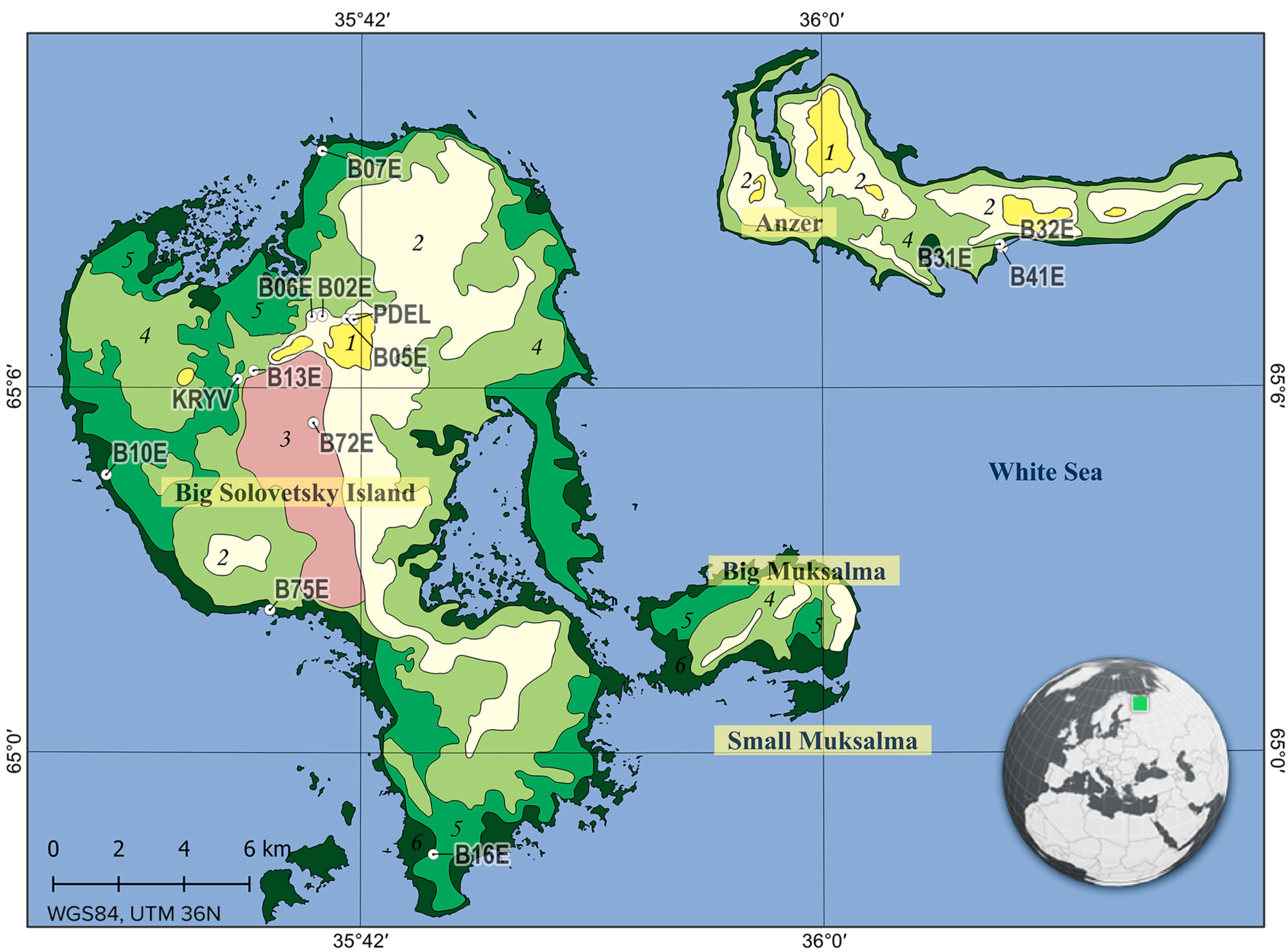

Fig. 1. The location of spruce tree-ring sites in Solovetsky Archipelago. The landscape map chosen as background where numbers representing landscape differentiation (1 - The group of stows of elevated plains with kames formations (h> 50 m) folded of boulder sandy loam with podzolic and bog-podzolic soils under spruce bilberry-green-mossed and shrubby-dense forests with a small admixture of pine and birch. 2 - The group of stows of the hollow-hilly surface of the moraine plain (from 25 to 50 m), folded of boulder sandy loam and sandy loam moraine (in dune slack) with podzols and marsh-podzolic soils under spruce and pine-spruce forests with a birch admixture, polytric undershrub forests. 3 - The group of stows of water-glacial plains with orientation of the North-South lake systems (from 14 to 24 m) folded of sandy-loamy moraine with marsh-podzolic soils under pine-spruce and spruce-pine forests with an admixture of birch, polytric undershrub and herbaceous-sphagnum forests. 4 - The group of stows of elevated sea terraces with numerous lake valleys and moraine ridges (from 14 to 24 m), folded of layered or silty-sandy sediments overlapped peat with peaty soils under the vegetation of sphagnum marshes and boggy polytric undershrub pine forests. 5 - The group of the stows of the 2nd and 3rd sea terraces (from 7 to 13 m) is inclined with ledges, folded of silt-sandy and sandy sediments rarely overhead marshes with bog soils under sedge-sphagnum marsh vegetation and swampy pine and spruce forests. 6 - The group of natural sites of the march of the modern shore (from 3 to 5 m) is folded of pebble-boulder deposits on eroded moraines with a fragmented vegetation cover represented in the littoral part by algae and halophytes in the supralythoral part with lithophilic salt-tolerant grasses on primitive strongly stony sod soils.) (by Anna Glukhova, MD thesis, geographical faculty, Moscow State University, generalized by A.Dobryansky).

tree-ring dating of some architectural and archaeological monuments in the archipelago were summarized in Matskovsky et al. (2013). Half of the chronologies used here have been already implemented as the main material to develop a composite tree-ring width chronology, for instance, chronologies PDEL, B02E, KRYV, B16E, B31E, B32E, B41E were already exploited in study of Matskovsky et al. (2013). Other sites (B05E, B06E, B07E, B10E, B13E) which were also developed in the 2011 fieldwork campaign are implemented in the current research for the first time. Two newly developed sites obtained during the most recent fieldwork in 2016 are B72E and B75E and have been recently uploaded to International Tree-Ring Data Base (ITRDB, Solomina et al., 2022) The main goal of the previous tree-ring studies in Solovki was to assess the ability to develop a millennia-long chronology based on samples from living conifers and architectural material. While the results presented here are concerning the detailed climate signal analysis of spruce growing in different landscapes.

In the paper, we focus on the new spruce chronologies based on living trees from the Solovetsky Islands, we analyze the climatic signal in the local chronologies from different habitats, and provide one of the versions of June temperature reconstruction for the period 341-years long and discuss the reason of the potential divergence observed in the first half of 18th century.

2. Materials and methods

2.1. Study area

The Solovetsky Islands (65°05′ N, 35°53′ E) are the largest archipelago of the White Sea. They are located in the relatively shallow part of the White Sea in the north of the Onega Bay, 165 km south of the Arctic Circle (Fig. 1). Complex interaction of tectonics, glaciation, sea-level dynamics and other factors was responsible for shaping the relief of the archipelago. The largest island of the archipelago stretches 24.5 km from north to south. The northern and central parts of the island are characterized by a dissected topography with meridionally oriented moraines. Most of the lakes are located in this area. The southern part of the island is dominated by swamped frontal aprons. The coastal sites are represented by a range of sea terraces (Shvartsman and Bolotov, 2007). The highest peaks of the largest Solovetsky Island are Mt. Podnebesnaya (80.7 m a.s.l.) and Mt. Sekirnaya (71.0 m a.s.l.).

The climate of the Solovetsky Islands is maritime temperate. Compared to the continental part of the White Sea shore the air temperature in Solovki is higher and less variable. The mean annual air temperature here is + 1.1 °C, i.e. 0.3 degrees C higher than in the closest big city, Arkhangelsk. Mean summer temperature in the Solovetsky Archipelago (+12.9 °C) is lower than in Arkhangelsk (+15.6 °C). The spring in Solovki is much colder than the fall (up to 5° C). March is colder than December. Positive temperatures are observed between late April and early November. The chance of frosts in summer is low. Thaws in winter and spring are quite often. Snow cover on the Solovetsky Islands lasts for 183 days. The winters are mild and humid. The mean total annual precipitation is 480 mm (Ipatov et al., 2009) (Fig. 2).

Western and southwestern winds prevail throughout the year on the Solovetsky Islands. Strong winds with the mean annual speed up to 4.8 m/sec are common due to the position of the islands in the area of intensive cyclonic activity. Northeast winds prevail during spring and summer, whereas in winter and autumn the winds are more often blowing from the southeast and from the south (Shvartsman and Bolotov, 2007).

Solovki are located on the tracks of numerous cyclones moving from Europe along the polar front. The centers of cyclones passing through this region shift northward in autumn and winter, and southward in spring and summer. This is another reason why autumn and winter temperatures on Solovki are higher than in the mainland south of the islands (Boguslavsky, 1978).

The sea ice regime is one of the important climate drivers in the area. The White Sea does not freeze completely: All land areas in cold season are surrounded by a strip of ice (fast ice). The width of unfrozen water between the mainland and islands even in the most severe winters was not less than 8–10 kilometers. This is the reason of the former isolation of the population of Solovki from the mainland from November to May.

2.2. Tree-ring data

The tree-ring network developed on the islands consists of 14 local tree-ring sites of spruce (*Picea abies* (L.) Karst and *Picea obovata* Lebed.), that grow in different types of landscapes (Fig. 1). We targeted healthy old trees at each site and extracted two increment cores per tree at breast height. 2–22 trees were sampled at each site, with the total number of 125 sampled trees (Table 1). We also used one sample buried in the moss at a channel (65.1 N, 35.7 E) that was successfully cross-dated to 1651–1885 CE.

There are 2 forest-forming conifers in Solovki - pine and spruce. Ipatov et al. (2009) have distinguished the natural hybrid between two spruces: Siberian (*Picea abies*) and Norway (*Picea obovata*). Authors found out that spruce on the islands grows on various soils - dry sandy, fresh sandy loam and marshy peat soils. Since the environmental conditions could be quite extreme, spruce trees have to adapt by changing trunk morphology. For example, under wind and snow loads, tree branches cover almost the entire trunk, descending to the ground. There are a lot of so-called "mini-trees", which are 30–40 years old, but their height does not reach 1 m, and century-old trees are slightly taller than a

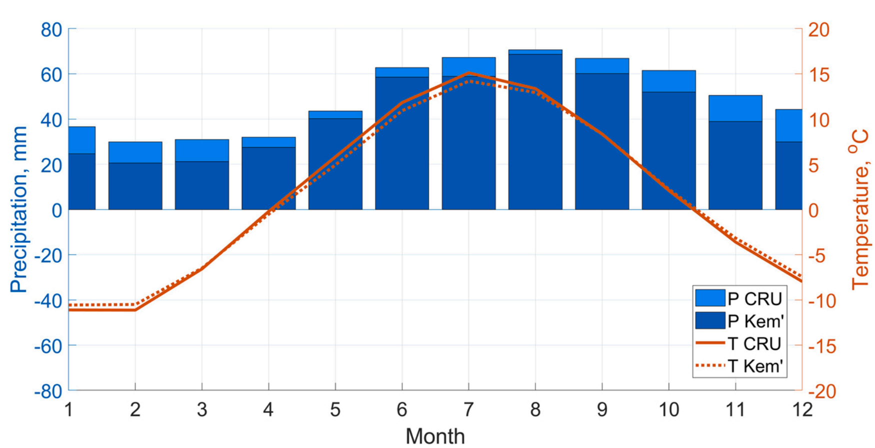

Fig. 2. Climatograms showing monthly precipitation (bars) and mean air temperatures (lines) computed for Kem'-Port (64.98 N, 34.80E, 1891–2018) weather station and for the grid point from CRU TS (64.75 N, 35.75E, 1901–2016).

Table 1
Site description.

No	Site code	Landscape type (number)	Short site description	Latitude	Longitude	Number of trees (cores)	Span (years)
	PDEL	1	Big Solovetsky Island, the Mt. Podnebesnya	65.11871	35.69505	8 (16)	1627–2008
	B05E	1	Big Solovetsky Island, the Mt. Podnebesnya	65.11887	35.6904	12(22)	1671–2011
	B02E	2	Big Solovetsky Island, slope of the Mt. Podnebesnya	65.11967	35.67458	8(15)	1667–2011
	B06E	2	Big Solovetsky Island, Shtany Lake shore	65.11786	35.67371	2(4)	1822–2011
	B72E	3	Big Solovetsky Island, Krasnoe Lake shore	65.09063	35.66825	22(44)	1789–2016
	B13E	4	Big Solovetsky Island, Kryvodorozhnoye Lake	65.10468	35.62995	8(17)	1740–2011
	KRYV	4	Big Solovetsky Island, Kryvodorozhnoye Lake shore	65.1024	35.619533	7(13)	1725–2008
	B16E	5	Big Solovetsky Island, the road to Cape Pechak, Gryaznoe Lake	64.97218	35.74722	5(10)	1689–2011
	B07E	6	Big Solovetsky Island, Ovsyannikov Cape	65.16492	35.67428	8(16)	1774–2011
	B10E	6	Big Solovetsky Island, Beluzhy Cape	65.07603	35.53442	10(19)	1737–2011
	B31E	6	Anzer Island, the flat forefield site	65.14106	36.11806	5(10)	1867–2011
	B32E	6	Anzer Island, the second flat forefield	65.14153	36.11836	5(10)	1838–2011
	B41E	6	Anzer Island, first sea terrace	65.14308	36.12625	5(5)	1908–2011
	B75E	6	Big Solovetsky Island, Cape Tolstik	65.03915	35.64086	20 (40)	1838–2016

person. Another feature of the spruce in the Solovetsky archipelago is increased growth at the butt end. Spruces are more prone to ground fires, which can lead to a change in species. According to researchers (Ipatov et al., 2009), over the past 78 years, the area of spruce forests has decreased, while the area of pine forests has increased.

2.3. Instrumental records

The monthly mean temperature and precipitation records were taken from the nearest land grid point (64.75 N, 35.75E) from the CRU TS 4.01 database (Harris et al., 2014), covering the period 1901–2016. In addition, we used monthly temperature and precipitation records from the nearest mainland weather stations: Kem'-Port (64.98 N, 34.80E, 8.0 m a.s.l.), where the observations begin in 1891, and Arkhangelsk (64.3 N, 40.44 E), where temperature records start from 1813, summer temperatures reordered since 1814 with one gap in 1832.

2.4. Historical data

In order to compare our reconstruction with the historical data we used the most complete inventories of climatic and other environmental phenomena published by (Borisenkov and Pasetskiy, 2002). Unfortunately, no records directly concerning the Solovetsky Archipelago for the period of 17th – 19th centuries were found in these publications. Instead, those entries that mention "Arckhangelskaya", "Olonetskaya" districts and "European Russian North" were identified and compared with the positive and negative extremes in our paleoclimatic reconstruction.

The long annalistic tradition existed in the Solovki Monastery itself. Manuscript production along with the salt industry was one of the main economic activities of the monks in this monastery. Many local chronicles were lost or willfully destroyed during the Soviet time, when Solovki hosted the first prison camp in the USSR. One Monastery chronicle "1853" written in the early 19th century was reprinted later and is available for the general public. There we found some useful information that helped us to date some wooden constructions (Matskovsky et al., 2013). It also contains the first meteorological data for Solovki for the years 1829–1833 but only for winter temperatures and winds. Unfortunately, climatically relevant information in this book is rather limited.

2.5. Methods

In the laboratory, the increment cores were glued on the wooden beams with fibers in a perpendicular direction (Stokes and Smiley, 1996) and sanded with gradually finer sand paper up to a 1200 grid. Tree-ring widths were measured with a resolution of 0.001 mm using the LINTAB ver. 3.0 system (Rinn, 1996). The TSAP software was employed for visual cross-dating of the samples. Quality control of measurements and cross-dating was assessed using the COFECHA software (Grissino-Mayer, 2001) with core segments having low correlation values with the master chronology being excluded from the analysis.

The resulting tree-ring series were standardized to dimensionless indices in order to remove the age trend and to preserve variations related to climate. The 'Signal-Free' detrending technique was applied to develop local chronologies for each site and to obtain the composite chronology using the RCSsigFree software (Melvin and Briffa, 2008). The common signal of the samples was estimated by means of the Expressed Population Signal (EPS, Briffa and Jones, 1990). A 30-year moving window with a 29-year overlap was employed to calculate the EPS values. The EPS value of 0.85 was used as a threshold value for the well-replicated part of each chronology (Wigley et al., 1984). Tree-ring data analyses were performed using the dplR package (Bunn, 2008) in the R environment.

The response functions were calculated using the Treeclim software in order to identify the relationship between the tree-ring chronologies and climate variables (Zang and Biondi, 2015). This software allows calculating bootstrapped statistics, the moving response and the correlation functions, as well evaluating the performance of the model used for the reconstruction. The chronologies were correlated with the monthly temperature and precipitation records using the 15-months period from June of the previous year to September of the current year.

Application of a linear model usually leads to the loss of amplitude in the reconstructed series (Esper et al., 2005). Therefore, the scaling method was used instead, wherein the standard deviation and the mean values for a given chronology were set equal to those of the meteorological records over the common period from 1901 to 2016 (Büntgen et al., 2017). The adequacy of the linear model performance was evaluated by splitting the data into the calibration and the verification periods with the calculation of the values of the reduction of error (RE) and the coefficient of efficiency (CE), as well as the Durbin-Watson statistics. Both RE and CE are measures of shared variance between the instrumental and reconstructed series. Values of RE and CE greater than zero indicate positive reconstruction skill of the model applied (Cook et al., 1999). Durbin-Watson statistics shows the presence of the first-order autocorrelation in the residuals (Durbin and Watson, 1971). The coherency between the tree-ring records and the explosive volcanic eruptions was explored with the Superposed Epoch Analysis (SEA; Lough and Fritts, 1987). SEA was computed in dplR (Bunn, 2008), bootstrapping were used to assess the significance of the departure temperatures. The wavelet coherence between the reconstruction and the instrumental records was computed. This analysis was performed in R programming language (R Development Core Team 2014) using the package "biwavelet" (Gouhier et al., 2018).

3. Results

3.1. Climate sensitivity of spruce

210 tree-ring width series were successfully cross-dated and used to develop 14 local chronologies (Fig. 1, Table 1). The six groups of habitats of spruce were used for analyzing their response function in order to select the sites with a similar reaction to climate and use them later on for the regional climate reconstruction.

Group 1 - elevated, hilly plains with kame landforms, composed of boulder sandy loams with podzolic and bog-podzolic soils covered with spruce shrub-green moss forests with a slight admixture of pine and birch (yellow color on the map, chronologies PDEL, B05E).

Group 2 - flat interfluve, a gently hilly moraine plain surface from 25 to 50 m a.s.l., composed of boulder sandy loam and sandy loam moraine with podzols and bog-podzolic soils covered with spruce and pine-spruce forests with an admixture of birch, dwarf-green moss forests (light brown on the map, chronology B02E, B06E).

Group 3 - water-glacial plains with lake systems oriented from North to South (from 14 to 24 m a.s.l) of terraces composed of sandy-loamy moraine with marsh-podzolic soils under pine-spruce and spruce-pine forests with an admixture of birch, sphagnum forests (pink color on the map, chronology B72E).

Group 4 - elevated sea terraces with numerous lake depressions and moraine ridges (elevation from 14 to 24 m a.s.l.), composed of layered silty-sandy deposits, covered with peat or bog-peat soils with the vegetation of sphagnum bogs and boggy shrubs; sphagnum pine forests (light green color on the map, chronologies B13E and KRYV).

Group 5 - 2nd and 3rd marine terraces (from 7 to 13 m a.s.l.) sloping with ledges, composed of silty-sandy deposits largely covered by peat of transitional bogs (less often raised bogs) with boggy soils covered with sedge-sphagnum bog vegetation and swampy pine and spruce forests (green color on the map, chronology B16E).

Group 6 - natural marches of the modern coast (from 3 to 5 m a.s.l.), composed of pebble-boulder deposits on an eroded moraine with a fragmented vegetation cover, represented in the littoral part by algae and halophytes, in the supralittoral part - by lithophilic salt-tolerant plant communities on primitive, very stony soils (dark green color on the map, chronologies B07E, B10E, B31E, B41E, B32E, B75E).

The response functions and graphs showing moving correlations between monthly temperatures and precipitation records with spruce ring width for all the six groups and in the Table 2 results are summarized (B06E was excluded from the further analysis because only one tree was sampled there).

The climatic response function for the entire period (116 years) shows that all the local chronologies without exception have a positive relationship with June temperature despite different local environmental conditions. The strongest link with June temperature is at the B05E site (regression coefficient 0.408), located at the highest elevation at the slope of the Podnebesnaya Mountains. The weakest connection is at the site B41E (regression coefficient 0.196), located at the first sea terrace of the southern coast of Anzer Island, where the shore conditions play a more important role in the local climate. Four chronologies are also sensitive to July temperature (B05E, B02E, B07E, B10E), one – to the temperature of August (B16E) (Table 2).

Eight out of 14 chronologies demonstrate a negative relationship with February temperature. The correlations are less strong than those with June temperature. This relationship is evident in all the five landscape groups and does not seem to have an obvious connection with the specific type of landscape.

We are targeting our reconstruction to the month of June having the strongest and most stable correlation over time (1901–2016) with tree-ring width of spruce. The values of the Pearson's coefficients of correlation for different chronologies vary from 0.26 to 0.56 ($p < 0.05$).

We combined all individual tree-ring series into a composite tree-ring width chronology. The resulting composite spruce ring width chronology covers the period 1626–2016 CE and consists of 210 samples (Fig. 3). The EPS value exceeds the threshold of 0.85 after 1676 CE, when at least 6 samples are present in the chronology. The final chronology is characterized by the following statistics: standard deviation 0.19, mean sensitivity 0.176, serial correlation 0.405, first-order autocorrelation 0.198.

The composite chronology positively correlates with June-July air temperatures of the current year and negatively - with the temperature of February (Fig. 4). There is also a positive response of spruce growth to July precipitation of the current year. June air temperature is the most distinct climatic parameter controlling spruce growth that is evident both for the full period and in the moving response function analysis. The computed moving correlations between the spruce chronology and the climatic factors show that the correlation with June temperature is also stable over time (Fig. 5). The relationship is somewhat weaker in the beginning of the instrumental records ($r = 0.3 – 0.4$, $p < 0.05$), but becomes stronger from the 1920 s to 2016 ($r = 0.5–0.6$, $p < 0.05$). The July air temperature signal is statistically insignificant at the beginning and at the end of the instrumental period. The moving correlations (see Fig. 5) also demonstrate negative correlations of ring width with the previous fall, but the response function in Fig. 4 does not confirm it and indicates the correlations for these months as statistically insignificant.

3.2. June temperature reconstruction

The composite chronology was scaled against the June air

Table 2

Climatic response function analysis of spruce growth to monthly climate variations. Analysis is performed for 15-months period (from previous June to current September) over period of calibration (1901–2016). Here'statistically significan ($p < 0.05$) regression coefficients showed only.

No	Site Code	Landscape	Months of the previous year					Months of the current year										
			6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
	PDEL	1													0.300T			
	B05E	1									-0.169T				0.408T	0.198P		
	B02E	2									-0.186T/0.232P				0.257T	0.161P		0.195
	B72E	3									-0.199T				0.202T			
	B13E	4													0.300T			
	KRYV	4									-0.135T				0.308T			
	B16E	5									-0.206T				0.279T		0.184T	
	B07E	6													0.350T	0.207P		
	B10E	6									-0.165T				0.357T	0.204T		
	B31E	6		-0.206T											0.294T			
	B32E	6									-0.177T				0.346T			
	B41E	6													0.196T			
	B75E	6									-0.172				0.348T			

where T is temperature series, P – precipitation series.

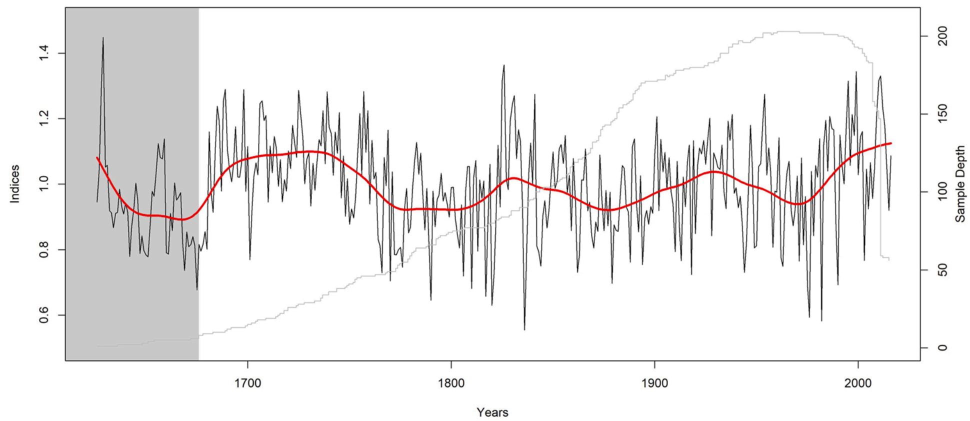

Fig. 3. Composite tree-ring width spruce chronology (black line) and sample depth (gray line) for the period 1626–2016. The chronology is smoothed by 50-year spline (red line). The gray area indicates the part of the chronology where the EPS values drop below critical level (0.85).

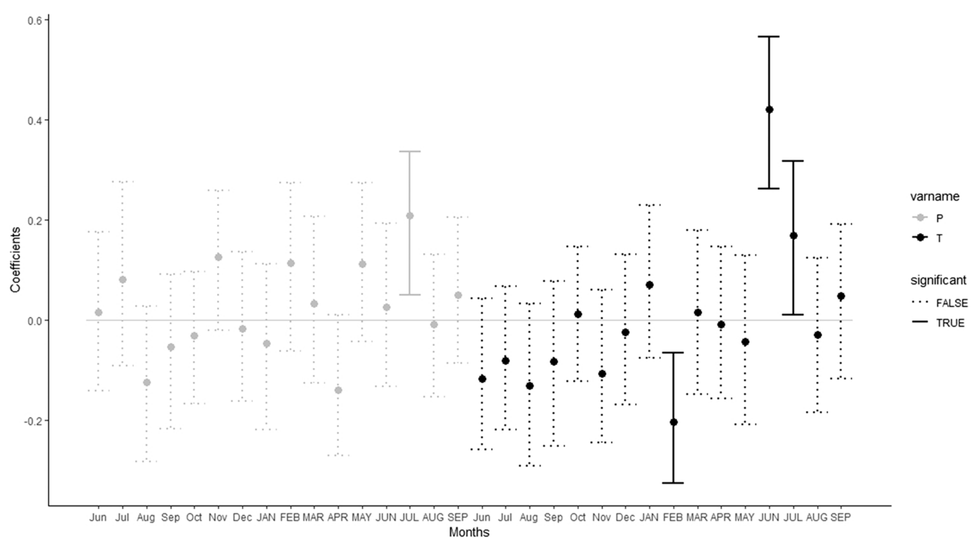

Fig. 4. Bootstrapped response function analysis of the spruce tree-ring width composite chronology from Solovetsky Archipelago and monthly mean precipitation and air temperatures. Response function was calculated over 15 months from June of the previous year (lowercase letters) to September of the current year (uppercase letters). Climate records were obtained from CRU TS 4 database (Harris et al., 2014) from the nearest land grid point (64.75 N, 35.75 E) starting from 1901.

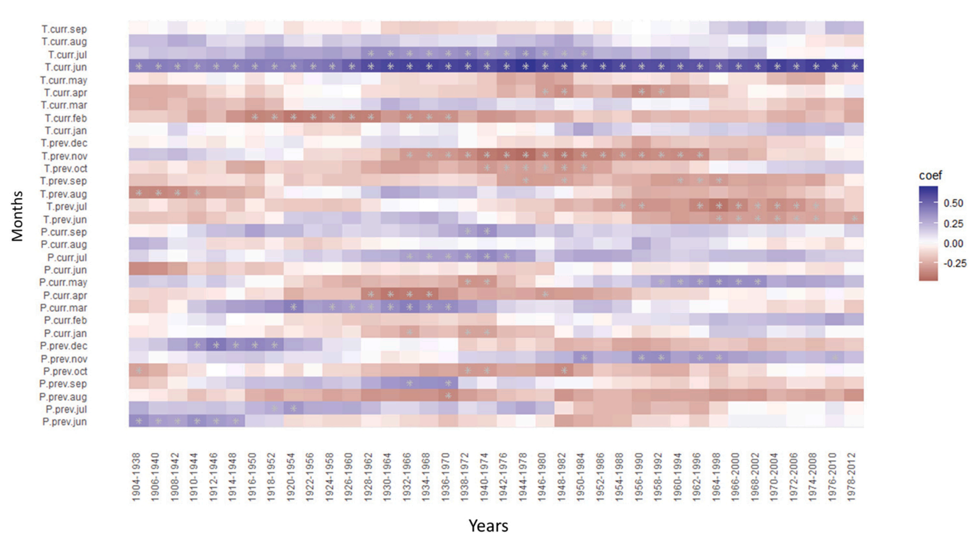

Fig. 5. Moving correlation between spruce composite chronology and mean monthly temperatures and the sum of precipitation over the common period of 1901–2016. The moving correlation is carried out in windows of 35 years with offset of 2 years. Asterisks denote significant coefficients of regression.

temperatures of CRU TS 4.01 in order to reconstruct it. The comparison of the reconstructed June temperatures to the actual values revealed a good agreement over the period 1901–2016 CE. The positive values of RE and CE statistics indicate the predictive skills of the applied model (Fig. 6). RE and CE statistics are higher when calibration of the beginning of the instrumental records is performed (1901–1956) achieving the values of 0.379 and 0.349, respectively. When chronology is calibrated using the most recent period (1957–2016) statistics become lower, reaching the values of 0.215 and 0.163. This finding allowed using the spruce tree-ring width chronology to reconstruct June air temperature from 1676 to 2016 (Fig. 7). Arkhangelsk - one of the longest meteorological series in Russia - provides a unique opportunity to check the stability of the signal in our spruce regional chronology over the period since 1814 CE. It is quite remarkable that our reconstruction matches the Archangelsk records not only in the 20th-early 21st centuries but also in the 19th century (Fig. 8) confirming the reliability of the reconstruction over more than two centuries. Correlation over the full period is $r = 0.48$ ($p < 0.05$, 203 years), while during the first 101 years correlation is lower ($r = 0.38$, 1814–1915, one year is missing) compared to the most recent period ($r = 0.58$, 1916–2016).

The spatial correlation between the reconstructed and gridded instrumental records from the CRU TS4.01 is shown in Fig. 9. The correlation field (with $R>0.6$, $p < 0.10$) spreads to the south and occupies a vast territory of European Russia roughly up to 50 N and between 27 and 47E. The strength of correlation decreases west- and eastward almost symmetrically, but is elongated in the southern direction demonstrating a relevance of our Solovki spruce chronology for a large spatial scale temperature reconstruction of European Russia.

3.3. *Searching for a more precise target-window*

Kem'-Port meteorological station, with its long records of daily observations (1916–2016), is located in the immediate vicinity of Solovki, and this makes it possible to estimate the target-window in more detail. DendroTools software (Jev and Levani, 2018) was used to identify the optimal sequence of consecutive days with the highest correlation between the series. Results of the dendroclimatic analysis carried out between the composite tree-ring width spruce chronology and daily temperature records are shown in Fig. 10. The highest value of explained variance between the series (0.234) is observed on the calendar day 157th, that means that the optimal target window lasts 37 days starting from the 6th of June to 12th of July.

These results show that response of spruce to daily temperature is not limited to June, but extends to almost a half of July (the highest response was calculated for the period from the 6th of June to the 12th of July). Previous studies have shown that the ring-width series of pine and spruce are highly correlated, a fact that allowed the development of a composite conifer chronology (Solomina et al., 2011). Response function analysis of pine chronologies revealed that pine growth from some sites shows significant positive response to mean July air temperature (Dolgova et al., 2019). Response function analysis of spruce chronologies to monthly climate variables presented here (Fig. 4) demonstrate that growth of spruce depends on mean June temperature. Hence, both pine and spruce may share a common response to end-of-June – beginning-of-July temperatures.

A newly obtained target window was used to develop temperature reconstruction (from the 6th of June to 12th of July). A visual comparison between the two reconstructions is shown in Fig. S1. Both curves coincide markedly and for the convenience of further comparison with the other data, monthly record reconstruction will be used below.

4. Discussion

4.1. *Climatic signal in conifer chronologies in Solovki and in other sub-Arctic spruce chronologies*

Previously, Matskovsky (2016) demonstrated the sensitivity of conifer chronologies growing north of 54 N in European Russia to the temperature of summer months. In agreement with this conclusion all of the tree-ring series of spruce from different environments in Solovki showed a significant positive correlation with June temperatures (Matskovsky, 2016).

It should be noted, that in addition to the demonstrated foremost role of June temperature, there are other climatic factors potentially affecting the growth of spruce in Solovki. The response function analysis showed the sensitivity of spruce to high temperatures in February, which is the coolest month in the archipelago (mean temperature is −10.1°C). Previously, Babst et al. (2013) reported that Norway spruce from alpine tree-line shows a negative reaction to high winter temperatures which is associated with the increased respiratory carbon costs

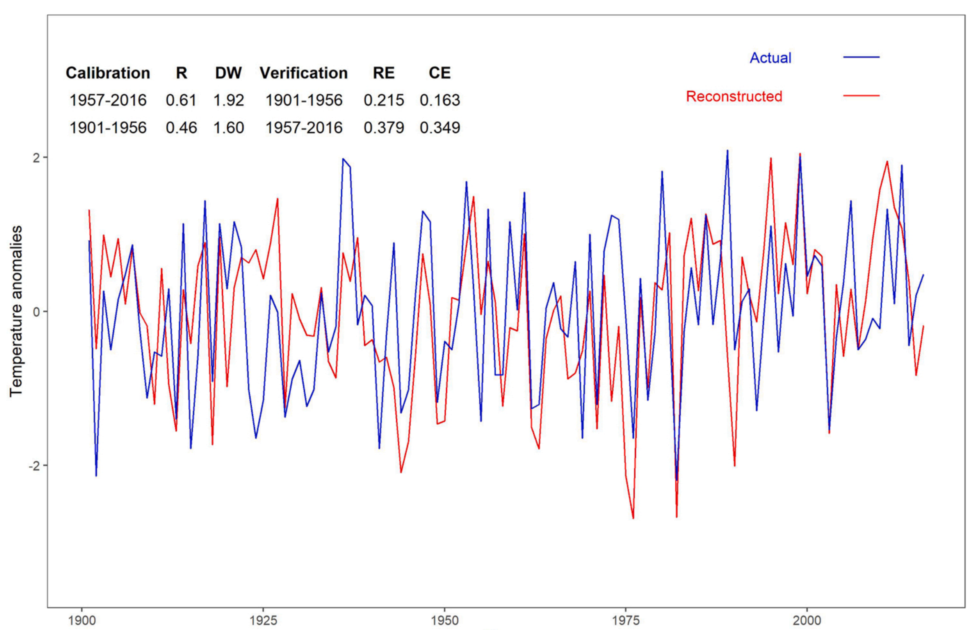

Fig. 6. Actual (blue) and predicted (red) June air temperature anomalies over the period of 1901–2016 with model verification and calibration statistics.

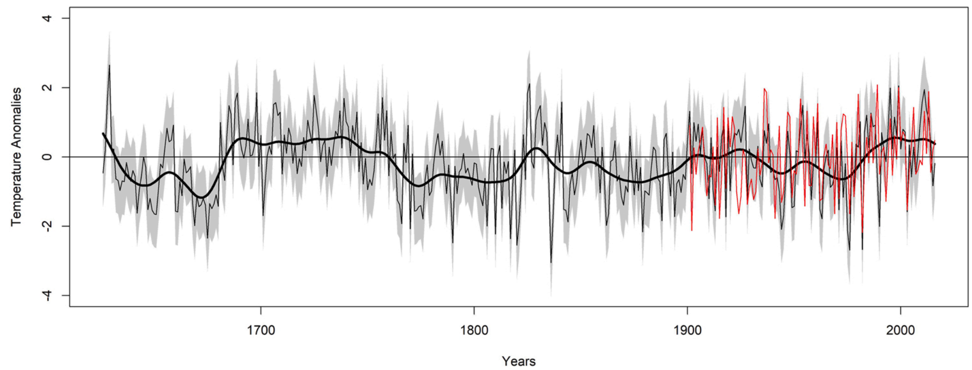

Fig. 7. Reconstructed mean June air temperatures expressed in anomalies (1901–2016) based on spruce composite tree-ring width chronology from Solovetsky Archipelago (thin black line) and instrumental records (red line). Reconstructed temperature smoothed by 50-year spline (thick black line) and +/− Root Mean Square Error limits (gray area) are shown.

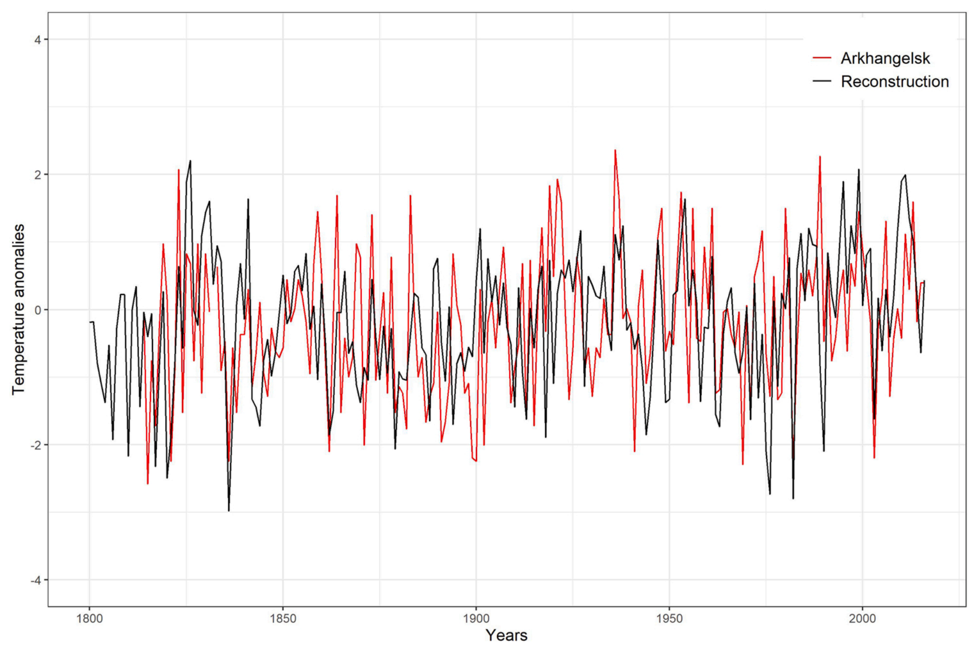

Fig. 8. Reconstructed June air temperatures expressed in anomalies (1901–2016) based on spruce composite tree-ring width chronology from Solovetsky Archipelago (thin black line) and June air temperatures recorded in Arkhangelsk weather station.

(Piao et al., 2009). The same pattern (negative correlation between tree-ring growth and temperature in February) was reported for the spruce located in the Arkhangelsk region (Aakala and Kuuluvainen, 2011).

Historically, climatic response analyses of conifers in Solovki were carried out on several levels. Initially, Solomina et al. (2011) identified positive responses to warm season temperatures for composite conifer chronology including pine and spruce. Later on, Dolgova et al. (2019) separately analyzed the climatic signal in 15 local tree-ring width pine chronologies and concluded that the growth of pine from mixed forest and pine-greenwood in Solovki mostly depends on air temperature in July. However, in contrast to the results presented here for spruce chronologies, pine chronologies from all habitats are weakly correlated with climatic parameters in the instrumental period and therefore they were not used for paleoclimatic reconstruction.

Climatic signals inferred from spruce in Solovki is spatially and temporally more stable, than in pine chronologies. Earlier in Fennoscandia Ording (1941) and Mikola (1950) it was observed that the growth variation of Norway spruce was more dependent on weather conditions in the earlier part of the growing season than was the growth variation of Scots pine (Mäkinen et al., 2000). That is similar to our findings: spruce ring width in Solovki depends more on June temperature, while pine reacts predominantly to the temperature of July.

4.2. Comparison of annual ring-width of spruce in Solovki with meteorological and historical records

The adequacy of the applied model of reconstruction is supported by the statistically significant ($r = 0.57$, $p < 0.05$) and temporally stable relation between the TRW spruce chronology and June air temperatures over the period 1901–2016 CE. The June temperature reconstruction in most cases matches closely the instrumental records (see Fig. 6). Mismatches between the reconstructed and the actual series were accounted as differences between them (Fig. S2) and the years with values that exceed 2 standard deviations are 1924 (positive deviation), and 1973, 1975 and 1989 (negative deviations). In 1924 June and July were colder than normal, but August, September and October were anomalously warm and the vegetation period was extended, compensating for the reduced growth in June and July. The reasons for the negative growth anomalies in 1973, 1975 and 1979 are not yet clear. In 1973 the temperature from May to August were slightly warmer than normal, in 1975 and 1979 May was warmer than average, so low summer temperature

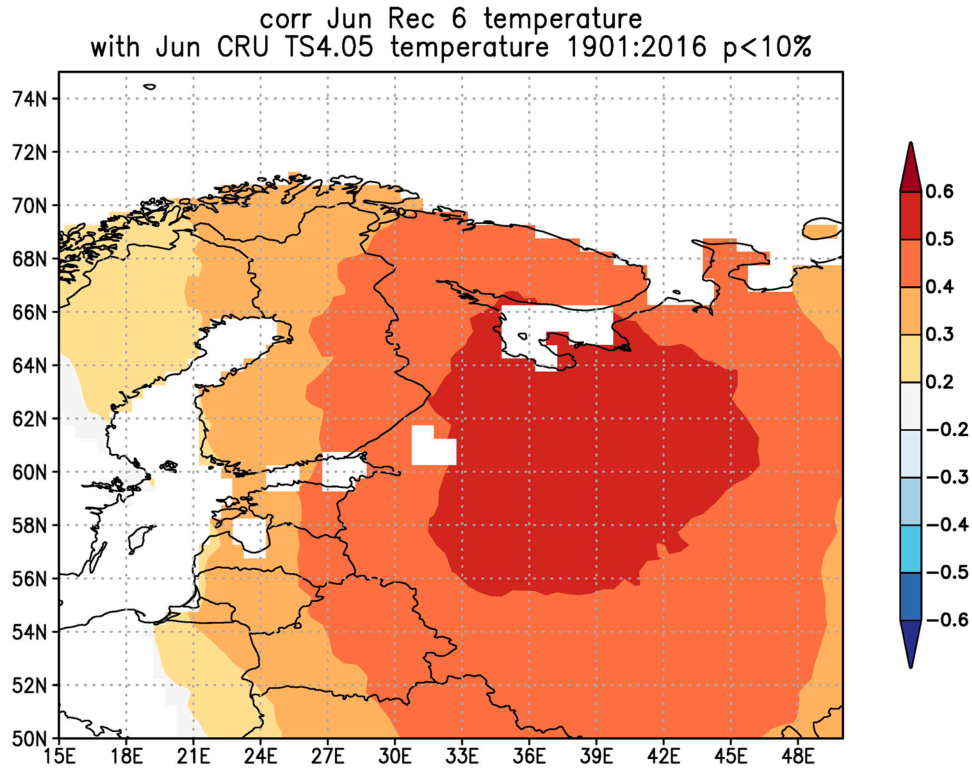

Fig. 9. Map of spatial correlation between reconstructed June air temperatures with the gridded data from the CRU TS4.01 database for the common period, 1901–2016. Analyses were performed using the KNMI Climate Explorer (http://www.knmi.nl/).

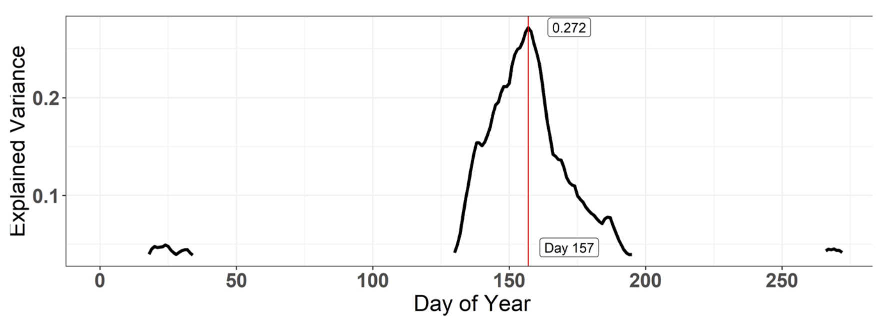

Fig. 10. Results of the dendroclimatic analysis carried out between composite tree-ring width spruce chronology and daily temperature records from Kem'-Port weather station over common period 1916–2016. The highest value of explained variance between series (0.234) is observed on calendar day 157th, that corresponds to the optimal target window that lasts 37 days starting from 6th of June to 12th of July.

was obviously not the reason of the observed negative growth deviations in these years. In 1979, February was cold and judging by our response function it was also not a potential reason for the observed discrepancies.

Our screening of the Inventories of climatic anomalies in the Arkhangelskaya and Olonetskaya districts in the end of the 17th-19th centuries in the European North of Russia recorded in the Russian chronicles (Borisenkov and Pasetskiy, 2002) did not return direct coincidences with our June temperature reconstruction in Solovki. However, we did not find any information contradicting our results there either (i.e., indication of warm/cold early summers coinciding with narrow/wide rings). Most probably, the completeness of historical documentary records for this region is not sufficient for our goals. We noticed a coincidence of extremely cold winters in 1701, 1810, 1817, 1836 and 1844 with spruce ring width minima. Although this is just 5 out of 31 cases of narrow rings, we cannot rule out that not only the early summer temperature, but also the extremely cold winters can affect the tree growth in such a northern location as the Solovki Archipelago.

The year 1826 is the warmest one in our reconstruction besides the other three that all occurred in the end of the 20th-early 21th centuries. In the local historical chronicle compiled in the Solovki Monastery (Dositheus, 1853) this year is also identified as being exceptionally hot. The chronicle says: "…In the summer of 1826, the warmth reached to more than 25 Reomur degrees, and was rather constant, even in the fall it was impossible to complain about the cold"." (Pt1, paragraph 9 page 22). 25 Reomur degrees is equal to 31.25 ºC and that is indeed exceptionally high for the Solovki region (mean temperature in July at Kem'-Port weather station in 1891–2018 was 14,2 Cº). According to our reconstruction, June temperature in this particular year exceeded 2 standard deviations. Three other peaks of similar magnitude in our reconstruction occurred in 1995, 1999, and 2011, i.e., they are all clustered in the most recent decades. This might be a local manifestation of the effect of anthropogenic warming in the region.

4.3. Multidecadal and centennial variability of spruce ring width and the problem of the 18th century bias

We compared our reconstruction with several available records of summer temperature in the nearby regions (The Polar Urals (Schneider et al., 2015), Scandinavia (Zhang et al., 2016), The Khibiny Mountains (McCarroll et al., 2013) and The Yamal peninsula (Briffa et al., 2013) (Fig. 11, Table S1). All these regional reconstructions along with many others were incorporated into the warm season (May – August) temperature field reconstruction across the extratropical Northern Hemisphere (Anchukaitis et al., 2017). The curves show a certain visual agreement, but also a strong regional variability that we expected judging by the spatial correlation of our reconstruction with June temperature (see Fig. 9). Cross-correlations between the reconstructions are presented in the Table S1 where coefficients computed for both annual and smoothed data. The Solovki June temperature reconstruction doesn't correlate significantly with any other reconstruction when comparison over the full common period is made (1676–2005) in annual domain. The highest correlation coefficient reaching the value of 0.55 was observed when comparing with the Yamal regional chronology in the 20th century. Although our June temperature reconstruction demonstrates a certain visual similarity with these curves in the 19th-early 21st centuries, a contrast in the end of the 17- late 18 tth centuries is evident.

The same discrepancy arises when we compare this part of our reconstruction with the Klimenko (2006) reconstruction based on historical evidence. He refers to extremely severe ice conditions in the Arctic seas during the Great Northern Expedition (1733–1743). He also mentioned that "it took four years for the western team to cover the long-known way from Arkhangel'sk to Obskaya Guba" (Klimenko and Astrina, 2006, p. 197). Our reconstruction did not capture this cooling. Klimenko (2006) also identified two warmings in the north of European Russia in 1695–1725 and 1775–1805 and claims that temperature in these periods "often exceeded the modern values in all the regions" (p. 197). The first of these periods (end of the 17th - first quarter of 18th century) is also warm and comparable by magnitude with the modern temperature in our reconstruction, while in the late 18th century spruce chronology from Solovki doesn't have wide rings and hence, does not indicate a warming in June.

Thus, we identified a problem in the low-frequency variations of the Solovki curve of June temperature in the 18th century that shows a prominent warming altering with moderate coolings in contrast to some other summer temperature reconstructions in this area. We consider the following hypothesis to explain this discrepancy:

1. Different seasonality of the records. While most of temperature reconstructions in the sub-Arctic target the whole summer (Linderholm et al., 2015; McCarroll et al., 2013; Zhang et al., 2016), the signal in the Solovki spruce chronologies is June and early July. We cannot exclude this explanation, but in our opinion, it is not very probable, since cold summer would normally include the early summer months as well.
2. Regional climatic conditions. A real local climate warm temperature anomaly occurred in June in Solovki, while the other Arctic regions experienced cooling. We do not have any direct local paleoclimatic evidence from Solovki to check this hypothesis, but the historical evidence from Arkhangelsk contradicts this version.
3. The method of standardization potentially influences the low-frequency trends. We experimented with several standardization techniques (negative exponential, signal-free age depended) as well as with the DIRECT method suggested by Matskovsky and Helama (2016) (Fig. S3). Applying different techniques led to different mean levels of temperatures in 18th century. To select the most suitable standardization method, further detailed research is needed.
4. Heterogeneity of the chronology in its earlier part. Such an increased growth of spruce observed in the early 18th century could be associated with the specific habitat of the trees used in this part of the chronology. However, careful analysis showed that the period of the 18th century was covered with tree-ring series from different sites. This part of the chronology is still well-replicated and includes from 20 to 40 samples covering this period. However, we believe that this is the most probable cause of the bias. The comparison with our earlier conifer chronology (Matskovsky et al., 2013) shows a different pattern in the 18th century and agrees better with the historical evidence in this time period. Büntgen et al. (2008) analyzing the ability of spruce to reproduce a temperature signal in the Alps noticed: "our results may contain bias originating from temporal changes in sample replication of the mean chronologies, their imbalance in the total number of series used, and differences in site elevation and location. This argument is particularly valid for the spruce record, which is characterized by a slight sample reduction in the post-1980 s that may account for some recent uncertainties" (p.2450) (Büntgen et al., 2008).

Thus, at the moment we cannot confidently explain the reason of discrepancies observed in a low-frequency domain in the 18th century in our spruce-based reconstruction. However, the reconstruction is very solid and reliable in its later part from the early 19th to the early 21st centuries. Below we discuss some of its properties, excluding the earlier

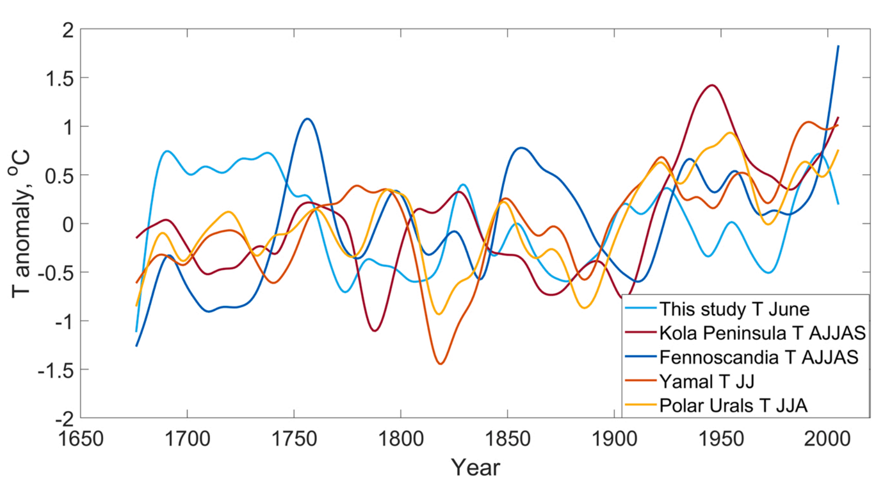

Fig. 11. Comparison of tree-ring based temperature reconstructions: this study (Solovetsky Islands, light blue), Kola Peninsula (brown, McCarroll et al., 2013), Yamal (red, Briffa et al., 2013), Polar Urals (yellow, Schneider et al., 2015) and Fennoscandia (dark blue, Zhang et al., 2016). All series were smoothed by 30-year cubic spline.

part of the records from our further analyses.

4.4. June temperature pattern in Solovki in the 19th-early 21st centuries

The wavelet analysis shows a coherence of high frequency variations of our chronology with the instrumental data (June temperature) (2, 4, 8 year cycles) and total solar irradiation (Shapiro et al., 2011) (32 and 128 years cycles) (Fig. S5). According to our reconstruction smoothed by a 30-year spline, the cold June anomalies in Solovki date back to the late 18th century-1823, 1836–1899, 1935–1952, and 1960–1979, while the warmings occurred in 1824–1835, 1900–1934, 1953–1959, and 1980–2016. The coolest reconstructed June air temperature occurred in 1836 CE. It was lower than the mean temperature by 2.9 °C for the reference period (1901–2016). Other strong cold anomalies for the month of June were identified for 1976 (−2.4 °C), 1982 (−2.4 °C), 1820 (−2.4 °C), 1790 (−2.3 °C), 1817 (−2.2 °C), 1879 (−2.1 °C), and 1810 (−2.1 °C).

Certain minima in the reconstruction correspond to the dates of major climatically effective explosive volcanic eruptions (Sigl et al., 2015), such as 1836, 1982, 1817, 1810, 1661 and 1674 CE or followed them within one to two years (Fig. S6). The coldest June temperature anomalies in the reconstruction occurred in 1836 CE after the eruption of Cosiguina (Nicaragua) that took place in June of 1835. The cooling effect of this eruption is also recognized during the following year 1837 CE in our chronology as well as in the hemispheric reconstructions and in some sub-arctic regions (Anchukaitis et al., 2017; Briffa et al., 1998).

Our spruce chronology does not show any "divergency" from the instrumental June temperature unlike many other tree-ring records at the northern tree-line. It means that our data can be safely used for regional and hemispheric June temperature reconstructions.

The reconstruction reproduces a warming trend in June temperature since the 1970s that closely follows the instrumental records. A weak longer-term positive trend is also evident since the 1870s or even from the late 18th century at the smoothed reconstruction (see Fig. 7). While the recent trend in the end of the 20th –early 21st centuries common to all reconstructions presented in Fig. 11 can be tentatively attributed to the anthropogenic warming effect, the longer-term trend over the past two centuries is most probably of natural origin. The range of variations of the reconstructed June temperature in the 20th century in Solovki still does not exceed the natural variability over the whole period of 200 year-long records.

5. Conclusions

1. Spruce ring width from six different types of habitats demonstrated a similar climatic response dominated by June temperature. The strongest correlation of ring width is observed for the temperature in the window lasting for 37 days from the 6th of June to 12th of July. Most sites also show a negative correlation with February temperature.
2. The strongest spatial correlation ($r > 0.6$, $p < 0.1$) of the chronology is observed with June temperature in the continental part of European Russia between 32 and 44 E and up to 57–64 N.
3. A good match of our June temperature reconstruction with long meteorological records in Kem'-Port (1891–2016 CE) and CRU reanalysis in the 20th-21st centuries. It is further supported by the longer records of Arkhangelsk (1813–2016 CE) indicating the stable relationship of spruce ring width and June temperature over two centuries.
4. The reconstruction does not show any sign of divergence in the 20th-21st century, but in the late 17th–18th centuries it contradicts the local historical and other regional proxy-based reconstructions despite sufficient replication of the samples included in the chronology. This evidence needs further exploration but it calls for caution and the cross-checking of some tree-ring based reconstructions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2022.126012.

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