CARBON CYCLE-CLIMATE FEEDBACK SENSITIVITY TO CHOICE OF THE GOVERNING PARAMETERS OF TERRESTRIAL CARBON CYCLE IN A CLIMATE MODEL OF INTERMEDIATE COMPLEXITY*

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Был проведен ансамбль численных экспериментов с совместной моделью климато-углеродного цикла. В качестве климатического блока совместной модели использовалась модель промежуточной сложности Института физики атмосферы им. А.М. Обухова РАН (КМ ИФА РАН). Углеродный цикл при этом описывается простейшей нульмерной моделью. В численных экспериментах задавались эмиссии углекислого газа за счет сжигания топлива и землепользования по наблюдательным оценкам в 19–20 вв. и по сценарию SRES A2 — в 21 в. В проведенных массовых расчетах варьировались определяющие параметры углеродного цикла модели, а также температурная чувствительность модели к росту концентрации углекислого газа в атмосфере. При этом интенсивность обратной связи между климатом и углеродным циклом изменяется в широких пределах вплоть до смены ее знака. Диапазон неопределенности для концентрации углекислого газа в атмосфере в конце 21 в. при указанном сценарии эмиссий составляет 765–1000 млн$^{-1}$.

Introduction

In recent years, three-dimensional climate models with an interactively coupled carbon cycle have emerged (for a review, see [1–3]). It was shown that this interactive coupling changes the build up of the carbon dioxide in the atmosphere $p\mathrm{CO}_{2(\mathrm{a})}$ in comparison to the hypothetical case, when the carbon cycle does not feel the climate changes. As a result, the so called climate-carbon cycle feedback term has been introduced.

Up to date, all the coupled models simulate a positive climate-carbon cycle feedback, i. e., an interactive coupling between the climate and the carbon cycle increases the build up of the carbon dioxide in the atmosphere. However, the simulated intensity of the carbon cycle falls into a rather broad range. For instance, in the Coupled Climate-Carbon Cycle Models

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Intercomparison Project (C^4MIP) [1] differences between fully interactive (coupled) simulations and simulations without influence of the climate changes on the carbon cycle (uncoupled) approach 20–200 ppmv.

Moreover, even the sign of the climate-carbon cycle feedback can be questioned. The positive feedback found in the simulations is basically associated either with an enhanced soil respiration in warmer climate (and to a smaller amount — to the enhanced plant respiration) or to an eventual decrease of the plant photosynthesis. However, in [4] it was noticed that the nitrogen limitation of the organic matter decomposition in the soils may lead to the final decrease of the soil respiration under growing temperatures. The response of gross plant photosynthesis to climate changes is ambigious as well due to possible enhancement of the photosynthesis in a warmer climate on one hand [5, 6], and due to possible dieback of tropical forests on the other [5, 7, 8].

The goal of the present paper is to examine the possible range of the climate-carbon cycle feedback, using a simple, but flexible, carbon cycle model, coupled to the climate model of intermediate complexity A.M. Obukhov Institute of Atmospheric Physics RAS (IAP RAS CM) [2,3,9]. In the paper, the terrestrial carbon cycle is perturbed, varying its governing parameters, based on the published ranges of their values. The climate part of the model is perturbed by artificial increase or decrease of the model sensitivity to the atmopsheric CO_2 content. To distinguish between realistic and unrealistic situations, the simulations are subjected to the constraint of the proximity to the observed carbon cycle characteristics. Other than mentioned above sources of the simulation uncertainty, e. g., forcings due to aerosols, other than CO_2 anthropogenic greenhouse gases, solar and volcanic activity and emissions (especially from land-use), and missing model processes (such as nitrogen cycling, fire activity or atmospheric chemistry) are not considered in the paper.

1. Model and performed simulations

The climate-carbon cycle model of intermediate complexity developed at the A.M. Obukhov Institute of Atmospheric Physics RAS (IAP RAS CM) is described and validated against the observed data in [2, 3, 9].

With this model, three sets of the model simulations were performed. These sets differ between each other with respect to the climate-carbon cycle interactions. In the first set (hereafter denoted as "REF"), the interactively coupled climate-carbon cycle model is ran. The coupled model is forced by the CO_2 emissions. For 1860–2000 the anthropogenic emissions of the carbon dioxide are prescribed according to the data [10, 11]. For 2000–2100 the scenarios for both emissions are taken from the SRES emission scenario A2 [12].

In the second scenario group (denoted as "NOCLIM"), the climate model is forced by the output of the carbon cycle model. The carbon cycle model is forced by the CO_2 emissions, but the carbon cycle dynamics does not feel the corresponding climate changes (due to zeroing of the temperature anomalies entering the carbon cycle routine).

As the intensity of the carbon cycle feedback may depend on the overall sensitivity of the climate model to the carbon dioxide loading in the atmosphere [13] and IAP RAS CM sensitivity to the doubling of the CO_2 concentration in the atmosphere (2.2 °C) is in the lower half of the range of the current generation of the climate models (1.5...4.5 °C, [12]), another set of the numerical experiments was perfomed. In this set (denoted as "SENS"), the temperature anomalies entering the carbon cycle routine have been multiplied by 1.7 in order to mimic a climate model with a greater sensitivity to the doubling of the CO_2 concentration in the atmosphere (1.7×2.2 °C = 3.7 °C). One notes that the simulations NOCLIM corresponds to the other limiting case of negligible climate sensitivity of the model to the doubling of the carbon dioxide content in the atmosphere.

In every set of numerical experiments, a subset of governing parameters of the terrestrial carbon cycle is perturbed, based on their published values (for more detailed description, see [3]).

All model simulations were started from the preindustrial equilibrated model state. In every simulation, the first model year with the non-zero carbon dioxide emissions corresponds to the julian year 1859. Simulations end in the year corresponding to the julian year 2100.

The cumulative length of the simulations is 278,784 model years. Such long simulations are precluded currently for the state-of-the-art general circulation model due to technical reasons. This advocates the usage of the climate model of intermediate complexity for the purposes of the present study.

2. The sensitivity of the climate-carbon cycle to the choice of the governing parameters

Difference $\Delta p\mathrm{CO}_{2(\mathrm{a})}^{\mathrm{xxx}}, \mathrm{xxx} = \mathrm{REF}, \mathrm{SENS}$ between either REF or SENS on one hand, and NOCLIM on the other, in year the 2100, span rather broad interval, from -118 ppmv up to 445 ppmv. Nevertheless, one may not consider the whole interval, because the simulations have to fulfil the important constraint of the realism for the 20th century simulation. In the present paper, this constraint is formulated via two terms. Firstly, the maximum deviation of the simulated $p\mathrm{CO}_{2(\mathrm{a})}$ from the Mauna Loa observations are not allowed to exceed some prescribed value $\epsilon_{p\mathrm{CO}_{2(\mathrm{a})}}$. It is impossible to zero this value due to finiteness of the grid in the parameter space. The minimum studied here $\epsilon_{p\mathrm{CO}_{2(\mathrm{a})}} = 2$ ppmv roughly corresponds to the observed year-to-year variations of $p\mathrm{CO}_{2(\mathrm{a})}$ [14]. Secondly, simulated terrestrial and oceanic carbon uptakes (F_l and F_as, respectively) in the last two decades of the 20th century must be in the range figured in [15]: in 1980's $F_\mathrm{l} = 0.3 \ldots 4.0$ GtC/yr, $F_\mathrm{as} = (1.8 \pm 0.8)$ GtC/yr, in 1990's $F_\mathrm{l} = 1.6 \ldots 4.8$ GtC/yr, $F_\mathrm{as} = (2.1 \pm 0.7)$ GtC/yr. These two terms may be considered either separately or in combination. The results are presented in Table 1. From this Table, one sees that this constraint can narrow the uncertainty range for the climate-carbon cycle feedback condiderably. In particular, if one imposes only the $\epsilon_{p\mathrm{CO}_{2(\mathrm{a})}}$ — term with the allowed range of $p\mathrm{CO}_{2(\mathrm{a})}$ is $-45 \ldots +450$ ppmv. If, alternatively, one imposes the uptake term, one gets the respective range $-118 \ldots +385$ ppmv. In this, the terrestrial uptake leads to the stronger constraint than the oceanic ones. It is notable that even the relatively strong version of this

T a b l e 1. Ranges of the climate-carbon cycle feedback strength in terms of $\Delta p\mathrm{CO}_{2(\mathrm{a})}$, for different values of the allowed deviations $\epsilon_{p\mathrm{CO}_{2(\mathrm{a})}}$ of the simulated concentration of the carbon dioxide in the atmosphere from the Mauna Loa observations for 1959–2000, and for different constraints on the simulated uptakes

$\epsilon_{p\mathrm{CO}_{2(\mathrm{a})}}$, ppmv	None	F_l	F_as	F_l and F_as
None	$-118 \ldots +445$	$-118 \ldots +385$	$-118 \ldots +403$	$-118 \ldots +385$
10	$-98 \ldots +403$	$-98 \ldots +385$	$-98 \ldots +403$	$-98 \ldots +385$
5	$-65 \ldots +403$	$-65 \ldots +385$	$-65 \ldots +403$	$-65 \ldots +385$
2	$-45 \ldots +403$	$-45 \ldots +280$	$-45 \ldots +403$	$-45 \ldots +280$

constraint, corresponding to the maximum allowed deviations from the Mauna Loa observations $\epsilon_{pCO_{2(a)}} = 2$ ppmv can not exclude the possibility of the negative feedback (with the magnitude up to 45 ppmv). It is also unable to exclude the highest positive feedback value among those simulated by the C^{4}MIP models. This is true even for the simulations sets REF–NOCLIM, while, generally, the intensity of the climate-carbon cycle feedback (either positive or negative) is higher for the pairs SENS–NOCLIM.

The landborne fraction of the anthropogenically emitted carbon dioxide for 1860–2100 are shown, if no constraint is imposed, may vary in a rather broad range $-42\ldots{+}60\,\%$. This range is broader than that simulated by the C^{4}MIP models, $1\ldots45\,\%$ [1]. If one constrains the simulated uptakes, the respective range become narrower, $-10\ldots+53\,\%$, but is still wider than the C^{4}MIP one. However, if one imposes constrains the simulated $pCO_{2(a)}$ with $\epsilon_{pCO_{2(a)}} = 2$ ppmv, the allowed range becomes $-13\ldots+22\,\%$ and is narrower than that simulated by the C^{4}MIP ensemble. For the strong constraint $\epsilon_{pCO_{2(a)}} = 2\ldots10$ ppmv, this range is even narrower, and some of the C^{4}MIP simulations lie outside this range. If both $pCO_{2(a)}$ and uptakes are constrained, the range for the landborne fraction is $-6\ldots+22\,\%$.

The oceanborne fraction of the emitted carbon dioxide, if unconstrained, also vary in a rather wide range, 15...54 %. This range is wider to the corresponding C^{4}MIP range 15...35 % [1]. However, if one constraines the uptakes, the range shrinks to 18...42 % with one C^{4}MIP model lying outside this range. If, in contrast, the simulated $pCO_{2(a)}$ is constrained, the respective range becomes narrower (for instance, 29...43 % for $\epsilon_{pCO_{2(a)}} = 2$ ppmv). The most narrow range one obtaines if both the simulated $pCO_{2(a)}$ and uptakes are constrained: 29...40 % for $\epsilon_{pCO_{2(a)}} = 2$ ppmv.

The airborne fraction of the emitted carbon dioxide (Table 2, second figure at every raw), if unconstrained, fills the range 12...89 % which is wider than the corresponding C^{4}MIP range, 42...72 % [1]. If the uptakes are constrained, the simulated in the present paper range becomes 30...69 %. By decreasing $\epsilon_{pCO_{2(a)}}$ with the unconstrained uptakes, the range may be narrowed to 48...71 %. With the both terms constrained, this range is 48...66 %.

As a result of these uncertainties in the sequestration of the anthropogenically emitted carbon dioxide by the terrestrial and oceanic ecosystems, the expected values of $pCO_{2(a)}$ in year 2100 are uncertain as well (Table 2, first raw at every figure). The whole range of the unconstrained simulations is 408...1207 ppmv. If the simulated concentration in 1958–2000 is

T a b l e 2. Ranges of atmospheric CO_2 concentration (ppmv) for different values of the allowed deviations $pCO_{2(a)}$ of the simulated concentration of the carbon dioxide in the atmosphere from the Mauna Loa observations for 1959–2000, and for different constraints on the simulated uptakes. The corresponding ranges for the airborne fractions (per cents) of the emitted CO_2 are figured in parentheses

$\epsilon_{pCO_{2(a)}}$, ppmv	None	F_l	F_{as}	F_l and F_{as}
None	408 ... 1207 (12 ... 89)	408 ... 1000 (12 ... 69)	590 ... 1019 (30 ... 71)	590...1000 (30 ... 69)
10	706 ... 1047 (41 ... 73)	706 ... 1000 (41 ... 69)	732 ... 1018 (43 ... 71)	732 ... 1000 (43 ... 69)
5	765 ... 1019 (46 ... 71)	765 ... 1000 (46 ... 69)	765 ... 1019 (46 ... 71)	765 ... 1000 (46 ... 69)
2	785 ... 1019 (48 ... 71)	786 ... 974 (48 ... 66)	786 ... 1019 (48 ... 71)	786 ... 974 (48 ... 66)

constrained with $\epsilon_{pCO_{2(a)}} = 2$ ppmv, this range shrinks to 785...1019 ppmv. If both terrestrial and oceanic uptakes are constrained, the respective uncertainty range is 590...1000 ppmv. The narrowest uncertainty (786...974 ppmv) is obtained if both constrains are imposed.

3. Discussion and conclusions

In this paper, numerous simulations have been performed with a coupled climate-carbon cycle model of intermediate complexity IAP RAS CM. In the simulations, perturbing the governing parameters of the terrestrial carbon cycle and climate sensitivity to changes of the atmospheric concentration of carbon dioxide.

Perturbing the above mentioned governing parameters, one obtains a wide range of the climate-carbon cycle feedback strengths. Even the sign of this feedback can vary, changing from positive to negative, in dependence of the particular set of the governing parameters.

If the performed simulations are subjected to the constraint of the proximity to the observed carbon cycle characteristics in the second half of the 20th century, it becomes possible to rule out some of the simulations, performed in the present paper, and narrow the corresponding uncertainty range.

However, the imposed constraints on the simulated atmospheric carbon dioxide content, and terrestrial and oceanic uptakes are still unable to rule out both extremely strong positive and modest negative positive climate-carbon cycle feedback. This is not surpising, considering the relative smallness of the climate and carbon cycle perturbations in the currently available observations relative to those expected in the 21st century. Moreover, even under the strongest considered here constrains, the simulated $pCO_{2(a)}$ in year 2100 is quite uncertain filling the range 786...974 ppmv. For the commonly accepted logarithmic dependence of the radiative forcing R on the corresponding agents, this range translates into factor of about 1.5 in uncertainty of the globally averaged value of R.

Conclusion on weakness of the constraint imposed by the currently available carbon cycle observational estimates on the future is shared also by [16]. In this latter paper, it was shown that "the observational record proves to be insufficient to tightly constrain carbon cycle processes or future feedback strength with implications for climate-carbon cycle model evaluation". In addition, [17] were able to reproduce accurately the 20th century course of the carbon cycle characteristics with a model accounting only direct CO_2 influence on F_l and F_{as} without considering respective climate feedbacks. It is notable, that zero intensity of the climate-carbon cycle feedback lies within the estimated in the present paper range. For this reason, the results by [17] are in accord with the results of the present paper.

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