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# Estimated influence of extreme climate events in the 21st century on the radial growth of pine trees in Povolzhie region (European Russia)

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**Abstract.** The projected climate change in the 21st century is expected to affect various forest ecosystems with corresponding ecological, economic, and social impact. Adaptation measures for forestry need to be planned well in advance, because the forests being regenerated today will have to cope with future climate conditions in long time periods. Here we use a process-based forward model of tree growth, VS-Lite, calibrated and independently validated on tree-ring data and forced by climate projections according to various greenhouse gas emission scenarios. We estimate the ensemble radial tree growth of pine in Povolzhie region in the future. Our projections show a constant tree growth throughout the 21st century. The increased temperature will slightly favour the tree growth, especially in the case of an extended growth season, while mostly constant precipitation will not lead to any soil moisture deficit. The results of this study are crucial for the development of Povolzhie region in the near or remote future.

## 1. Introduction

Forests are particularly sensitive to climate change, because the long life-span of trees does not allow them to adapt rapidly to environmental changes. Therefore, adaptation measures for forestry need to be planned well in advance, because the forests regenerated today will have to cope with the future climate conditions in long time periods [1]. The results of climate models project increased air temperatures in the 21st century compared to those in the 20th century, under different scenarios of emissions of greenhouse gases [2]. These changes may directly and indirectly affect forest ecosystems [3] with corresponding ecological, economic, and social impacts.

One way to estimate the response of forests to future climate change is to model tree growth, in our case tree-ring increments. This can be done by means of different methodologies, including linear equations representing tree growth dependency on climatic parameters [4], process-based models [5], or some empirical dependencies [6]. The process-based models of tree-ring formation can represent mixed and non-linear tree growth responses to climatic factors, and, in this sense, they offer a more physically-based approach for studying the nature of growth responses to future climate variability, which is also consistent with the basic principle of limiting factors [7]. Previously we developed a methodology that uses a simplified Vaganov-Shashkin (VS) model [8], the VS-Lite one [9] for tree-growth projections and applied it for Central Chile and Northern European Russia [7]. The VS-Lite is a process-based model that has only 12 tunable parameters and uses meteorological data of monthly



resolution. These properties make the model easy to apply in different regions, including those with sparse meteorological record.

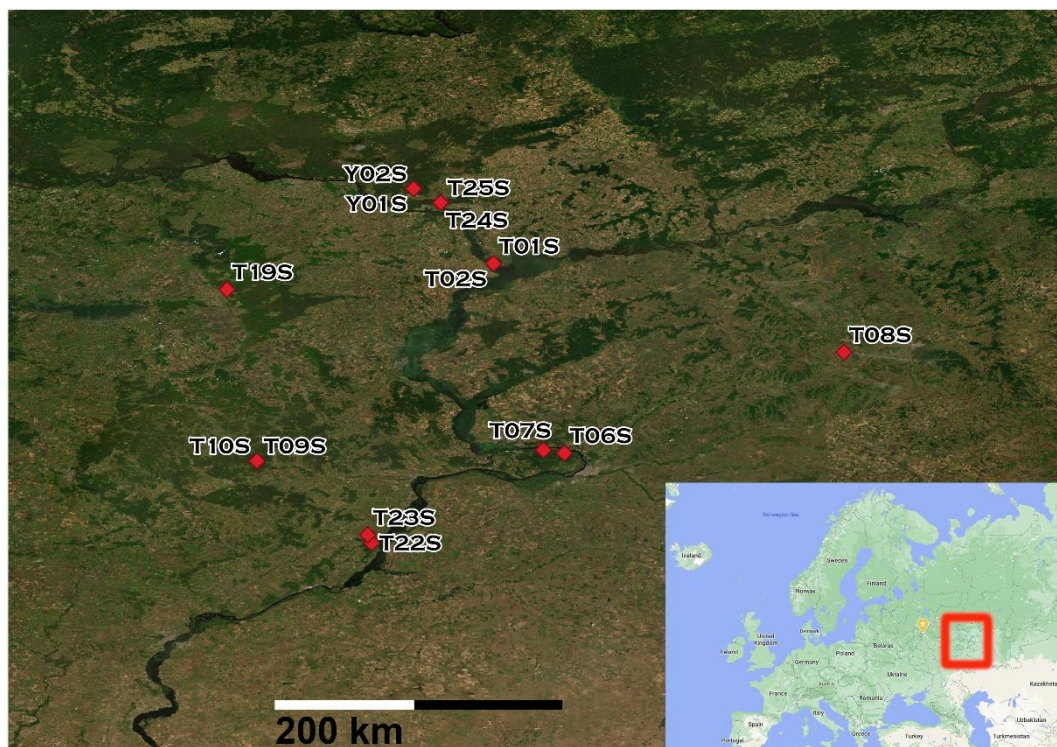
In this study, we use the VS-Lite model for pine (*Pinus sylvestris* L.) growth projections under two different Representative Concentration Pathways (RCPs) in Povolzhie region, European Russia. We also investigate changes in projected climate extremes and how these changes are going to influence the tree growth in the region.

## 2. Materials and Methods

### 2.1. Tree-ring data

We developed 14 tree-ring width chronologies for Povolzhie region (Figure 1, [10]). The sampling was performed in the 2015-2019 field seasons. We targeted healthy dominant trees at each site and extracted two increment cores per tree at breast height. In the laboratory, the increment cores were glued on wooden beams with perpendicular fibers direction [11] and sanded with gradually finer sand paper up to 1200 grid. The tree-ring widths were measured with a resolution of 0.001 mm using the LINTAB ver. 3.0 system. The TSAP software was employed for graphical presentations of the results [12]. Cross-dating and quality control of time-series was assessed using the COFECHA software [13] with core segments having low correlation values excluded from the analysis.

The resulting tree-ring series were standardized to dimensionless indices in order to remove the age trend and to preserve variations related to climate. We used the ARSTAN program for standardization and splines with a 50% variance cutoff on 67% of the series lengths for detrending. Local tree-ring chronologies were also united into several regional chronologies on the basis of principal component analysis [10]: Master chronology, including all sites, RG1 for the southern part of the region (T10S, T22S, T23S), RG2 for the northern part of the region (T01S, Y01S, Y02S), and RG3 for the eastern part of the region (T06S, T08S).



**Figure 1.** Study region and location of the tree-ring chronologies.

## 2.2. Meteorological data

The monthly mean temperature and precipitation records were taken from the CRU TS 4.02 database [14] from the nearest land grid point for the local chronologies or averaged for all grid points falling into the corresponding region for regional chronologies. The records start in 1901.

## 2.3. VS-Lite modelling

VS-Lite is a simplified version of the full Vaganov–Shashkin forward model [8]. For a full description of the model and the Bayesian algorithm of parameter estimation we refer to the VS-Lite forward model version 2.3 (available at <http://www.ncdc.noaa.gov/paleo/softlib/softlib.html>; [9]). It simulates annual tree-ring width using the principle of limiting factors and requires for input only latitude, monthly mean temperature, and monthly total precipitation. The representation of individual cambial cells and the biological processes that govern them, both important components of the full VS model, are completely absent in the VS-Lite. However, the representation of the nonlinear climatic controls on tree-ring growth, present in the full VS model in the form of threshold growth response functions and an implementation of the principle of limiting factors, remains largely unchanged in the VS-Lite.

The VS-Lite model estimates monthly soil moisture from temperature and total precipitation data via the empirical one-layer Leaky Bucket model of hydrology [15]. This bucket hydrology scheme estimates evapotranspiration, surface runoff, and groundwater flow as empirical functions of the input data, and subtracts them from incoming precipitation plus the previous month's soil moisture to compute the present monthly soil moisture [9]. Snow dynamics is not considered in the model and, thus, all precipitation is assumed to be liquid. Seasonal insolation or day length is determined from the site latitude and does not vary from year to year. For each year, the model simulates standardized tree-ring width anomalies from the minimum of the monthly growth responses to temperature (gT) and moisture (gM), modulated by insolation (gE).

In this study, most of the tunable model parameters (e.g., soil moisture, runoff, and root depth) were set to the default values proposed in [9]. The growth season was set from May to September. The growth function parameters were estimated for each site via Bayesian calibration over the entire period with climatic data spanning between 1901 and 2014. For this, the model was evaluated 15,000 times for each site using three parallel Markov Chain Monte Carlo (MCMC) sequences with uniform prior distribution for each parameter and a white Gaussian noise model error [9]. The posterior median for each parameter was used to obtain the “calibrated” growth response for a given site.

## 2.4. Assessment of growth projections

Tree growth projections were made on the basis of monthly values of temperature and precipitation from the output of 30 climate models from CMIP5 (Climate Model Intercomparison Project, phase 5) long-term experiments [16].

We used two future projection simulations forced with specified concentrations, high emissions scenario RCP8.5, and low emissions scenario RCP2.6 (so-called peak-and-decay [17]). These simulations provide the maximum range of the possible climate change during the 21<sup>st</sup> century within the framework of CMIP5. The labels for the RCPs provide a rough estimate of the radiative forcing in 2100 (relative to the preindustrial conditions). For example, the radiative forcing in RCP8.5 increases throughout the twenty-first century before reaching a level of about 8.5 W/m<sup>2</sup> at the end of the century. In RCP2.6, radiative forcing reaches a maximum near the middle of the 21<sup>st</sup> century (about 3 W/m<sup>2</sup>) before decreasing to a level of 2.6 W/m<sup>2</sup> at the end of the 21<sup>st</sup> century.

For comparison of the projected tree growth with the modern conditions, we use the results of a “historical” run (sometimes referred to as “twentieth century” simulations). This experiment is included into the core of the long-term simulations of CMIP5. The “Historical” run is forced by the observed atmospheric composition changes (reflecting both anthropogenic and natural sources), and includes the time-evolving land cover. The historical runs cover much of the industrial period (1850–2005).

The data from each model were interpolated to one geographical point representing an eastern sub-region of Povolzhie (53.93°N, 51.37°E). The monthly output of the models was used as input data to the VS-Lite model calibrated on the full period of the overlap between the tree-ring and instrumental climatic data to make tree growth projections. We used the output of each model as an input to the VS-Lite model, and then all VS-Lite outputs were averaged to obtain the ensemble chronology. We calculated the modeled growth for the historical period 1901-2005 and the projected period 2006-2099.

### 2.5. Assessment of climate extremes and their influence on tree growth

Extreme climate events were defined as seasonal values (the mean temperature and total precipitation for May-September) beyond 5<sup>th</sup> and 95<sup>th</sup> percentiles for the “historical” model run. We selected all models and all years that produced values outside these bounds and calculated the mean modeled tree growth for these outputs.

## 3. Results and discussion

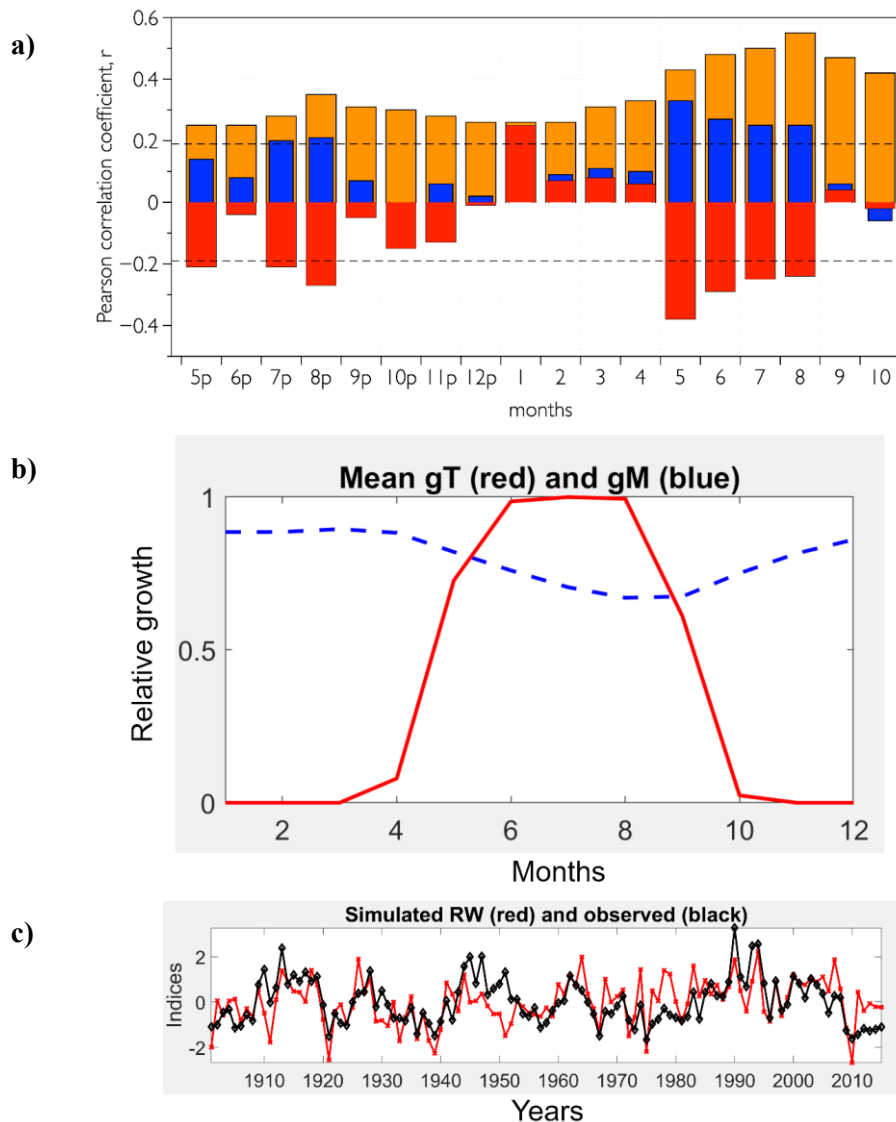
### 3.1. VS-Lite model calibration and validation

The robustness of the VS-Lite modeling was assessed by validation of its performance in the period withdrawn from the calibration. The whole period was divided into two equal periods of 58 years (1901-1958, 1959-2016); first the model was calibrated on one of them and validated on another one, and then vice versa. Finally, the model was run over the entire 1901–2016 period by using the calibrated parameters to produce a simulated tree-ring chronology that represents an estimate of the climate signal of tree growth. We tested all 14 local chronologies, as well as 4 regional chronologies. Finally, we selected the RG3 chronology for the growth projections, because it showed the strongest climatic response, covered an extended region, and was successfully modeled by the VS-Lite. Other chronologies either could not be successfully modeled by the VS-Lite (most likely due to a weak climatic response) or were included in the RG3. All of the following results are based on the RG3 regional chronology and represent an eastern sub-region of the study region.

The climatic response of the RG3 chronology shows negative correlations with temperatures of the current and previous growth season and positive correlations with the precipitation in the same months (Figure 2a). Consequently, there are stable positive correlations with the Palmer Drought Severity Index throughout the year. The growth limitations due to temperature and soil moisture estimated from the VS-Lite model (Figure 2b) confirm the same pattern: the tree growth is limited by soil moisture from June to August and by temperature in the other months. Although May and September are, on average, temperature limited according to the modeling results, they are close to become moisture limited, at least in warmer years. The calibrated model reproduces well the measured tree growth (Figure 3c), including all major growth declines. The correlation coefficients of the measured and modeled values vary from 0.55 to 0.69, which is rather good for this model. The calibration results and validation tests are shown in Table 1. The coefficients of correlation between the modeled and measured annual tree growth are significant for all experiments and do not change substantially with the changing calibration period. This confirms the robustness of the model used and its suitability for tree growth projections. A slightly poorer performance in the first half of the 20th century may be due to lower quality of the meteorological data at the beginning of the instrumental period and a weaker climatic response of trees in this period.

**Table 1.** VS-Lite model calibration and validation results. Coefficients of correlation between modeled and measured values are shown.

Calibration 1901-1958	Validation 1959-2016	Calibration 1959-2016	Validation 1901-1958	Calibration 1901-2016
0.59	0.67	0.69	0.55	0.59



**Figure 2.** a) Climatic response of the RG3 regional chronology: red bars show correlations with temperature, blue ones with precipitation, and orange ones with the Palmer Drought Severity Index (PDSI). Letter p marks months of the year previous to the growing season, b) growth limitations due to temperature (gT, red) and soil moisture (gM, blue) represented by VS-Lite: the lower line limits the maximum tree growth in the corresponding month of the growing season, c) results of the final VS-Lite model calibration: measured tree growth is shown in black and modeled values in red.

### 3.2. Tree growth projections

The results of the VS-Lite model driven by projected climatic variables show that the ensemble growth average iterates around the mean value throughout the 21<sup>st</sup> century, independently of the RCP used (Figure 3c). In previous studies for Central Chile and Northern European Russia we saw a distinct picture: for the drought intensive region in Chile the projected growth declined significantly already in the middle of the 21<sup>st</sup> century, and in a colder region of Northern European Russia it increased significantly driven by a temperature increase [7]. Here, although drought sensitive, the tree ring chronologies reproduced by the VS-Lite model did not respond negatively to the projected temperature increase (Figure 3a). On the contrary, when we extended the growth season from May-September to April-October (an extension that may be expected taking a significant projected

temperature increase), the projected tree growth also increased, especially for the RCP 8.5 scenario (Figure 3d). These results suggest that the projected increase in the temperature and the corresponding increase in evapotranspiration will not lead to a significant soil moisture deficit given a relatively stable amount of projected precipitation (Figure 3b). However, this result may also be an artifact of the Leaky Bucket soil moisture model utilized by the VS-Lite.

Climate extremes for historical and future scenarios and the corresponding average tree-growth indices are presented in Table 2. We see a significant increase in the extremely hot events for RCP 2.6 and especially for RCP 8.5. However, the number of dry and wet events is rather stable for both future scenarios and does not differ significantly from the historical period. Interestingly, the number of simultaneously hot and wet events is mostly similar for the historical and RCP 2.6 scenarios, with all extremely wet events being also hot. For RCP 8.5 only 36 of 148 wet events are also hot, and also some 98 hot and dry events are present (contrary to the historical and RCP 2.6 scenarios). Hot and wet extremes favor tree growth, with its values during such extremes higher than average. Cold and dry extremes, on the contrary, reduce tree growth (Table 2). Combinations of hot and dry, as well as cold and wet extremes lead to reduced growth, while hot and wet extremes expectedly lead to increased growth.

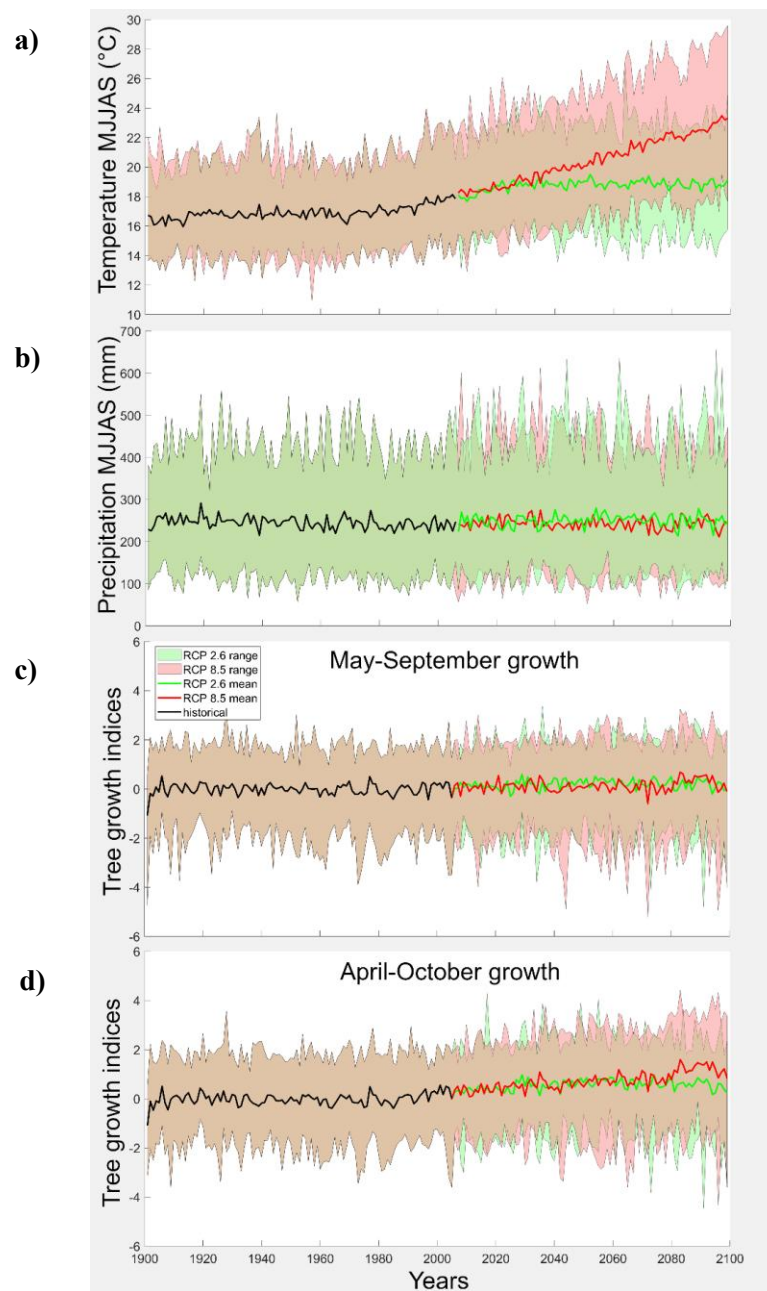
**Table 2.** The number of extreme events\* and mean modeled tree-growth index for the corresponding years and model outputs.

	Cold	Hot	Dry	Wet	Cold and dry	Hot and dry	Cold and wet	Hot and wet
Historical	184	316	248	135	0	0	21	135
RCP 2.6	13	642	113	155	0	0	2	155
RCP 8.5	6	1343	222	148	0	98	2	36
Mean tree-growth index	-0.30	0.35	-0.48	1.09	-	-0.31	-0.92	1.13

\* mean seasonal temperature and total seasonal precipitation beyond 5<sup>th</sup> and 95<sup>th</sup> percentiles of the historical period data

### 3.3. Limitations of the methodology

Despite the advantages over the linear models for tree-growth projections, the applied VS-Lite model has multiple limitations which should be taken into account when the results are interpreted. The model accounts only for climatic drivers of tree growth. It does not take into account possible effects of increased atmospheric CO<sub>2</sub> and its fertilization. It also does not account for possible tree dieback, i.e. even minimal modelled tree growth does not kill the model tree and lets it grow next year. Negative effects of forest fires, pest outbreaks, and other factors that may significantly change in the future are not taken into account by the model. All or mostly all of these effects, however, may be estimated separately by other methods and united for more realistic projections.



**Figure 3.** Ensemble means and ranges for the modeled mean May-September temperature (a), total May-September precipitation (b), and growth of pine (c, d) in the eastern sub-region according to three scenarios: historical, RCP 2.6, and RCP 8.5.

#### 4. Conclusions

We applied a previously developed methodology based on a simplified process-based Vaganov-Shashkin model (VS-Lite) and CMIP5 climatic simulations to project tree growth in Povolzhie region in the 21st century.

Our projections show a constant tree growth throughout the 21st century. The extension of the growth period in the model parameters from May-September to April-October gives an increase in tree growth, especially in the RCP 8.5 scenario.



The climate extremes during the growth period (except high temperatures) are projected to be stable throughout the century. The increased temperatures alone are not going to significantly change the tree growth or endanger the forests in the region, according to our modelling results.

### Acknowledgements

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