Assessment of the response of Russian forest ecosystems to different climatic conditions from model data

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Abstract. The response of extra-tropical evergreen and deciduous Russian forest ecosystems to a wide range of atmospheric background conditions is considered. This study is performed by using a land-surface model, JSBACH. Two numerical experiments are carried out: with hotter and more humid (model PLASIM) and more moderate (model INMCM4) atmospheric background conditions. A perturbation in the climate system is set by using the RCP 8.5 climate scenario. The study has shown a geographical redistribution of the extra-tropical evergreen and deciduous forests across Russia as well as an increase in their fractions in some already forested regions. An increase in the gross and net CO\textsubscript{2} assimilation and respiration of these types of forest vegetation, as their response to the climatic disturbances, is obtained. However, even under the conditions of extremely intense climatic disturbances the Russian forest ecosystems will continue to act as CO\textsubscript{2} sinks.

1. Introduction

Due to its geographical location Russia has a wide variety of surface characteristics, such as orography, vegetation types, and greenhouse gas fluxes (carbon dioxide, methane). Forests in general and Russian forests in particular act as natural greenhouse gas sinks. Assessing the carbon budget of forests and carbon dioxide fluxes for Russia is particularly important in the context of the Paris Agreement [1].

The biosphere is an essential component of the Earth climate system in terms of the global cycle of main greenhouse gases, the hydrological and energy cycles. The interaction of the surface and the atmosphere is one of the key characteristics for an understanding of the climate system dynamics, which determines the energy, water, and greenhouse gases (such as CO\textsubscript{2}, CH\textsubscript{4}) fluxes [2,3]. The surface plays an essential role in climate modeling. It affects biophysical and biogeochemical processes [4,5], controls the distribution of energy. The energy cycle is associated with the hydrological cycle, which redistributes the precipitation to surface runoff, drainage and infiltration, determining the soil moisture and, as a result, the total evaporation. The biogeochemical processes of the carbon cycle are mainly represented by the carbon sink on the surface, which is closely related with the hydrological cycle through the stomatal control of the leaves during photosynthesis and transpiration [6-8].

Climatic conditions are a governing factor in the growth of various types of vegetation. At the same time, vegetation affects climate by controlling energy balance, surface water, and CO\textsubscript{2} concentration budget [9-13]. In the context of global climate change, it is important to understand what changes are possible for a given territory, how energy and greenhouse gas fluxes and the distribution limits of different types of vegetation and surface types can change. This knowledge will allow assessing the risks associated with these changes and developing the most effective ways to adapt the population, industry, and agriculture to the predicted changes.

In an earlier paper the authors have already studied the response of plant ecosystems (extra-tropical forests, shrubs and grass vegetation) to climatic changes for Siberia [14]. In the current study, the area
of consideration has been increased, and the entire territory of Russia is considered. Attention is focused only on the forest ecosystems (extra-tropical evergreen and deciduous forests). A wide range of atmospheric background conditions is considered, that allow us to estimate the possible variety of the ecosystem response to the applied climatic disturbances.

2. Data and method
In the study, two numerical experiments were carried out, differing in the atmospheric background conditions. Each of the experiments consisted of two parts: simulation for the historical period and the climate scenario RCP 8.5 [15].

2.1 Experimental design
In this study, for the numerical experiments a technique used in a previous paper was applied [14]. As in that paper, the land surface model JSBACH [16-18] was used. The JSBACH gives a complete description of the processes in the soil-vegetation-atmosphere system and can work offline with external climate data as forcing. The model reproduces the soil hydrology, the heat transfer in soils and the energy balance on the soil surface [19], dynamic processes of carbon absorption and emissions from soils and plants, photosynthetic and phenological processes, variation of the surface radiation and background albedo [20, 21], changes in the vegetation cover (including damage by wind and fire) [18, 22]. For the experiments of this study, the atmospheric background conditions required for the JSBACH model were set using two data sets previously obtained using the global large-scale model of intermediate complexity PLASIM [23] and the global climate model INMCM4 [24].

The numerical experiment with each of the atmospheric datasets consisted of two parts: the historical part and the part (until 2005) of the climatic scenario RCP 8.5 (until 2100). The climatic conditions for the historical pre-industrial period (until 2005) were set in the case of the PLASIM model by fixing the global atmospheric CO$_2$ concentration at 360 ppm, and in the case of the INMCM4 model according to the CMIP5 protocol "Historical simulation". Further, following the RCP 8.5 climate scenario (until 2100), an exponential increase in the global atmospheric CO$_2$ concentration was established from the current value to a level of 936 ppm. This final CO$_2$ concentration value is almost 2.3 times higher than its pre-industrial value.

2.2 Background atmospheric conditions
The climatic scenario RCP 8.5 used in the work allowed us to set conditions for extreme climate warming for Russia (Table 1). For a given increase in the carbon dioxide concentration, the model PLASIM demonstrated an increase in the time-period average of the minimum ($T_{\text{min}}$) and maximum ($T_{\text{max}}$) daily temperature. In the north of the territory under consideration, the difference reached 8°C. A slight increase in the average precipitation ($P_{\text{sum}}$) was obtained over most of Siberia, and a slight decrease was along the southern border of Russia. The surface specific humidity ($Q_{\text{air}}$) increased with anthropogenic load rising throughout the territory. The wind speed (Wind) increased by 0.3-0.6 m/s in the north of Eastern Siberia and the Far East and decreased by 0.3-1.2 m / s in the rest of the territory. As a result of an increase in the global atmospheric CO$_2$ concentration rise, the radiation parameters were changed as well. There was an increase in the surface downward longwave radiation ($R_{\text{lwb}}$) and a decrease in the surface balance of solar radiation with a cloudless sky throughout Russia. The surface downward shortwave radiation ($R_{\text{s wb}}$) increased in southwestern Siberia and decreased in the rest of the Russian territory.

For the Russian territory, the climate reproduced by the INMCM4 model in the same conditions of the global atmospheric CO$_2$ concentration growth turned out to be significantly less hot, less humid, and less windy than the climate of the PLASIM model. Moreover, in comparison with the PLASIM model, the INMCM4 model demonstrated, under the given conditions, a stronger increase in the precipitation, a more intensive growth of minimum and less intensive growth of maximum daily temperatures (Table 1). The intensity of changes of the other mean territory atmospheric parameters is similar to each other for these models. Comparing the models INMCM4 and PLASIM, the patterns of
the geographical distribution over Russia, changes of all used atmospheric background parameters are similar.

Table 1. Background atmospheric parameters mean for 20-year periods averaged over Russia.

|          | $T_{\text{min}}$, °C | $T_{\text{max}}$, °C | $P_{\text{raino}}$, mm | $Q_{\text{air}}$, $10^{-3}$ kg/kg | Wind, m/s | $R_{\text{lw}}$, W/m$^2$ | $R_{\text{sw}}$, W/m$^2$ |
|----------|-----------------------|-----------------------|-------------------------|----------------------------------|----------|-------------------------|-------------------------|
| PLASIM   | 1981-2000             | 4.45                  | 6.87                    | 956.33                           | 5.03     | 7.71                    | 298.13                  | 104.07                 |
|          | 2081-2100             | 9.79                  | 11.89                   | 1029.86                          | 6.82     | 7.47                    | 328.82                  | 99.72                  |
| Difference|                       | 5.35                  | 5.02                    | 73.54                            | 1.78     | -0.24                   | 30.69                   | -4.35                  |
| INMCM4   | 1981-2000             | -11.30                | -0.13                   | 563.32                           | 3.48     | 3.61                    | 257.85                  | 126.95                 |
|          | 2081-2100             | -5.87                 | 4.10                    | 670.67                           | 4.59     | 3.63                    | 281.42                  | 123.54                 |
| Difference|                       | 5.44                  | 4.23                    | 107.34                           | 1.11     | 0.03                    | 23.57                   | -3.41                  |

3. Results

Extra-tropical evergreen and extra-tropical deciduous forests were considered. Here deciduous means summergreen forests (leaf-bearing forests including larches), and evergreen means forests which are green all year (including pines and fir-trees). Estimates of the response of the spatial distribution of the above forest types, as well as their gross and net CO$_2$ assimilation, to assigned climatic perturbations are presented. The total CO$_2$ flux from the surface of the Russian territory to the atmosphere, in whose formation all vegetation types (including shrubs and grass, not just forests) simulated by the JSBACH model are involved was also assessed.

3.1. Forest vegetation

The numerical experiments performed for different background atmospheric conditions demonstrate similar, but not identical, nature of the spatial distribution of the forest vegetation throughout Russia (Figures 1 and 2).

At the end of the 20$^{th}$ century extra-tropical evergreen forests became more widespread throughout the territory under the atmospheric conditions specified by the INMCM4 model than in the climate conditions specified by the PLASIM model (Figure 1). It is especially clearly seen in the Far East of Russia and the Kamchatka Peninsula, where the fraction of this type of vegetation is substantially larger for the INMCM4 climate conditions than for the PLASIM.

By the end of the 21$^{st}$ century, after injecting climate perturbations according to the RCP 8.5, extra-tropical evergreen forests shift to the north with a decrease of their fraction at the southern Russian borders and an increase in the North of Russia for the atmospheric conditions specified by the PLASIM model. The milder (in general) atmospheric conditions set by the INMCM4 model with a similar intensity of climatic disturbances cause significantly less dramatic changes in the spatial distribution of extra-tropical evergreen forests than the conditions of the PLASIM model. They cause only a small increase in the fraction in the north of the European part of Russia and Western Siberia, and also on the eastern coasts of Russia.

For the distribution of the extra-tropical deciduous forests, as compared with the extra-tropical evergreen, a different picture was obtained at the end of the 20$^{th}$ century. The deciduous forests have become more widespread in a milder climate defined by the INMCM4 model. Under these conditions, the extra-tropical evergreen forests fraction more or less remains throughout Russia. Unlike the INMCM4 conditions, under the conditions specified by the PLASIM this vegetation type is almost absent in the Far East of Russia.
Figure 1. Extra-tropical evergreen forests, vegetation fraction (a, b) and difference between the end of 21st century (2081-2100) and 20th century (1981-2000) (c, d) for atmospheric conditions from PLASIM (a, c) and INMCM4 (b, d) model output.

Figure 2. The same as Figure 1 but for extra-tropical deciduous forests.
As in the case of extra-tropical evergreen forests, the response of extra-tropical deciduous forests to injected climatic disturbances differs for the atmospheric conditions given by the INMCM4 and PLASIM models. By the end of the 21st century, under the PLASIM atmospheric conditions the fraction of this vegetation type increases in the north of the central part of Russia, especially in the North Siberian Lowland, along the Lena River and in Transbaikal. However, in the area of the Vilyui River and at the southern borders of Russia a focal reduction of the extra-tropical deciduous forests fraction was obtained. Under the conditions specified by the INMCM4 model changes in the distribution of the vegetation fraction of this type are less intense. These conditions cause a slight increase of the fraction in the Taymyr Peninsula and the north of Kolyma and Chukotka.

3.2. Canopy CO$_2$ assimilation

When the geographic distribution and density (fraction) of vegetation cover change, it is quite natural to expect a change in the amount of carbon dioxide absorption by it from the atmosphere.

In the whole territory, an increase in the total gross and net CO$_2$ assimilation was obtained by the end of the 21st century compared to the end of the 20th century for both types of forest vegetation considered (Table 2). Within each numerical experiment for both the end of the 20th century and the end of the 21st century, comparable values between the evergreen and deciduous forest vegetation types gross and net CO$_2$ assimilation were obtained. In the warmer and more humid atmospheric conditions specified by the PLASIM model, as compared with the INMCM4, for both types of forest vegetation under consideration there is more intensive absorption of CO$_2$ from the atmosphere, accumulation of CO$_2$ in the biomass, and more intense respiration (which is the difference between the gross and net CO$_2$ assimilation). However, the evergreen and deciduous forest vegetation shows various responses to climatic disturbances under different background atmospheric conditions. The gross CO$_2$ assimilation of the evergreen forest vegetation demonstrates a higher percentage of the response to the disturbances injected to the background conditions set by the INMCM4 model than those set by the PLASIM. For the deciduous forest vegetation, the situation is opposite: a higher gross CO$_2$ assimilation response was obtained for the atmospheric conditions specified by the PLASIM model. The respiration of these vegetation types demonstrates a similar response. However, the response of the net CO$_2$ assimilation to the injected disturbances differs from the gross one. By the end of the 21st century, as compared with the end of the 20th century, for both types of forest vegetation under consideration there is a more intensive increase in the CO$_2$ accumulation in vegetation under the conditions specified by the INMCM4 model than by the PLASIM.

| Table 2. Mean annual gross and net CO$_2$ assimilation by canopy and canopy respiration for Russia, [Gt C yr$^{-1}$]. |
|---|---|---|---|---|
| | Gross assim. | Net assim. | Respiration |
| | Evergreen | Deciduous | Evergreen | Deciduous | Evergreen | Deciduous |
| PLASIM atm. | | | | | | |
| 1981-2000 | 4.881 | 4.385 | 4.538 | 4.080 | 0.343 | 0.305 |
| 2081-2100 | 5.876 | 5.785 | 5.409 | 5.286 | 0.467 | 0.499 |
| Difference | 0.995 (20.39 %) | 1.399 (31.90 %) | 0.872 (19.21 %) | 1.206 (29.57 %) | 0.124 (36.15 %) | 0.194 (63.61 %) |
| INMCM4 atm. | | | | | | |
| 1981-2000 | 3.759 | 3.248 | 3.529 | 3.035 | 0.230 | 0.213 |
| 2081-2100 | 4.987 | 4.263 | 4.653 | 3.956 | 0.334 | 0.307 |
| Difference | 1.228 (32.66 %) | 1.016 (31.27 %) | 1.125 (31.87 %) | 0.921 (30.35 %) | 0.104 (45.22 %) | 0.094 (44.13 %) |
The spatial distribution of changes in the gross and net CO₂ assimilation by the forest vegetation was also affected by different climatic conditions from the numerical experiments (Figure 3).

Under the PLASIM atmospheric conditions the spatial distribution pattern of the change in the gross CO₂ assimilation by extra-tropical evergreen forests is similar to the pattern of the spatial distribution of this vegetation type. A reduction in the gross CO₂ assimilation was obtained in those areas where a reduction in the fraction of this vegetation type occurred, and its increase in areas where the extra-tropical evergreen forests fraction increased (Figures 1c and 3a). A slightly different picture was obtained for the extra-tropical deciduous forests. An increase in the gross CO₂ assimilation was obtained not only in areas where the deciduous forests fraction increase was present, but also in already forested areas where the fraction increase did not occur (Figures 2c and 3c).

Similar changes were obtained for the atmospheric background conditions specified by the INMCM4 model. However, in this case the vegetation types seemed to reverse roles. By the end of the 21st century for the extra-tropical deciduous forests the gross CO₂ assimilation increase was obtained only in regions with an increased fraction of this vegetation type (Figures 2d and 3d). For the extra-tropical evergreen forests growth was additionally shown in already forested regions where the vegetation fraction has not changed (Figures 1d and 3b).

![Figure 3](image)

**Figure 3.** Difference between the end of 21st century (2081-2100) and 20th century (1981-2000) for annual gross CO₂ assimilation by extra-tropical evergreen (a, b) and deciduous (c, d) forests in atmospheric conditions from PLASIM (a, c) and INMCM4 (b, d) model output, [Mt C m⁻² yr⁻¹].

The spatial distribution of the net CO₂ assimilation response to the climatic forcing in the given atmospheric conditions is similar to the gross CO₂ assimilation response (not shown in the figures).
3.3. CO₂ flux to the atmosphere

Forests cover a substantial part of the territory of Russia. Their spatial redistribution, as well as a change in their CO₂ absorption properties, will contribute significantly to the geographical distribution of CO₂ fluxes to the atmosphere.

For the Russian territory as a whole, by the end of the 21st century the numerical experiments showed a decrease of CO₂ absorption from the atmosphere. Moreover, for some regions the CO₂ fluxes to the atmosphere even change their sign (Figure 4). The nature of the spatial distribution of the CO₂ fluxes changes similarly to the nature of the changes obtained for the gross CO₂ assimilation by extratropical evergreen and deciduous forests (Figure 3). In particular, for the atmospheric conditions specified by the PLASIM model the reduction in the annual CO₂ flux to the atmosphere was obtained in the same regions where the decrease in the gross CO₂ assimilation was shown (Figure 4 e and Figure 3 a, c). For the conditions specified by the INMCM4 model the result was the same but with a less magnitude of values.

![Figure 4](image)

**Figure 4.** Annual CO₂ flux to the atmosphere for 1981–2000 (a, b) and 2081–2100 (c, d), and the difference between the ends of the 21st century (2081–2100) and 20th century (1981–2000) (e, f) for atmospheric conditions from PLASIM (a, c, e) and INMCM4 (b, d, f) model output, [Mt C m⁻² yr⁻¹].
The total CO$_2$ flux to the atmosphere for the Russian territory for both time periods considered varies for different background atmospheric conditions (Table 3). For warmer and more humid conditions set by the PLASIM model lower values of the CO$_2$ flux to the atmosphere were obtained than for milder conditions set by the INMCM4 model. The response of the CO$_2$ flux to the atmosphere integral over the territory to the injected climatic disturbances (RCP 8.5) also depends on the background atmospheric conditions. By the end of the 21st century, a higher percentage of the response to the climatic disturbance was obtained for the PLASIM atmospheric conditions than for the conditions set by the INMCM4 model. However, despite high intensity of the injected disturbances the sign of the annual CO$_2$ flux to the atmosphere accumulated over Russia has not changed and remains negative.

|                | PLASIM   | INMCM4  |
|----------------|----------|---------|
| 1981-2000      | -0.763   | -0.849  |
| 2081-2100      | -0.121   | -0.360  |
| Difference     | 0.641    | 0.489   |

(-84.08 %)  (-57.64 %)

4. Conclusions
The above numerical experiments allowed us to estimate the sensitivity of Russian forest ecosystems to climatic changes. This research has shown that the sensitivity of the extra-tropical evergreen forests is higher than that of the deciduous forests, to global climate changes. A reduction in the vegetation fraction and growing areas near the southern borders of Russia and an increase in the northern regions of the territory were obtained. Thus, under warmer and more humid climate conditions on the territory of Russia, a significant geographical redistribution of the growing forest vegetation types is to be expected. A logical consequence of this, for each of the above-considered plant types, is a redistribution over the territory of the gross and net CO$_2$ assimilation. The increase in vegetation amount also contributes to the increase in CO$_2$ absorption from the atmosphere, which, in turn, contributes to the increase in the vegetation biomass. Of course, these mutually reinforcing processes cannot be infinite. A natural limiter is the climatic conditions formed in the territory (temperature and humidity conditions, in particular).

It should be noted that in some areas of Russia, due to injected extreme climate changes and the decrease in the vegetation amount, a change in CO$_2$ absorption up to emission was observed. However, the total CO$_2$ flux to the atmosphere for the Russian territory, even under extreme disturbances (RCP 8.5), remains negative by the end of the 21st century. It indicates that the vegetation cover of Russia provides CO$_2$ absorption from the atmosphere even in highly aggressive climatic conditions.

Forest vegetation, due to its biological properties, is quite an inert component of the climate system. These studies have shown that, no matter how extreme the climatic changes are, the Russian forest ecosystems will act as CO$_2$ sinks from the atmosphere. The Russian forests will play this role as long as the climatic conditions are suitable for the growth of biomass, and the CO$_2$ emissions to the atmosphere will not exceed the absorptive capacity of the forest ecosystems.

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