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GEOGRAPHY

The Vologda and Solovki Dendrochronological "Chronicles" as a Source of Information about the Climate Conditions of the Last Millennium

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Dendrochronological data are an important source of information about climate conditions in the past and an indispensable instrument for dating of archaeological and historical sites. They are used for the reconstruction of annual changes in temperature and humidity over the last few millennia, for the dating of moraines, avalanches and landslides, volcanic eruptions, historical, cultural, and archaeological sites.

A significant constraint on the possible application of the dendrochronological method in the East European Plain is the short life of trees. Chronologies with a duration of a few centuries can only be developed in this region using archaeological and building wood. These studies were initiated in 1960s in Novgorod [4] and have been continued in archeological studies up to the present [3, 6, 7]. However, a feature of these chronologies is that they are usually not connected with modern chronologies, constructed on the basis of living trees and dated with an accuracy of one year. Moreover, when dating the archaeological sites, questions are usually not raised about what climatic factors cause ring width variations. In this work we present two conifer chronologies, developed for Vologda Region ("Vologda") and Solovki Islands ("Solovki") over the period from the eleventh and twelfth centuries, respectively, to the twenty-first century. The advantage of these chronologies is in the absolute age dating of each annual tree-ring and the further use of these chronologies for dating of historical, archaeological, and natural sites of different origin, as well as potential high-resolution paleoclimate reconstructions.

The samples for this work were taken in living trees (two cores from each tree) with an increment Pressler borer at a height of 1–1.5 m above the ground. To extend the chronologies, the cores and disks were taken also from the walls, floor boards, ceiling beams, and other wooden constructions of historical buildings. The further processing of the samples was carried out at the Dendrochronological Laboratory of the Institute of Geography, Russian Academy of Sciences, in accordance with generally accepted methodological requirements for the tree-ring analysis [8]. The tree-ring width was measured by a semiautomatic LINTAB device with an accuracy of up to 0.01 mm. For the quality control of measurements and the search for outliers and false rings, the COFECHA program was used [13]. In addition, we used the data of the archaeological wood samples from the Vologda region, provided by A.A. Karpukhin, IA RAS.

Samples with known sampling data were dated for each sampling area; the wood samples from different sites were combined into unified chronologies separately for pines and firs. After that, they were grouped into the regional chronology of coniferous trees for each region. At first the cores taken from buildings were dated relatively to the conventional year. After that, they were connected by cross-dating to the chronology, developed on the basis of the data from living trees. At each stage all dates were controlled by the COFECHA program. For additional control of dating of the "Vologda" samples, the continuous millennial ring width chronology from Finland from the International Tree-Ring Data Bank ITRDB NOAA (www.cdc.noaa.gov) was used. As a result, we have developed regional absolutely dated chronologies for the Vologda (1085–2009) and Solovki (1186–2008) regions. The pointer years (that is, the years of positive and negative anomalies in the chronology of the majority of trees) were determined by using the program for pointer year identification (www.paleoglaciology.org). Those years were considered as pointer years, when more than 20% of trees had a growth with a standard deviation of more (or less) than 1.64 (which corresponds to 10% sampling for a normally distributed data set). The measurement series were smoothed with a 13-year moving average [15].

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Since, the tree-ring width, along with the climate conditions, depends on many other factors (in particular, on the age of trees), it is accepted in dendrochronology to use not the absolute values of the growth rate, but their relative values (tree-ring width indexes). In this work, we used two standardization methods, developed with the ARSTAN program by dividing the ring width for each year to a value of an approximating function for this year and the regional curve standardization (RCS) [11].

In order to answer the question of how the variability in the tree ring width is distributed in space, we have constructed maps of growth rate isocorrelates, taking into account, along with the two chronologies discussed in this work, all the chronologies for the Northern European part of Russia, presented in the International Tree-Ring Data Bank ITRDB NOAA (www.cdc.noaa.gov) chronologies.

In order to identify a climatic signal, determining the growth rate of trees of different species in different regions, correlation analysis between the standard chronologies and meteorological parameters measured at the nearest weather stations was conducted. According to the daily meteorological data obtained at these meteostations, the monthly values of minimum, maximum, and average temperatures, precipitation data, and agroclimatic characteristics were calculated: annual sums of temperatures more than 0°C ($T > 0$), 5°C ($T > 5$), 10°C ($T > 10$) and 15°C ($T > 15$), the amount of precipitation for the period with a negative temperature $P(T < 0)$ and for the periods with the sum of temperatures of more than 0°C ($P(T > 0)$), 5°C ($P(T > 5)$), 10°C ($P(T > 10)$) и 15°C ($P(T > 15)$).

The "Solovki" regional chronology includes several local chronologies of Scots pine and Finnish spruce that are based on wood samples from living trees and historical buildings of the Solovki archipelago.

The "Vologda" samples are presented by pine trees, sampled in the fir–birch–pine forest in the shrub–sphagnum bogs of the Kovardinskoe forestry, the construction wood from nineteenth century buildings, located in the museum of wooden architecture of the village of Semenkovo (the Vologda region) and other buildings, as well as in the archaeological wood. The datings of the samples from pine and fir species, sampled from living trees on the Solovki Islands, are confidently correlated with each other. This makes it possible to combine them into the conifer chronology developed for the Solovki region and to use the samples of old wood constructions for the extension of the chronology duration assuming confirmation of the correctness of the age dating with the COFECHA program. The conifer chronology development for the Vologda region ("Vologda") is based on the same principle. We used the suitability criterion (Express Population Signal value; EPS) of chronologies for the climate reconstruction in dendrochronological studies, which exceeds 0.85. The "Vologda" chronology meet this criterion from 1221; the "Solovki" chronology, from 1393 (Fig. 1).

The "Vologda" chronology is weakly correlated with the "Solovki" chronology (the correlation coefficient over the common period is only about $R = 0.16$).

In these chronologies only 13 out of 32 segments cross-date (50-year segments with an overlap of 25 years). Moreover, the average correlation value for these segments is also quite low ($R = 0.46$).

In the "Solovki" and "Vologda" chronologies, only six minimum (1466, 1482, 1581, 1582, 1836, 1963) and seven maxima (1577, 1578, 1704, 1738, 1841, 1938, 1954) pointer years occur synchronously. Taking into account the fact that in the "Solovki" chronology the 36 minimum and 34 maximum pointer years and in the "Vologda" chronology, 32 and 54 pointer years, correspondingly, were noted, then the percentage of coincidence is less than 20%. We have compared our chronologies with the "Finland" one (the combined chronology of finl00l and finl034 from the ITRDB). As a result, it was found that the "Finland" chronology has more coincidences (nine maxima in 1240, 1337, 1344, 1535, 1537, 1923, 1924, 1954, 1974 and four minima in 1408, 1605, 1806, 1906) than the "Vologda" chronology and less (six maxima in 1417, 1536, 1648, 1826, 1885, 1954 and two minima in 1696 and 1770) than the "Solovki" chronology. These results bring evidence about the greater similarity between the "Finland" and "Vologda" chronologies with respect to their climatic signal.

The only case of coincidence of all three chronologies is a positive anomaly in 1954. It is interesting that in 1954 the actual value of the growth rate in our chronologies was not outstanding and did not reach the double standard deviation value.

Figure 2 presents the correlation maps between the "Vologda" and "Solovki" tree-ring chronologies and other chronologies of living conifer in this region over the total period of 1901–1990. In particular, they show that the "Solovki" chronology is better correlated with the northern chronologies, whereas the zone of positive correlations of the "Vologda" chronology is located to the south and very rarely intersects with that of the "Solovki" chronology. The analysis of the correlation between the chronologies and meteorological parameters has shown that the "Vologda" tree-ring chronology, presented by pine samples for the interval of instrumental-meteorological observations is sensitive to the sum of temperatures of more 15°C from the 1910s. During the period of 1880–1930, a negative correlation with the same parameter was recorded (Fig. 3a). In addition, during the period of 1910–1990, a negative correlation with the amount of precipitation was recorded, especially in the winter season. This can be explained by the fact that within the region studied pines grow in a swamp area. The combined Solovki pine and fir chronology correlates with the sum of temperatures of more 10°C and 15°C. However, a negative correlation with an amount of

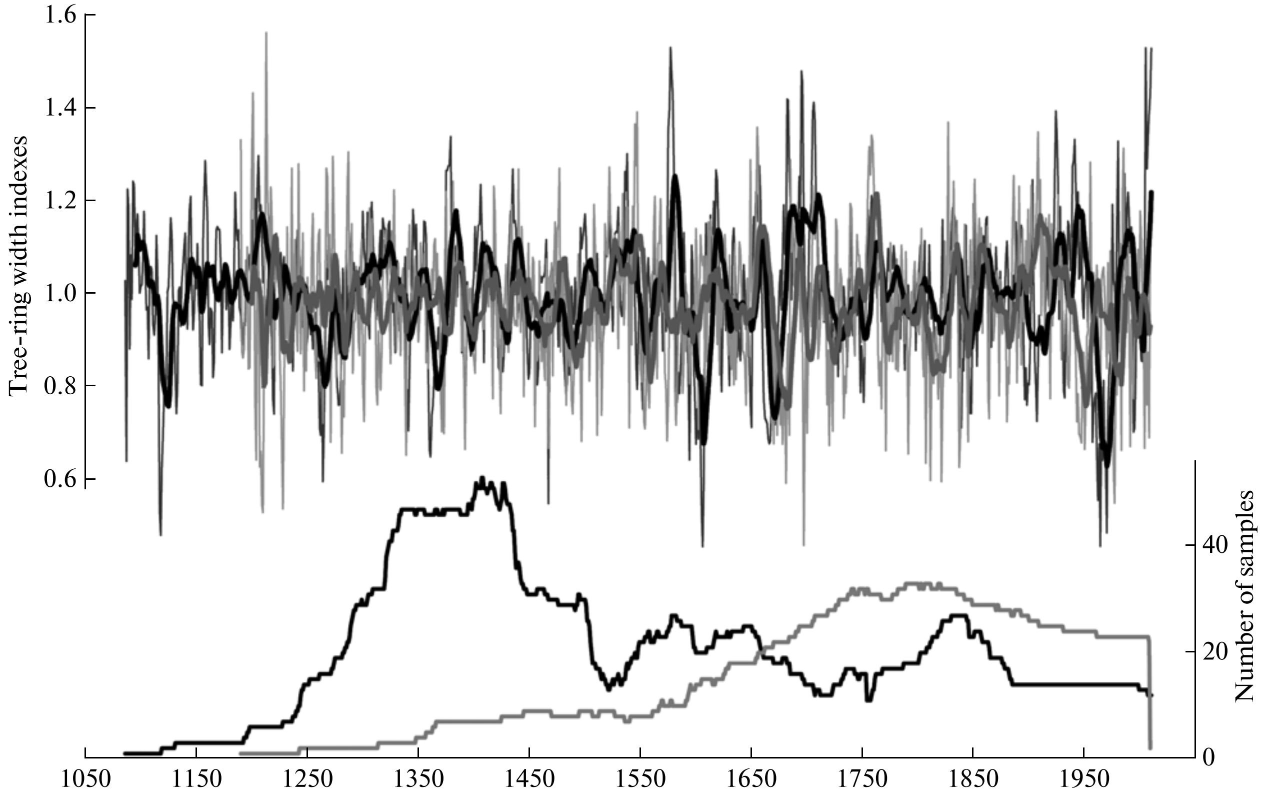

Fig. 1. Chronology of a conifer tree-ring width of "Solovki" (gray) and "Vologda" (black). Thick lines are chronologies, smoothed with a 10-year moving average. The sample depth in the chronologies are shown below.

precipitation was not noted. Conversely, there are periods in which the correlation is positive (Fig. 3b). Thus, the tree-ring width in both chronologies depends largely on the heat supply during the growing season, which can explain the similarity between them. However, this factor affects the growth rate of trees to a varying degree in different geographical locations. Together with this factor, the influence of other factors is also essential. Moreover, their contribution may also vary depending on the season.

For comparison with our data, we chose 76 extreme climatic events in the north of European Russia from 1203 to 1909, recorded in historical documents [1]: cold winters, droughts, and crop failures due to climate change. For the 78 negative years (for all three chronologies, Solovki, Vologda, and Finland, there are 26 coincidences, according to the chronicles (that is, a third); for the 96 positive pointer years, 24 coincidences (that is, a quarter). The fact that only some evidence coincides with the dendrochronological anomalies is explainable. This is due to the peculiarities of the paleoclimate sources compared: historical records are fragmentary and often they indicate local events, whereas the dendrochronological records fix the complex signal. According to this the cause of the negative anomalies in the growth rate can be a different set of climate parameters. For example, in 1969, an anomalous low growth rate in the "Vologda" chronology was caused by low temperatures in the winter and early summer and a summer drought. The temperature in 1993 was close to the average value. However, the year was an extremaly wet in March and June–August. The decadal variability in the "Solovki" and "Vologda" chronologies is characterized by a greater synchronicity than the interannual one. As seen in Fig. 1, the variations in the two chronologies during some periods, smoothed with a 11-year moving average, are almost synchronous (the period of the fourteenth century to the mid sixteenth century, as an example). Sometimes the peaks are shifted by a few years relative to each other (a deep minimum in the 1660s in the "Vologda" chronology and in the 1670s for the "Solovki" chronology). A systematic delay or an advance of the peaks in one chronology relative to another is not observed. In fact, this weak correlation of the chronologies was preserved until the end of the nineteenth century. In the period of 1890s—1950s, the interdecadal curves tends to be antiphase. The amplitude of the growth rate index variations in both chronologies varies with time. As an example, in the second half of the fifteenth century it is higher in the "Solovki" chronology; in the second half of the sixteenth century, by contrast, in the "Vologda" chronology.

The most promising method to preserve the long-term variability in the chronologies is the regional curve standardization (RCS). In Fig. 4, the two northern

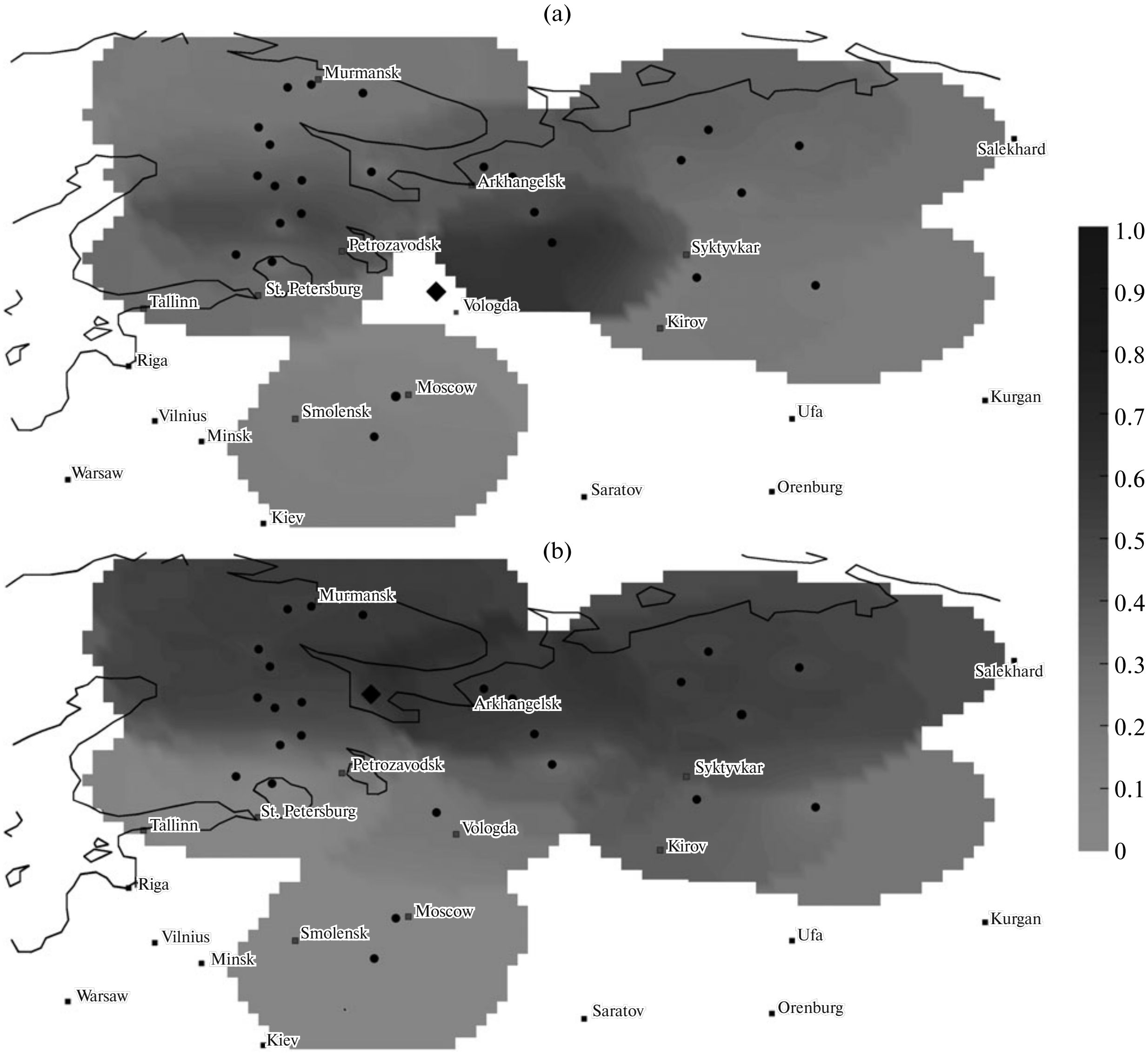

Fig. 2. Spatial correlations between “Vologda” (a) and “Solovki” (b) chronologies and other tree-ring chronologies of this region. The correlation coefficient is on the right.

chronologies developed using this method and smoothed with a 11-year moving average are shown. It is evident that both chronologies during the last 1.5–2 centuries have a positive trend, which is clearly manifested in the *Vologda* chronology since the mid-nineteenth century. In the “Solovki” chronology it began two decades earlier. In the beginning of the twenty-first century, both chronologies have the largest rings. For the “Vologda” chronology, this was the absolute maximum for the last eight centuries. In the “Solovki” chronology, similar growth rates have been noted three times: at the end of the nineteenth century and in the beginning of the seventeenth and fourteenth centuries. The minimum growth rates in the “Vologda” chronology were in the “Time of Troubles” (about 1600s); in the “Solovki” chronology, a century earlier.

In our work, we compared two long northern tree-ring chronologies developed with high-resolution climatic reconstructions, based on palynological and historical data [14] (Fig. 4). In spite of the fact that these paleoclimate sources of information are essentially different, statistically significant correlation coefficients and the general similarity of curves of the “Vologda” chronology with the summer temperature values and the Solovki chronology with the annual average and winter temperature values are noted.

Table 1 shows the distribution of positive and negative growth anomalies in both chronologies over centuries. The largest number of positive anomalies are characteristic for the sixteenth (11) and the eighteenth (6)

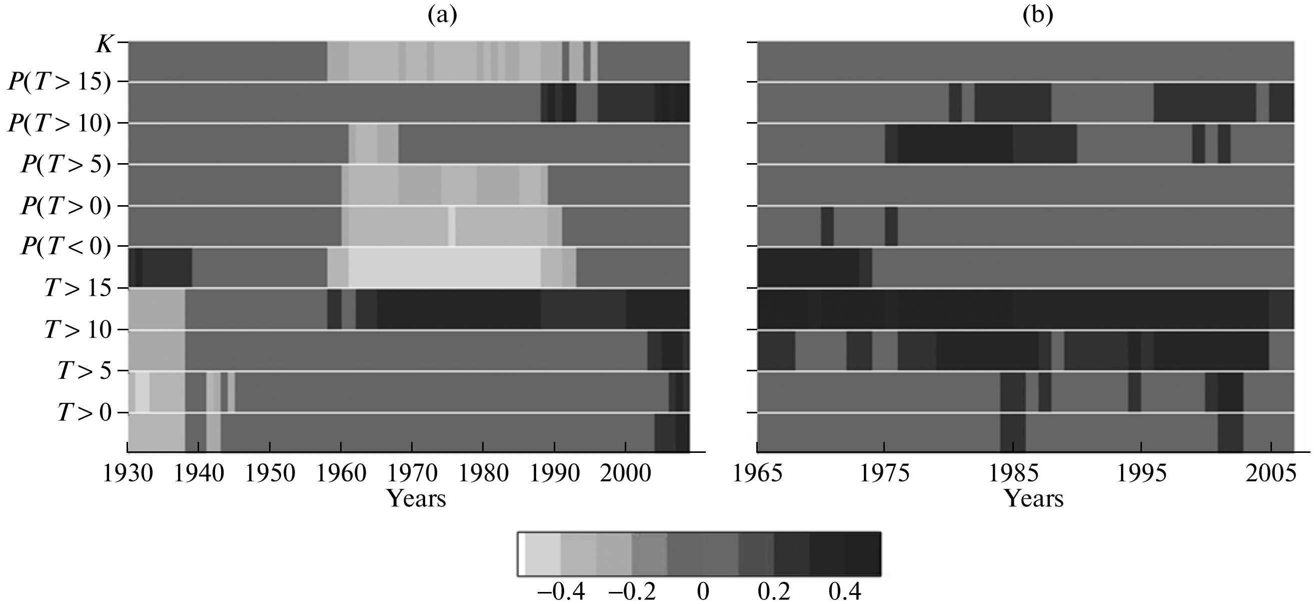

Fig. 3. Correlations between chronologies and meteorological parameters with a sliding window with a width of 50 years. On the horizontal axis, the year corresponds to the last year in the window. (a) The "Vologda" chronology and agroclimatic characteristics, obtained at the Vytegra meteostation. (b) The "Solovki" chronology and agroclimatic characteristics obtained at the Kem' meteostation.

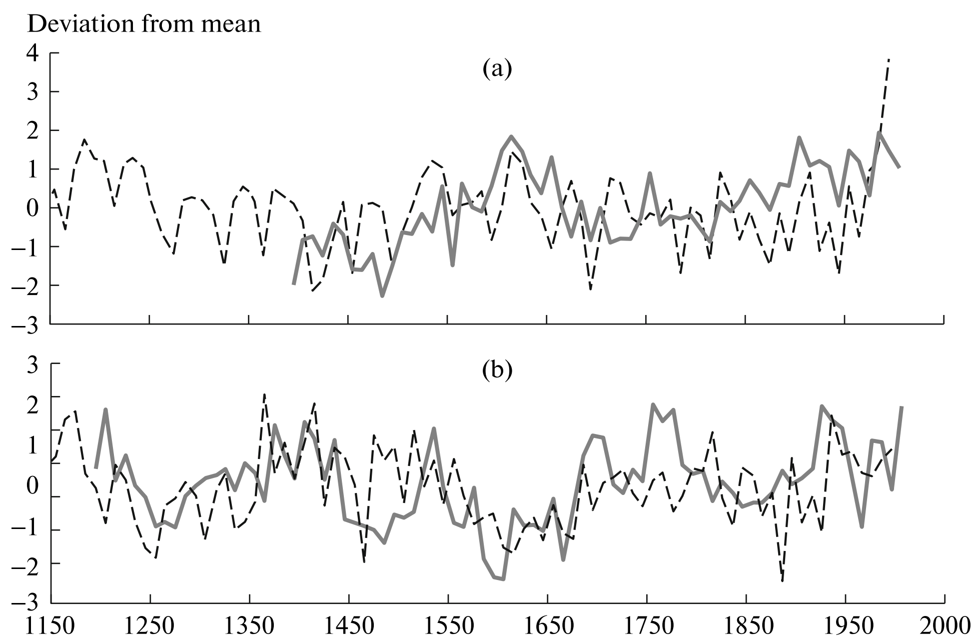

Fig. 4. (a) The RSC chronology of *Solovki* (gray line) and a reconstruction of winter temperatures ($R = 0.34$), based on palynological and historical data [14](dashed line); (b) the RSC chronology of *Vologda* (gray line) and a reconstruction of summer temperatures ($R = 0.31$), based on the same source [14] (dashed line). All curves were smoothed with a 10-year moving average.

centuries; the negative ones for the seventeenth and twentieth centuries (10 in both cases).

The conditions in the fourteenth century were the most contrasting, when only three positive and negative anomalies are recorded in both chronologies. Similar conditions were in the sixteenth, seventeenth, and twentieth centuries (13, 15, and 15 anomalies, respectively).

If we consider the twentieth century together with the first decade of the twenty-first century, then the number of anomalies (21) in this period is highest for all seven centuries. Wavelet analysis and Fourier anal-

The number of years per centuries with the ring exceeding two standard deviations

Century	"Vologda" (+)	"Solovki" (+)	"Vologda" (–)	"Solovki" (–)
XIV	1	1	0	2
XV	0	2	1	5
XVI	5	6	2	0
XVII	4	1	8	2
XVIII	3	3	0	2
XIX	0	1	0	4
XX	3	2	8	2
2000–2009 yr.	5	0	0	1

ysis carried out showed that the high-frequency periodicity in the "Solovki" and "Vologda" tree-ring chronologies are weakly expressed. In these chronologies as well as the "Finland" chronology, periodicity of 17–18 and 34–37 years are distinguished. The curves of the "Solovki" and "Finland" chronologies also show a variations with a duration of 43–44 years and 114 years. In turn, the "Solovki" and "Vologda" chronologies are characterized by a cyclicity of 79 years (89 years in the "Finland" chronology). The cycles of the higher order are different for the chronologies considered (431 years in the "Solovki" chronology, 124, 205, and 512 years in the "Vologda" chronology, 171 and 410 years in the "Finland" chronology). Cycles with a duration of 15–17, 25–40, and about 100 years, recorded in the long tree-ring chronologies (Solovki, Vologda, Finland) we also identified in shorter but more temperature-dependent chronologies of maximum densities in the north of the Russian Plain [5].

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