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GEOPHYSICS

Sensitivity of the IFA RAN Global Climatic Model with an Interactive Carbon Cycle to Anthropogenic Influence

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The estimates of the sensitivity of the IFA RAN Global Climatic Model [1] with an interactive carbon cycle to anthropogenic influence were obtained. In the numerical calculations using the IFA RAN model, anthropogenic emission of carbon dioxide into the atmosphere was specified on the basis of data from observations in 1860–2000, and according to the SRES-A2 and SRES-B2 scenarios for 2000–2100 [2, 3]. Inclusion of the interaction with the carbon cycle into the global climatic model enhanced its temperature sensitivity to the increase of carbon dioxide emission into the atmosphere in the 21st century. This is a consequence of less intense sink of CO_2 from the atmosphere into land ecosystems under the condition of anthropogenic warming of the climate.

Along with the account for the complete interaction of the climatic model with the carbon cycle blocks (version I), we also analyzed the results of numerical calculation, excluding the interaction between model blocks, to estimate the role of different factors and feedbacks. In particular, we analyzed the changes related to anthropogenic increase of carbon dioxide emission into the atmosphere without corresponding climatic changes (version II). In this case, the variation in carbon dioxide content in the atmosphere influences the photosynthesis and thus influences the land vegetation without the contribution of climatic changes to this process.

The IFA RAN model is the first Russian 3D climatic model (with account of the carbon cycle), which was used to carry out a series of numerical experiments at different scenarios of continuously changing anthropogenic influence in the 19th–21st centuries. The vertical structure in the model is described by eight layers in the atmosphere (in the troposphere, stratosphere, and mesosphere to a level of 80 km), four layers in the oceanic block (upper mixed layer, seasonal thermocline, deep ocean, and the layer of bottom friction), and active layer of land. The horizontal spatial resolution of IFA RAN model is 4.5° by latitude and 6° by longitude. In addition to the variations in the characteristics of the atmosphere, ocean, and land, the model takes into account the changes in sea ice and the biosphere. The parameterizations of synoptic processes used in the model allow us to significantly increase the efficiency of numerical calculations and perform a series of comparatively fast numerical experiments. The IFA RAN model successfully contributed to the EMIP international project for comparing models of intermediate complexity (see, for example, [4]).

The carbon cycle in the model includes the exchange between the atmosphere, ocean, soil, and continental biota. In the simplest version, the model uses a zero-dimensional block of the global carbon cycle.

The equation for the content of CO_2 well mixed in the atmosphere q_a is written as

$$\frac{dq_a}{dt} = E_{in}(t) + E_{lu}(t) - F_l - F_{oc}, \qquad (1)$$

where t is time, E_{in} and E_{lu} are CO_2 emissions into the atmosphere related to industrial production and land tenure, F_{oc} and F_l are sinks of CO_2 from the atmosphere to the ocean and into the land (vegetation–soil system) (in carbon units), respectively. The variations in the carbon resources in land ecosystems C_{lb} and in soil C_s are determined by equations

$$\frac{dC_{lb}}{dt} = F_{NPP} - F_{lf} - E_{lu}, \qquad \frac{dC_s}{dt} = F_{lf} - F_{sr}, \qquad (2)$$

where

$$F_{NPP} = F_{ph} - F_{br}$$

the net primary production (NPP) of the continental vegetation, F_{ph} is photosynthesis, F_{br} is autotrophic biota respiration, F_{lf} is carbon flux from vegetation to the soil, and F_{sr} is heterotrophic (soil) respiration.

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Components in the right part of Eq. (2) are functions of the corresponding carbon resources and anomalies $\Delta T_{s,g}$ of the annual global mean surface temperature (GMST) with respect to the basic regime. The following relations were used for the description of the temperature dependence on carbon fluxes [5, 6]:

$$\begin{aligned} F_{ph} &= A_{ph} g_f C_{lbc} Q_{10,ph}^{(\Delta T_{s,g}/\Delta T_0)}, \\ F_{br} &= A_{br} C_{lb} Q_{10,br}^{(\Delta T_{s,g}/\Delta T_0)}, \\ F_{lf} &= A_{lf} C_{lb}, \\ F_{sr} &= A_{sr} C_s Q_{10,sr}^{(\Delta T_{s,g}/\Delta T_0)}, \end{aligned} \quad (3)$$

where $\Delta T_0 = 10$ K, $Q_{10,xx}$ ($xx = ph, br, sr$), g_f, C_{lb}, C_{lbc}, C_s, A_{ph}, A_{br}, A_{lf}, and A_{sr} are constants. Fertilization parameter g_f is determined according to Michaelis–Menton dependence as

$$g_f = \frac{q_{at} - q_c}{q_{at} + q_{1/2} - q_c},$$

where $q_{1/2}$ is a semi-saturation regime, q_c is the threshold concentration of CO_2 in the atmosphere needed for the onset of photosynthesis.

Variable C_{lbc}, which characterizes the regime of living biomass corrected for agricultural activity, is determined by the following equation [6]:

$$\frac{dC_{lbc}}{dt} = -A_D E_{lu},$$

where A_D is a constant. We neglect the river discharge of carbon into the ocean. As a result, the carbon flux into soil and vegetation is determined by the difference

$$F_1 = F_{NPP} - F_{sr}. \quad (4)$$

According to [6], the optimal values are $Q_{10,ph} = 1.5$, $Q_{10,br} = 2.2$, $Q_{10,sr} = 2.4$. The $q_{1/2}$ and q_c values for the carbon cycle in the IFA RAN model, equal to 150 and 29 ppm, respectively, were chosen according to [6], while A_D was equal to 0.27. The values of other model parameters correspond to the stationary state of the carbon cycle in the preindustrial period: $q_{a,0} = 280$ ppm, $C_{s,0} = 1.5 \cdot 10^{15}$ kg C, $C_{lb,0} = 0.55 \cdot 10^{15}$ kg C, $F_{br,0} = 5 \cdot 10^{14}$ kg C/yr [7]; $A_{lf} = A_{br} = 0.09$ yr^{-1}, $A_{sr} = A_{lf}C_{lb,0} = C_{s,0} = 0.03$ yr^{-1}, $A_{ph} = (A_{lf} + A_{br})(q_{at,0} + q_{1/2} - q_c)/(q_{at,0} - q_c) = 0.29$ yr^{-1}. Variable $\Delta T_{s,g}$ in the model characterizes the deviation of GMST from the stationary regime in the preindustrial period.

In the description of the exchange of inorganic carbon between the atmosphere and the ocean, the solubility of carbon in seawater is taken into account as a function of the difference between partial pressures of carbon dioxide in the atmosphere and ocean. Assuming the passive role of oceanic chemistry [8], it is possible to correlate the partial pressure of carbon dioxide in the upper layer of the ocean with the sea surface temperature (SST) and 3D oceanic circulation. On the global scale, SST can be used as an indicator of oceanic circulation. This makes it possible to correlate the carbon sink into the ocean with annual mean global SST $T_{oc,g}$ and with q_a. In this work, we used the following linear correlation [9]:

$$F_{oc} = u_C \frac{dq_a}{dt} - u_T \frac{dT_{oc,g}}{dt}. \quad (5)$$

In the stationary regime, $F_{oc} = 0$. In the version of the model analyzed here, we used the following values: $u_C = 1.3 \cdot 10^{12}$ kg/ppm, $u_T = 0.33 \cdot 10^1$ kg/K, at which estimates of carbon sink into the ocean are based on the data of observations in the 1980s and 1990s [2, 10–12] and changes in the GMST [13] and q_a [14] in the 20th century are reproduced well.

The changes of q_a in the 19th–21st centuries according to the calculations based on the IFA RAN model in the SRES-A2 and SRES-B2 scenarios of anthropogenic emissions (version I) compared to the data of observation in 1959–2004 at the Mauna Loa observatory are shown in Fig. 1 [14]. (The maximal difference between the model and empirical values of q_a does not exceed 8 ppm.) The calculations without account for the influence of the changes in the carbon cycle on the variations of q_a (version II) are also shown here. By the end of the 21st century, the q_a value would reach 866 ppm, which is 88 ppm greater than in version II. This increase of q_a characterizes the intensity of the corresponding positive feedback.

The difference between versions I and II is strongly related to the differences in the sink of carbon from the atmosphere to land (Fig. 2) in the SRES-A2 scenario of anthropogenic emissions. In version I, the F_l flux monotonously increases up to the end of the 20th century, with a maximum in 1994, and slightly decreases later (by the end of 2013). After a short period of slight increase, the flux decreases again (from 2026) until the end of the 21st century to ~0.1 GtC/yr. This is less than in the middle of the 19th century. The variations during the changeover from the 20th to the 21st century are related to the peculiarities of the land tenure scenarios used in the research. The maximal F_l values (in 1994 and 2026) are ~1.6–1.7 GtC/yr. In version II, the F_l flux increases monotonously, in general (excluding a slight local decrease with a weak minimum in 2006), and reaches 3.9 GtC/yr by the end of the 21st century.

A total increase of F_l by the end of the 20th century is related to the domination of fertilization with a large increase in vegetation with increasing q_a. The subsequent total decrease of F_l is related to the influence of climate variation on the processes of land ecosystems. If the influence of the climate is excluded (version II), the trend of decreasing F_l were not noted in both scenarios of anthropogenic emissions SRES-A2 and SRES-B2.

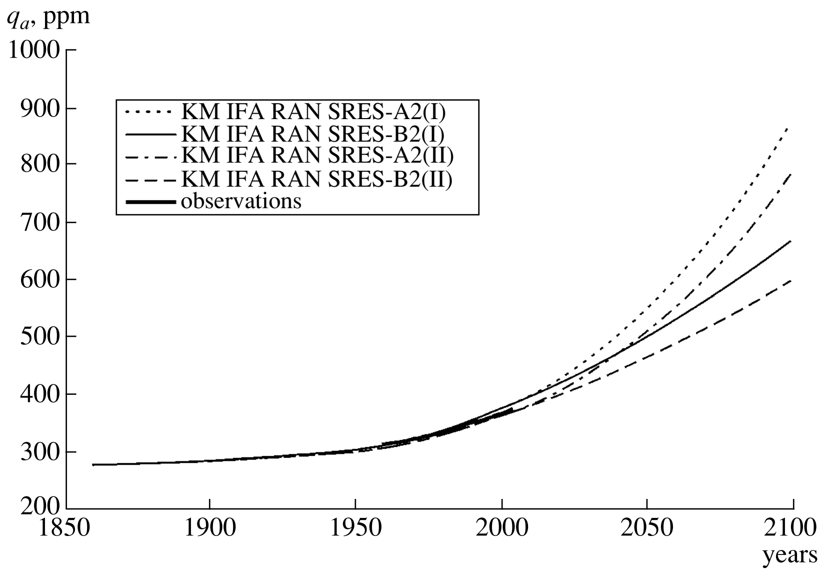

Fig. 1. Variations in q_a according to the calculations using the IFA RAN model with carbon cycle (version I) and without account for the influence of climatic changes on q_a (version II) in SRES-A2 and SRES-B2 scenarios of anthropogenic emissions compared to the data of observations.

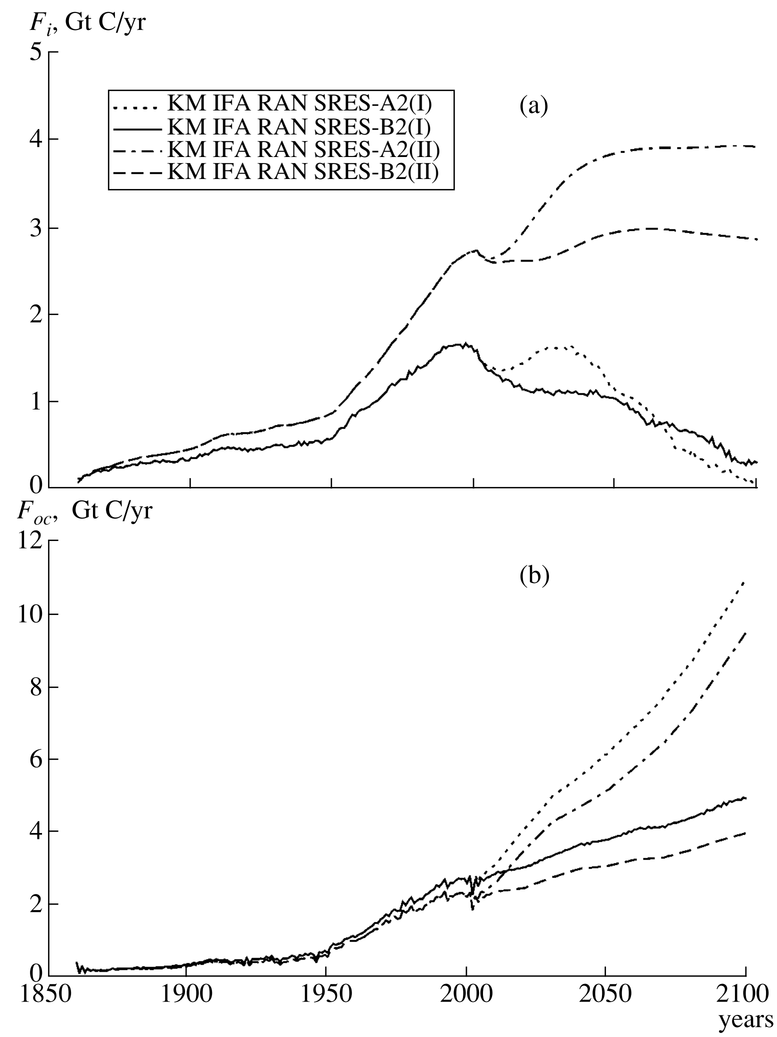

Fig. 2. Variations in the CO_2 precipitation from the atmosphere into the (a) land ecosystems and (b) ocean according to the calculations using the IFA RAN model with carbon cycle (versions I and II) in SRES-A2 and SRES-B2 scenarios of anthropogenic emissions.

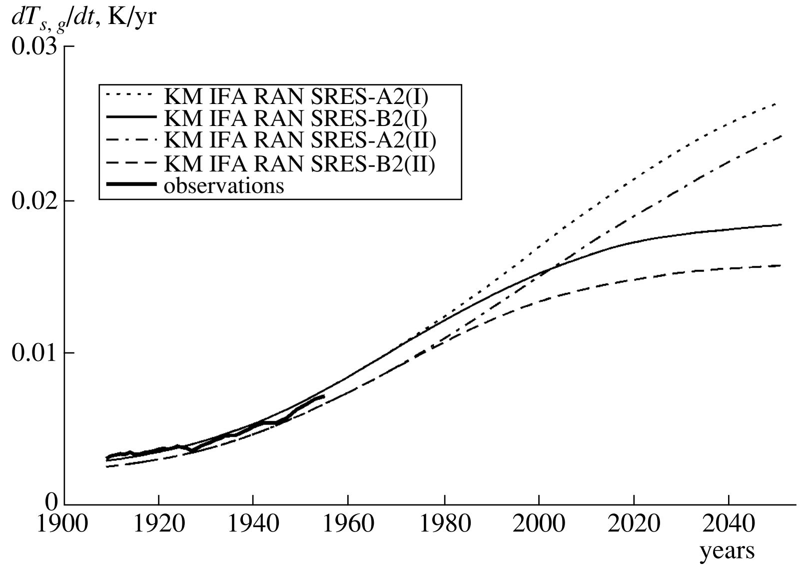

Fig. 3. Trends in GMST for running 100-yr intervals in the 19th–21st centuries according to the calculations using the IFA RAN model in SRES-A2 and SRES-B2 scenarios of anthropogenic emissions (versions I and II) compared to the corresponding estimates based on the data of observations.

No principal differences between versions I and II were distinguished for the sink of CO_2 into the ocean (Fig. 2b). The F_{oc} values obtained in these versions for the end of the 21st century are ~10 GtC/yr and differ not greater than by 15%.

The GMST trends for 100-yr running intervals are shown in Fig. 3 for the 19th–21st centuries based on calculations using the IFA RAN model in the SRES-A2 and SRES-B2 scenarios of anthropogenic emissions (versions I and II), as compared to the corresponding estimates based on the observation data [14]. The model calculations agree well with the observation data, with an increase of the 100-yr GMST trend from 0.3 K/100 yr for the 1860–1959 period to 0.7 K/100yr for the 1905–2004 period. In the case considered here, the interaction with the carbon cycle based on the IFA RAN model is characterized by a positive feedback with increase of the greenhouse effect. The mean GMST trend in the 21st century in version I of the SRES-B2 scenario is 1.8 K/100 yr, which is 0.3 K/100 yr greater than in version II.

In principle, the manifestation of negative feedback is also possible at certain values of parameters of the carbon cycle. The corresponding feedbacks are characterized, in particular, by parameters β_l and γ_l in the linear dependence of the carbon sink from the atmosphere to land on the rate of change in the atmospheric CO_2 content CO_2 $\frac{dq_{at}}{dt}$ and trend in the global surface temperature $\frac{dT_{s,g}}{dt}$ (see [9]):

$$F_l = \beta_l\left(\frac{dq_{at}}{dt}\right) - \gamma_l\left(\frac{dT_{s,g}}{dt}\right). \quad (6)$$

The parameters in this model are $\beta_l = 0.52$ GtC/ppm, $\gamma_l = -82$ GtC/K for the 1860–2100 content as a whole. In the 21st century, the absolute values of these parameters are greater: $\beta_l = 0.64$ GtC/ppm, $\gamma_l = -100$ GtC/K. Such β_l and γ_l values are characteristic of the other modern climatic models with carbon cycle [9] (see also [15]). Parameter γ_l characterizes the temperature sensitivity (climate) of carbon sink from the atmosphere to land; parameter β_l characterizes the fertilization effect (increase in bioproductivity of vegetation with the increase in CO_2 content in the atmosphere). Investigation of the sensitivity of feedback characteristics on the leading parameters of the carbon cycle is planned to be published in a more detailed article.

In general, the IFA RAN model realistically describes the modern temperature regime of the Earth's climatic system and components of the carbon cycle, as well as trends in their variation in the 20th and beginning of the 21st centuries. According to the results obtained, the intensity of the positive feedback is determined in the model considered here mainly by the dynamics of the vegetation–soil system, due to the interaction of the carbon cycle with the climatic regime.

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