Siberian vegetation cover response to projected future climate change

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Abstract. Vegetation plays a key role in the global climate system via modification of the water and energy balance. Response of different vegetation types to present and projected climatic conditions was assessed for Siberia. The study was performed using JSBACH land surface model with atmospheric conditions obtained from INMCM4 modelling results. A climate change was determined according to the RCP 8.5 scenario. A geographical redistribution of extratropical forest and grass vegetation and weakening of a canopy ability to absorb carbon dioxide from the atmosphere were obtained for climate warming conditions for Siberia. It was established that Eastern Siberia is more sensitive to climate forcing than Western Siberia.

1. Introduction
Based on results of global circulation model (GCM) simulations, the Intergovernmental Panel on Climate Change (IPCC) expects a mean global warming by 1.4 – 5.8° C during 1990–2100 [1]. According to energy and fuel use statistical estimates during 1750–2010, the fossil fuel combustion and cement production have reached 365 ± 30 Pg C. In 2000–2009 the average fossil fuel and cement manufacturing emissions were 7.7 ± 0.5 Pg C yr$^{-1}$ with an average growth rate of 2.9 % per year, which is higher than during the 1990’s (1.0 % per year). In 2012 the fossil fuel emissions were 9.4 ± 0.8 Pg C. For the same period according to observations and modelling data a land-use change (mainly deforestation) was 180 ± 80 Pg C. In 2000–2009 the land-use change emissions were caused by tropical deforestation, and are estimated at 0.9 ± 0.5 Pg C yr$^{-1}$. This includes gross deforestation emissions of around 3 Pg C yr$^{-1}$ compensated by 2 Pg C yr$^{-1}$ of forest regrowth absorption in some regions (mainly abandoned agricultural land). Observations show the increase in the atmospheric CO$_2$ concentration from 278 ± 3 ppm in 1750 to 390.7 ppm in January 2011, which indicates accumulation in the atmosphere of 240 ± 10 Pg C. The atmospheric CO$_2$ concentration grew by 4.0±0.2 Pg C yr$^{-1}$ in the first decade of the 21st century.

According to the IPCC, the estimated land carbon pool consists of 275–565 Pg C in the living organisms and 1500–2400 Pg C in the soil near the Earth’s surface (excluding permafrost) [1]. By comparison, there is only approximately 800 Pg C in the atmosphere. The carbon amount stored in the terrestrial ecosystem is three times more than in the atmosphere. Change of the terrestrial carbon amount can significantly affect the concentration of atmospheric greenhouse gases (e.g., CO$_2$ and CH$_4$).
Climatic conditions are the main factor controlling the vegetation type diversity for different regions. At the same time, vegetation affects the state of the climate by managing the land surface water, energy balance, and CO$_2$ concentration [2–6]. There are all major vegetation zones (except for tropical rain forests) in the Russian territory (from grassy steppes in the South to tundra in the polar North). The treeless marshy tundra covers almost 10% of the country.

More than a half of the Russian territory is located above 60° N and snow-covered almost half a year. In Russia the annual mean surface temperature increased by 0.8–0.9°C over the 20$^{th}$ century and is estimated to continue increasing by 0.1–0.5°C per decade over the 21$^{st}$ century [1]. The average length of the growing season increased by 10–11 days since the beginning of 1960.

The Siberian ecosystems are considered to be highly sensitive to the climate change, because they are limited by low temperatures. A prolonged growing season and increased temperature will remove some of the environmental limitations and open areas for invading vegetation types from the lower latitudes. As a result, a polarward shift of their areas is expected. The diversity of the local species is expected to increase, since species from the lower latitudes invade faster than the present species become locally extinct. For example, Claussen M. and Esch M. expect favorable conditions for the temperate deciduous forest in Sweden and a shift of the taiga into the present areas of tundra in Siberia and Alaska [7]. A total reduction of tundra and cold deciduous forest and a total increase of cool mixed forest, cool conifer, and taiga are expected as well.

The purpose of this paper is to assess the response of the geographical distribution of extratropical forest and grass vegetation types and their ability to absorb carbon dioxide from the atmosphere to the climatic forcing assigned by the RCP 8.5 scenario.

2. Data and methods
2.1. Experimental design
The study of the Siberian vegetation cover response to global climate change was carried out using the JSBACH land surface model developed at the Max-Planck Institute for Meteorology (MPI-M) [8–10]. This model is a component of the Earth system model MPI-ESM. The JSBACH model allows one to calculate a large number of surface characteristics. The JSBACH model allows one to simulate soil processes (soil hydrology, heat transfer in soils, and energy balance on soil surfaces) [11], the dynamics of assimilation, storage and carbon emissions from plants and soils, photosynthetic and phenological processes, canopy radiation and dynamic background albedo [12,13], and vegetation cover change (including damage by wind and fires) [10,14]. This model can be launched in offline mode, which allows one to simulate the behavior of different surface characteristics depending on any given atmospheric conditions.

The results of numerical simulation obtained using the global climate model INMCM4 [15] were used to determine the atmospheric conditions for the JSBACH land surface model. These data were taken from the CMIP5 data bank. The simulation was made for 1901–2100. The concentration of atmospheric carbon dioxide in the atmosphere corresponded to the CMIP5 protocol “Historical simulation” for the first part of the period under review (1901-2005) and to the RCP 8.5 climatic scenario [16] for the second part (2006–2100). The climatic scenario RCP 8.5 is the most aggressive one, according to it the concentration of atmospheric carbon dioxide increases exponentially from 296 ppm to 936 ppm during 1901–2100, thus increasing by 2.3 times at the end of the simulation.

2.2. Region
In this work attention was focused on the territory of Siberia (both Western and Eastern Siberia). The boundaries of the territory were set as 50–70° N and 60–130° E.
3. Results
3.1. Atmospheric forcing
The state of the vegetation cover depends directly on the given background atmospheric conditions, in particular, on the temperature and humidity.

Here and below, we consider the difference between the 20-year average modeling data obtained for the late 20th and 21st centuries (2081–2100 minus 1981–2000). The choice of the period length is not accidental. It is explained by a high growth rate of the atmospheric CO$_2$ concentration determined by the chosen climatic scenario. Under these conditions the use of 30-year periods for averaging may underestimate the response under study.

The climate scenario used in this paper allowed us to set conditions for a strong climate warming in Siberia. On average, throughout the territory under consideration the mean daily surface air temperature ($T_{\text{mean}}$) by the end of the 21st century increased by 4.64$^\circ$C in comparison to the end of the 20th century (Table 1). The minimum daily temperature ($T_{\text{min}}$) increased more than the maximum daily temperature ($T_{\text{max}}$): 5.46$^\circ$C vs. 4.19$^\circ$C. The surface specific humidity ($Q_{\text{air}}$) increased by 1.16 $\times$ 10$^{-3}$ kg/kg and the annual precipitation amount ($P_{\text{r, sum}}$) increased by 109.29 mm. The change was not only in the wind speed ($\text{Wind}$).

Taking into account that the climate of Western and Eastern Siberia (WS and ES, respectively) differs significantly due to the geographic features, the average values of the above-mentioned characteristics were considered separately for each region. The boundaries of WS were determined as 50–70$^\circ$ N and 60–90$^\circ$ E and those of ES, as 50–70$^\circ$ N and 90–130$^\circ$ E.

ES was more sensitive to the atmospheric CO$_2$ concentration growth than WS. There was a more intensive growth of all atmospheric parameters for ES than for WS, except for the wind speed that had not changed significantly. In addition, the difference in growth between $T_{\text{min}}$ and $T_{\text{max}}$ for ES was larger than for WS. Thus, the difference between the growth of $T_{\text{min}}$ and $T_{\text{max}}$ at the end of the 21st century compared to the end of the 20th century was 1.17$^\circ$C (5.56$^\circ$C minus 4.39$^\circ$C) for WS against 1.36$^\circ$C (5.40$^\circ$C minus 4.04$^\circ$C) for ES. But, in general, the nature of changes of the considered atmospheric parameters for WS and ES was the same as for the whole Siberia.

| Region | $T_{\text{mean}}$, $^\circ$C | $T_{\text{min}}$, $^\circ$C | $T_{\text{max}}$, $^\circ$C | $P_{\text{r, sum}}$, mm | $Q_{\text{air}}$, 10$^{-3}$ kg/kg | Wind, m/s |
|--------|----------------|----------------|----------------|------------------|----------------|----------|
| Siberia | 1981–2000 | -5.55 | -12.31 | -0.31 | 522.32 | 3.40 | 3.45 |
| | 2081–2100 | -0.91 | -6.84 | 3.88 | 631.62 | 4.56 | 3.45 |
| Difference | 4.64 | 5.46 | 4.19 | 109.29 | 1.16 | 0.00 |
| WS | 1981–2000 | -3.34 | -10.17 | 1.86 | 530.76 | 3.62 | 3.67 |
| | 2081–2100 | 1.21 | -4.62 | 6.25 | 619.02 | 4.75 | 3.70 |
| Difference | 4.54 | 5.56 | 4.39 | 88.26 | 1.13 | 0.03 |
| ES | 1981–2000 | -7.23 | -13.96 | -1.96 | 517.60 | 3.24 | 3.29 |
| | 2081–2100 | -2.52 | -8.56 | 2.07 | 644.03 | 4.43 | 3.27 |
| Difference | 4.71 | 5.40 | 4.04 | 126.43 | 1.19 | -0.02 |

The changes of the atmospheric parameters were not distributed evenly throughout the territory (Figure 1). The greatest temperature increase ($T_{\text{mean}}$, $T_{\text{min}}$, and $T_{\text{max}}$) was in the
north of the territory under consideration, and the growth of $Pr_{sum}$ and the mean annual $Q_{air}$ were in the central part of the territory.

The distribution of these changes throughout the year was also uneven (not shown in the figures). The surface air temperatures ($T_{mean}$, $T_{min}$ and $T_{max}$) on average for the year increased mainly due to strong warming in winter. There was even a small temperature decrease in summer. In particular, at the end of the 21st century in comparison to the end of the 20th century, $T_{max}$ decreased by 2° C in the north-west and 1° C in the north-east of Lake Baikal in June and July, respectively. At the same time, the $Q_{air}$ and $Pr_{sum}$ on average for the year increased mainly due to the warm period of the year (May-September). In the cold period these parameters varied slightly.

![Figure 1. Difference between the end of 21st (2081-2100) and 20th (1981-2000) for $T_{min}$ (a), $T_{max}$ (b), $Q_{air}$ (c) and $Pr_{sum}$ (d), INMCM4.](image)

3.2. Vegetation cover response

The simulation carried out using the land surface model JSBACH with the atmospheric conditions obtained by the INMCM4 model with the climatic scenario RCP 8.5 allowed us to reveal the following features of some vegetation cover characteristics.

An extension of the extratropical forests (both evergreen and deciduous) to the North of the territory under consideration without a reduction of the forest fraction on the already forested areas was obtained (Figure 2 (a) and (b)). A similar result was obtained for the deciduous shrubs fraction (Figure 2 (c)). At the same time, the C3 grasses fraction was reduced in the North and in the South of the territory under consideration (Figure 2 (d)).

Along with the geographical redistribution of the vegetation types, there is a redistribution of the gross CO$_2$ assimilation by these types (Figure 3). The increase of gross CO$_2$ assimilation was obtained in the areas where the vegetation fraction also increased. However, for the extratropical evergreen and extra-tropical deciduous forests, a gross CO$_2$ assimilation increase was
Figure 2. Difference between the end of 21\textsuperscript{st} (2081-2100) and 20\textsuperscript{th} (1981-2000) for the fraction of extra-tropical evergreen (a), extra-tropical deciduous (b), deciduous shrubs (c) and C3 grasses (d), JSBACH.

noted also in regions where the fractions did not change (Figure 3 (a) and (b)). In addition, for the C3 grasses a gross CO\textsubscript{2} assimilation increase was obtained even for areas where a small reduction in the vegetation fraction of this type was detected (Figure 3 (d)).

In general, there is the assimilation of atmospheric CO\textsubscript{2} by the canopy only (as indicated by the negative sign of the CO\textsubscript{2} flux to the atmosphere) due to a large amount of vegetation in Siberia (Figure 4). In the climate warming conditions the increase of the atmospheric CO\textsubscript{2} absorption was obtained in Northern Siberia and in the Baikal region in areas where the forest and shrub vegetation fractions increased. At the same time, there was a total CO\textsubscript{2} absorption weakening in the South of WS and in the central part of ES.

Totally for the territory under consideration, the CO\textsubscript{2} absorption decreased by 20.40 % at the end of the 21\textsuperscript{st} century relative to the end of the 20\textsuperscript{th} century (Table 2). ES demonstrated higher sensitivity to the given climatic forcing than WS (22.74 % vs. 17.13 %, respectively), while the CO\textsubscript{2} absorption in ES is much higher than in WS.

4. Conclusion
Summarizing the results of the geographical redistribution of the vegetation types considered, we can conclude that the C3 grasses are displaced by forest types in the North of Siberia. The increase of the photosynthetically active radiation (400-700 nm) absorption in this part of the region (not shown in the figures), which is normal for the vegetation volume increase, is also evidence in favor of the conclusion. The least sensitive to the global climatic changes are deciduous shrubs. This type showed weak response both in terms of the geographical distribution.
Figure 3. The same as Figure 2 but for the annual gross CO$_2$ assimilation, [g C m$^{-2}$ yr$^{-1}$].

Figure 4. The annual CO$_2$ flux to the atmosphere for 1981–2000 (a), 2081–2100 (b) and the difference between the ends of the 21$^{st}$ (2081–2100) and 20$^{th}$ centuries (1981–2000) (c), [g C m$^{-2}$ yr$^{-1}$], JSBACH.
Table 2. Accumulated over the regions annual CO\(_2\) flux to the atmosphere, [g C yr\(^{-1}\)].

|       | Siberia    | WS         | ES          |
|-------|------------|------------|-------------|
| 1981–2000 | -26465.78  | -10999.43  | -15466.35   |
| 2081–2100 | -21065.13  | -9115.71   | -11949.42   |
| Difference | 5400.65    | 1883.72    | 3516.93     |
|         | (20.40 %)  | (17.13 %)  | (22.74 %)   |

and in terms of the gross CO\(_2\) assimilation changes. Extratropical forest vegetation (both evergreen and deciduous) showed high sensitivity to the atmospheric forcing. Under the given conditions, not only a significant expansion of this vegetation type area, but also a significant increase of the gross CO\(_2\) assimilation in the territory of this type take place.

The general increase in the amount of biomass in the North of Siberia, provoked by the given climate warming, led to an increase in CO\(_2\) absorption from the atmosphere. However, weakening of the total CO\(_2\) absorption in the South of WS and in the central part of ES can indicate a change of the vegetation types absorbing properties due to the climatic forcing.

Summarizing all the results obtained, it can be concluded that the intensive climate warming given by the climate scenario RCP8.5 can provoke significant changes in the geographical distribution of extratropical forest and grass vegetation and weakening of the canopys ability to absorb carbon dioxide from the atmosphere. It was also shown that ES is more sensitive than WS to the climatic forcing.

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