Estimation of Changes in Characteristics of the Climate and Carbon Cycle in the 21st Century Accounting for the Uncertainty of Terrestrial Biota Parameter Values

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Abstract—ensemble simulations with the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS) climate model (CM) for the 21st century are analyzed taking into account anthropogenic forcings in accordance with the Special Report on Emission Scenarios (SRES) A2, A1B, and B1, whereas agricultural land areas were assumed to change in accordance with the Land Use Harmonization project scenarios. Different realizations within these ensemble experiments were constructed by varying two governing parameters of the terrestrial carbon cycle. The ensemble simulations were analyzed with the use of Bayesian statistics, which makes it possible to suppress the influence of unrealistic members of these experiments on their results. It is established that, for global values of the main characteristics of the terrestrial carbon cycle, the SRES scenarios used do not differ statistically from each other, so within the framework of the model, the primary productivity of terrestrial vegetation will increase in the 21st century from \(74 \pm 1\) to \(102 \pm 13\) PgC yr\(^{-1}\) and the carbon storage in terrestrial vegetation will increase from \(511 \pm 8\) to \(611 \pm 8\) PgC (here and below, we indicate the mean \(\pm\) standard deviations). The mutual compensation of changes in the soil carbon stock in different regions will make global changes in the soil carbon storage in the 21st century statistically insignificant. The global CO\(_2\) uptake by terrestrial ecosystems will increase in the first half of the 21st century, whereupon it will decrease. The uncertainty interval of this variable in the middle (end) of the 21st century will be from \(1.3\) to \(3.4\) PgC yr\(^{-1}\) (from \(0.3\) to \(3.1\) PgC yr\(^{-1}\)). In most regions, an increase in the net productivity of terrestrial vegetation (especially outside the tropics), the accumulation of carbon in this vegetation, and changes in the amount of soil carbon stock (with the total carbon accumulation in soils of the tropics and sub-tropics and the regions of both accumulation and loss of soil carbon at higher latitudes) will be robust within the ensemble in the 21st century, as will the CO\(_2\) uptake from the atmosphere only by terrestrial ecosystems located at extratropical latitudes of Eurasia, first and foremost by the Siberian taiga. However, substantial differences in anthropogenic emissions between the SRES scenarios in the 21st century lead to statistically significant differences between these scenarios in the carbon dioxide uptake by the ocean, the carbon dioxide content in the atmosphere, and changes in the surface air temperature. In particular, according to the SRES A2 (A1B, B1) scenario, in 2071–2100 the carbon flux from the atmosphere to the ocean will be \(10.6 \pm 0.6\) PgC yr\(^{-1}\) (8.3 \(\pm\) 0.5, 5.6 \(\pm\) 0.3 PgC yr\(^{-1}\)), and the carbon dioxide concentration in the atmosphere will reach \(773 \pm 28\) ppmv (662 \(\pm\) 24, 534 \(\pm\) 16 ppmv) by 2100. The annual mean warming in 2071–2100 relatively to 1961–1990 will be \(3.19 \pm 0.09\) K (2.52 \(\pm\) 0.08, 1.84 \(\pm\) 0.06 K).

Keywords: terrestrial carbon cycle, scenarios of future changes, ensemble simulations, IAP RAS CM.

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1. INTRODUCTION

It is reasonable to estimate future changes in characteristics of the climatic system not only in terms of the average (often interpreted as the most probable) trajectory, but also in terms of the uncertainty interval (for example, the confidence interval or the standard deviation) of such estimates [1–6]. Such uncertainty can arise due to insufficient knowledge of the initial conditions [1, 4, 7, 8], the uncertainty of the governing parameters of the mathematical model [2, 6, 9, 10], the uncertainty of scenarios of anthropogenic forcings [11], or structural uncertainty (associated with insufficient knowledge of the structure of governing equations and numerics of the problem) [4, 10].

The construction of probability distribution functions for characteristics of climate changes is the most rigorous approach to estimating the uncertainty characteristics of climatic calculations [12]. The calculation of such distribution functions and their changes during changes in the climatic state requires the per-
formance of ensemble simulations with large computational cost. Due to the latter circumstance, ensembles of modern climatic models are used [13], for example, the ensemble of climatic models recommended by the Fourth report of the Intergovernmental Panel on Climate Change [14]. Numerical experiments with these models are conducted in accordance with the specified common protocol (see, for example, [15, 16]). However, this ensemble, speaking generally, does not describe all possible values of the governing parameters of the system and admissible (not contradicting the current knowledge) set of initial conditions. This is why this ensemble is called the ensemble of opportunity in English literature [17]. One would expect that this statement is also valid in respect to another ensemble, i.e., an ensemble of climatic models with the carbon cycle, which is used in Coupled Climate—Carbon Cycle Intercomparison Project (C³MIP) [18].

Therefore, it is reasonable to perform special ensemble simulations with climatic models in which certain model parameters are varied systematically [6, 7, 9, 10, 19–22]. However, along with large computational expenditures in the course of such experiments, it is rather difficult to identify ensemble members, which realistically reproduce specific features of climatic changes. The influence that unrealistic members of these experiments have on statistical characteristics of estimates of future climatic changes must be excluded [6, 7, 9, 10, 19–22].

The goal of this work is to estimate the future characteristics of the climate and carbon cycle in the 21st century under realistic scenarios of anthropogenic forcings on the system. In this work, this estimate is constructed both in terms of the mathematical expectation of the response and in terms of the characteristics of its uncertainty arising during systematic changes in the governing parameters of terrestrial biota. The latter substantially distinguishes this work from other works where similar estimates are obtained [23, 24].

In order to solve this problem, we use the climatic model developed at the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM) [9, 21, 22, 25–30]. This work takes into account (partially) two sources of the uncertainty of estimates of future climatic changes: the governing parameters of the carbon cycle of the model and the uncertainty of future scenarios of land use. For other anthropogenic forcings on the climate (CO₂ emissions caused by fossil-fuel combustion and industrial activities; changes in the atmospheric concentrations of other anthropogenic greenhouse gases and aerosols) we use three marker scenarios of the SRES family [31]. Natural external actions on the climate associated, for example, with changes in the solar constant and volcanic activity evidently do not noticeably contribute to the uncertainty of climatic changes in the 21st century [28, 29]. The degree of realism of the model calculations in this work is estimated with the use of Bayesian statistics [9].

Unlike similar calculations analyzed in [9], in this work we use a new version of the IAP RAS CM [30] which incorporates a spatially explicit scheme of the terrestrial carbon cycle. As a consequence, we can analyze the uncertainty of not only globally averaged characteristics of the carbon cycle but also its spatial structure. The IAP RAS CM version used in this work was previously used in [30] for analyzing the uncertainty of the response of characteristics of the climate and carbon cycle associated with the uncertainty of future scenarios of land use. However, the influence of changes in the governing parameters of the model and the uncertainty of anthropogenic scenarios, which differs from that associated with scenarios of land use, was not considered in the last work (see [30] for greater detail).

2. DESCRIPTION OF THE MODEL

The IAP RAS CM version described in [30] was used in this work. Unlike the previous versions of this model (see, for example, [22, 32–35]), this version incorporates a spatially explicit module of the terrestrial carbon cycle. The physical components of the model used and the reproduction of climate by it are comprehensively described in [25–27, 36–40]. The module of the terrestrial carbon cycle is described in detail in [30] (and for the convenience of the Russian reader, in the Appendices). In model calculations, the productivity of terrestrial ecosystems and the carbon storage in different reservoirs change annually. However, for a more adequate accounting for seasonal features of the climate, the IAP RAS CM module of the terrestrial carbon cycle uses the fields of input variables (surface air temperature \(T_\text{s} \), soil moisture fractional saturation \(w \), and net short-wave radiation at the surface \(R_{\text{sub}} \)) taking into account their seasonal changes. The scheme takes into account six plant functional types (PFTs): tropical forests, temperate forests, taiga, grasses, shrubs, and agricultural lands. The model cell is divided into two parts, one of which contains natural vegetation (one of the first five PFTs) and the other contains agricultural lands. The fractions of these parts of the cell are designated, respectively, as \(s_{\text{n}} \) and \(s_{\text{ag}} \). The dynamics of the carbon mass in vegetation \(c_{v,y} \) and in the fast and slow soil reservoirs \(c_{v,z} \) (here and below, \(Y = \text{nat}, \text{agro}, Z = \text{fast}, \text{slow} \)) per unit area is described by the corresponding balance equations. Below we also use designations of the corresponding variables averaged over the entire model cell: \(c_{\text{v}} = s_{\text{n}}c_{v,\text{nat}} + s_{\text{ag}}c_{v,\text{agro}} \).
The nonlinear globally averaged model described in [34, 35] is now used in the IAP RAS CM as a module of the oceanic carbon cycle. We subsequently plan to replace it with a detailed model of the oceanic carbon cycle.

The carbon cycle module in the IAP RAS CM is closed by the equation for the carbon dioxide content in the atmosphere $q_{\text{CO}_2}$ on the approximation of a well-mixed gas:

$$c_0 \frac{dq_{\text{CO}_2}}{dt} = E_f + E_i - F_i - F_o,$$

(1)

where $c_0 = 2.123$ PgC/ppmv, $t$ is time, $E_f$ are the global emissions of carbon dioxide due to fossil-fuel combustion and industrial activities, $E_i$ are the global CO$_2$ emissions due to land use, $F_i$ is the global carbon dioxide uptake from the atmosphere by terrestrial ecosystems, and $F_o$ is the corresponding uptake by the ocean.

The verification of the standard IAP RAS CM version is performed in [30]. On the whole, the model realistically reproduces the preindustrial state of the carbon cycle and changes in its characteristics up to the end of the 20th century.

3. NUMERICAL EXPERIMENTS

In this work we conducted ensemble experiments with the IAP RAS CM for the period 1500–2100. In numerical experiments for 15th–20th centuries, we prescribed the annual emissions of carbon dioxide due to fossil-fuel combustion and industrial activities [41], which were continued backward in time as in [28, 29]; agricultural land areas [42]; annual mean concentrations of methane [43], nitrous oxide [43], freons CFC-11 and CFC-12 [44] (all of these gases were regarded as well-mixed in the atmosphere), and tropospheric sulfates [45]; as well as changes in the solar constant [46] and in the zonal mean optical thickness of stratospheric aerosols (annual mean values [47] up to 1889 and monthly mean values [48] for 1890–2000). For the 21st century, the listed anthropogenic forcings (except for the scenarios of land use) were prescribed in accordance with the SRES B1, A1B, and A2 scenarios [31]; the CH$_4$, NO$_x$, CFC-11, and CFC-12 concentrations were prescribed from calculations with the use of the BernCC model [31], and the concentration of tropospheric sulfates were prescribed from calculations with the use of the MOZART-2.0 model [45]. Possible variations in the solar constant and thickness of stratospheric aerosols in the 21st century were disregarded. Two extreme scenarios, which were obtained within the framework of the Land Use Harmonization (LUH, http://luh.unh.edu/data.shtml) project [42] from calculations with the use of the MESSAGE and MiniCAM models, were used as scenarios of $s_{\text{sagro}}$ changes in the 21st century. Calculations with the use of these models completely characterize the interval of possible scenarios of changes in agricultural land areas obtained within the framework of the LUH project. For the MESSAGE model, the agricultural land area in the 21st century increases, whereas it decreases for the MiniCAM model. Version 1 of the project data was used for both of the models (see http://luh.unh.edu/data.shtml for more detail). The fraction of natural vegetation in the model cell was calculated according to the formula $s_{\text{nat}} = s_{\text{agro}} - s_{\text{sagro}}$ and the fraction $s_{\text{agro}}$ of the cell covered by vegetation was prescribed from annual mean data [49]. It should be noted that $s_{\text{agro}}$ in the IAP RAS CM affects both changes in the vegetation carbon stock and in the CO$_2$ emission into the atmosphere due to land use (see [30] and Appendices) and the albedo of the surface [50–52]. The fields obtained in the equilibrium preanthropogenic numerical experiment with the IAP RAS CM and averaged over 50 model years served as the initial conditions.

Different members within these ensembles were constructed by varying two parameters of the terrestrial carbon cycle: the half-saturation constant $q_{1/2}$ (see [A. 4]) in the interval from 150 to 450 ppmv (in all, five values of this variable were used) and the coefficient $k_{s, \text{agro/nat}}$ describing the influence of cultivation on soil respiration (see Appendices) in the range from 1.0 to 1.4 (also five values). Therefore, the $N_{\text{mem}} = 5 \times 5 = 25$ simulations of the IAP RAS CM, which differ in values of the parameters $q_{1/2}$ and $k_{s, \text{agro/nat}}$, were performed for each SRES scenario and each LUH scenario of land use. The choice of the boundary conditions for the first interval depended on the range of $q_{1/2}$ values used in different modern climatic models (see reviews in [22, 28, 29, 53]). The boundaries of the second interval are somewhat wider than the range of $k_{s, \text{agro/nat}}$ values obtained in field experiments on estimating the influence of cultivation on soil respiration (from 1.1 to 1.3 [54]). These parameters are global for the model of the carbon cycle and make it possible to use globally averaged observational data (which, on the one hand, are characterized by the least uncertainty and, on the other hand, describe the climatic system as a whole rather than its state in some regions) for comparison. In addition, the parameter $q_{1/2}$, which determines the direct effect of carbon dioxide fertiliz-
In this work the conditional probabilities \( P(M_k|D) \) were calculated with the aid of the Bayesian theorem [56–58]:

\[
P(M_k|D) = \frac{P(D|M_k)P(M_k)}{\sum_{i=1}^{N_{\text{mem}}} P(D|M_i)P(M_i)}
\]

with the prior probabilities for each member of the ensemble \( P(M_k) \equiv 1 \) at \( k = 1, 2, \ldots, N_{\text{mem}} \).

The data set \( D \) included estimates of the carbon dioxide fluxes from the atmosphere to the ocean and terrestrial ecosystems \( (F_a \text{ and } F_r, \text{ respectively}) \) for the 1980s and 1990s [14] and changes in the atmospheric carbon dioxide concentration \( q_{\text{CO}_2} \) in 1958–2004 from observations at the Mauna Loa observatory (Hawaii, USA) [63]; so

\[
P(D|M_k) = P(D_{q_{\text{CO}_2}}|M_k)P(D_{F_a}|M_k)P(D_{F_r}|M_k),
\]

where \( P(D_{q_{\text{CO}_2}}|M_k) \) is the conditional probability for each of the variables \( X = q_{\text{CO}_2}, F_a, F_r \). The Gaussian distribution function with the standard deviation \( \Sigma_{q_{\text{CO}_2}} \) in the interval from 2 to 5 ppmv was chosen as the PPDF for \( q_{\text{CO}_2} \). The value of \( \Sigma_{q_{\text{CO}_2}} \) does not affect the results of this work very much, so we present below only the results obtained at \( \Sigma_{q_{\text{CO}_2}} = 5 \) ppmv. For the carbon dioxide fluxes from the atmosphere to the ocean and terrestrial ecosystems \( (F_a \text{ and } F_r, \text{ respectively}) \), we used the Gaussian distributions, in which the uncertainties of observational estimates reported in [14] were interpreted as the corresponding 95% intervals. With the Bayesian averaging, the land-use scenarios obtained with the use of the MESSAGE and MiniCAM models were regarded as equally probable to each other.

It should be noted that, with the Bayesian averaging, the homogeneous probability distribution functions represent the most well-grounded PPDF type [56, 57]. However, modern climatic models with the carbon cycle are characterized by large errors in the reproduction of \( q_{\text{CO}_2} \) (up to 14 ppmv [14]), which often exceed the technical error in the measurement of this variable (1.5 ppmv [63]) and the standard deviation of the carbon dioxide concentration in the atmosphere due to the short-period annual variability (1.5 ppmv [64]). The latter circumstance makes it more convenient to choose the Gaussian PPDF for \( q_{\text{CO}_2} \). The normal prior probability distribution function was also used at the Bayesian averaging in [9]. Both for the atmospheric carbon dioxide concentration and for the carbon dioxide fluxes from the atmosphere to the ocean and terrestrial ecosystems, the
Gaussian PPDF makes it possible (1) to impart a larger weight to the calculations characterized by the values of these variables located near their most probable values estimated from the standard data and (2) to avoid Bayesian weight discontinuities at the boundaries of uncertainty intervals of the standard estimates. Criteria 1 and 2 were also used in [65] in the choice of weight multipliers for calculations with climatic models. It was established in [9] that the choice of the Gaussian or homogeneous PPDF does not noticeably affect the results of calculations.

Since the value \( k_{s, agro/nat} = 1.4 \) lies outside the interval of the corresponding experimental values, model calculations with such a value of this parameter are excluded from the Bayesian averaging [21, 57]. This somewhat narrows the uncertainty intervals for variable changes in the 21st century obtained below, but it does not change the basic results of the paper. Nevertheless, some numerical experiments with \( k_{s, agro/nat} = 1.4 \) are discussed in the next section for a better understanding of the carbon balance components in the climatic system.

### 4. THE DEGREE OF REALISM OF INDIVIDUAL MEMBERS PARTICIPATING IN THE ENSEMBLE EXPERIMENT

The degrees of realism of different members of the ensemble simulations constructed in this work differ substantially. At the same degree of realism, the Bayesian weights \( P(M_i|D) \) of individual ensemble members after their normalization would be close to \( 1/N_{mem} = 0.04 \). However, the largest values of such weights (0.51, 0.51, and 0.45) are characteristic of calculations with the parameters \( q_{1/2}, k_{s, agro/nat} \) equal to (150 ppmv, 1.1), (200 ppmv, 1.2), and (300 ppmv, 1.3), respectively. The last pair of parameter values was used in the IAP RAS CM version, the results of calculations with which are published in [30]. Noticeable values of Bayesian weights in the interval from 0.12 to 0.32 are also obtained for calculations with the pairs of values of the indicated governing parameters (200 ppmv, 1.1), (300 ppmv, 1.4), (400 ppmv, 1.4), and (450 ppmv, 1.4).

### Table 1. Global annual mean characteristics of the climate and carbon cycle in ensemble simulations with the IAP RAS CM under the SRES scenarios of anthropogenic forcings

<table>
<thead>
<tr>
<th>Variables</th>
<th>A1</th>
<th>A1B</th>
<th>B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide concentration in the atmosphere in 2100, ppmv</td>
<td>773 ± 28</td>
<td>662 ± 24</td>
<td>534 ± 16</td>
</tr>
<tr>
<td>Change in the global annual mean surface air temperature in 2071–2100 relatively to 1961–1990, K</td>
<td>3.19 ± 0.09</td>
<td>2.52 ± 0.08</td>
<td>1.84 ± 0.06</td>
</tr>
<tr>
<td>Carbon storage increase in vegetation in 2071–2100 relatively to 1961–1990, PgC</td>
<td>163 ± 48</td>
<td>147 ± 44</td>
<td>109 ± 38</td>
</tr>
<tr>
<td>Carbon storage increase in soil in 2071–2100 relatively to 1961–1990, PgC</td>
<td>45 ± 60</td>
<td>64 ± 56</td>
<td>58 ± 44</td>
</tr>
<tr>
<td>Net primary productivity of terrestrial ecosystems in 2071–2100, PgC yr(^{-1})</td>
<td>107 ± 7</td>
<td>102 ± 6</td>
<td>94 ± 5</td>
</tr>
<tr>
<td>Carbon uptake from the atmosphere by terrestrial ecosystems in 2071–2100, PgC yr(^{-1})</td>
<td>1.7 ± 1.4</td>
<td>1.4 ± 0.7</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Carbon uptake from the atmosphere by the ocean in 2071–2100, PgC yr(^{-1})</td>
<td>10.6 ± 0.6</td>
<td>8.3 ± 0.5</td>
<td>5.6 ± 0.3</td>
</tr>
</tbody>
</table>

Note: The Bayesian ensemble mean ± standard deviations are indicated for each variable.

### Fig. 2. Changes in the surface air temperature at the global and annual averagings in the ensemble simulations with the IAP RAS CM. The Bayesian ensemble mean values (thin black lines) and the uncertainty intervals characterized by the Bayesian intraensemble standard deviations (regions in gray) are presented for each of the SRES scenarios (indicated in the figure). The HadCRUT3v empirical data [101] (thick black curve) are presented for comparison.
Therefore, this model reproduces the observed characteristics of the carbon cycle either at simultaneous relatively small values of both parameters or at simultaneous relatively large values of them. Physically, this corresponds to the mutual compensation of changes in the net primary productivity of terrestrial ecosystems (controlled by the half-saturation constant included in the Michaelis–Menten law) and heterotrophic soil respiration (depending on $k_{s,\text{agro/nat}}$).

Changes in carbon dioxide characteristics in the atmosphere and climate warming markedly vary even between the three realizations with the largest Bayesian weights. Thus, in these realizations, the carbon dioxide concentration under the SRES A2 (A1B, B1) anthropogenic forcings scenario attains values from $765$ to $844$ ppmv (from $635$ to $699$ ppmv, from $508$ to $551$ ppmv) by the end of the 21st century, and the global warming by 2071–2100 is from $2.7$ to $3.0$ K (from $2.3$ to $2.6$ K, from $1.7$ to $1.9$ K) relatively to 1961–1990. Larger values from these intervals correspond to realizations with a smaller half-saturation constant of the Michaelis–Menten law. An increase in this constant increases the growth of the net primary productivity of terrestrial vegetation. As a consequence, if the half-saturation constant of the Michaelis–Menten law increases, the carbon accumulation in the 21st century in terrestrial vegetation and in soil for these simulations with the SRES A2 (A1B, B1) scenario will increase from $90$ to $208$ PgC (from $86$ to $196$ PgC, from $61$ to $155$ PgC) and from $-43$ to $132$ PgC (from $-27$ to $142$ PgC, from $-16$ to $120$ PgC), respectively.

The values of the constant $q_{1/2}$ for the first two of the indicated realistic scenarios of the constructed ensemble (150 and 200 ppmv, respectively) are noticeably smaller than the values characteristic of vegetation of the C$_3$ type ($\geq 450$ ppmv, see [66]), which dominates terrestrial ecosystems [67]. Nevertheless, such values, and even smaller ones, of $q_{1/2}$ are often used in modern climatic models [22, 32, 33, 53, 68]. This is dictated by the necessity of compensating for effects which are disregarded in some models, such as the limitation of bioproductivity by the available amount of nutrient substances (for example, nitrogen, phosphorus or iron) [53, 69–73] or by the harmful action of ozone and sulfur compounds on vegetation [74–77].

5. ESTIMATION OF THE UNCERTAINTY OF CHANGES IN THE CLIMATE AND CARBON CYCLE IN THE 21ST CENTURY

In the constructed ensemble simulations, the atmospheric carbon dioxide concentration $q_{CO_2}$ increases by the middle of the 21st century to $546 \pm 16$ ppmv under the SRES A1B and SRES A2 scenarios and to $502 \pm 12$ ppmv under the SRES B1 scenario (Fig. 1; here and below, the symbol “$\pm$” separates the Bayesian ensemble mean and the intraensemble standard deviation). By the end of the 21st century, $q_{CO_2}$ increases to $773 \pm 28$ ppmv under the SRES A2 scenario, to $662 \pm 24$ ppmv under the SRES A1B scenario, and to $534 \pm 16$ ppmv under the SRES B1 scenario (Fig. 1, Table 1).

For all three scenarios of anthropogenic forcings, the estimates of $q_{CO_2}$ changes obtained with the use of the IAP RAS CM are no farther than $2 \times \sigma(q_{CO_2} | D)$ from the corresponding values obtained in [31] with the use of the BernCC model. They also agree well (differing by less than $\sigma(q_{CO_2} | D)$) with the results of calculations with the use of the CaESM1 and UVic ESCM models [76] but are somewhat smaller than the values obtained with the CLIMBER-2 model [23]. In addition, for the SRES A2 scenario, the values of $q_{CO_2}$ obtained with the use of the IAP RAS CM are inside the range obtained for the C$^3$MIP ensemble models. However, for the SRES A1B scenario of anthropogenic forcings, the values obtained with the IAP RAS CM are noticeably (by more than $3 \times \sigma(q_{CO_2} | D)$) smaller than the values obtained with the climatic model developed at the Institute of Numerical Mathematics, Russian Academy of Sciences (INM RAS) [24].

Under scenario SRES A2 (SRES A1B, SRES B1), the global warming in 2071–2100 relatively to 1961–1990 is $3.19 \pm 0.09$ K (2.52 $\pm$ 0.8, 1.84 $\pm$ 0.06 K) (Fig. 2, Table 1). In this period, the ensemble–mean annual mean warming over the land of extratropical latitudes is 5–8, 4–6, and 3–4 K under scenarios SRES A2, SRES A1B, and SRES B1, respectively (Figs. 3a, 3b). The corresponding warmings over the land of the tropics are smaller: 1–3 K under scenarios SRES A2 and SRES A1B and 0.5–2 K under scenario SRES B1. For the surface air temperature $T_a$, the intraensemble standard deviation $\sigma(T_a | D)$ depends only slightly on the chosen scenario of anthropogenic forcings. Its values vary from 0.2 to 0.05 K over the land of the extratropical latitudes and from 0.1 to 0.4 K over the land of the tropics.
ESTIMATION OF CHANGES IN CHARACTERISTICS OF THE CLIMATE

(a)

(b)

(c)
tropics; they do not exceed 0.2 K over most oceanic regions (except for the Arctic) (Fig. 3c). For all three scenarios of anthropogenic forcings on the climate, the indicated changes in the global temperature lie within the uncertainty intervals obtained for other modern climatic models [14].

In the IAP RAS CM, the annual mean surface warming is accompanied by a decrease in the amplitude of the annual harmonic $T_{a,1}$ (Fig. 4), which is in agreement with the empirical and model results [14, 66, 79–88]. Depending region, the Bayesian mathematical expectation of $T_{a,1}$ changes over the land of the extratropical latitudes at the end of the 21st century vary from $-1$ to $-6$ K, from $-1$ to $-5$ K, and from $-0.5$ to $-4$ K under the SRES A2, SRES A1B, and SRES B1 scenarios, respectively. In these regions the indicated values noticeably exceed the standard deviations $\sigma(T_{a,1}|D)$, which vary from 0.2 to 0.5 K; larger values of $E(T_{a,1}|D)$, as a rule, correspond to regions with larger absolute values of $\sigma(T_{a,1}|D)$. On the contrary, over the land of the tropics, the ensemble-mean decrease in the amplitude of the surface temperature annual harmonic, whose absolute value does not exceed 0.5 K, is

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**Fig. 4.** (a) Bayesian mean changes in the amplitude of the annual harmonic of the surface air temperature (K) in the ensemble simulations with the IAP RAS CM between the periods 1961–1990 and 2071–2100 under the SRES A1B scenario of anthropogenic forcings and (b) Bayesian intraensemble standard deviations of these changes.
already comparable with the Bayesian intraensemble standard deviation.

For the global net primary productivity of terrestrial ecosystems $F_{NPP}$, the uncertainty intervals under different scenarios of anthropogenic forcings (SRES B1, A1B, and A2) overlap each other throughout the entire simulation (Fig. 5, Table 1). The Bayesian ensemble-mean values of this variable increased from 74 PgC yr$^{-1}$ in 1961–1990 to 91–95 PgC yr$^{-1}$ in the middle of the 21st century and to 94–107 PgC yr$^{-1}$ at its end. The spatial structure of changes in the net primary productivity of terrestrial ecosystems per unit area $f_{NPP}$ for the three SRES scenarios used in this work differ little from each other. The ensemble-mean value of $f_{NPP}$ increased in all regions except for deserts. Under the SRES A2 scenario, this increase by the end of the 21st century will be from 0.2 to 0.5 kgC m$^{-2}$ yr$^{-1}$ with the maxima in some regions in Eurasia and Africa and, to a lesser degree, in North and South America (Fig. 6a).

Under the SRES A1B and B1 scenarios of anthropogenic forcings, these changes are somewhat smaller: from 0.1 to 0.4 kgC m$^{-2}$ yr$^{-1}$. In regions of tropical forests in Africa and South America, the Bayesian intraensemble standard deviation of $f_{NPP}$ changes is about a half of the corresponding mean-ensemble value (Fig. 6b). Outside the tropics, $\sigma(f_{NPP}|D)$ does not exceed 20% of $E(f_{NPP}|D)$.

The $f_{NPP}$ changes in the 21st century obtained in the IAP RAS CM, on the whole, agree with those obtained within the framework of the C$^4$MIP project [18] under the SRES A2 scenario. Additionally, the results of calculations with the IAP RAS CM differ by less than $\sigma(f_{NPP}|D)$ from the corresponding results obtained with the Can ESM1 and UVic ESCM models [78]. The spatial structure of $E(f_{NPP}|D)$ obtained with the IAP RAS CM differs from the spatial structure of changes in the net productivity of terrestrial ecosystems obtained in the calculations with the INM RAS model [24] by no more than $\sigma(f_{NPP}|D)$. Regions occupied by tundra are an exception. For such regions, the IAP RAS CM yields a substantially larger $f_{NPP}$ increase than the INM RAS model.

The global carbon storage in terrestrial vegetation $C_v$ decreases by the end of the 20th century relatively to the preanthropogenic state of the model by 113 ± 8 PgC, attaining 511 ± 8 PgC (Fig. 7). This decrease is markedly larger than the corresponding decrease obtained with the use of the INM RAS model [24]. The main reason for such a decrease in the IAP RAS CM is the spread of agricultural lands with the corresponding intensification of carbon turnover in terrestrial vegetation; this is partially compensated for by the direct effect of vegetation fertilization due to the increase in carbon dioxide content in the atmosphere [30]. However, in the 21st century, the loss of vegetation biomass in the model changes its growth (Fig. 7) due to both the indicated effect of fertilization and climatic changes [30]. By the end of the 21st century, $C_v$ will increase to a value of 601 ± 35 PgC, which is close to the preanthropogenic value. By the end of the 21st century, the carbon storage in terrestrial vegetation will reach 646 ± 70 PgC (Fig. 7, Table 1). The carbon content increase in terrestrial vegetation by unit of area $C_v$ takes place in most regions of the world, except the African subtropics of the Northern Hemisphere (Figs. 8a, 8b). The latter is caused by changes in the area of agricultural lands in this region, which increases for the scenario obtained with the MESSAGE model and a decrease for the scenario obtained with the MiniCAM model. On average over the ensemble, the extension of

<table>
<thead>
<tr>
<th>PFT</th>
<th>Classes of ecosystems [89]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical forests</td>
<td>Tropical dry forest, tropical seasonal forest, tropical moist forest</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>Temperate forest, warm temperate forest</td>
</tr>
<tr>
<td>Taiga</td>
<td>Taiga</td>
</tr>
<tr>
<td>Grasses</td>
<td>Tundra, steppe</td>
</tr>
<tr>
<td>Shrubs</td>
<td>Forested tundra, forested steppe, chaparral, tropical semideserts</td>
</tr>
<tr>
<td>Agricultural lands</td>
<td>Agricultural lands</td>
</tr>
</tbody>
</table>
agricultural lands prevails in the northern subtropics of Africa. However, in this region, as well as in the remaining regions of the tropics, the \( E(c,|D) \) change is comparable with \( \sigma(c,|D) \) and, therefore, is statistically insignificant (Fig. 8c). In turn, at higher latitudes, and especially at middle and subpolar latitudes of Eurasia and North America, the ensemble mean \( c_v \) increase (changing in some regions by 1–10 kgC m\(^{-2}\) yr\(^{-1}\)) exceeds the corresponding Bayesian intraensemble standard deviation by an order of magnitude (typical values of this deviation vary from 0.5 to 1 kgC m\(^{-2}\) yr\(^{-1}\)). According to the IAP RAS CM, the \( C_v \) increase in the 21st century does not differ statistically from the corresponding increase obtained in the numerical experiments with the INM RAS [24] and UVic ESCM models [78]. However, it is noticeably smaller than the value obtained in calculations with the Can ESM1 model [78]. It should be noted that, notwithstanding the statistical closeness of \( C_v \) changes in the 21st century in accordance with the IAP RAS CM and INM RAS model, the spatial structures of the corresponding \( c_v \) changes differ noticeably, especially over land of

![Fig. 6. (a) Bayesian mean changes in the net primary productivity of terrestrial ecosystems (kgC m\(^{-2}\) yr\(^{-1}\)) in the ensemble simulations with the IAP RAS CM between the periods 1961–1990 and 2071–2100 under the SRES A2 scenario of anthropogenic forcings and (b) the Bayesian intraensemble standard deviations of these changes. The two LUH scenarios of land use taken for the Bayesian averaging were regarded as equally probable.](image-url)
The ensemble-mean value of the global soil carbon stock $C_s$ increases nearly monotonically throughout the entire duration of the numerical experiments performed in this work (Fig. 9). Beginning from the pre-anthropogenic value $1849 \pm 6$PgC [30], this value increases to $1916 \pm 20$PgC by 1961–1990, to $1949 \pm 31$PgC by 2035–2065, and to $1970 \pm 65$PgC by 2071–2100 (see also Table 1). It should be noted that, in spite of the monotonic character of $E(C_s|D)$ variations, the change in this quantity in the 21st century is statistically insignificant. For the carbon content in soil per unit area $c_s$, the Bayesian ensemble-mean is substantially inhomogeneous in space. The total carbon accumulation is observed in the soils of the tropics and subtropics. In some regions at higher latitudes, $E(c_s|D)$ can both increase and decrease (Fig. 10a). The general spatial structure of $E(c_s|D)$ variations in the 21st century changes little between the SRES A2, A1B, and B1 scenarios; however, absolute values of these variations in the regions, where this quantity decreases, are larger for the SRES A2 scenario than for the SRES A1B scenario and still larger for the SRES B1 scenario. In such regions, typical values of the $E(c_s|D)$ decrease in this period from $-0.5$ to $-2$ kgC m$^{-2}$ yr$^{-1}$ for the last two scenarios and from $-1$ to $-5$ kgC m$^{-2}$ yr$^{-1}$ for the first scenario. For all of the three SRES scenarios, the characteristic Bayesian ensemble-mean $c_s$ change in the 21st century in regions where this variable decreases is from 0.5 to 5 kgC m$^{-2}$ yr$^{-1}$. In most regions the absolute values of $E(c_s|D)$ changes exceed $\sigma(c_s|D)$ (Fig. 10b). Changes in the spatial structure of the soil carbon stock and its global mean value in the 21st century for the IAP RAS CM do not differ statistically from those obtained with the INM RAS [24], UVic ESCM [78], and Can ESM1 models [78].

On average over the ensemble, the global carbon uptake by terrestrial ecosystems $F$ increases in the first half of the 21st century attaining $2.0–2.5$ PgC yr$^{-1}$, depending on the SRES scenario, with the Bayesian ensemble-mean standard deviation, which varies from 0.7 to 1.0 PgC yr$^{-1}$, depending on the scenario (Fig. 11). Then $F$ decreases, reaching $1.7 \pm 1.4$, $1.4 \pm 0.7$, and $0.6 \pm 0.3$ PgC yr$^{-1}$ in last decades of the 21st century under the SRES A2, SRES A1B, and SRES B1 scenarios, respectively (Fig. 11, Table 1). On average over the ensemble, a noticeable carbon uptake by terrestrial ecosystems per unit area $f$ is observed in 2071–2100 in the regions covered by forests, where its characteristic values vary from 0.01 to 0.2 kgC m$^{-2}$ yr$^{-1}$ (Figs. 12a, 12b). For all three scenarios, $E(f|D)$ is the largest at the extratropical latitudes of Eurasia. Comparable $E(f|D)$ values for tropical forests and for the ecosystems of North America are noted only for the SRES A1B and A2 scenarios, whereas, for the SRES B1 scenario at the end of the 21st century, in these regions, $E(f|D) \leq 0.01$ kgC m$^{-2}$ yr$^{-1}$. Moreover, under all three scenarios, $E(f|D)$ is comparable with $\sigma(f|D)$ in these regions, whereas for the extratropical ecosystems of Eurasia, especially for taiga regions, the ratio $E(f|D)/\sigma(f|D)$ markedly exceeds unity (Figs. 12c, 12d).

For global carbon storage in terrestrial vegetation and soil, as well as for the global carbon dioxide uptake by terrestrial ecosystems, the intervals whose centers are specified by the corresponding Bayesian ensemble-mean values and half-widths and by the corresponding Bayesian intraensemble standard deviations are overlapped between the three SRES scenarios used in this work. A similar result was also noted above for the total primary productivity of terrestrial vegetation. This fact indicates that, in terms of bioproductivity and carbon accumulation in terrestrial vegetation, the SRES scenarios do not differ from each other statistically.

The global carbon uptake from the atmosphere to the ocean monotonically increases in the 21st century, attaining in its middle $5.8 \pm 0.3$PgC yr$^{-1}$ ($5.9 \pm 0.3$, $4.9 \pm 0.3$PgC yr$^{-1}$) under the SRES A2 (A1B, B1) scenarios of anthropogenic forcings and $10.5 \pm 0.6$PgC yr$^{-1}$ ($8.3 \pm 0.5$, $5.6 \pm 0.3$PgC yr$^{-1}$) at the end of the 21st century.
Compared with the calculations performed in [30] for the SRES A2 scenario of anthropogenic forcings, this work yields a less intense increase in the productivity of terrestrial vegetation and the carbon storage in it at the end of the 21st century. However, changes in the soil carbon stock determined for the specified period in [30] and this work are similar to each other. As a consequence, in the 21st century, the \( E(q_{CO_2}|D) \) determined in this work will be larger (773 ppmv) than that determined in [30] (depending on the LUH scenario of land use, from 752 to 763 ppmv). However, with consideration for the standard deviation \( \sigma(q_{CO_2}|D) = 28 \) ppmv, the values of \( q_{CO_2} \) at the end of the 21st century obtained in this work and in [30] do not differ from each other statistically. Such a statement is also valid in relation to the productivity of terrestrial vegetation and the carbon storage in this vegetation and in soil, both on global and regional levels.

### 6. CONCLUSIONS

In this work we analyzed the ensemble simulations with the IAP RAS CM for estimating climate changes in the 21st century. The anthropogenic forcings was prescribed by the SRES A2, A1B, and B1 scenarios, except for the agricultural land area, whose changes were prescribed by the scenarios obtained with the MESSAGE and MiniCAM models within the framework of the Land Use Harmonization (LUH) project. Possible external natural actions on the climatic system in the 21st century were disregarded. Different realizations inside these ensemble experiments were constructed by changing two model parameters controlling the direct effect that fertilization has on the productivity of terrestrial vegetation and the intensification of soil respiration caused by cultivation, respectively.

The realism of individual members of the ensemble simulations was estimated with the use of Bayesian sta-
tistics by comparing the results of modeling and empirical data on characteristics of the carbon cycle in the second half of the 20th century. In particular, the mathematical expectation and standard deviation (the characteristic of the uncertainty) were calculated to characterize the changes in the climate state and the carbon cycle. Taking into account that not all of the governing parameters of the IAP RAS CM were varied, the results for the standard deviation (and, consequently, for the width of the uncertainty interval of the variables analyzed in the work) should be regarded as estimates from below. The algorithm used for calculating the ensemble characteristics made it possible to eliminate the influence that unrealistic members of the ensemble experiments have on the results of these calculations.

It was established in the course of these experiments that, for the global values of the main characteristics of the terrestrial carbon cycle (the productivity of vegetation, vegetation carbon stock and soil, and carbon uptake by terrestrial ecosystems), the used SRES scenarios do not differ from each other. According to the IAP RAS CM, in the 21st century, the net primary productivity of terrestrial vegetation increases from

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**Fig. 10.** (a) Bayesian mean changes in the soil carbon stock (kg C m$^{-2}$) in the ensemble simulations with the IAP RAS CM between the periods 1961–1990 and 2071–2100 under the SRES A1B scenario of anthropogenic forcings and (b) the Bayesian intraensemble standard deviations of these changes. The two LUH scenarios of land use taken for the Bayesian averaging were regarded as equally probable.
74 ± 1 to 102 ± 13 PgC yr\(^{-1}\), and the carbon storage in terrestrial vegetation increases from 511 ± 8 to 611 ± 8 PgC (here and below, the intraensemble standard deviations ± are indicated). According to the IAP RAS CM, changes in the global soil carbon stock in the 21st century are statistically insignificant. The global carbon uptake by terrestrial ecosystems increases in the first half of the 21st century and then decreases. The uncertainty interval of this variable in the middle (at the end) of the 21st century varies from 1.3 to 3.4 PgC yr\(^{-1}\) (from 0.3 to 3.1 PgC yr\(^{-1}\)). In most regions the primary productivity of terrestrial vegetation (especially outside the tropics) and the carbon accumulation in vegetation stably increase, as do changes in the soil carbon stock (the total carbon accumulation takes place in soils of the tropics and subtropics; soils of the regions located at higher latitudes can both accumulate and lose carbon). In the 21st century, CO\(_2\) is stably absorbed from the atmosphere only by the ecosystems of the extratropical latitudes of Eurasia, first and foremost, by those of the Siberian taiga.

Such spatial differences in the model response are associated with the different contributions of the processes controlling changes in the productivity of terrestrial vegetation and the vegetation carbon stock and soil during climatic changes in different regions of the land. Thus, in accordance with the results of calculations with the use of other modern models [14], the IAP RAS CM shows that, under the SRES scenarios of anthropogenic forcings, climate changes in the tropics in the 21st century will be small [36, 51] at these latitudes. The main contribution to changes in the productivity of vegetation and the carbon storage is introduced by the effect of the fertilization of terrestrial vegetation due to an increase in the carbon dioxide content in the atmosphere, which increases the net productivity and biomass resources and, as a consequence, the annual mean intensity of litter fall and the soil carbon stock. At higher latitudes, at noticeable changes in temperature and precipitation, along with the effect of fertilization, a marked contribution to \(f_{\text{NPP}}, c_r\), and \(c_s\) changes is introduced by the feedback between the climate and the carbon cycle, which, on the one hand, additionally (with respect to the specified effect of fertilization) increases productivity and, on the other hand, intensifies soil respiration [30].

At the same time, substantial differences in the atmospheric emissions for different SRES scenarios in the 21st century lead to statistically significant differences in the carbon dioxide uptake by the ocean, car-
Eliseev

Carbon dioxide content in the atmosphere, and changes in the surface air temperature. In particular, in 2071–2100, the carbon flux from the atmosphere to the ocean, according to the SRES A2 (A1B, B1) scenario, will be $10.6 \pm 0.6 \text{PgC yr}^{-1}$ ($8.3 \pm 0.5, 5.6 \pm 0.3 \text{PgC yr}^{-1}$), and the carbon dioxide concentration in the atmosphere by 2100 will attain $773 \pm 28 \text{ppmv}$ ($662 \pm 24, 534 \pm 16 \text{ppmv}$). The annual mean warming in 2071–2100 relatively to 1961–1990 will be $3.19 \pm 0.09 \text{K}$ ($2.52 \pm 0.08, 1.84 \pm 0.06 \text{K}$) and will be accompanied by a stable decrease in the amplitude of the annual cycle of the surface air temperature.

APPENDICES

DESCRIPTION OF THE SCHEME OF THE CARBON CYCLE IN THE IAP RAS CM

APPENDIX A

Vegetation

The module of carbon cycle of the IAP RAS CM takes into account six plant functional types (PFTs): tropical forests, temperate forest, taiga, grasses, shrubs, and agricultural lands. The PFTs in the model are constructed by aggregation of vegetation classes in accordance with the simplified Holdridge classification.
tion [89] (Table 2). The model cell is divided into two parts, in one of which only natural vegetation can exist (one of the five PFTs); in the other part, only agricultural lands can exist. In the model, the fractions of the cell area occupied by these parts \( s_{\text{nat}} \) and \( s_{\text{agro}} \), respectively) are specified as external parameters. The equations for the vegetation carbon stock \( c_{v, Y} \) per unit area (here and below, \( Y \) designates PFT) are

\[
\frac{\partial c_{v, Y}}{\partial t} = f_{\text{GPP}, Y} - r_{v, Y} - f_{lY, Y} - d_{Y},
\]

where \( f_{\text{GPP}} \), \( r_{v} \), and \( f_{lY} \) are the intensities of photosynthesis, autotrophic respiration, and total litter–debris fall-out per unit area, respectively; and \( t \) is time. The term \( d_{Y} \) describes \( c_{v, Y} \) changes caused by natural fires and land use:

\[
d_{Y} = d_{\text{fire}, Y} + d_{\text{lu}, Y}.
\]

At present, the carbon transport by rivers into the ocean is not taken into account, because transformations of organic carbon in the oceanic part of the carbon cycle of the model are disregarded.
The intensity of photosynthesis (or the total primary productivity [90–93]) of terrestrial ecosystems is calculated in accordance with the equation

\[ f_{GPP, Y} = \frac{A_{GPP}}{N_a} \sum_{T_a \geq T_{vac}} g_1 g_2 g_3 R_{SW, j}. \]  

(A. 3)

In (A. 3) and further, the subscript “\(j\)” at the variables points to the time moment inside the year; \(N_a\) is the number of time steps of the IAP RAS CM atmospheric module per one model year; the summation is performed only for \(T_j \geq T_{vac} = 273.15\) K. The dependences of the total primary productivity on \(q_{CO_2}\) (the Michaelis–Menten law), the relative soil saturation with moisture \(w\), and the temperature \(T_a\) are described by the relations

\[
g_1 = \frac{q_{CO_2}}{q_{CO_2} + q_{1/2}},
\]

(A. 4)

\[
g_2 = w,
\]

(A. 5)

\[
g_3 = \frac{Q_{10, GPP}^{(T_{a, j} - T_{vac, GPP})/10\ K}}{1 + e^{0.3(T_{a, j} - T_{vac, GPP})}} \{1 + e^{0.3(T_{a, j} - T_{vac, GPP})}\}. \]

(A. 6)

The half-saturation constant \(d_{1/2}\) in the model version used in [30] is 300 ppmv. In the expression for \(g_3\), the temperature constants \(T_{up, Y}\) and \(T_{down, Y}\) restrict the intensity of photosynthesis from above and from below, respectively, and depend on the PFT (see Table 3); \(Q_{10, GPP} = 1.8\); and \(T_{opt, GPP} = 298.15\) K [94]. It is assumed that the intensity of photosynthetically active radiation is proportional to the total balance of shortwave radiation at the surface \(R_{SW}\). Currently, the possible dependence of bioproductivity on the vegetation carbon stock (which is important at small values of \(c_{v, Y}\) [67, 95, 96]) is disregarded in the IAP RAS CM. The value of the constant \(A_{GPP}\) is assumed to be \(3.58 \times 10^{-2}\) (PgC yr\(^{-1}\))/(W m\(^{-2}\)).

The intensity of autotrophic respiration is calculated with the use of the Arrhenius relation:

\[ r_{v, Y} = \left[ \frac{A_v}{T_{a, j}^2} \right] \sum_{T_a \geq T_{vac}} \exp\left(\frac{-E_v}{RT_{a, j}}\right) c_{v, Y}, \]  

(A. 7)

where \(E_v = 5.5 \times 10^4\) J mole\(^{-1}\) is the activation energy [97], \(R\) is the universal gas constant, and the constant \(A_v = 6.1 \times 10^8\) yr\(^{-1}\).

The fraction of leaves in the biomass \(\alpha_{leaf, Y}\) and the lifetimes of leaves and wood (\(\tau_{leaf, Y}\) and \(\tau_{wood, Y}\), respectively; see Table 3) are specified for each PFT. The masses of leaves and wood per unit area are equal to

\[ c_{v, Y}, \alpha_{leaf} = \alpha_{leaf} c_{v, Y}, \]

\[ c_{v, Y}, wood = (1 - \alpha_{leaf}) c_{v, Y}, \]

respectively, and the intensities of defoliation and wood fall-out are, respectively,

\[ f_{flf, Y, leaf} = c_{v, Y}, \alpha_{leaf} \tau_{leaf, Y}, \]

\[ f_{flf, Y, wood} = c_{v, Y}, wood \tau_{wood, Y}, \]

(A. 9)

The total intensity of leaf–wood fall-out per unit area is

\[ f_{flf, Y} = f_{flf, Y, leaf} + f_{flf, Y, wood}. \]  

(A. 10)

APPENDIX B

**Influence that Natural Fires and Land Use Have on Changes in the vegetation carbon stock**

Changes in the biomass caused by natural fires are described in accordance with [98]. The length of fire season as a fraction of in the calendar year duration is

\[ p_{fire} = \frac{1}{N_a} \sum_{T_a > T_{vac}} \exp\left(-\pi\left(w_j/w_e\right)^2\right). \]

The value of the parameter \(w_e\) is \(w_e = 0.7\). “The fuel stock” per unit area in the cell is

\[ C_{fuel} = c_{v, Y, leaf} + m_{fire, wood} c_{v, Y, wood}, \]

where \(m_{fire, wood} = 0.1\) is the fraction of wood burning during the fire [98]. If \(c_{fuel} = c_{fuel, 0} = 0.15\) kgC m\(^{-2}\), the fraction of the model cell area burning up annually is

\[ a_{fire} = (s + 1)\exp\left(\frac{s}{0.45s^3 + 2.83s^2 + 2.96s + 1.04}\right), \]

where \(s = p_{fire} - 1\). Otherwise, \(s_{fire} = 0\). It is assumed in the IAP RAS CM that the entire carbon in the burnt biomass is emitted into the atmosphere as carbon.
dioxide, so that the annual CO\textsubscript{2} emissions into the atmosphere from unit of area are

\[ e_{\text{fire}, y} = d_{\text{fire}, y} - k_{\text{res}, y} \cdot \varepsilon_{\text{fuels, fire}} \]  

(B.11)

where the coefficient \( k_{\text{res}, y} \) depends on the PFT (Table 3).

The change in the amount of carbon in natural vegetation caused by land use from the year \( k \) to the year \( k + 1 \) is

\[ d_{\text{lu, nat}} = c_{v, \text{ nat}} \times \max[(s_{\text{nat}}^{(k+1)} - s_{\text{nat}}^{(k)}), 0]. \]  

(B.12)

In this case, for agricultural lands, \( d_{\text{lu, agro}} = 0 \). It is assumed in the model that the entire amount of carbon \( d_{\text{lu, nat}} \) is transported into the atmosphere during one year [99], so that the CO\textsubscript{2} emission into the atmosphere as a result of land use from unit of area of the model cell is

\[ e_{\text{lu}} = d_{\text{nat, lu}}. \]  

(B.13)

The global carbon dioxide emissions into the atmosphere due to land use \( E_{\text{lu}} \) (see (1)) is calculated through the integration of \( e_{\text{lu}} \) over the entire area of the land. The possible delay of the emissions with respect to a decrease in the mass of natural vegetation caused by incomplete combustion of the corresponding biomass (see, for example, [100]) is disregarded in the IAP RAS CM version used here. This is at least partially compensated for by neglecting the biomass losses due to logging. It should be noted that \( e_{\text{lu}} \) includes only the so-called direct emissions due to land use without regard for soil carbon losses caused by the respiration intensification as a result of cultivation and without regard for the repeated growth of natural vegetation after agricultural lands are abandoned. Emissions of the two last types are included into the empirical estimates presented in [100]; however, they are described in the model through the corresponding parametrizations of the carbon-cycle module.

### APPENDIX C

**Soil**

In the IAP RAS CM, soil carbon is divided into the fast and slow reservoirs \((Z = \text{fast, slow})\), respectively. The equations of dynamics of the carbon storage per unit area \( c_{s, y, Z} \) in them are

\[ \frac{\partial c_{s, y, Z}}{\partial t} = f_{s, y, Z} - r_{s, y, Z}, \]  

(C.14)

where \( f_{s, y, Z} \) is the leaves–wood fall-out into the soil reservoir \( \{Y, Z\} (Y \text{ = nat, agro}) \) and \( r_{s, y, Z} \) is the respiration from this reservoir. For simplicity, it is assumed that \( f_{s, y, \text{fast}} = f_{s, y, \text{leaf}} \) and \( f_{s, y, \text{slow}} = f_{s, y, \text{wood}} \).

Heterotrophic respiration is described by analogy with the TRIFFID model [94] but in a simplified form, because the annual cycle of \( q_{\text{CO}_2} \) is not described in the IAP RAS CM model:

\[ r_{s, y, Z} = \frac{A_{s, y, Z}}{N_{a}} \sum_{T_{s, y, Z} > T_{v}} g_4 g_5 c_{s, y, Z}, \]  

(C.15)

with

\[ g_4 = \begin{cases} 
0.2, & \text{at } w < w_{\text{wilt}}; \\
0.2 + 0.8(w - w_{\text{wilt}})/(w_{\text{opt}} - w_{\text{wilt}}), & \text{at } w_{\text{wilt}} \geq w \geq w_{\text{opt}}, \\
1 - 0.8(w - w_{\text{opt}}), & \text{at } w > w_{\text{opt}}, 
\end{cases} \]

\[ g_5 = \sqrt[10]{Q_{10, s, Z}}. \]

In this model, \( w_{\text{wilt}} = 0.2, w_{\text{opt}} = (1/2)(w_{\text{wilt}} + 1), \) and \( T_{\text{agro}} = 298.2 \text{ K} \). The values of \( Q_{10, s, Z} \) and \( A_{s, y, Z} \) for the model version used in [30] are given in Table 4. In this version, the increase in \( A_{s, Y, Z} \) values at \( Y = \text{agro} \) compared with these values at \( Y = \text{nat} \) by a factor of \( k_{s, \text{agro/nat}} = 1.3 \) is explained by the parametrization of the cultivation effect on soil respiration [54].

To retain the carbon amount in soil during the change in the area of agricultural lands from the year \( k \) to the year \( k + 1 \), its mass is recalculated between the parts of the model cell with natural vegetation and agricultural lands:

- if \( s_{\text{agro}}^{(k+1)} > s_{\text{agro}}^{(k)} \),
  \[ c_{s, \text{nat}}^{(k+1)} = c_{s, \text{nat}}^{(k)}, \]
  \[ c_{s, \text{agro}}^{(k+1)} = \frac{c_{s, \text{agro}}^{(k)} - s_{\text{agro}}^{(k)}}{s_{\text{agro}}^{(k)} - s_{\text{agro}}^{(k+1)}} + c_{s, \text{agro}}^{(k)} s_{\text{agro}}^{(k+1)}/s_{\text{agro}}^{(k+1)} ; \]
- if \( s_{\text{agro}}^{(k+1)} < s_{\text{agro}}^{(k)} \),
  \[ c_{s, \text{nat}}^{(k+1)} = \frac{c_{s, \text{agro}}^{(k)} s_{\text{agro}}^{(k)} s_{\text{agro}}^{(k+1)}}{s_{\text{agro}}^{(k+1)} - s_{\text{agro}}^{(k)}}, \]
  \[ c_{s, \text{agro}}^{(k+1)} = c_{s, \text{agro}}^{(k)}. \]

**Table 4.** Governing parameters of the soil module of the IAP RAS CM carbon cycle

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Soil reservoir</th>
<th>( Q_{10, s} )</th>
<th>( A_s ), g\textsuperscript{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural vegetation</td>
<td>Fast</td>
<td>2.2</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Slow</td>
<td>1.5</td>
<td>0.04</td>
</tr>
<tr>
<td>Agricultural crops</td>
<td>Fast</td>
<td>2.2</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Slow</td>
<td>1.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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APPENDIX D

Net Primary Productivity and Carbon uptake by Terrestrial Ecosystems

The net primary productivity of vegetation per unit area is calculated in accordance with the equation

\[ f_{NPP} = \sum_{y = nat, agro} s_y (f_{GPP, Y} - r_y - \gamma). \]

The carbon uptake by terrestrial ecosystems per unit area is determined in the model as

\[ f_I = \sum_{y = nat, agro} s_y (f_{NPP, Y} - r_y - e_{fire, Y}). \]

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