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Changes in the Dendroclimatic Response of the *Picea Jezoensis* (Siebold & Zucc.) Carriere along Altitudinal Gradient in the Southern Sikhote-Alin

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Abstract—We have studied the influence of precipitation and surface air temperature on the radial growth of Yezo spruce *Picea jezoensis* (Siebold & Zucc.) Carriere, as well as changes in this influence with increasing altitude in southern Sikhote-Alin. For the purpose of the study, 444 cores were taken from eight sites located within the small river basin at altitudes from 460 to 1060 m a.s.l. As a result of the study, for the first time for the south of the Russian Far East, eight tree-ring chronologies were created based on Yezo spruce tree rings measurements with a duration of 171 to 267 years. An analysis of the correlation between the chronologies and climate data shows that the radial growth of the Yezo spruce within the southern Sikhote-Alin is influenced by precipitation in July–August of the current year ($r = -0.33$ to -0.60), the average maximum temperature in July–August of the previous year ($r = -0.25$ to -0.47), and the maximum temperature in November of the previous year ($r = -0.34$ to -0.54). It is shown that the values of the correlation coefficient of chronologies with maximum temperatures quickly decrease with increasing altitude above sea level. At the same time, there is no significant change in the value of the correlation coefficient of chronologies with precipitation with an increase in altitude above sea level. The results show the complexity of the relationship between the radial growth of Yezu spruce and climate data and suggest that climate warming in southern Sikhote-Alin will have the greatest negative impact on the growth the spruce trees at altitudes up to 600–650 m a.s.l. The increase in precipitation will adversely affect Yezo spruce growth in the upper mountain belt.

Keywords: dendrochronology, tree ring, tree-ring chronology, *Picea jezoensis*, Sikhote-Alin, elevation gradient

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Global climate change in the south of the continental part of the Russian Far East is expressed in a rapid increase in temperatures in the second half of the year, as well as in a change in the precipitation regime under the influence of processes occurring in the Pacific Ocean (Ukhvatkina et al., 2018, 2021, *Tretii otsenochnyi doklad*..., 2022). It has also been established that there are indirect manifestations of climate change through the increase in the number and intensity of tropical cyclones and their greater advance to the north (Altman et al., 2018; Janda et al., 2020).

Understanding the impact of climate change on forest ecosystems and assessing the impact of past, current, and projected changes on them is necessary to adapt strategies for the management and sustainable use of forests (Tardif et al., 2003; Andreassen et al., 2006; Sidor et al., 2015). Here it is especially important to know how the dominant species (key tree species) react to climate change, which, due to their large size, long life span, and the scale of natural disturbances that occur after their death, form the appearance and structure of forest communities and have the greatest impact on dynamic processes.

Yezo spruce (*Picea jezoensis* (Siebold & Zucc.) Carriere) is one of the dominant species in the Far East and the main industrial species in logging. Yezo spruce trees reach 35 m in height and 110 cm in diameter, and the maximum life expectancy is up to 500 years (Manko, 1987). The range of the Yezo spruce covers the Russian Far East (up to 57° N), northeast China, and Japan (Manko, 1987). According to N.V. Usenko (1969), Yezo spruce prefers habitats with humid cool air, does not tolerate the close occurrence of permafrost, avoids stagnant moisture and waterlogging, and prefers well-drained soils. Revealing the relationship between the radial growth of the Yezo spruce and climate data (meteoparameters) is important both for understanding possible changes in forest communities in the light of global climate change and for solving problems related to the conservation of biological diversity.

Despite the fact that the number of dendroclimatic studies in the south of the Russian Far East has increased in recent years, there is no information about what climatic conditions are important for the growth of Yezo spruce in this area. The latest studies on the ecology and physiology of the species were carried out as early as the middle of the 20th century (Orlov, 1955; Kalinichenko, E.P. and Kalinichenko, V.P., 1974; Yim and Yang-Jai, 1977; etc.). Similar studies carried out in other regions show that, within the range of the species, habitat characteristics change depending on altitude and create spatial variability in factors affecting the radial growth and sensitivity of the species to climatic variability (Sidor et al., 2015; Dapao et al., 2006; Gao et al., 2013; etc.). A significant part of the range of Yezo spruce falls on the Sikhote-Alin ridge. Due to the large length of the ridge—more than 1000 km—the natural and climatic conditions in its different parts are very different. Within the southern Sikhote-Alin, Yezo spruce is found on slopes of various exposures at altitudes from 300 to 1600 m a.s.l. (Manko, 1987). In the upper belt of mountains, it forms dark coniferous fir–spruce forests, and below, in the zone of Korean pine–broadleaved forests, it is an important dominated species (Kolesnikov, 1956). At the same time, it should be noted that, in the mountainous conditions of the Sikhote-Alin, due to the strong dissection of the relief and temperature inversions, favorable temperature conditions can be created on the slopes of the southern exposure at relatively high altitudes and, conversely, severe on the gently sloping terraces of stream valleys (Tarankov, 1974).

According to forecasts (*Tretii otsenochnyi doklad*..., 2022), in the southern Sikhote-Alin and in the south and southwest of Primorsky krai, in the future there will be a significant increase in winter temperatures, changes in the amount of precipitation and the nature of their distribution during the year. Taking into account the fact that this territory is located close to the southern border of the range of the Yezo spruce, it can be assumed that the range of this species will undergo changes under the influence of a changing climate in the coming decades. At the same time, the lack of information on climate data important for the growth of Yezo spruce trees does not make it possible to predict changes in the range of the species in the future. Therefore, the purpose of this study was to identify the response of the radial growth of the Yezo spruce to climatic variations and determine how the significance of various climate data changes along the altitudinal gradient in southern Sikhote-Alin.

MATERIAL AND METHODS

Territory and object of study. The study was carried out in southern Sikhote-Alin, on the territory of the Verhneussuriysky Research Station of the Federal Scientific Center for Biodiversity, Far East Branch, Russian Academy of Sciences (Fig. 1) (44°02′ N, 134°12′ E). The station occupies the Pravaya Sokolovka River basin (area 4400 ha), a third-order tributary of the Ussuri River. The relief of the territory of the station is low-mountainous, with rounded mountains; the average slope is 20°–25°. The minimum and maximum heights above sea level are 460 and 1060 m; about 70% of the area of the Yezo spruce in the southern Sikhote-Alin is located in this altitude range. The climate is monsoonal; about 830 mm of precipitation falls annually, with most of the precipitation falling in the summer (Fig. 2). The average annual air temperature is 0.9°C (Kozhevnikova, 2009). Forest vegetation occupies more than 99% of the territory of the station (Yakovleva, 2004; Omelko et al., 2019), while the area is dominated by Korean pine–broadleaved (55%) and fir–spruce forests (30%) (Yakovleva, 2004). In terms of relief, climate, and vegetation, the territory of the Verhneussuriysky Research Station is typical of the entire mountain belt of the southern Sikhote-Alin.

On the territory of the Verhneussuriysky Research Station, Yezo spruce is found at all heights. Depending on the exposure of the slopes, starting from a height of 700–900 m a.s.l., it forms a belt of fir–spruce forests; below it participates in the composition of forest stands of Korean pine–broadleaved forests (Kolesnikov, 1956, Omelko et al., 2018). Small areas of fir–spruce forests are also not uncommon in the valleys of rivers and streams, which is due to temperature inversions (Tarankov, 1974).

Data collection. The material was collected in 2020–2022. At the Verhneussuriysky Research Station, eight stands of about 0.5 ha were selected, distributed in such a way as to cover the maximum available altitude range (Fig. 1b). In the process of selection, areas of forest stands with traces of anthropogenic disturbances (cutting) and recent fires (less than 300 years old) were excluded. Within the selected plots, 1–2 cores at a height of 1.3 m were extracted from each middle- and old generative Yezo spruce tree. The coring of the trees was carried out perpendicular to the slope and/or slope of the tree in order to avoid the formation of compression wood (Stokes and Smiley, 1968). From 50 to 70 cores were taken at each site, 444 in total (Table 1).

Creation of tree-ring chronologies. The preliminary processing of cores in laboratory conditions was carried out in accordance with generally accepted dendrochronological procedures (Cook and Kairiuktis, 1990) and consisted of drying, trimming, and increasing contrast until individual tracheids in annual rings became visible under a binocular microscope. Tree rings were measured using a semiautomatic Velmex measuring system (Velmex INC., Bloomfield, NY, United States) with an accuracy of 0.01 mm. Further, the series of annual ring width measurements from each site were cross-dated using the TSAP software (Rinn, 1996), for which the individual series were

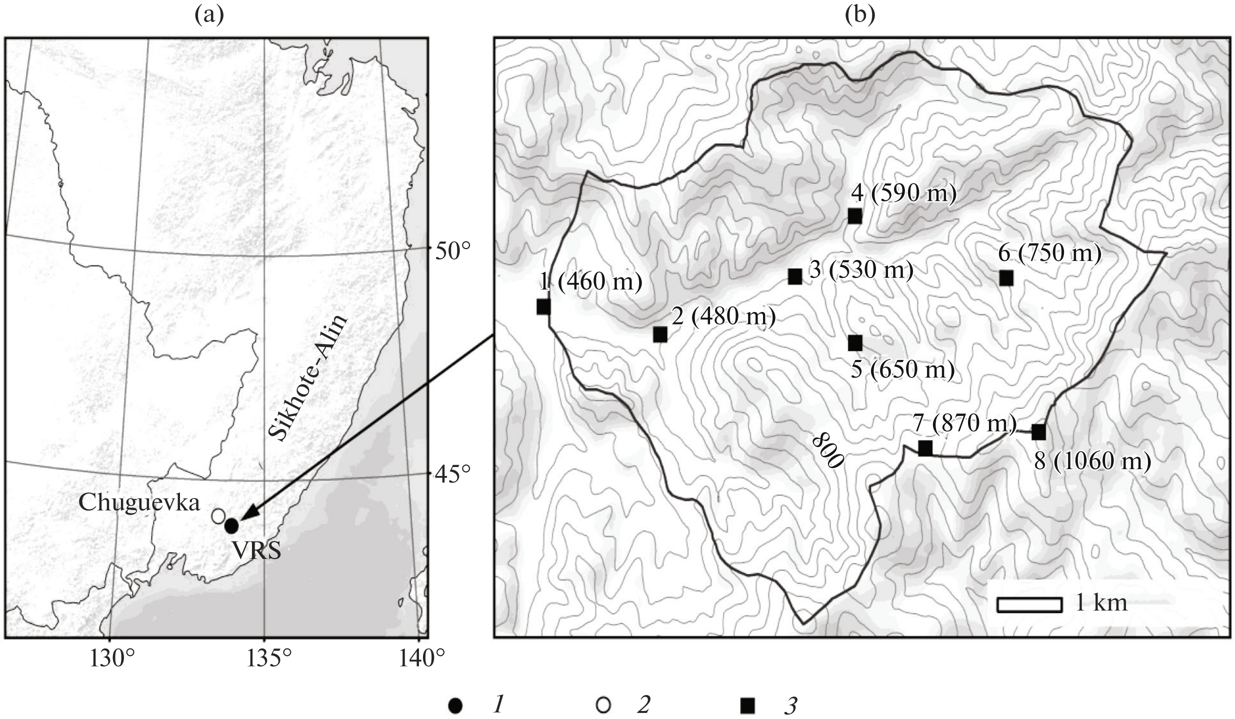

Fig. 1. Research area: (a) location of the Verhneussuriysky Research Station of the Federal Scientific Center for Biodiversity, Far Eastern Branch, Russian Academy of Sciences (*1*) and weather station Chuguevka (*2*); (b) scheme of the territory of the Verhneussuriysky Research Station and sampling sites (*3*) indicating the site number and altitude above sea level.

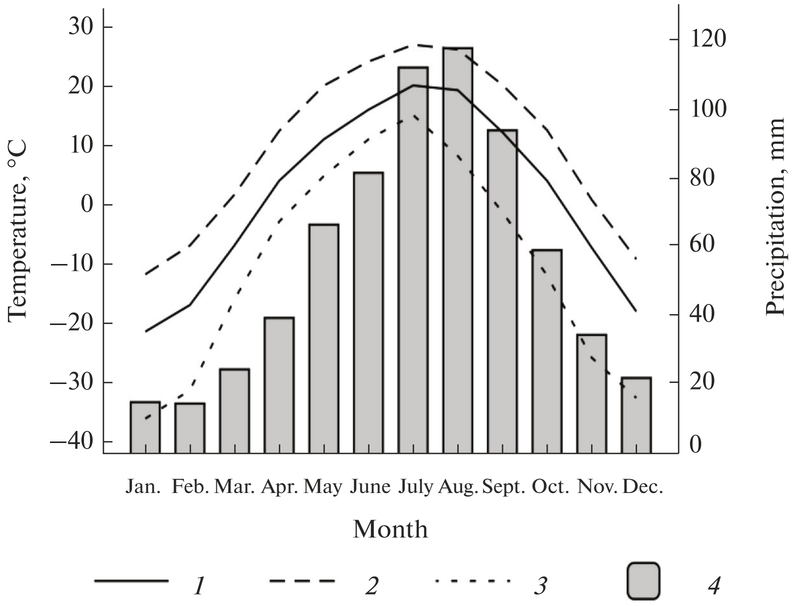

Fig. 2. Climatogram of the Chuguevka meteorological station: (*1*, *2*, *3*) average, maximum, and minimum air temperature; (*4*) monthly precipitation.

visually compared with the series obtained by averaging. The estimation of dating reliability and the search for missing rings were performed using the COFECHA software (Holmes, 1983). Further data processing was carried out using the dplR package (Bunn, 2008) for statistical software R (R Core Team, 2019). In order to minimize variations in radial growth due to age changes and phytocenotic relationships and to maximize “climatic” information in the tree-ring chronology, individual series were standardized using spline

Table 1. Characteristics of core sampling sites for Yezo spruce

Site number	Height, m a.s.l.	Slope, deg	Exposition	Position in relief	Number of cores, pcs.
1	460	3–5	NE	Lower slope	64
2	480	5–7	NW	Lower slope	56
3	530	2–3	NW	Lower slope	54
4	590	12–14	NW	Lower slope	50
5	650	22–26	SW	Top of the slope	50
6	750	15–20	SW	Mid-slope	70
7	870	1–3	NW	Flat crest	50
8	1060	2–3	SW	Crest	50

smoothing (40-year low-pass filter). This standardization method was chosen because trees growing in the forest experience several growth releases during their life, associated with the formation of light windows (Petrenko et al., 2016). In this case, standardization using, for example, a decreasing exponential curve does not allow leveling all such periods. Chronologies were created by averaging the values of individual series ("biweighted robust mean" (Cook, 1985)).

To characterize the chronologies and assess their quality, the following statistical indicators were calculated: mean sensitivity (*MS*) (Fritts, 1976), *RTOT* (average correlation between series, including correlation between series obtained from the same tree), *RWT* (average correlation between the series obtained from the same tree), *RBT* (average correlation between series from different trees), *REFF* (weighted average correlation based on *RWT* and *RBT*), *EPS* (expressed population signal) (used to assess the reliability of the chronology), (*SNR*) is the signal-to-noise ratio (Cook, Kairiuktis, 1990), autocorrelation (*AR1*), and standard deviation (*SD*) (Wigley et al., 1984; Brifa and Jones, 1990).

Climate data. Climatic observation data were obtained from the Chuguev meteorological station (Chuguevka settlement, 44°09′ 05″ N, 133°52′ 10″ E, altitude 260 m a.s.l.), located 30 km west of the study area (Fig. 1a). The following were used for analysis: the monthly precipitation (the available period of observations from 1936 to 2019), the monthly average (the available period from 1936 to 2019), and the maximum and minimum surface air temperatures (the available period from 1959 to 2019). It should be noted that meteorological observations have also been carried out at the Verhneussuriysky Research Station since 1966 (meteorological station MP7), but in 2000 they were discontinued. Therefore, the available observation period is only 34 years and there are no data for the last decades.

Relationship between tree-ring chronologies and climate variables. The influence of climate on the radial growth of trees was studied using correlation analysis with the treeclim package (Zang and Biondi, 2015) for the R software. The correlation (Pearson's correlation coefficient with estimation of confidence intervals by bootstrapping) between the values of the obtained tree-ring chronologies, i.e., indices, and climate data for the month from June of the year preceding the growth year to September of the current year was analyzed (Fritts, 1976). After a monthly analysis, the correlation between the indices and total precipitation, as well as the average values of the average, minimum and maximum temperatures for conditional seasons lasting from 2 to 9 months, was studied.

RESULTS

Characteristics of tree-ring chronologies. On the basis of cross-dating for eight sites, a total of 348 out of 444 cores with the best mean correlation between trees were selected and tree-ring chronologies were created on their basis (Fig. 3). The characteristics of the chronologies are presented in Table 2. The length of the chronologies ranged from 171 to 267 years; the length of the chronologies from the moment when the EPS value becomes higher than 0.85 is approximately one-third as long: from 104 to 199 years. The average EPS varies from 0.88 to 0.975, mean correlation between trees from 0.500 to 0.613, and mean sensitivity from 0.250 to 0.324. It should be noted that most indicators, with the exception of *AR1* and *SNR,* vary within relatively narrow limits.

Correlation between tree-ring chronologies. In the case of relatively low altitudes (up to 600 m a.s.l.), the correlation between chronologies is generally higher than the correlation between chronologies for high altitudes (Table 3). The exception is the correlation between chronologies for sites 7 and 8. With an increase in the difference in height above sea level between the sites, the correlation between chronologies naturally decreases. In particular, in the case of chronologies for sections 1 and 2, the value of the correlation coefficient is 0.71, while for sections 1 and 8 it is 0.37. Finally, the correlation between the chronologies obtained at "neighboring" altitudes also regularly decreases with increasing altitude. For example, the correlation between chronologies for the 2nd and

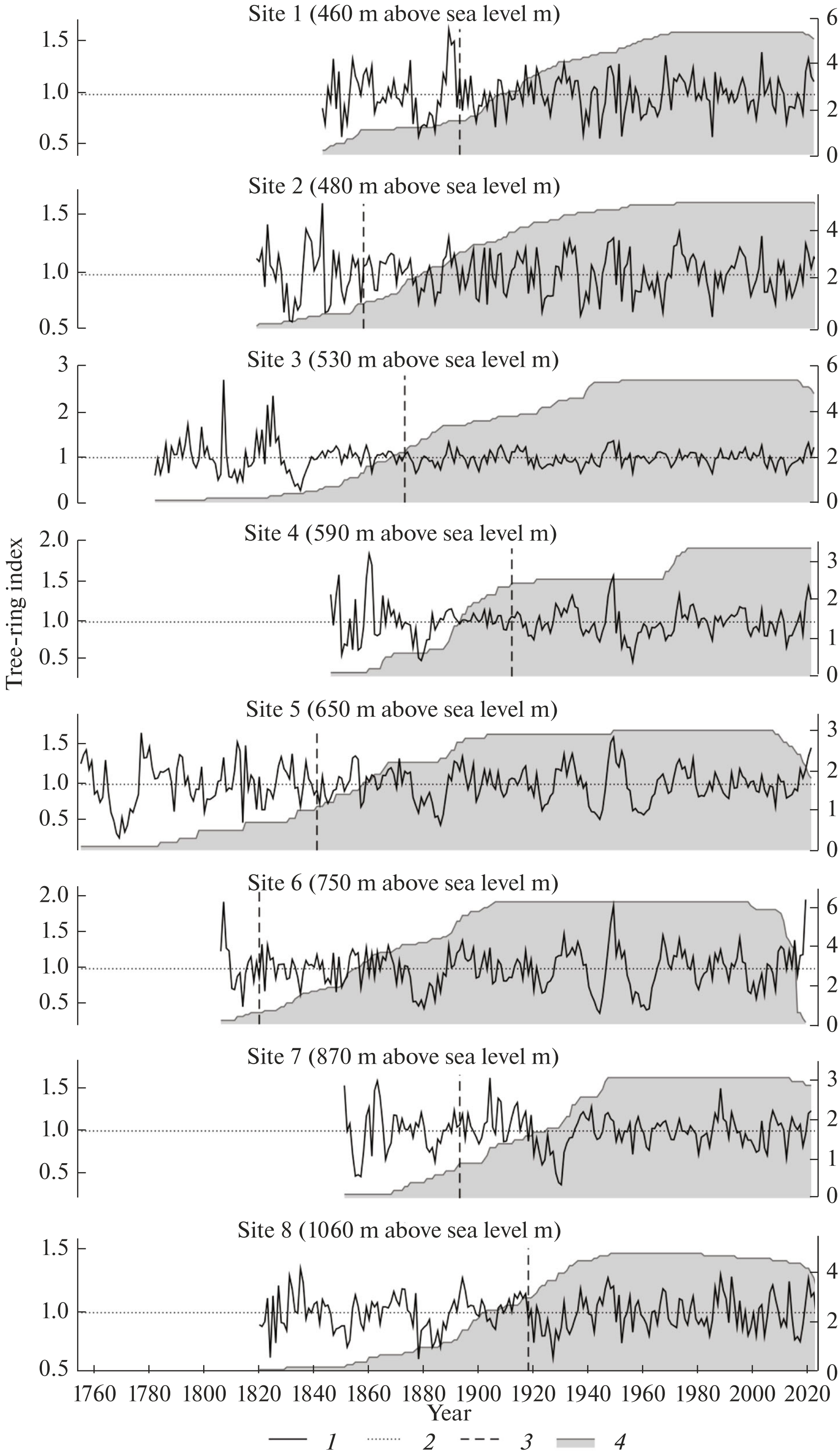

Fig. 3. Tree-ring chronologies and the number of cores: (*1*) tree-ring index, (*2*) average value of the growth index, (*3*) *EPS* threshold ≥ 0.85, and (*4*) number of cores.

Table 2. Characteristics of chronologies

Indicators	Site number							
	1	2	3	4	5	6	7	8
Number of trees/cores/ trees with two cores/ cores used for analysis, pcs.	65/65/0/54	56/56/0/51	68/68/0/54	17/33/16/33	16/30/15/30	63/63/0/63	16/31/15/31	43/48/5/32
Average series length, years	115.8	136.1	139.1	113.4	168.8	153.0	108.8	119.0
Time interval	1843–2022	1818–2022	1781–2022	1846–2021	1755–2021	1806–2020	1851–2021	1820–2022
Length of tree-ring chronology, years	180	203	242	176	267	214	171	204
Time interval at *EPS* > 0.85	1893–2022	1854–2022	1873–2022	1912–2021	1841–2021	1820–2020	1893–2021	1918–2022
Mean correlation between trees	0.5	0.57	0.55	0.53	0.53	0.60	0.56	0.5
Missed rings, %	0.496	0.173	0.373	0	0.375	1.535	0.474	0.228
MS	0.3	0.259	0.264	0.25	0.28	0.324	0.257	0.25
SD	0.166	0.168	0.156	0.179	0.219	0.263	0.192	0.141
AR1	0.171	0.333	0.392	0.57	0.662	0.528	0.498	0.348
RTOT	0.304	0.362	0.303	0.237	0.27	0.381	0.301	0.26
RWT	–*	–	–	0.496	0.54	–	0.523	0.462
RBT	0.304	0.362	0.303	0.229	0.261	0.381	0.293	0.259
REFF	0.304	0.362	0.303	0.301	0.327	0.381	0.378	0.267
EPS	0.959	0.967	0.959	0.88	0.886	0.975	0.907	0.94
SNR	23.6	29	23.4	7.3	7.76	38.8	9.71	15.7

* The value was not calculated, since one core was obtained from each tree for this area. *MS* is mean sensitivity, *SD* is standard deviation, *AR1* is the first order autocorrelation, *RTOT* is the average correlation between series including correlation between series obtained from the same tree, *RWT* is the average correlation between the series obtained from the same tree, *RBT* is the average correlation between series from different trees, *REFF* is the weighted average correlation based on *RWT* and *RBT*, *EPS* is the expressed population signal, and *SNR* is the signal-to-noise ratio.

3rd sites is 0.77, while for the 6th and 7th sites it is 0.41. Here, again, the exception is the chronologies for the 7th and 8th sections.

Climatic response. An analysis of the correlation between chronologies and climate data showed that, for the growth of Yezo spruce, the most important are precipitation and the maximum temperature of the month, with the maximum climatic sensitivity (when the correlation was greatest) observed in the period from 1983 to 2012. Both in the case of precipitation and maximum temperatures, significant correlations are negative; i.e., the higher the maximum temperature of the month or the greater the amount of precipitation, the smaller the increment indices. Significant correlations of chronologies with the average and minimum temperature of the month are in the single digits, and their values are lower than with other climate data. Therefore, the average and minimum temperatures were not considered further.

The correlation between chronologies and precipitation can be analyzed in more detail using the example of the chronology obtained at an altitude of 590 m: site 4 (Fig. 4a). The figure shows that the monthly correlation of chronology and precipitation of the previous calendar year is positive, but not significant. The correlation with precipitation of the current year is generally negative, and significant values are revealed for February, July, and August. It should be noted that a significant correlation with precipitation in February of the current year was found only for two of the eight chronologies, while significant correlations with precipitation in July or August were detected in most of them. At the same time, if we consider the total precipitation in July–August of the current year, then the absolute value of the correlation is higher compared to the values for individual months. This is true for all chronologies for which significant correlations with precipitation have been found; therefore, it is the July–August season that was considered below, and not individual months. The only exception was the chronology obtained at an altitude of 1060 m a.s.l. (section 8), in the case of which the correlation with the total precipitation in July–August turned out to be insignificant (Fig. 5a).

The correlation with the maximum temperatures of the month can also be analyzed using the example of the chronology for area 4 (Fig. 4b). In the case of

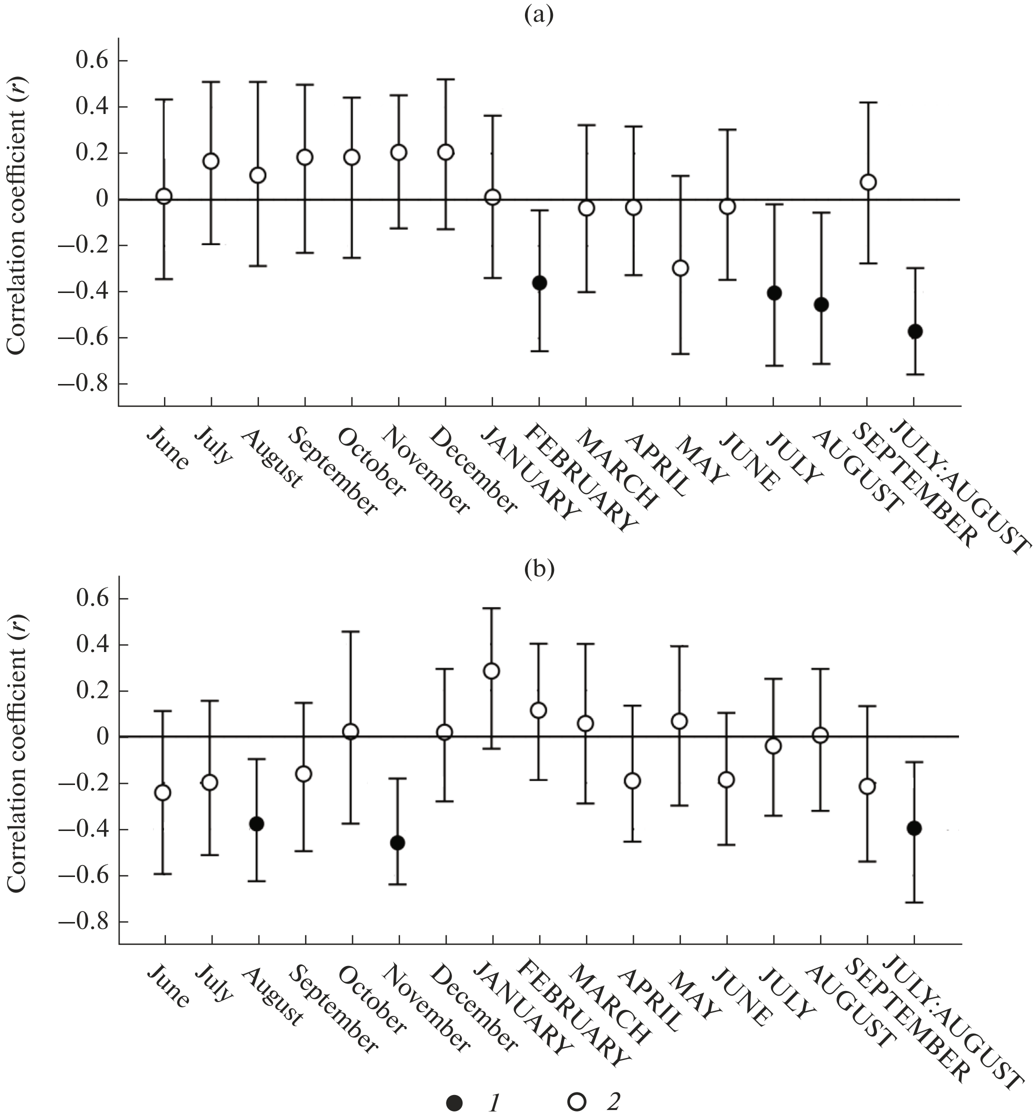

Fig. 4. Results of the analysis of the correlation between the values of the growth index (section 4 at an altitude of 590 m a.s.l.) and two climate data, precipitation (a) and the maximum temperature of the month (b); (*1*, *2*) significant and insignificant correlation coefficients, respectively. Lowercased months precede the year of tree growth; uppercase months are the current year.

Table 3. Cross correlation between chronologies

Site number and altitude, m a.s.l.	1 (450)	2 (470)	3 (530)	4 (600)	5 (650)	6 (750)	7 (870)	8 (1060)
1 (450)	1.0	******	******	******	***	***	++	++
2 (470)	0.71	1.0	******	******	***	***	+	+
3 (530)	0.66	0.77	1.0	******	***	++	++	++
4 (600)	0.67	0.84	0.78	1.0	******	***	***	++
5 (650)	0.55	0.57	0.59	0.60	1.0	***	++	+
6 (750)	0.48	0.44	*0.22*	0.57	0.51	1.0	***	++
7 (870)	*0.36*	*0.16*	*0.32*	0.46	*0.22*	0.41	1.0	******
8 (1060)	0.37	*0.14*	*0.31*	*0.32*	*0.16*	*0.36*	0.81	1.0

The lower part of the table is the value of the correlation coefficient (*r*), the upper part of the table is categories of values of the correlation coefficient: ****** values above 0.60, *** values from 0.40 to 0.59, ++ values from 0.20 to 0.39, and + values up to 0.19. Italics indicate insignificant values of the correlation coefficient ($p > 0.05$).

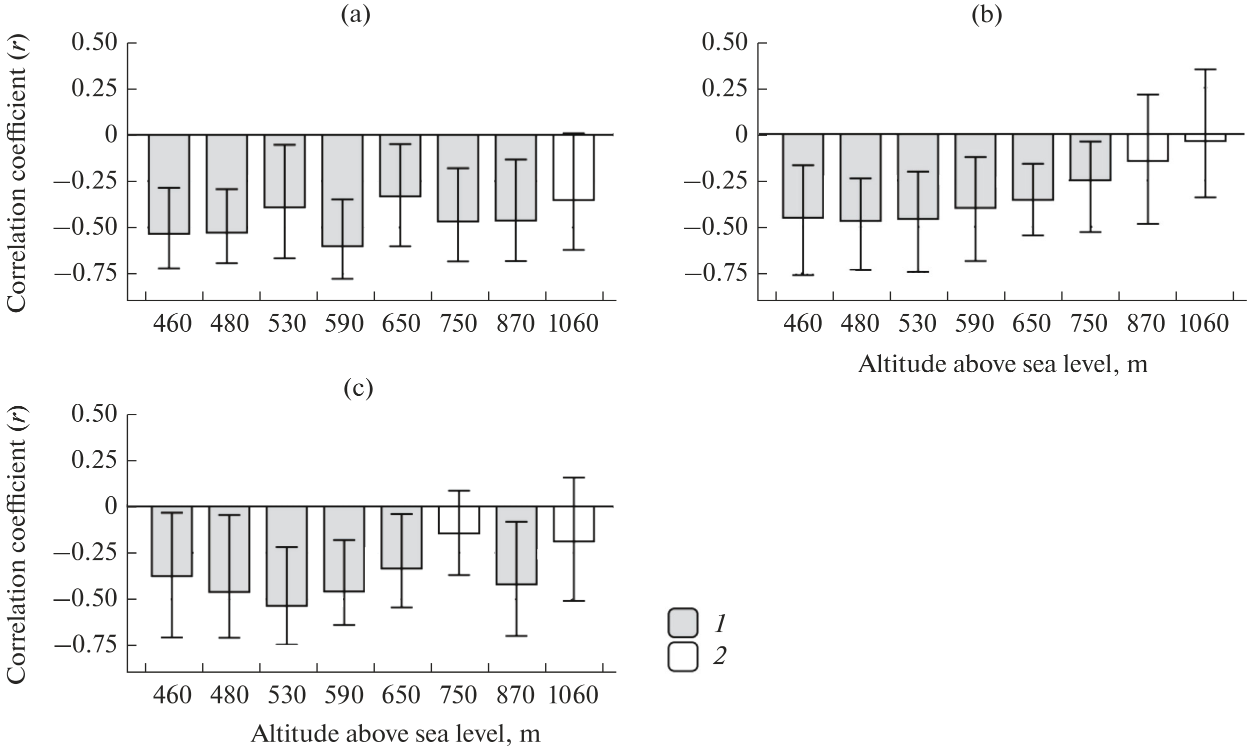

Fig. 5. Correlation between growth indices and three climate variables: (a) amount of precipitation in July–August of the current year, (b) average maximum temperature in July–August of the previous year, and (c) maximum temperature in November of the previous year; (*1, 2*) significant and insignificant correlation coefficients.

months of the previous year, the correlation is negative and there are significant values for August and November. As for the current year, the correlation is initially positive and then gradually decreases and becomes negative, but there are no significant values. If we consider the average maximum temperature in July–August of the previous year, then a significant negative correlation is revealed, which can be traced in 6 out of 8 chronologies, and its value is higher than separately for August. Therefore, two options were further analyzed: the average maximum temperature in July–August and the maximum temperature in November (Figs. 5b, 5c). The average maximum temperature in July–August of the previous year turned out to be insignificant for the chronologies of sites 7 (870 m a.s.l.) and 8 (1060 m a.s.l.). No significant correlation with the maximum temperature in November of the previous year was found for the chronologies of sections 6 and 8 (750 and 1060 m a.s.l.).

Change in climate response with altitude. On the graphs showing the change in the significant values of the correlation coefficients with increasing height above sea level, positive trends can be noted (Fig. 6). However, the correlation with height is significant only for the average maximum temperature in July–August of the previous year ($r = 0.94$, $p = 0.004$). For precipitation, it is 0.34 ($p = 0.453$), and the maximum temperature in November of the previous year was 0.38 ($p = 0.451$).

If we consider nonsignificant correlation coefficients between chronologies and three selected climate variables along with significant ones to identify general patterns (as, for example, was done in the work of Sidor et al. (Sidor et al., 2015)), then in the case of maximum temperatures, the positive relationship between their change and altitude becomes more pronounced (Figs. 6b, 6c). The correlation for the November maximum temperatures of the previous year becomes significant ($r = 0.73$, $p = 0.040$), and the correlation for the average maximum temperature of July–August of the previous year increases ($r = 0.99$, $p < 0.001$). For precipitation, the trend practically does not change (Fig. 6a), and the correlation with height remains insignificant ($r = 0.55$, $p = 0.156$). Thus, if we talk about precipitation, then its effect on the radial growth of Yezo spruce does not change significantly with increasing height above sea level. The effect of maximum temperatures decreases rapidly with height above sea level.

DISCUSSION

The results of the study show that, on the one hand, the tree-ring chronologies have a mean sensitivity sufficient for dendroclimatic studies (from 0.250 to 0.367). On the other hand, the question of the suitability of the Yezo spruce for the reconstruction of long-term climatic changes for the territory of the southern Sikhote-Alin remains controversial.

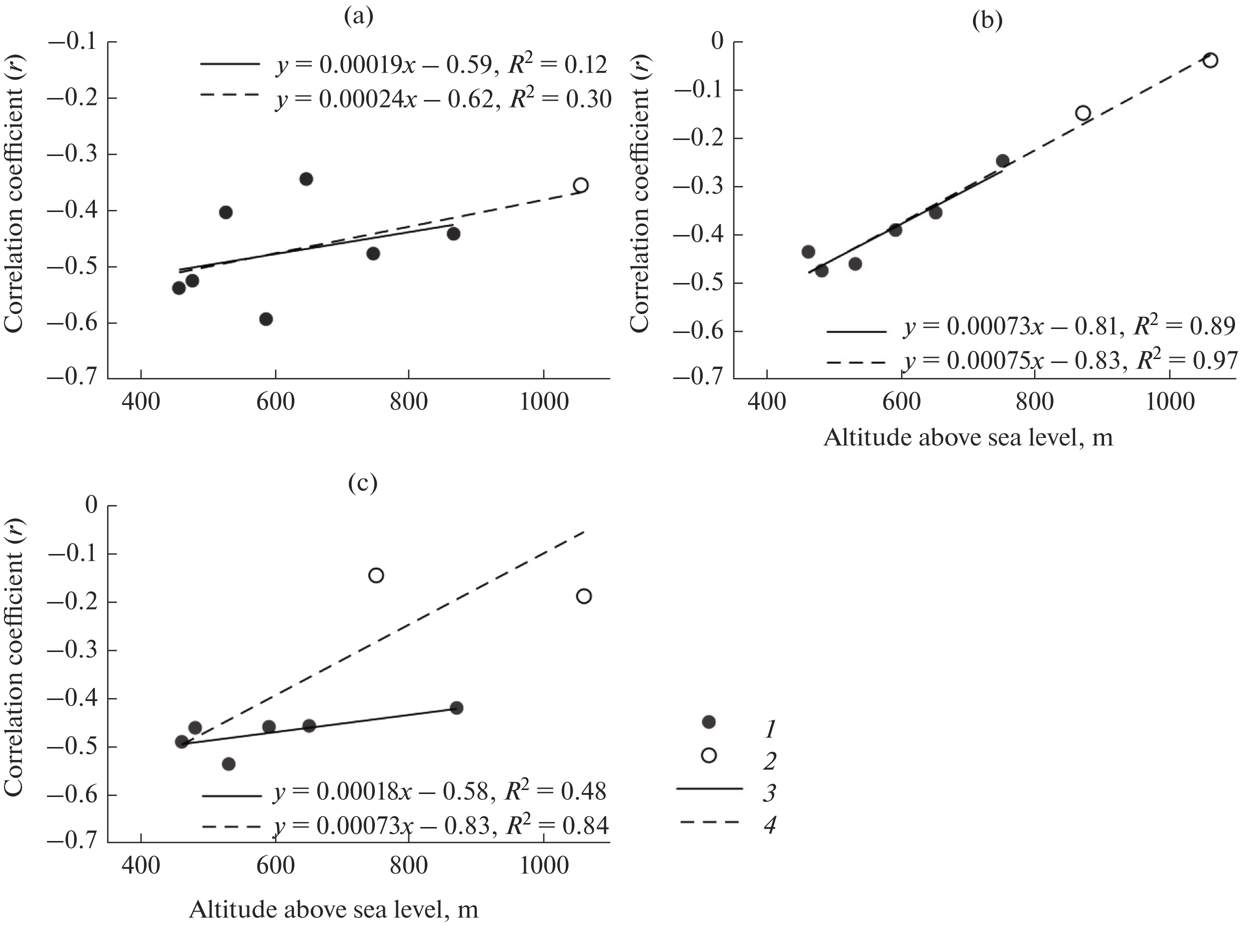

Fig. 6. Dependence of the values of the correlation coefficient between chronologies and climate variables on altitude above sea level: (a) precipitation in July—August of the current year, (b) average maximum temperature in July—August of the previous year, and (c) is the maximum temperature in November of the previous year; (*1, 2*) significant and insignificant values of the correlation coefficient, respectively, (*3*) trend line for significant values, and (*4*) common trend line for significant and insignificant values.

Although Yezo spruce is considered a long-lived species and its age can reach 500 years (Manko, 1987), under forest conditions, generative trees of the maximum calendar age differ from generative trees of a similar size of a younger age in that they were suppressed for a long time (Petrenko et al., 2016). The period of suppression of Yezo spruce trees before entering the canopy, i.e., before the transition from the virginal to the generative stage, can be 250—270 years (Omelko et al., 2018). In other words, the maximum tree age is achieved not due to a long stay in the generative state (as, for example, the Korean pine (Omelko et al., 2018)), but due to a long period of suppression in the immature and virginal stages. Under suppressed conditions, the growth of trees is more determined by phytocenotic interactions than by the influence of climate (Shiyatov et al., 2000). Therefore, the initial part of a series of tree-ring width measurements obtained from an old tree will be of little use for climate reconstruction. It should also be taken into account that, in the work indicated by Yu.I. Manko (1987), the maximum age is typical for trees growing on the northern border of the range.

Secondly, the wood of the Yezo spruce is highly prone to decay, especially in the humid and warm conditions of the southern Sikhote-Alin (Omelko et al., 2016). For this reason, the main cause of the death of Yezo spruce trees in the forests of southern Sikhote-Alin is trunk core rot (Omelko et al., 2018). This leads to the fact that old-growth generative trees are practically not found in forest stands (Omelko et al., 2018). It is not possible to obtain wood samples suitable for dendrochronological studies from deadwood of Yezo spruce. This is an important difference from the Korean pine, in the case of which the reconstruction of climate based on wood from dead trees (deadwood) is possible (Ukhvatkina et al., 2018). Thus, the length of reconstructions of climate data based on measurements of the width of the annual rings of the Yezo spruce (if we consider the interval from *EPS* > 0.85) will rarely exceed 150—200 years.

An analysis of the correlation between tree-ring chronologies and climate data made it possible to establish that the radial growth of Yezo spruce within the southern Sikhote-Alin is most influenced by the precipitation of July–August of the current year and the maximum temperature (the average value of July–August of the previous year and November of the previous year). Both in the case of precipitation and in the case of maximum temperatures, the relationship is negative. The insignificant response of the radial growth to the average monthly and minimum monthly temperatures can be explained by the fact that in the southern Sikhote-Alin the Yezo spruce is located closer to the southern border of its range and its growth is affected precisely by high temperatures.

As for the negative correlation of chronologies with sediments, this result was unexpected, since all species of the spruce genus, and, in particular, Yezo spruce, are considered to be moisture-loving (Manko, 1987; Usenko, 1969). A possible reason is that the Yezo spruce, despite the fact that it prefers damp and cool habitats, does not tolerate waterlogging (Manko, 1987; Usenko, 1969). In the southern Sikhote-Alin, the Yezo spruce does not experience a lack of moisture, and its excess leads to the stagnation of water in the soil, which has a negative effect on the formation of the annual ring, which is indirectly confirmed by poor growth of Yezo spruce in conditions of waterlogging of the soil (Usenko, 1969; Manko, 1987). At the same time, about 230 mm of precipitation falls on average in July–August, i.e., about 34% of the annual norm. The maximum amount of precipitation for these months in some years reached 474 mm, which led to very strong waterlogging. Abundant summer precipitation, due to the monsoonal climate, affects the middle and end of the period of radial growth formation.

In a similar study of the relationship between climate and radial growth of Yezo spruce along an altitudinal gradient in northeastern China, Changbaishan Mountain (Dapao et al., 2006), it was shown that precipitation in April–May of the current year negatively affects the growth of spruce in Korean pine–broadleaved and dark-coniferous forests, i.e., the lower and middle mountain belts, and precipitation for the entire period of formation of the ring (from October of the previous year to September of the current year) negatively affects the growth of Yezo spruce in forests with the participation of Erman's birch, i.e., in the upper belt of mountains. The amount of precipitation falling on Mount Changbaishan per year is 750 mm, which is similar to the amount of precipitation for the territory of the southern Sikhote-Alin (830 mm).

No significant change in the correlation coefficients between chronologies and precipitation with increasing height above sea level was found. However, it should be noted that the correlation with precipitation is maximum for plot 4 (altitude 590 m, lower part of the slope, close to the stream valley), minimal for the chronology obtained for plot 5, located on a steep slope (altitude 650 m), and insignificant for plot 8 (height 1060 m, crest). Based on the relief features of these areas, it can be assumed that the correlation with precipitation decreases in those places where soil moisture does not stagnate. However, further studies are needed to substantiate this conclusion.

A negative reaction to the maximum temperatures of the summer period of the previous year was revealed in dendrochronological studies for *P. jezoensis, Picea crassifolia,* and a number of other species (Dapao et al., 2006; Liang et al., 2010; Gao et al., 2013; Qi et al., 2022). Elevated temperatures can affect the growth of trees in different ways, including through an increase in respiration, which is accompanied by a large consumption of nutrients, through a temporary cessation of transpiration (when the temperature rises to a certain level, the stomata of the needles close), and through an increase in the evaporation of soil moisture (which leads to its deficiency). One way or another, these processes lead to a decrease in the supply of nutrients that is created in the current year and is necessary for the formation of the annual ring in the next year (Fritts, 1976; Cook and Kairiukstis, 1990).

The mechanism of the negative reaction to the November maximum temperatures seems to be more complex. The end of the formation of the annual ring in the Yezo spruce in the territory of the southern Sikhote-Alin occurs in early or mid-September. Prior to the onset of spring, spruce photosynthesis proceeds according to a reduced type and nutrients are not stored (Schaberg et al., 1995, Bag et al., 2020). Long periods of thaw, interspersed with cold waves during the change in atmospheric circulation at the boundary of the interaction of air masses over the mainland and the Pacific Ocean in November, lead to the thawing and subsequent freezing of water in the needles, accompanied by the beginning and suspension of reduced type photosynthesis. This, in turn, leads to the fact that the resources accumulated over the summer are spent on photosynthesis without their replenishment (Strimbeck et al., 1995).

Thus, the negative effect of the maximum temperatures in July–August and November leads to a decrease in the supply of nutrients, which causes the formation of a narrower annual ring in the next year (Shiyatov et al., 2000). Taking into account the uneven nature of warming during the year, namely, the fact that there is an increase in temperatures in the autumn–winter period (Ukhvatkina et al., 2018; *Tretii otsenochnyi doklad...*, 2022), it can be assumed that climate change in the future can significantly affect the growth and development of Yezo spruce trees.

The values of the correlation of chronologies with maximum temperatures (both the average value of July–November of the previous year and November of the previous year) rapidly decrease with increasing altitude. For the tree-ring chronology obtained at a height of 1060 m, no significant correlations were found with either of the two variants of maximum temperatures.

The decrease in the values of correlation with maximum temperatures with increasing altitude is explained by the fact that, in general, Yezo spruce is adapted specifically to cool conditions (Usenko, 1969; Manko, 1987). It is also important that seasonal temperature differences change with increasing altitude. There are no observations of the temperature gradient directly in the study area, but it is possible to compare temperatures according to the Chuguevka meteorological station located at an altitude of 200 m a.s.l. and a weather station at the Verhneussuriysky Research Station (MP7), located at an altitude of 800 m a.s.l. The maximum temperature in August, according to long-term observations at the Chuguev meteorological station, is 26.7°C, while at the hospital it is 21.3°C (temperature difference 5.4°C). In November, according to the weather station Chuguevka, the maximum temperature averages 1.3°C and, according to the MP7 weather station, –2.54°C (the temperature difference decreases and in absolute terms is 1.24°C). At the same time, the difference in maximum temperatures at the Chuguevka meteorological station from August to November is 25.4°C and, at the weather station of the hospital, 18.8°C. Consequently, at a higher altitude, not only is it relatively cooler, but the temperature difference is smaller during the Yezo period, which is important for the radial growth of spruce. This is probably why a higher correlation with maximum temperatures is observed at relatively low altitudes.

Based on the obtained, it can be said that, with continued climate warming, which in southern Sikhote-Alin occurs precisely due to an increase in autumn–winter temperatures (Ukvatkina et al., 2018), the greatest negative impact on the growth of Yezo spruce trees will be manifest itself at altitudes up to 600–650 m. At these altitudes, the correlation between the chronologies and the maximum temperature in November of the previous year has the highest values. According to meteorological observations and the results of dendrochronological studies (Ukhvatkina et al., 2021), there are no long-term trends in the change in precipitation in the region; however, according to calculations, with a decrease in altitude there is a trend for climate aridization and, with an increase, there is a trend for humidization (Van and Sharaya, 2021). In this scenario, increased rainfall will adversely affect the growth of Yezo spruce trees in the upper mountain belt.

CONCLUSIONS

As a result of the study, tree-ring chronologies for Yezo spruce were created for eight forest stands distributed in height from 460 to 1060 m a.s.l. Chronology metrics such as mean sensitivity, mean correlation between trees, and *EPS* value indicate that the chronologies for the Yezo spruce obtained in the southern Sikhote-Alin can be used for dendroclimatic studies.

An analysis of the relationship between chronologies shows that at relatively low altitudes up to 600 m a.s.l., the correlation between chronologies is generally higher than the correlation for high altitudes. The correlation between the chronologies obtained at "neighboring" heights naturally decreases with increasing height above sea level.

It has been established that the radial growth of Yezo spruce within the southern Sikhote-Alin is influenced by precipitation in July–August of the current year and the maximum temperature of the previous year (average July–August and November temperature). Both in the case of precipitation and in the case of maximum temperatures, the correlation is negative. Significant correlations with mean monthly and minimum monthly temperatures are rare. There was no significant change in the correlation coefficient between chronologies and precipitation with increasing height above sea level. Taking into account the peculiarities of the location of the sites where the cores were taken, it can be assumed in the relief that the response of the radial growth to precipitation depends on the possibility of retaining moisture in the soil in the place where the trees grow. However, this assumption requires further research involving more data. The correlation of Yezo spruce chronologies with maximum temperatures rapidly decreases with increasing altitude.

Thus, as a result of the study, for the first time, climate data were identified that determine the radial growth of Yezo spruce trees in the southern Sikhote-Alin. The results show that, with further climate change, the greatest negative impact on the growth of Yezo spruce trees will manifest itself at altitudes up to 600–650 m a.s.l. The results are important for further analysis of the impact of climate change on the growth and distribution of forest-forming species in the south of the Russian Far East.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare that they have no conflicts of interest.

Statement of the welfare of humans or animals. The article does not contain any studies involving humans or animals in experiments performed by any of the authors.

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