Radial growth projections for spruce on Solovetskiye Islands, the White Sea, for the 21st century

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Abstract. Climate change projected for the 21st century is expected to affect different forest ecosystems with corresponding ecological, economic, and social impacts. Modeling is extensively used to estimate the impacts of climate change on tree species distributions, but only several studies produced tree growth projections based on climate change scenarios. However, those studies have been based on multiple regression models without considering the basic principles of dendroclimatology – principle of limiting factors and uniformitarian principle. Here we describe the methodology for tree growth projections that takes advantage of the process-based forward model of tree growth, VS-Lite, calibrated and independently validated on tree-ring data and driven by climate projections. We further use this methodology for spruce growth projections on Solovetskiye islands according to two extreme greenhouse gases emissions scenarios. Even according to the conservative one, which is peak-and-decay scenario, tree growth is projected to be significantly higher throughout the 21st century, than in the 20th century. These results are crucial for the strategies of Arctic region development in the near and remote future.

1. Introduction
Instrumental air temperature measurements over the globe provide high confidence that it is continue to increase for more than 100 years [1]. In addition, results of climate models project increased air temperatures in 21st century compared to those in 20th century, under different scenarios of emissions of greenhouse gases [2]. That condition directly affects different forest ecosystems [3] with corresponding ecological, economic, and social impacts. In high latitudes and altitudes, the effect of warming is known to be amplified [4], leading to observed temperature trends being higher than global average, and higher pronounced consequences.

Modeling is extensively used to estimate the impacts of climate change on tree species distributions [5], but only several studies produced tree growth projections based on climate change scenarios. The studies that we are aware of were based on multivariate regression models [6], although those models have not been validated on the data withheld from their calibration. Highly acknowledged standards of modeling in palaeoclimatology assume robustness of a model for its use for climate reconstructions and are commonly referred to as uniformitarian principle [7]. Applying these standards to tree-growth projections, we first have to make sure that the model we use for climate-growth inferences is robust, at least within the period with instrumental data, and then to apply this model to future climate data. On the other hand, in aforementioned studies the response of tree growth to climatic conditions was considered as a linear combination of many climatic variables, the assumption that goes against another basic principle of dendroclimatology – the principle of limiting factors [7]. Processed-based
forward models of tree-ring formation can represent mixed and non-linear tree growth responses to climatic factors, and in this sense 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. If these models are also validated on the data withheld from their calibration, their use will be also consistent with the principle of uniformitarianism.

Vaganov-Shashkin (VS) model [8] is one of the most explicit processed-based forward models of tree growth. However, it is rather sophisticated in application, since it has 42 tunable parameters and daily resolution. This model has been adapted for more practical monthly resolution with only 12 tunable parameters left, and the adapted model was called “VS-Lite” [9].

In this study, we use the VS-Lite model for spruce (Picea abies (L.) Karst and Picea obovata Lebed.) growth projections under different Representative Concentration Pathways (RCPs) on Solovetskiye islands.

We selected Solovetskiye Islands for our study because of the following reasons:
- Availability of many tree-ring chronologies from different ecological habitats and weakly disturbed forests, including trees older than 400 years, situated in a small, climatically homogeneous region;
- Growing importance of Arctic regions for social and economic development in the 21st century.

This paper aims on two main targets:
- Development of the methodology of tree growth projections based on process-based model of tree growth;
- Application of this methodology to spruce trees growing on Solovetskiye Islands to project their growth in 21st century according to two extreme RCP scenarios.

2. Materials and Methods

2.1. Tree-ring data

The field work in the Solovetskii Archipelago was started during the field season of 2009 and continued in 2012. The tree-ring network developed on the islands consists of 10 local tree-ring sites of spruce (Picea abies (L.) Karst and Picea obovata Lebed.), that grow in different types of landscapes: sea terraces, peat bog surfaces, and slopes of the hills (table 1). 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 the wooden beams with perpendicular fibers direction and sanded with gradually finer sand paper up to 600 grid [10]. 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 representation of the measurements [11]. Cross-dating and quality control of time-series was assessed by the COFECHA software [12], with core segments having low correlation values being excluded from the analysis.

The resulting tree-ring series were standardized to dimensionless indices in order to remove the age trend and to preserve variations related to climate. We used ARSTAN program for standardization, and splines with 50% variance cutoff on 67% of series’ lengths were used for detrending. All the 135 tree-ring series from 10 sites were united to acquire composite chronology representing average growth of spruce on the islands.

Statistics were computed for local and composite tree-ring width chronologies by means of five coefficients commonly used in dendroclimatology: mean sensitivity, standard deviation, the expressed population signal (EPS), the effective signal (Rbar.eff) and the signal-to-noise ratio (SNR). Mean sensitivity is a measure of the year-to-year variation. Expressed population signal (EPS) indicates the extent to which the sample size is representative of a theoretical population with an infinite number of individuals [13]. Signal-to-noise ratio is calculated following [14] and represents the strength of the observed common signal among the trees in a chronology. The effective chronology signal is the measure of the mean correlation between tree-ring series.
Table 1. Statistics of the local and composite tree-ring width spruce chronologies from Solovetskiy Archipelago.

| Site Code | N     | E       | H (m, asl) | Cores (Trees) | First Year | Last Year | Length | Mean Sensitivity | Standard deviation | Rbar.eff | EPS | SNR |
|-----------|-------|---------|------------|---------------|------------|-----------|--------|-----------------|-------------------|----------|-----|-----|
| B02E      | 65.11967 | 35.67458 | 69         | 15 (8)       | 1720       | 2012      | 293    | 0.185           | 0.280             | 0.281    | 0.684 | 2.162 |
| B05E      | 65.11887 | 35.6904  | 62         | 22 (12)      | 1636       | 2011      | 341    | 0.194           | 0.198             | 0.44     | 0.85  | 0.73 |
| B06E      | 65.11786 | 35.67371 | -          | 12 (6)       | 1822       | 2011      | 190    | 0.241           | 0.230             | 0.139    | 0.24  | 0.315 |
| B07E      | 65.16492 | 35.67428 | 6          | 16 (8)       | 1774       | 2011      | 238    | 0.194           | 0.197             | 0.314    | 0.738 | 2.815 |
| B10E      | 65.07603 | 35.53442 | -          | 19 (9)       | 1737       | 2011      | 275    | 0.175           | 0.198             | 0.246    | 0.634 | 1.731 |
| B13E      | 65.10468 | 35.62995 | -          | 14 (7)       | 1740       | 2011      | 272    | 0.169           | 0.198             | 0.246    | 0.634 | 1.731 |
| B16E      | 64.97218 | 35.74722 | 10         | 9 (5)        | 1689       | 2011      | 323    | 0.180           | 0.255             | 0.267    | 0.527 | 1.114 |
| B31E      | 65.14106 | 36.11806 | 32         | 10 (5)       | 1867       | 2011      | 145    | 0.178           | 0.205             | 0.554    | 0.843 | 5.386 |
| B32E      | 65.14153 | 36.11836 | 38         | 9 (5)        | 1838       | 2011      | 174    | 0.202           | 0.268             | 0.385    | 0.705 | 2.389 |
| B41E      | 65.14308 | 36.12625 | 11         | 9 (5)        | 1936       | 2011      | 76     | 0.257           | 0.272             | 0.457    | 0.773 | 3.403 |
| Composite | -     | -       | -          | 135 (70)     | 1626       | 2012      | 387    | 0.169           | 0.193             | 0.227    | 0.956 | 21.6 |
2.2. Meteorological data
The monthly mean temperature and precipitation records were taken from the nearest land grid point (64.25°N, 35.75°E) from the CRU TS 4.01 database [15], where the records start in 1901. In addition, we used temperature and precipitation records from the nearest mainland weather station Kem'-Port (64.98°N, 34.8°E, 8 m a.s.l.), where the observations begin from 1891.

2.3. VS-Lite modelling
VS-Lite is a simplified version of the full Vaganov–Shashkin forward model [8]. For the 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 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 [7], remains largely unchanged in VS-Lite.

VS-Lite model estimates monthly soil moisture from temperature and total precipitation data via the empirical one-layer Leaky Bucket model of hydrology [16]. 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 are not considered in the model and thus all precipitation is assumed to be liquid. Seasonal insolation or day length is determined from 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, root depth) were set to the default values proposed in [9]. 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 [17]. The posterior median for each parameter was used to obtain the “calibrated” growth response for a given site.

The robustness of the VS-Lite modeling was assessed by validation of its performance on the period withdrawn from the calibration. The whole period was divided into two equal periods of 55 years (1901-1955, 1956-2010). First the model was calibrated on one of them and validated on another and then vice versa. Finally, we ran the model over the entire period 1901–2011 using the calibrated parameters.

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, including those from CMIP5 (Climate Model Intercomparison Project, phase 5) long-term experiments [18].

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 [19]). These simulations provide the maximum range of the possible climate change during the 21st century in the framework of CMIP5. The labels for the RCPs provide a rough estimate of the radiative forcing in the year 2100 (relative to 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/m2 at the end of the century. In RCP2.6, radiative forcing reaches a maximum near the middle of the 21st century (about 3 W/m2) before decreasing to a level of 2.6 W/m2 at the end of the 21st century.
For the aims of comparison of projected tree growth with the modern conditions we use the results of the “historical” run (sometimes referred to as “twentieth century” simulations). This experiment is included into the core of the long-term simulations of CMIP5. “Historical” run is forced by observed atmospheric composition changes (reflecting both anthropogenic and natural sources), and includes time-evolving land cover. The historical runs cover much of the industrial period (1850-2005). Direct comparison of modeled radial growth based on CRU TS data and on “historical” run data is not applicable here, because inter-annual variability is not reproduced well enough by the climate models. On the other hand, climate models reproduce the mean values of monthly temperature and precipitation for historical period well enough for the study region. This allowed us to use the output of the climate models without additional adjustments to correspond to the CRU TS data.

Data from each model were interpolated to one geographical point, representing Solovetskiye Islands (65.08°N, 35.7°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 tree-ring and instrumental climatic data to make tree growth projections. We used output of each model as an input to VS-Lite model, and then all the VS-Lite outputs were averaged to get the ensemble chronology. We calculated the modeled growth for historical period 1901-2005, and projected period 2006-2095. We divided the projection period into three 30-years-long periods: near (2006-2035), intermediate (2036-2065), and remote (2066-2095) future. To compare the projected tree growth by periods, we use ANOVA test, and the differences were tested using the post hoc Turkey’s test.

3. Results and discussion

3.1. VS-Lite model calibration and validation

The simulated tree-ring chronology represents an estimate of radial tree growth driven by climate variability (figure 1c). Partial growth rates due to temperature and soil moisture estimated from the model (figure 1b) are typical for a northern location with sufficient precipitation. Tree growth is mainly limited by temperature, and only in July mean temperature is high enough to make soil moisture act as primary limiting factor. The results of calibration and validation tests are shown in the table 2. Coefficients of correlation between modeled and measured annual tree growth are significant for all the experiments and do not change substantially from the calibration to the validation period. This confirms the robustness of the model used and its suitability for tree growth projections.

| Table 2. VS-Lite model calibration and validation results. Coefficients of correlation between modeled and measured values are shown. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Calibration 1901-1955 | Validation 1956-2010 | Calibration 1956-2010 | Validation 1901-1955 | Calibration 1901-2011 |
| 0.55 | 0.45 | 0.55 | 0.46 | 0.51 |
3.2. Tree growth projections

From the modelled partial growth rates according to temperature and soil moisture (figure 1b) we may assume an increase of tree growth in 21st century due to increasing temperatures in all the CMIP5 projections. The results of VS-Lite model driven by projected climatic data confirm these expectations (figure 2). According to both considered scenarios ensemble tree ring growth increases with respect to historical period (table 3). ANOVA results indicate significant (p<0.001) differences.
between groups of mean ensemble values of radial growth for historical, near, intermediate and remote future for both RCP scenarios (table 4). Even the conservative peak-and-decay emissions scenario (RCP 2.6) results in significantly increased tree growth throughout the 21st century. Under the more extreme scenario RCP 8.5, growth increase is much higher, confirming that projected changes in temperature are supported by sufficient supply of moisture from projected precipitation. Mean projected tree growth for the far future (2066-2095) according to RCP 2.6 and RCP 8.5 correspond to 90th and 99th percentiles of the modeled tree growth for the historical period (1901-2005). Already in the near future (2006-2035) ensemble growth projection is higher than 87% of all historical values (table 3).

Table 3. Descriptive statistics of projected tree-ring indices to near (2006-2035), intermediate (2036-2065), and remote (2066-2095) future.

| Statistics | Historical | Near | Intermediate | Remote |
|------------|------------|------|--------------|--------|
| Mean ± STD | -0.02 ± 0.98 | 1.02 ± 0.96 | 1.31 ± 1.0 | 1.17 ± 1.14 | 2.43 ± 1.16 |
| Min | -5.43 | -2.18 | -2.80 | -2.68 | -2.43 | -1.87 |
| Max | 3.57 | 4.11 | 4.37 | 4.63 | 5.47 | 4.32 | 6.11 |
| Median | 0.05 | 1.05 | 1.04 | 1.29 | 1.78 | 1.22 | 2.26 |
| Q1 | -0.57 | 0.43 | 0.48 | 0.7 | 1.18 | 0.59 | 1.72 |
| Q3 | 0.63 | 1.6 | 1.57 | 1.91 | 2.43 | 1.82 | 3.2 |
| PRC* | - | 87 | 87 | 93 | 98 | 90 | 99 |

*the mean value of tree growth projection for the period corresponds to this percentile of the distribution of the modeled values for the historical period (1901-2005).

Table 4. Results of ANOVA and subsequent multiple comparison of the groups. Ones indicate significant difference of group means (p<0.05), zeros indicate that there is no difference at this significance level. Groups correspond to historical period (1976-2005), near (2006-2035), intermediate (2036-2065), and remote (2066-2095) future.

| RCP 2.6 | RCP 8.5 |
|---------|---------|
| Near | Intermediate | Remote | Near | Intermediate | Remote |
| Historical | 1 | 1 | 1 | 1 |
| RCP 2.6 | - | 1 | 0 | 0 | 1 |
| Intermediate | 1 | - | 0 | 1 | 1 |
| Remote | 0 | 0 | - | 0 | 1 |

3.3. Methodological limitations
It is important to mention that VS-Lite model used here for radial growth projections accounts only for climatic drivers of tree growth. Even under the assumption that the model will adequately reproduce radial growth under significantly altered climatic conditions, other factors that are not included in the model can equally affect tree growth. These factors include fertilization effect of elevated atmospheric carbon dioxide (CO₂), climate-triggered outbreaks of insect pests and other diseases, changes in extreme weather events, etc. Concerning the former factor, photosynthesis rate of trees depends on atmospheric CO₂ variation. Elevated atmospheric CO₂ leads to increased photosynthesis, decreased stomatal conductance in leaf and consequently trees use less moisture [20]. At the same time,
increased temperatures have opposite effect on trees making them use more water and photosynthesize less [21]. Recent model experiments were concerning whether elevated CO$_2$ and acclimation are able to compensate negative influence on trees from raised temperatures [22]. For the study region, however, climate projections suggest sufficient moisture availability. Hence, the fertilization effect of elevated CO$_2$ may only increase the projected radial tree growth. Quantification of the effects of other factors that can significantly contribute to increased tree mortality and thus affect the projections of average tree growth is beyond the scope of our study.

3.4. Scientific and social significance of the results
The acquired radial growth projections for spruces growing on the Solovetsliye islands might be important for the strategies of adaptation to climate change in the Arctic region, especially for the forest management. Increased radial growth suggested by our results will lead to higher wood production, which is important to consider in economic forecasts. Another consequence will be increased carbon storage in spruce forests in the region, which is crucial for quantification of global carbon budget. Our results constitute the first step to such estimates, presuming additional efforts for translating them to other regions and species, and also transforming them to quantitative estimates of specific parameters of interest.

Our results suggest rather favorable conditions for the future spruce growth in the region. However in other regions and for other species, projections may indicate decreased radial growth, and thus increased probability of tree mortality and forest decay. We encourage such studies in the regions where trees are known to be vulnerable to recent climatic changes. The methodology proposed in our study may bring new insights for the future of such vulnerable ecosystems and make contribution for their sustainable development, or warn about anticipated risks.

4. Conclusions
In this study we give an example of tree growth projections for the 21st century based on newly developed methodology, which uses process-based forward model of tree growth driven by climate projections from an ensemble of state-of-the-art climate models. Applied to spruces growing in Solovetskiye islands in Russian Arctic, this methodology provides evidence of significantly increased tree growth throughout the 21st, even according to the conservative peak-and-decay emissions scenario.

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