Contribution of different external forcings to the terrestrial carbon cycle variability in extratropical Eurasia in the last millennium

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Abstract. The simulations for the last millennium with an Earth system model developed at the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM) are performed. These simulations are forced by changes of the parameters of the Earth orbit, total solar irradiance, volcanic (stratospheric) aerosols optical depth (only since 500 C.E.), atmospheric concentrations of greenhouse gases (CO2, CH4, and N2O), land use, tropospheric sulphate burden, and population density. It is found that the externally forced part of the terrestrial carbon cycle (TCC) interannual variability (IAV) was mostly driven by volcanic activity in the preindustrial part of the last millennium with an increase of importance of anthropogenic forcing during the 20th century. The latter enhanced IAV in the 20th century. For different time intervals and for different kinds of external forcing, coefficient of variation of IAV in different TCC characteristics is smaller (typically, up to few percent) in forested regions and larger in the regions covered by grasses (e.g., in tundra), where it could be as large as several tens of per cents for fire return interval. We show that the externally forced IAV of gross primary production during the 20th century dramatically increased as compared to that during the preindustrial period. In addition, the land use activity increases the relaxation time scale of the vegetation carbon stock by one order of magnitude.

1. Introduction

Interannual variability (IAV) is an important component of the Earth system variability. It leads to large year–to–year variations of weather and climate patterns (e.g., [1]) and affects ecosystem functioning and biogeochemical cycles even at the global scale [2–17]. Interannual variability of carbon fluxes between the atmosphere, the ocean and the land surface may be used to evaluate the skill of Earth system models in simulating terrestrial and oceanic branches of the Earth’s biochemical cycles [18,19] and derive relationships between characteristics of different ecosystem processes (e.g., [3]).

Interannual variability in the Earth system may be subdivided into internal and forced components (e.g., [20,21]). The internal component arises due to non–linear interactions in the Earth system. In turn, the forced IAV may be traced to some external forcing. One notes that subdivision into internal and forced components is incomplete because of possible interactions
between the processes in the Earth system. Nonetheless, it is useful because it allows to classify the IAV components and, in principle, link them either with specific processes in the Earth system or to external (either natural or anthropogenic) climate forcing.

Our paper focuses on the forced part of IAV in the terrestrial branch of the carbon cycle. Moreover, we limit ourselves to Northern Eurasia, where the strongest climate changes are observed in the 20th century [22] and projected in the 21st century [23] together with the strongest relative changes in biogeochemical fluxes [23–26]. In addition, Northern Eurasia is the only region where the sign of the feedback between temperature, on one hand, and net primary production and net biome production, on the other, may change even under moderate global warming [17]. Thus, we force an Earth system model by a suit of natural and anthropogenic external forcing operating at different time scales to isolate the forced IAV in the terrestrial carbon cycle (TCC).

2. The model and the setup of simulations

In this paper, the climate model (CM) developed at the A.M. Obukhov Institute of the Atmospheric Physics, Russian Academy of Sciences (IAP RAS) is used [26–30]. The IAP RAS CM is the only Russian model that belongs to the class of the Earth system models of intermediate complexity (EMICs) [31–35].

Common to other Earth system models, the IAP RAS CM consists of modules for the transfer of shortwave and longwave radiation, convection, cloud formation and precipitation. The contemporary version of the short–wave radiation transfer scheme handles the influence of the parameters of the Earth’s orbit, surface albedo, characteristics of cloudiness, water vapour, and sulphate aerosols (separately in the troposphere and in the stratosphere). Longwave radiation transfer is calculated in the IAP RAS CM by taking into account the temperature and humidity of the atmosphere, cloudiness, CO$_2$, CH$_4$, and N$_2$O. A specifics of the IAP RAS CM is that the large–scale atmospheric dynamics (with a scale above approximately 1 mo) is considered explicitly, while synoptic processes are parametrised. This allows to significantly reduce the time required for model calculations and make our model a suitable tool for long simulations. The characteristics of sea ice in the model are computed from the surface temperature and the ocean surface temperature. In addition, the IAP RAS CM implements the detailed module of soil thermophysics [36], and the cycles of carbon [28] and methane [37]. The horizontal resolution of our model is 4.5$^\circ$ in latitude and 6$^\circ$ in longitude.

At the interdecadal timescale, the model is able to reproduce realistically the climate response to external forcings [26, 27, 29, 30, 33, 37]. Changes in the characteristics of the state of climate and ecosystems in the model under various scenarios of anthropogenic forcing on climate in the 21st century are within the interval obtained from the results of simulations with other modern climate models [26, 27, 29, 34, 37]. The equilibrium sensitivity of the global and annual mean surface air temperature to a doubling of the carbon dioxide content in the atmosphere is 2.2 K, which is in the lower part of the interval from 2 K to 4.5 K as estimated for state–of–the–art Earth system models [38].

In this paper, a suit of simulations for the last millennium simulations with our model was performed. These simulations were forced by the following external forcings: i) changes of the parameters of the Earth orbit, which are calculated internally according to the Berger equations [39]; ii) total solar irradiance as reconstructed from $^{10}$Be ice–core derived data [40]; iii) optical depth of stratospheric (volcanic) aerosols [41]; iv) ice core–derived concentrations of well–mixed greenhouse gases (CO$_2$, CH$_4$, and N$_2$O) in the atmosphere [42]; v) change of crops and pastures extent and change of population density as supplied by the HYDE–3.2 (History Database of the Global Environment, version 3.2) [43]; vi) total burden of tropospheric sulphates [44] which were extended back in time assuming that the data for 1850 C.E. reflect the distribution of natural sulphates and, thus, are representative for the preindustrial period.
For brevity, different combinations of these forcings are combined to 5 groups, and the model simulation with each group is performed. These groups are: ORB (forcing $i$), SOL (forcing $ii$), VOL (forcing $iii$), ANT (forcings $iv$ to $vi$), and ALL (forcings from $i$ to $vi$). In this paper, we focus only the last millennium of our simulation, when the volcanic forcing, an important contribution to the carbon cycle IAV, is available.

3. Results

Interannual variability of surface air temperature (SAT), as well as other climatic parameters, before the 20th century in the model is basically caused by volcanic activity (not shown). For 1000-1799 CE, the typical values of the standard deviation (STD) for SAT IAV is several tenths of Kelvins. In turn, the surface air temperature IAV in the 20th century is due to mostly volcanic and anthropogenic forcings with similar to each other contributions to the total SAT STD.

Consistent with this, STD of the annual gross primary production per unit area (GPP) before the onset of the industrial period is basically linked to the volcanic forcing. For 1000-1799 CE, GPP STD, $\sigma_{GPP}$, amounts from about 5 gC m$^{-2}$ yr$^{-1}$ in the subpolar region to about 30 gC m$^{-2}$ yr$^{-1}$ in temperate regions (Fig. 1). All this contrasts with the second half of the 20th century, in which a drastic increase of GPP STD is simulated in numerical experiment ALL: while in the earlier time intervals this characteristic in these regions and in this simulation never exceeded 15 gC m$^{-2}$ yr$^{-1}$, it became larger than 20 gC m$^{-2}$ yr$^{-1}$ in 1950–1999. This increase is basically due to anthropogenic influence exerted on the Earth system (cf. simulations ALL and ANT). Anomalies of the same order but of a larger magnitude (from several tenths to few gC m$^{-2}$ yr$^{-1}$) were obtained for net primary production in the Eurasian extratropics for the El Niño and La Niña years based on satellite retrievals [4]. The IAP RAS CM–simulated $\sigma_{GPP}$ correspond to 1–2% of vegetation gross primary production variations relative to the long–term mean GPP in forested area and up to 10% of respective variation in grass–covered regions (e.g., in tundra).

Volcano–induced GPP STD is not reflected in the corresponding STD of the vegetation carbon stock per unit area ($\sigma_{C_v}$; Fig. 2). This is due to the compensation of GPP change by respective changes of autotrophic respiration and litterfall. However, even in the preindustrial time interval, large $\sigma_{C_v}$ (up to 0.6 kgC m$^{-2}$) is simulated in the temperate European region in simulations ALL and ANT. This is caused by the land use activity. The land use activity extends into the Asian grasslands during the first half of the 20th century. Nonetheless, anthropogenically–induced climate changes also lead to the development of the marked (from 0.1 to 0.2 kgCm$^{-2}$) vegetation carbon stock IAV in the boreal Eurasia as well. In most North Eurasian regions covered by natural ecosystems, all kinds of the forced IAV lead to vegetation carbon stock variations that do not exceed 5% relative to its long–term mean. The only exception is the disturbance due to land use. The coefficient of variation (CV) for this disturbance is > 20%.

The spatial structure of standard deviation of the soil carbon stock per unit area in different simulations is basically similar to that of $\sigma_{C_v}$, but with smaller magnitudes. For instance, in the land use–affected regions, STD of soil carbon stock per unit area is not larger than 0.2 kgC m$^{-2}$. This is likely linked to the time scales of carbon decomposition in soil, which are much longer relative to the corresponding time scales for autotrophic respiration and litterfall (which are the major sinks of vegetation carbon). In all natural ecosystems, the forced IAV corresponds to the CV values which are of the order of few tenths of per cent. Again, the CV maximum (up to several per cent) is simulated in the land use–affected regions.

The area annually burned by natural fires may be characterised by fire return interval (FRI), which is a reciprocal of the annually burned fraction of a grid cell. We do not discuss FRI STD because it could be misleading: small STD of fire return interval is meaningful in regions with frequent fires (thus, with a small FRI), but is meaningless in regions with large FRI. As a result, we discuss only FRI CV. It’s value is rather stable with respect to time interval and to type of
Figure 1. Standard deviation of the annual gross primary production per unit area (gC m$^{-2}$ yr$^{-1}$) for simulations ALL, ORB, SOL, VOL, and ANT, (respectively, from top to bottom) for time intervals 1000–1799, 1900–1949, and 1950–1999, and (correspondingly, from left to right).

We define the relaxation time scale of vegetation carbon stock IAV as $\tau_{c_v,R} = \sigma_{c_v}/\sigma_{GPP}$. This variable is interpreted as a time scale for relaxing the vegetation carbon stock disturbance to the value which is in equilibrium to the long–term mean of imposed forcing. We found that in most areas (e.g., in tundra) $\tau_{c_v,R}$ equals to several years increasing to $\approx 15$ yr in boreal forests. However, there is a peculiarity with $\tau_{c_v,R}$ is up to 40 yr in temperate European regions in simulations ALL and ANT. This feature is exhibited even in the preindustrial period and caused by the land use activity in these regions.

We note that the relaxation time is different from the commonly used stationary–state residence time of carbon in vegetation, which is defined as $\tau_{c_v,SS} = c_v/GPP$, where $c_v$ is vegetation carbon stock per unit area. Thus defined time scale is of the order of few years in grasslands and of few decades in forests (not shown) in agreement with the commonly assumed values (e.g., [45]).

4. Conclusions
We studied the forced part of interannual variability (IAV) of climate and the terrestrial carbon cycle (TCC) characteristics in North Eurasia by employing simulations for the last millennium with an Earth system model developed at the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM). These simulations were forced by changes of the parameters of the Earth orbit, total solar irradiance, volcanic (stratospheric) aerosols optical
It is found that anthropogenic forcing (especially, in the last half of the 20th century) lead to the TCC IAV which is principally different from that in the preindustrial period. In particular, the externally forced part of the IAV with time scales up to few decades became much stronger in the second half of the 20th century relative to the earlier time intervals. Volcanic activity was a principal driver for this variability in the preindustrial period. In turn, TCC IAV at these timescales is mostly driven by anthropogenic forcing in the last half of the 20th century. For different time intervals and for different kinds of external forcing, coefficient of variation of IAV in different TCC characteristics is smaller (typically, up to a few percent) in forested regions and larger in the regions covered by grasses (e.g., in tundra), where it could be as large as several tens of percent for fire return interval. We found that the land use activity increases the relaxation time scale of the vegetation carbon stock by one order of magnitude.

We note that, currently, there is an urgent need to estimate the feedback gain between climate and carbon cycle [24]. However, the presently available observations of carbon cycle changes characterise only the last few decades and, therefore, are too short to make such estimates from long–term trends. However, for time being, this gain may be estimated from interannual variability [46]. While the climate–carbon cycle feedback characteristics have to depend on time scale [47], such estimates are useful. Thus, the results of our paper may contribute to estimate the Northern Eurasia contribution to the climate–carbon cycle feedback. We plan to perform the respective global–scale analysis in a separate paper.

We acknowledge a number of limitations of our study. First, vegetation distribution is prescribed in our model, which makes terrestrial plant overly ‘resilient’ to external forcing and likely lead to underestimated TCC IAV [48]. This drawback, however, is partly compensated by...
a known resilience of terrestrial plants to climate changes [49–52]. Second, our model neglects interactions between the carbon cycle and other biogeochemical cycles (e.g., with the nitrogen cycle), despite these interactions potentially being able to substantially modify climate–carbon cycle interactions [53,54].

Finally, we highlight that we study only the forced part of the coupled climate–carbon cycle IAV. Another part of this IAV, which is generated by internal variability of the Earth system, is beyond the scope of the present paper.

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Figure 4. Similar to Fig. 1, but for the relaxation time scale (yr) for interannual variability of vegetation carbon stock.

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