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Dendroclimatic signals in the pine and spruce chronologies in the Solovetsky Archipelago

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A B S T R A C T

Searching for a robust tree-ring parameter useful for paleoclimatic purposes is one of the most demanding topics in the modern paleoscience. Since Blue Intensity has already expressed itself in different geographical locations all over the world as a possible replacement for maximum density, close attention is paid to investigate features of the inferred signal. The Solovki Islands is a unique location in Northern Russia where two important factors that make this territory attractive for developing a long tree-ring chronology have been met: modern long-living trees and building activities using old trees that were started by monks in the middle of the 16th century. The main goal of the research is to develop pine and spruce chronologies based on tree-ring width (TRW) and delta Blue Intensity (dBI) and to assess the ability of these parameters to be used as climate predictors. As a result, 14 conifer chronologies from 7 sites (4 for pine and 3 for spruce) were developed. The composite pine and spruce chronologies span a period of 474 and 378 years each. Cross-correlation of dBI-based chronologies of both conifers is high (r = up to 0.71 while for TRW-based chronologies it is lower on average (−0.18 to 0.63). Intraspecies correlation of TRW chronologies in some cases achieved even negative values (r = −0.18. Discrepancies found between TRW chronologies of pine and spruce could be explained by differences in climatic signals. Response function analysis with monthly temperatures revealed that growth of pine depends on the previous August, while spruce has a temporally stable and strong relation to June temperatures. Compared to TRW, dBI-based chronologies have a high correlation with summer temperatures (r = 0.64 and 0.66 for spruce and pine, respectively). Presented research points out the importance of the response function analysis suggesting that depending on goals of the study several tree-ring parameters could be used, e.g., tree-ring width of spruce responses to June temperatures, while dBI to the whole summer.

1. Introduction

Our modern knowledge about past climate change over several thousand years is mostly inferred from tree-ring data (Anchukaitis et al., 2017). Compared to other natural proxies, tree-rings stand out because they have an annual or even seasonal resolution. During the last decades huge advances were made especially in the field of collecting tree-ring samples in remote places and developing new and long tree-ring chronologies. Huge amounts of tree-ring data obtained by various laboratories is now available from ITRDB (International Tree Ring Data Bank) for every researcher, which is evidence of the global success of the dendro community. The state-of-the-art hemispheric and global past climate reconstructions are based on this vast tree-ring network (Briffa et al., 2004; Anchukaitis et al., 2017). Tree-ring width (TRW) chronologies constitute the majority of this tree-ring network, because the width of tree rings is the most common parameter to measure because of its relative ease and cheapness. However, tree-ring width is not the best parameter for climate reconstructions because of the weak and/or mixed climate signal and high autocorrelation (Rydval et al., 2014; Björklund et al., 2019). Maximum density (MaxD), on the other hand, usually has a stronger climate signal than the TRW,a wider target climate window and a lower autocorrelation, resulting in a better ability to reproduce the amplitude of variability of a reconstructed climatic series. Mass character of the maximum density measurements is not achievable because its cost is high and the sample preparation in the lab is time-consuming. The main characteristics of the recently developed method of delta Blue Intensity (dBI) are placed between the TRW and MaxD parameters because dBI method is as cheap as ring-width measurements, while the signal strength is almost as high as in maximum density. These findings make BI a subject of investigation in terms of its ability to substitute

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MaxD. During the last decade the amount of published BI-based reconstructions has dramatically increased, indicating the high quality of this climatic proxy (Wilson et al., 2012; Linderholm et al., 2015).

The Solovetsky Archipelago (Solovky) is a unique place located near the Arctic circle with partly undisturbed forests. This place is a unique location, because the border between two natural zones (tundra and forest-tundra) passes across the archipelago. Finding a tree-ring parameter suitable for climate reconstructions is still an urgent task of modern dendroclimatology. Here we present the results of dendroclimatic research carried out in Solovky. The main goal of the research is to assess climate signals in TRW and dBI in both pine and spruce. In this research we present the results of the comparison of climate signals in TRW and BI in pine and spruce that were measured on the same samples. All tree-ring sites represent different and unique local landscape conditions. For this reason, we:1) measured and developed chronologies based on two tree-ring parameters (TRW and dBI) for both pine and spruce; 2) computed climatic response of TRW and dBI based chronologies; 3) compared climatic signals inferred from TRW and BI of pine and spruce; and 4) identified the most suitable parameter for climatic reconstructions.

2. Materials and methods

2.1. Study area

The Solovetsky Islands (65°10' N, 35°53' E) are the largest archipelago of the White Sea basin. They are located in the relatively shallow western half of the White Sea, at the entrance to the Onega Bay, forming western and eastern passages into it (Boguslavsky, 1978).

The Solovetsky Islands are of glacial origin. The basis of the islands are moraine deposits brought by the glacier, consisting of boulders, gravel, sand and clay. In addition to the hilly-moraine type of relief, the relief of sea terraces and swampy sand surfaces are distinguished (Boguslavsky, 1978).

Despite the fact that the Solovetsky Islands are located near the Arctic Circle, climatic conditions uncharacteristic of this geographical latitude have formed here. The climate of the islands is relatively mild, moderately warm marine, transitional to continental and differs from the mainland at the same latitude. The difference is expressed in a smaller temperature difference compared to the continent, in high humidity and in a relative delay of the seasons. The growing season with average daily temperatures above + 5 degrees on lasts for 128 days on average, from May 20 to October 1. The active part of the growing season with temperatures above 10 degrees lasts for almost 74 days, from June 20 to September 3 (Ipatov et al., 2009). The average monthly air temperature on the Solovetsky Islands varies from − 11.2 °C in February to 15 °C in July.

The Solovetsky Islands are characterized by strong wind loads. They adversely affect the growth of trees, since strong wind desiccation during the cold period can be disastrous. More information about climate could be found in paper (Dolgova et al., 2022).

According to the forest-growing zoning, the Solovetsky Archipelago belongs to the northern subzone of the taiga (Ipatov et al., 2009). The border of the two natural zones lies here – forests and tundra, between which there is a band of transitional landscapes.

In the work of Shvartsman et al. (2007), the following natural complexes were identified: 1 – spruce forests; 2 – sphagnum pine forests and swamps with pine; 3 – lichen pine forests; 4 – birch forests and aspen forests; 5 – birch crooked forests in combination with fragments of crow tundra and swamps; 6 – crow tundra with fragments of birch crooked forests and swamps; 7 – unforested shrub-sphagnum swamps; 8 – birch-spruce forests.

2.2. Tree-ring data

2.2.1. Field work and lab preparation

TRW and dBI data were measured from a network of 7 sites (Fig. 1, Table 1) in the Solovetsky Islands sampled during multiple field campaigns between 2008 and 2017. Samples were taken using an incremental Pressler borer at a height of 1–1.5 m from the ground surface.

Before taking measurements, the resins were removed from the wooden coresby means of heated solvent (ethyl alcohol – C_2H_5OH) in the Soxlet apparatus for 48 h at least.

After extraction, the cores were dried in a fume hood and glued onto special wooden substrates. Next, on the microtome, the top layer of wood was cut off to obtain a flat surface. Then the samples were sanded on a belt sander with successive changes of sandpaper (up to 1000 grains) to obtain a smooth surface that allows us to clearly observe the wood structures under magnification.

2.2.2. Tree-ring measurements: delta Blue Intensity and tree-ring width

To provide a direct comparison of both methods, delta blue intensity (dBI) and tree-rings width (TRW) have been measured on the same cores. The surface of the cores was scanned with a resolution of 3200 dpi on an Epson Perfection V700 scanner paired with the Silverfast software. The scanned cores were measured in the CooRecorder program, which allows measurements of various parameters of an annual ring on a single core (Larsson., 2013). The operator working with this program sets the boundaries of annual rings in semi-automatic mode. For measuring optical density, an important aspect is the optimal size of the selection of the “window” from which the data will be “read”.

2.2.3. Analysis of the tree-ring data

dBI and TRW measurements were cross-dated in the CDendro program and the quality of the measurements and cross-dating were checked using the COFECHA software (Grissino-Mayer, 2001), and a search for the missing and false rings was carried out (Fritts, 1976). Then, for each parameter the chronologies were constructed by dividing the annual values by the corresponding value of the approximating curve (negative exponent) for each series of measurements and the bi-weight robust mean was used to obtain average values for each year. The chronology quality was estimated by means of the Expressed Population Signal (Briffa and Jones, 1990), applying a 30-year moving window with a 29-year overlap to calculate the EPS values. EPS values > 0.85 were used as a threshold representing the reliable part of the chronologies (Wigley et al., 1984).

Standard chronologies constructed this way were then used for statistical analysis and the determination of their response to monthly temperatures and precipitation. All the processing of tree-ring series was carried out in the dendrochronological software package DplR in the R environment (Bunn, 2008).

To identify the strength of the relationship between tree-ring parameters and meteorological parameters, the climatic response function was used, namely the coefficients of multiple linear regression of tree-ring chronology indices on the principal components of monthly climatic data (Zang, Biondi, 2015). The statistical significance of the regression coefficients was estimated by the bootstrap method (Guiot, J, 1991). This statistical method, consisting of the repeated calculation of the statistics of interest based on a set of samples formed from the original data, allows us to correctly assess the significance of the obtained statistics values in the condition of a complex data structure. Chronologies were compared with climate data for 15 months (from June of the previous year to September of the current year). In addition, an analysis of the stability of the signal in time for each parameter was carried out. For this purpose, the climatic response function was calculated in a moving 35-year window with an overlap of 2 years. In this work, dendroclimatic analysis was carried out in the TreeClim dendrochronological package (Zang, Biondi, 2015), implemented in the R environment.

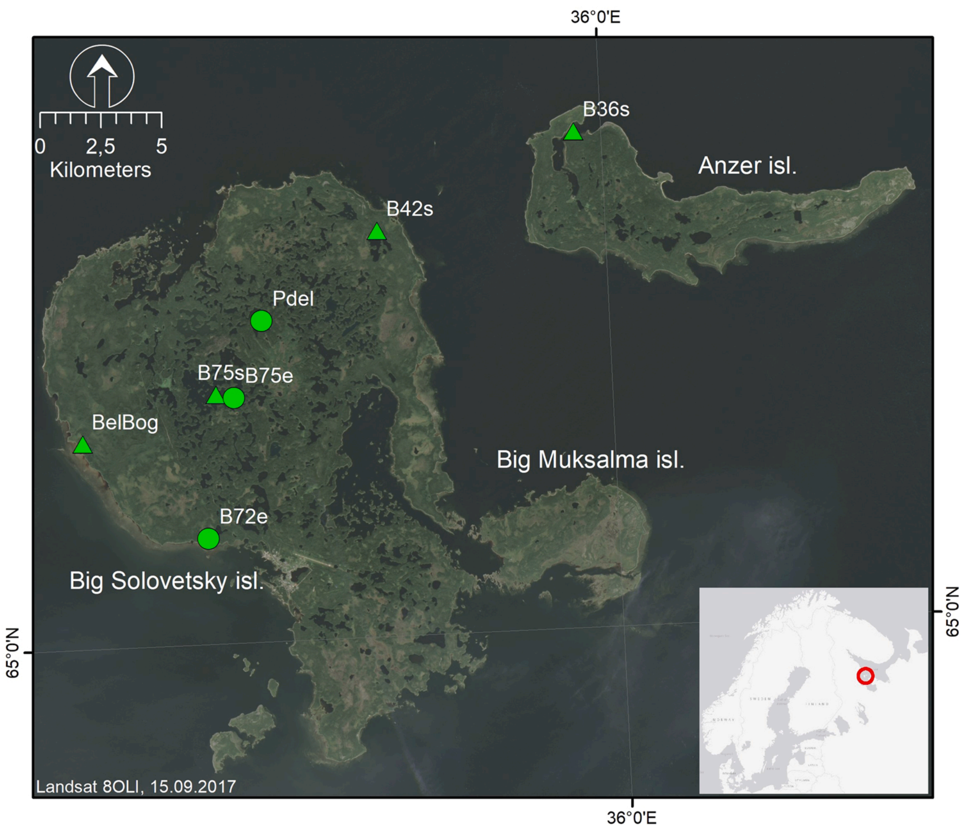

Fig. 1. Location of the tree-ring sites in the Solovki Islands used in the study; dot -spruce, triangle- pine.

Table 1
Short description of the tree-ring sites and chronologies statistics.

Site code (species)	Parametr	Latitude	Longitude	Number of trees (cores)	first	last	Chronology length (years)	Standard deviation (mm)	Mean sensitivity (MS)	First order autocorrelation	Rbar	EPS > 0,85 (samples)
B36s (pine)	TRW	65.18352	35.97603	14 (27)	1549	2011	463	0.29	0.2	0.821	0.297	1727 (16)
	dBI							0.13	0.134	0.557	0.338	1713 (13)
B42s (pine)	TRW	65.15011	35.8	13 (24)	1538	2011	474	0.225	0.2	0.726	0.425	1605 (11)
	dBI							0.1	0.151	0.12	0.307	1586 (6)
B75s (pine)	TRW	65.09217	35.65277	21 (42)	1840	2016	177	0.222	0.185	0.721	0.23	1877 (7)
	dBI							0.157	0.158	0.45	0.375	1866 (5)
BelBog (pine)	TRW	65.07603	35.53442	9 (11)	1600	2008	409	0.23	0.171	0.747	0.325	1703 (5)
	dBI							0.117	0.126	0.274	0.314	1683 (4)
B72e (spruce)	TRW	65.09063	35.66825	22 (44)	1789	2016	228	0.234	0.223	0.56	0.455	1868 (14)
	dBI							0.135	0.181	0.369	0.327	1870 (15)
B75e (spruce)	TRW	65.03915	35.64086	20 (40)	1838	2016	179	0.219	0.238	0.621	0.36	1905 (19)
	dBI							0.124	0.146	0.487	0.274	1884 (12)
Pdel (spruce)	TRW	65.118717	35.695050	8 (15)	1630	2007	378	0.317	0.251	0.712	0.432	1752 (10)
	dBI							0.124	0.131	0.583	0.272	1737 (9)

2.3. *Climate data*

Climatic data are represented by a series of instrumental observations of the average monthly temperature and precipitation of the CRU TS 4.01 gridded archive (Harris et al., 2014) from the grid point (64.75 N., 35.75 E), the closest grid point to the study region.

3. Results

3.1. *TRW and BI chronologies*

The resulting 14 chronologies include 8 pine and 6 spruce chronologies (TRW and dBI chronologies for 4 and 3 sites, respectively). Pine chronologies reach the length of 177–474 years. Spruce trees on the studied sites reach the age of 179–378 years (Table 1). Inter-parameter comparison of years with EPS higher than the threshold of 0.85 revealed differences between TRW and dBI chronologies. Thus, in most cases (6 cases out of 7) the length of the reliable part of dBI chronologies is bigger than in TRW chronologies, revealing higher average inter-series correlation of dBI measurements. Besides this, in the case of dBI cronologies, a smaller number of samples is needed to achieve EPS > 0.85. In some cases, sample depth needed for a reliable chronology development differs almost twice (chronology B42S, 11 and 6 samples were demanded for TRW and dBI, respectively). Standard deviation, which is the measure of the variance, is higher in the TRW chronologies (0.21–0.31) than in dBI (0.124–0.157). High first-order autocorrelation is a well-known phenomenon observed in the TRW time-series (Briffa and Jones, 1990) and is usually interpreted as an influence of the climate conditions of the previous year on the current year growth. This effect is strongly displayed in the TRW chronologies achieving values of 0.74 – 0.82 and 0.56 – 0.71 in pine and spruce chronologies, respectively (Table 1). Compared to TRW, dBI-based chronologies reveal a much lower dependence on the previous year’s climate conditions, achieving the values of first-order autocorrelation 0.12–0.56 and 0.37–0.58 for pine and spruce, respectively.

Some patterns can be determined in the cross-correlation matrix, showing correlation coefficients of all the 14 chronologies (Fig. 2). For example, the distinctly traced area of the matrix is responsible for spruce chronologies and is colored with bright red indicating high values of correlation. dBI-based chronologies are higher correlated ($r = 0.53$, 0.59, 0.67) than the TRW-based chronologies ($r = 0.27$, 0.4, 0.49). Concerning the inter-parameter correlation of the spruce chronologies, the r values are highly variable: from − 0.11–0.63. The spruce chronology Pdel_TRW has the weakest correlation with the other two TRW-based spruce chronologies (0.027, 0.4) but attains a value of 0.44 when correlated with the dBI-based chronology for the same site.

In the case of the pine chronologies, the heatmap representing the cross-correlation strength is more faded compared to spruce. dBI-based pine chronologies are highly cross-correlated ($r = 0.34$ 0.71), while TRW-based chronologies show less correspondence ($r = 0.22$–0.63). The lowest values ($r = 0.02$ – 0.06) are observed when comparing dBI with TRW in 4 cases but some chronologies are still significantly cross-correlated ($r = 0.15$ – 0.54). BelBog_TRW chronology is the only one that significantly correlates with all the other pine chronologies.

Inter-species comparison of cross-correlation between the dBI and TRW chronologies is shown on the bottom left side of the graph. There are vertical bars with blue colored values identifying negative correlations on the graph. This reveals that TRW-based pine chronologies poorly correspond with spruce in most cases, with the exception when pine and spruce were obtained from the same site (B75 and when comparing BelBog_TRW with Pdel chronologies). Low inter-species correlation is also obtained when comparing composite TRW conifer chronologies (Fig. 3, Fig. S3). At the same time, all dBI-based chronologies have statistically significant cross-correlations with no regard to tree species and coefficients of correlation vary from 0.17 to 0.66. (Fig. 3, Fig. S4).

3.2. Response to climate

To assess which climate parameter is responsible for the variation of a certain tree-ring parameter, a response climate analysis was applied using the TreeClim package (Zang, Biondi, 2015). Results of the response climate analysis are presented in Figs. 4 and 5. Considering TRW chronologies, pine and spruce generally showed a weak response to temperature variation. Temperature signals inferred from TRW of spruce and pine differ – there are no months with coinciding significant coefficients of regression on the graph. In the case of pine, the highest absolute values of the regression coefficients (negative) were found for the previous August for the two out of four chronologies (B36S and B75S). Also, BelBog pine chronology positively correlates with

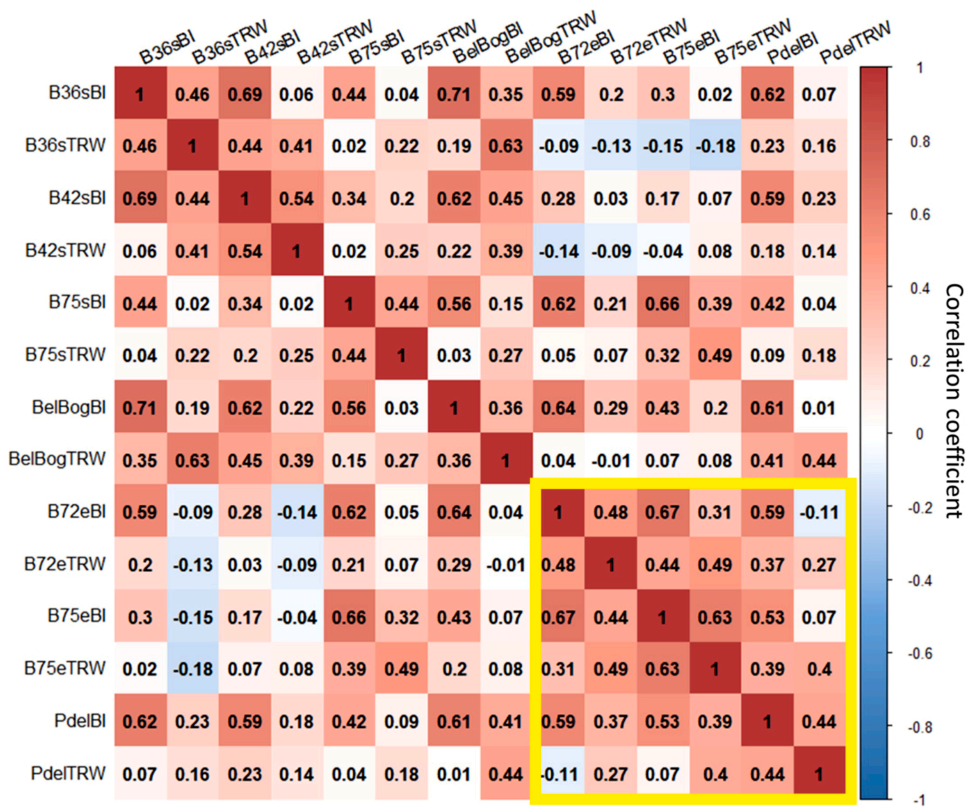

Fig. 2. Pearson’s cross-correlation coefficients between 14 tree-ring time-series where each of 7 local chronologies based on TRW and dBI parameters. Correlation coefficients were computed over the common 1840–2007 period and values higher than 0.14 refer to statistically significant coefficients ($p < 0.05$). The yellow square indicates the part of the matrix where spruce analysis occurs.

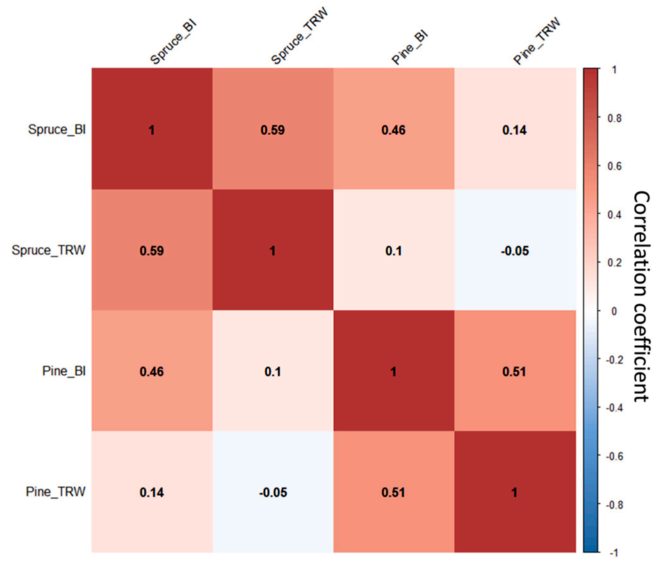

Fig. 3. Pearson's cross-correlation coefficients between 4 conifer chronologies based on TRW and dBI parameters. Correlation coefficients were computed over the common 1630–2016 period and values higher than 0.14 refer to statistically significant coefficients ($p < 0.05$).

temperature variations in January, while the remaining regression coefficients are not statistically significant. In the case of the TRW spruce chronologies, it is found that growth of spruce depends on June temperatures and this signal is presented in the two chronologies out of three. June is the month where the highest correlation is observed. Also, current year February temperatures negatively influence spruce growth (two chronologies out of three).

An examination of the dBI series response to temperatures has detected a lot more months with significant regression coefficients, compared to TRW (Figs. 4 and 5). As seen from the graph, significant coefficients are grouped around summer months in both conifers. Summer temperature signals contained in all the examined spruce dBI chronologies are very consistent during the whole period from June to August. Besides summer months, all the three spruce chronologies showed a positive relation to current year January temperatures and two out of three chronologies showed a negative relation to the previous year September temperatures. Looking at the temperature signal in the dBI pine chronologies, it can be noted that only July is the month in which all the four chronologies have a significant response while in August and May only two and three of them have a significant response, respectively. Chronology B75S is the only examined pine chronology with a wide target window lasting from April to August. Chronology BelBog, on the contrary, is the only one among all pine dBI chronologies, in which the response in summer is observed in one single month – July. Speaking about the year previous to growth period, there are two negative correlations observed on the graph: with August and November.

Precipitation was another climatic parameter used for response analysis (Figs. 4 and 5). TRW pine chronologies showed more significant correlations with precipitation, compared to temperature. Distribution of the response values on the graph behaves disorderly without any grouping. Higher amounts of precipitation the previous summer govern wider TRW in pine (previous July- B42S, previous August – BelBog). Increased winter precipitation also positively influences the tree-ring growth of pine (previous December-B36S, current February – B36S and B75S). Variations of precipitation in current April and May play opposite roles – negative and positive, respectively. Also, increased summer precipitation in July led to increased growth in the only chronology – B75S, and increased precipitation in September positively

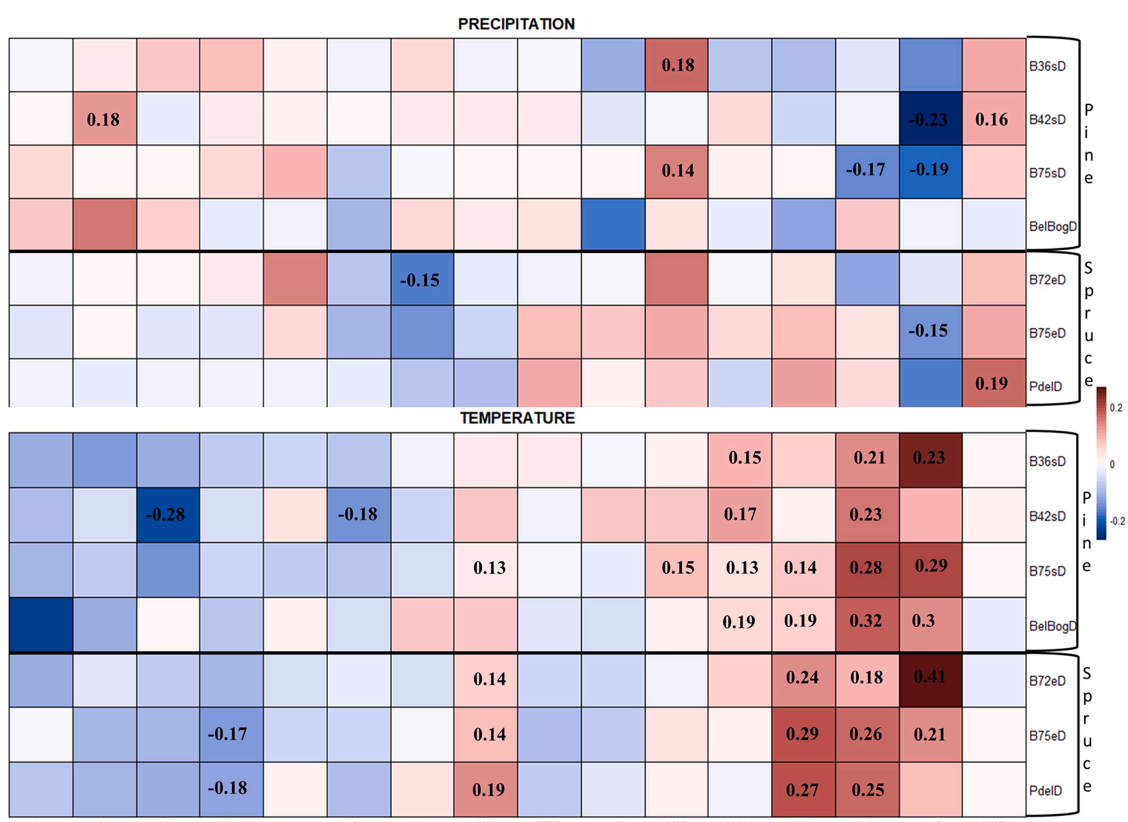

Fig. 4. Heatmap of the regression coefficients representing response climate analysis results between dBI pine and spruce chronologies and precipitation (upper part) and monthly mean temperatures (lower part). Number refer to statistically significant values ($p < 0.05$).

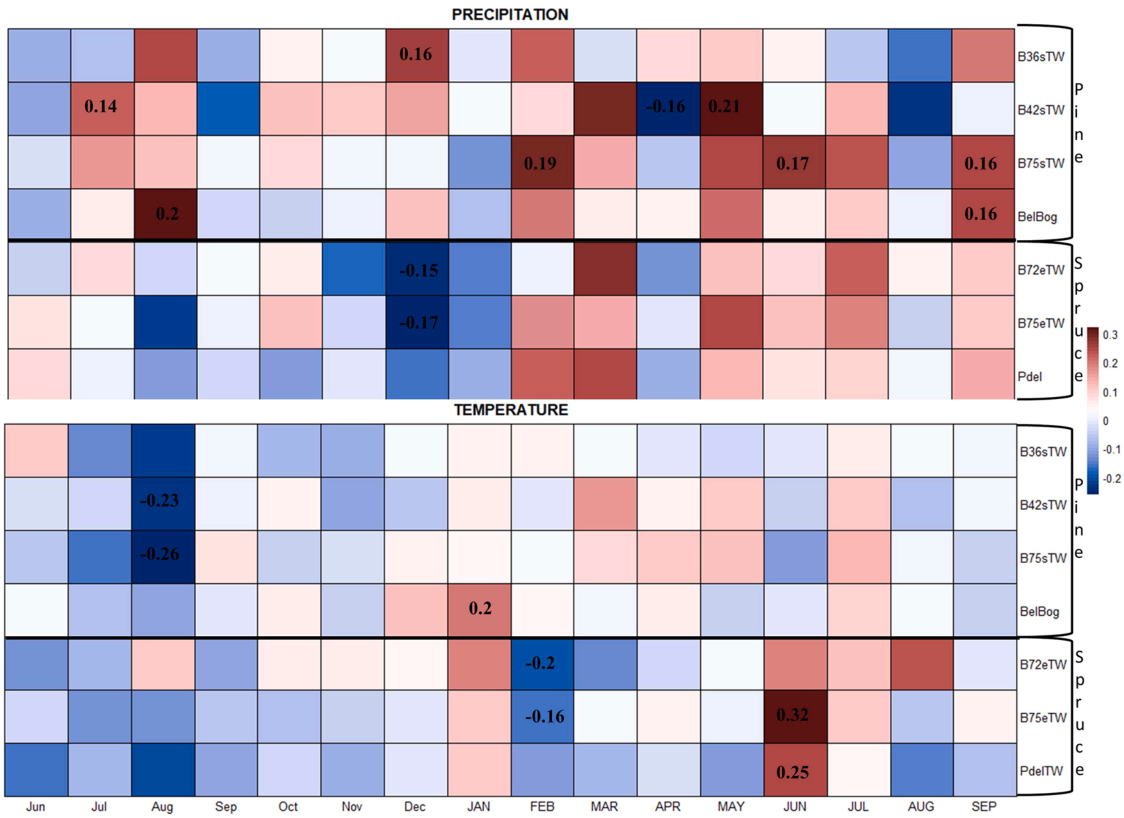

Fig. 5. Heatmap of the regression coefficients representing response climate analysis results between TRW pine and spruce chronologies and precipitation (upper part) and monthly mean temperatures (lower part). Number refer to statistically significant values ($p < 0.05$).

influenced TRW at B75E and BelBog sites. Compared to TRW pine chronologies, TRW spruce chronologies have much fewer months with significant response coefficients (Fig. 5). The increased amount of precipitation in previous December is leading to decreased growth of spruce of the two chronologies out of three (B72E and B75E).

In the case of the response of pine dBI chronologies to precipitation variations, the number of months with significant values of regression coefficients is lower than for the TRW chronologies. The previous year does not play an important role in dBI variation – higher amounts of precipitation in previous the July led to higher dBI only in the chronology B42S. During the year of growth, more months with significant regression coefficients were found, e.g. increased precipitation in July and August negatively influencing the dBI of pine (B75S – July, B42S and B75S in August). Spruce showed a fragmented relationship with precipitation, e.g., negative in previous December (B72E), positive in current February (Pdel), negative in current August (B75E) and positive in September (Pdel).

Besides the moving correlation, another way to identify climate signal strength is to apply such statistics as squared regression coefficient, R2; root mean squared error, RE and CE and which are highly recommended for using by the National Research Council (North et al., 2007). Detailed mathematic formulas of RE and CE are given, for instance, in the paper (Cook et al., 1994). RE, CE and R2 are equal during the calibration period, while over the verification period, both CE and RE can differ because CE is calculated based on verification period instrumental records mean, whereas RE continues to use the calibration period mean for this calculation. Thus, by construction, CE is incapable of recognizing the ability of a reconstruction to successfully detect changes in mean state between the calibration and verification periods (Wahl and Ammann, 2007), so RE is a suitable statistic to detect whether or not tree-ring series represent low-frequencies in climate records. Positive values of RE and CE indicate some predictive skills of the applied model.

All statistics were computed for each local chronology and the final results presented in the Table S1. All 4 pine dBI chronologies showed positive significant correlation to temperature variation in May, while no one from these chronologies showed positive CE and RE values at the same time. In contrast to pine, spruce dBI chronologies didn't respond to May air temperatures. All dBI chronologies generally are characterized by close-to-zero or even negative values of RE and CE. Notably, that dBI B75SD chronology has the highest values of correlation with summer temperatures during each divided period ($r = 0.70$ and 0.72), as well as during the whole period ($r = 0.62$) and the same time RE and CE statistics are extremely low. This pattern (combination of high correlation with low RE and CE statistics) also could be seen in the spruce dBI chronology from the same site (B75ED). All statistics become higher when pine and spruce local chronologies are combined into mean chronologies. The highest values of statistics were found when all series were used to develop conifer chronology. In this case the target window is wider covering the period from April to August. Notably, in cases when mean April to August air temperatures are used as the target, the highest correlations ($r = 0.77$ and 0.72, 0.67 for each split and whole periods respectively) are observed with positive RE (0.22) and even negative close-to-zero CE. When April and May were excluded from the target window, correlations became lower ($r = 0.53$, 0.69 and 0.65 for each split and whole periods respectively) but RE and CE much higher (0.30 and 0.19, respectively).

4. Discussion

4.1. Tree-ring widths

According to the response function analysis results shown in Figs. 4 and 5, the temperature signal in TRW of pine and spruce differs greatly, i.e., there is no single month with the same signal in conifers. However, in some cases a signal could be considered as a statistical tendency, e.g., July is the month when a positive temperature signal is observed in the three chronologies of pine and two chronologies of spruce. This finding could explain the cross-correlation between some but not all of the pine and spruce chronologies (Fig. 2): both species share the same signal observed in July (not statistically significant). Agreement becomes even higher when comparing spruce and pine TRW chronologies from the same site (site B75, r = 0.49, Fig. S5). Multidecadal variability of both conifers agrees less before the 1900 s, and behaves very similarly after.

So generally, we conclude that spruce widths from Solovki are more sensitive to summer temperatures than pine. This finding (sensitivity of spruce to June temperatures) is in general agreement with the other available knowledge about conifer tree-ring responses to climate. For example, Düthorn et al. (2015) have reported that spruce growth is mainly dependent on temperatures in June (r = 0.49) while pine insignificantly correlates with temperatures in July (r = 0.30). The results of this research are in absolute agreement with our study, although the distance between the two studied sites exceeds 800 km. The authors pointed out that their study area is situated 8 km southwest of the well-known sites where temperature sensitive pines were growing (r = 0.50) (McCarroll et al., 2003). At the same time, Kononov et al. (2009) developed regional summer temperature reconstruction based on strong correlation of pine growth with July-August temperatures (r = 0.58). This site is located in Khibiny Low Mountains (Kola Peninsula) and even closer to Solovki, just about 500 km. Such high climatic sensitivity of pines from Kola Peninsula could be explained by the location of the sites at the altitudinal timberline.

Recently published research of Rocha et al. (2021) showed that Norway spruce growing in the Swedish part of the Central Scandinavian Mountains is highly sensitive to June-July air temperatures (r = 0.6). Roche's spruce sites are located more than 1200 km West of Solovki. The authors also discussed the reasons for different target windows observed in the climate signals of two conifers. This discrepancy is explained by the variations in snow accumulation under the trees (Vaganov et al., 1999; Rocha et al., 2021).

Our analysis showed that pine TRW chronology (B75S) in Solovki has a response to precipitation in July. This finding is in agreement with recent research by Semenyak et al. (2022), in press, in Russian). The main focus of the research was to investigate the response of the four parameters measured in pine samples such as total tree-ring width, latewood width (LW), earlywood width (EW) and delta Blue Intensity to mean temperatures and sums of precipitation using the SeasCorr function (Meko et al., 2011). A significant effect of July precipitation on the LW is observed when precipitation is used both as a primary and as a secondary factor. It is noteworthy that if temperature is assigned to the primary variable and precipitation is assigned to the seconddary variable, the July precipitation signal becomes stronger.

4.2. delta Blue Intensity

Compared to TRW, dBI-based conifer chronologies show a remarkably high relationship with summer temperatures. These results correspond with the results of dendroclimatic studies made in Fennoscandia (e.g. Briffa et al., 1990; McCarroll et al., 2003). Although signal strength computed over the 116-year period is high enough, still some heterogeneous behaviors were found when the response function was computed in the moving window (Fig. S6-9). Thus, it is shown that a statistically significant signal disappeared during the period of calibration in particular months. Among pine chronologies, B42S has a very pronounced weakening character of the signal. In the remaining chronologies, July and August are the months when the signal is particularly stable over time. The same phenomenon of an unstable signal was observed in the summer temperature response function inferred from maximum density (MXD) of pine growing in Fennoscandia (Tuovinen et al., 2009). Authors reported that the model of the reconstruction will be more statistically reliable when using a large target window rather than single months with a stable and strong signal. In Solovki, the signal inferred from dBI chronologies of spruce behaves more consistently and covers three summer months only. In contrast to dBI-based pine chronologies, TRW spruce chronologies show an extremely strong consistency of the response to June temperatures which is especially noticeable in B75E chronology.

The advantage of using the Blue Intensity instead of Ring-Width resulted from its unprecedented strong and spatially stable correlation with summer temperatures. This finding has already been reported in many geographical locations and the dBI-based reconstructions were published in high-ranked journals. The main question concerning dBI is its possible limitations to represent mid-to-low frequencies of the instrumental records (Rydval et al., 2014; Wilson et al., 2014). To answer this question, both dBI-based conifer chronologies from Solovki and climate records were filtered using 5 and 32-year cubic splines (Fig. S10-12). Coefficients of regression between filtered data of pine were r = 0.2, 021 (JJ) at 5-year domain and not found at all in 32-year filtering. Spruce also showed decreased values at 5-year filtering (r = 0.23) and the signal had moved from June to August at 32-year filtering (r = 0.18). Most likely, the ability of dBI to catch the signal in mid-to-low frequency domains of the climate records could be approved after applying an "adjusting" procedure as was performed in the study of Björklund et al., (2013), (2014), (2015), Fuentes et al. (2018). Since there are no maximum density measurements available for the Solovki Islands, we are unable to check this statement for the moment.

5. Conclusions

We have presented 14 newly developed chronologies including 8 pine and 6 spruce chronologies. The longest lifetime of pine and spruce is 474 and 378 years, respectively. Total tree-ring width and delta Blue Intensity were measured at each site and compared between each other and analyzed in terms of response to climate. Compared to TRW, dBI chronologies are more attractive because in most cases the length of the reliable part is longer than in TRW and a smaller number of samples is needed to achieve EPS > 0.85. Spruce and pine dBI-based chronologies correlate among each other at high levels (r = up to 0.67), whereas TRW-based chronologies are less coherent (r = 0.27–0.49). TRW of pine and spruce is controlled by different climatic factors: pine growth mostly depends on the temperatures of previous August, while spruce growth rather depends on temperatures of the current June. There is not a single month in which a statistically significant signal was observed for both conifers. Compared to TRW, dBI-based conifer chronologies show a remarkably high correlation with summer temperatures (r = 0.64 and 0.66 for spruce and pine, respectively). However, the strongest temporal stability of the signal is found in TRW spruce chronologies (during June), while the signal inferred from the temperature sensitive dBI of both conifers behaves inconsistently. Our results are in agreement with the context of the Fennoscandia area. The strength of pine growth response to climate depends on micro-site conditions and can achieve high values in harsh conditions. On the other hand, spruce growth represents a spatially stable response to June (or June-July). Depending on the goals of the research, there are several parameters that could be potentially used for dendroclimatic studies. Early summer temperatures could be reconstructed based on tree-ring width of spruce because of stable temporal and spatial signals. Tree-ring width of pine growing in Solovki is not suitable for climate reconstructions, since the signal is weak and depends mainly on micro-site conditions. Despite some heterogeneity found in dBI-based signals, which potentially could be solved by applying a wide target window, this parameter is the most suitable for the summer temperature reconstruction in the Solovki Islands.

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

The authors do not have permission to share data.

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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.2022.126029.

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