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Simulation results from a coupled model of carbon dioxide and methane global cycles

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ABSTRACT

The problem of greenhouse effect due to the anthropogenic influence on the global cycles of greenhouse gases is discussed extensively in the scientific literature. This paper aims to contribute solving this problem by presenting the simulation results of a new model of combined carbon and methane biogeochemical cycles considering the spatial structure of their sources and sinks on a global scale. All reservoirs and fluxes of the carbon and methane that are taken into consideration in the model have different temporal scales, while the spatial scale for sources and sinks of carbon and methane on the land is considered as 4° by latitude and 5° by longitude. The World Ocean is parameterized by two-point models with four levels in depth with a separation between pelagic and upwelling zones. In addition, the interaction between the atmosphere and carbon reservoirs on the land and in the ocean includes the processes of photosynthesis, decomposition, respiration and burning. The global cycle of methane in the atmosphere-hydrosphere-land system is described by the scheme that takes into account the potential of the radiation fluxes, which is a function of time. Furthermore, the structure of the model used for the coupling of the carbon and methane cycles consists of 12 blocks, which carry out basic calculation procedures for their fluxes. Finally, the results of simulation experiments are discussed considering scenarios for changes in forest areas, showing their significant role in the climate change issue.

1. Introduction

The global cycles of CO_2 and CH_4 are the subject of many international and national research programs aimed at parameterization and understanding of the feedbacks in the climate-biosphere-society system (CBSS). The Global Carbon Project (GCP) provides a comprehensive picture of the global carbon cycle taking into account its biophysical and human components. There are several mathematical models of this cycle by examining the interactions and feedbacks between the various environmental subsystems (Varotsos and Cartalis, 1991; Siegenthaler, 1993; Varotsos and Cracknell, 1994a,b; Varotsos et al., 1994; Cracknell and Varotsos, 1994, 1995; Doney et al., 2003; Kondratyev et al., 2003; Ondov et al., 2006; Ebel et al., 2007; Krapivin and Varotsos, 2008; Efstathiou and Varotsos, 2010, 2012, 2013; Chattopadhyay et al., 2012; Xue et al., 2014; Krapivin et al., 2015). GCP and relevant publications are intended for the implementation of the various procedures to accumulate knowledge about greenhouse gases and their sources and sinks. According to existing data, the main CO_2 emissions are the cement industry, the burning of the fossil fuels, and land use. Unfortunately, this knowledge provides only 80–85 percent of the global carbon cycle completeness. Such uncertainty also exists in global cycles of other greenhouse gases (Kondratyev and Varotsos, 1995,2002; Kondratyev and Varotsos, 1995). One of the methods to overcome this uncertainty is to develop models of global cycles of greenhouse gases, which makes it possible to detect the most critical aspects of these cycles.

It is well-known that CH_4 has more than 20 times greater global warming potential than CO_2. Many authors attempt to better understand the behavior of CH_4 in the carbon cycle and to develop models of coupled carbon and CH_4 cycles (Panikov and Dedysh, 2000; Smemo and Yavitt, 2000; Tang et al., 2016). Unfortunately, the knowledge about methane's sources and its involvement to the carbon cycle is still incomplete and contradictory. Nevertheless, the use of a combined model of CO_2 and CH_4 cycles would be useful for understanding the global problem of climate change and to reduce the existing uncertainties in the relevant simulations. In multiple discussions of this issue the available data were analyzed in detail particularly with regard to the existing contradictions in the study of the global ecodynamics (Kondratyev

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et al., 2003). Cracknell et al. (2009) grouped the climate change disasters in twelve classes that are connected with environmental stability (including human life) and indicated that only one of them has anthropogenic character. Therefore, the coupled model of CO_2 and CH_4 cycles must take into account all the causes of environmental changes, ie direct and feedbacks (Cracknell and Varotsos, 2011). This is feasible within the CBSS because Krapivin and Varotsos (2008) showed that CBSS allows the combination of different environmental processes in the unique structure of the model components that are supported by existing global and regional databases. In this regard, Degermendzhi (2009) developed an alternative approach to the biosphere-climate system modeling taking into account the incompleteness of the existing databases.

This paper discusses new simulation results of a coupled model of CO_2 and CH_4 cycles, where the soil-plant formations and oceanic ecosystems exhibit spatial distribution.

2. Conceptual scheme of global carbon dioxide and methane global cycles

It is well known that global carbon and methane cycles include a series of natural and anthropogenic processes that determine their dynamics and have different temporal scales from tens to hundreds and thousands years. For example, the atmospheric CO_2 concentration varies significantly during the year. The difference between maximum and minimum concentrations of CO_2 varies by 10 ppm at the South Pole and 15 ppm at the North Pole. The existing global models of the CO_2 do not take into account these seasonal CO_2 fluctuations, which are registered by many measurements that are taken regularly, and span from the South Pole to the Arctic. These fluctuations arise from many causes like the following:

- carbon accumulates in forests and in the rest of vegetation of the Northern Hemisphere, especially during summer;
- without photosynthesis, the dominant process of the CO_2 regime is the exhalation of CO_2 from bacteria and living organisms;
- the seasonal fluctuations in CO_2 emissions (including permafrost melting) are important.

Bearing in mind these conditions it is possible to employ an advanced global model of CO_2 and CH_4 cycles with specific structure of their sinks and sources. In relation to this, Tables 1 and 2 show the basic components of these cycles with the spatial heterogeneity of land and ocean ecosystems. In this regard, Figs. 1 and 2 illustrate the main features of CO_2 and CH_4 cycles, while Fig. 3 shows the structure of the above-mentioned coupled model of CO_2 and CH_4 cycles (CMCDMC). As shown in Table 1 all carbon reservoirs and fluxes are divided into categories that vary on time scales. It is obvious that CMCDCM describes CO_2 fluxes between its reservoirs. However, the existing databases are unable to provide detailed input information on the role of every tree, animal, microorganism, leaf, lake, river, oceanic aquatory, landscape, etc. Therefore, the global carbon cycle models are built with specifications characterized by increased complexity (Kondratyev et al., 2003). Fig. 1 illustrates an achieved level of complexity of the biogeochemical carbon cycle.

The employed CMCDMC takes into consideration 30 types of soil-plant formations that are shown in Fig. 2 and Table 2. A soil-plant formation occupies the spatial pixel Ξ=[4° × 5°], in which atmospheric temperature and solar radiation are uniform in space. The spatial structure of the World Ocean is described by the Tarko's model (Tarko, 2003), which provides exchange processes in the atmosphere-ocean boundary, taking into account its spatial heterogeneity by separating pelagic and upwelling zones (Krapivin and Varotsos, 2016). In particular, the seasonal variations in the atmospheric CO_2 are carried out with introduction of permafrost thawing time only.

In the following, the CO_2 fluxes shown in Fig. 1 and Table 1 are used for the synthesis of the balanced equations:

$$\frac{\partial C_{As}(\varphi,\lambda,t)}{\partial t} + V_{\varphi s}\frac{\partial C_{As}(\varphi,\lambda,t)}{\partial \varphi} + V_{\lambda s}\frac{\partial C_{As}(\varphi,\lambda,t)}{\partial \lambda} = \sum_{i\in I_s} F_i - \sum_{j\in J_s} F_j \quad (1)$$

where C_{As} is the carbon reservoir in the s-th pixel of the spatial structure of land and ocean; I_s and J_s are the carbon sources and sinks, respectively; φ is latitude; λ is longitude; t is time; $V_s(V_{\varphi s},V_{\lambda s})$ is the wind components in the sth pixel.

Interaction between the atmosphere and carbon reservoirs on land and in ocean is revealed by the carbon fluxes formed by the ecological, geophysical and biogeochemical processes, including photosynthesis, respiration, decomposition, burning, earthquake, soil erosion, etc. Detailed description of these processes are given in Bjorkstrom (1979); Alexeev et al. (1992); and Williams and Follows (2011). Some of them are determined through CMCDMC items listed in Table 3.

The photosynthesis production of the k-th type of vegetation in the pixel $\Xi_{ij}(\varphi_i,\lambda_j)$ at the time t is given by:

$$P_k(\varphi,\lambda,t) = NPP_\kappa(\varphi,\lambda,t) + R_\kappa(\varphi,\lambda,t) \quad (2)$$

where the net primary production (NPP) and the respiration R are functions of CO_2. The symbols W, T and E stand for the precipitation (mm/yr), atmospheric temperature (°C) and solar radiation (W/m^2), respectively. The item CFCV of CMCDMC uses the climate model of Mintzer (1987) which was modernized by Krapivin et al. (2015) and the model of global water cycle of Kondratyev et al. (2002). Net primary production (NPP) and respiration (R) are calculated with the use of the following models:

$$NPP_\kappa(\varphi,\lambda,t) = P^*_\kappa(\varphi,\lambda)\min\left\{\begin{array}{l} k_p\dfrac{C_A-\Gamma}{k_s+C_A+\Gamma}, \dfrac{\rho_1 E(\varphi)}{\rho_2+E(\varphi)}, \dfrac{\mu_a W}{\mu_b+W}, \\ \max[0, \dfrac{T(\varphi)-T_{\min}(\varphi)}{T_{opt}(\varphi)-T_{\min}(\varphi)}\exp(0.56-0.42\dfrac{T(\varphi)-T_{\min}(\varphi)}{T_{opt}-T_{\min}(\varphi)})] \end{array}\right\}$$

$$T(\varphi) = T_g + (T_N - T_e)(sin^2\varphi_T - sin^2\varphi),\ R_\kappa(\varphi,\lambda,t) = k_B B^*_\kappa(\varphi,\lambda)\max\left\{0, \frac{\psi_a T(\varphi)}{\psi_b+T(\varphi)}, \frac{d_a W}{d_b+W}\right\},$$

where k_p (3.226) is the photosynthesis rate constant, Γ (5–50) is the photosynthesis compensation constant, k_s (930) is the photosynthesis stabilizing constant, ρ_1 (1.177) and ρ_2 (60.538) are empirical constants, reflecting the correlation between E = APAR and NPP; T_{opt} (25 °C) is the optimal temperature for the photosynthesis; $T_{\min}(\kappa)$ is the minimal temperature, when photosynthesis rate does not zero; T_g is the global average temperature; T_N is the global average temperature on the pole; T_e is the global average temperature on the equator; φ_T is the latitude at which $T(\varphi) = T_g$; μ_a (4.742), μ_b (592.357), ψ_a (1.214), ψ_b (5.714), d_a (2.941) are empirical constants. Information about $P^*_\kappa(\varphi,\lambda)$ and $B^*_\kappa(\varphi,\lambda)$ is given in Table 2 and in Figs. 3 and 4.

The carbon flux between atmosphere and living biomass in the pixel Ξ_{ij} is described by the simple expression:

$$F_6(\varphi_i,\lambda_j,t) = c_6 P_k(\varphi_i,\lambda_j,t) \quad (3)$$

where c_6 (≈0.546) is the coefficient reflecting the efficiency of the photosynthetic response mechanism. The average values of P_k are