Environmental Informatics Archives, Volume 1 (2003), 125-130
EIA03-011
ISEIS Publication #002

Computer Modelling the Global Cycle of Carbon Dioxide in System of "Atmosphere-Ocean" and Environmental Consequences of Climate Change

A.V. Glushkov[(1)*] , V.N. Khokhlov[(2)], N.S.Loboda[(2)] , E.L.Ponomarenko[(2)]
[(1)] Innovative Geosciences Research Centre and Inst. Applied Mathematics, P.O. Box 116, Odessa-9, 65009, Ukraine
[(2)] Institute of Hydrometeorology, OSEU, P.O. Box 116, Odessa-9, 65009, Ukraine

Abstract. Using mathematical modelling the dynamics of carbon cycle in the system of "atmosphere-ocean" is investigated. The analysis of the model solution sensitivity from changing of model parameters is carried out. It is obtained a temporal and space distribution for concentration of non-organic carbon in the ocean, partial pressure of dissolute CO_2 and value of exchange on the atmosphere-ocean interface. A role of the wind intermixing in the upper ocean layer is obtained. The master differential equations system, describing a dynamics of the CO_2 cycle, is numerically integrated by the four-order Runger-Cutt method under given initial values of valuables till output of solution on periodic regime. It is indicated on possible realization of the chaos scenario in system. Specially, it is considered situation when the possible chaotic phenomenon is realized in the system "atmosphere-ocean" that may have environmental consequences, including an impact on climate change.

Keywords: Carbon dioxide, Global cycle, Atmosphere-ocean interactions, Climate change, Chaos scenario

1. Introduction

Carbon dioxide is the most important greenhouse gas after water vapor in the atmosphere of the earth. More than 98% of the carbon of the atmosphere-ocean system is stored in the oceans as dissolved inorganic carbon. The key for understanding critical processes of the marine carbon cycle is a sound knowledge of the seawater carbonate chemistry, including equilibrium and non-equilibrium properties as well as stable isotope fractionation.

A modelling of CO_2 global cycle in the system of "atmosphere-ocean" is related to one of most important and actual problem (see, e.g. Baes, 1982; Parkinson and Young, 1998; Enting, 1999; Bates and Merlivat, 2001; Zeebe and Wolf-Gladrow, 2001). An increase of CO_2 concentration in the atmosphere owing to some factors, in particular of human economic activities, results the climate warming and bioprocesses change on the Earth. It is naturally, above problem have been considered in the numerous studies (e.g. Stephens et al., 1998; Caldeira et al., 2000; Plattner et al., 2001; Jin and Shi, 2001). The model of Plattner et al. (2001) is forced by emissions of CO_2 and other greenhouse agents from scenarios developed by the Intergovernmental Panel on Climate Change and by CO_2 stabilization profiles. According to their results, the uptake of atmospheric CO_2 by the ocean is reduced between 7 to 10% by year 2100 compared to simulations without global warming. Jin and Shi (2001) used a three-dimensional ocean carbon cycle model which is a general circulation model coupled with simple biogeochemical processes is used to simulate CO_2 uptake by the ocean. Calculated oceanic uptake of anthropogenic CO_2 during the 1980s is $2.05 \cdot 10^{15}$ g per year.

The realization of most of existing models is carried out in mean-annual regime and, as a rule, in the most general form taking into account the heterogeneities of carbon distribution in the biosphere. Exceptions are the large-scale zonal models of Nefedov and Tarco (1995) and Bacastow et al. (1990).

In this study, starting with above models, we investigate the carbon cycle dynamics in the system of "atmosphere-

* Corresponding author: glushkov@paco.net

ocean" subject to its zonal structure using mathematical modelling. In our model of the CO_2 global turnover of the ocean (its surface is ice-free) is divided into 28 latitudinal belts (zones) with 5º width. Typical vertical stratification of the ocean include: a) the upper quasi-uniform (or mixed) layer, which have about 100 m thickness in the tropics, 10÷20 m thickness in summer extratropics and few hundred meters thickness in winter extratropics, b) the layer of temperature's sudden change (seasonal thermocline), c) the main thermocline, and d) the deep-sea layer. In the model, in each zone three layers are picked out: the upper quasi-uniform layer (UQL) with variable thickness during year, thermocline and deep-sea layer (DL). Thus, the ocean have 84 blocks on the whole. It is supposed the water between 40 S and 40 N goes slowly up (upwelling) and at the high latitudes goes slowly down (downwelling); the water movement is from equator to pole in the UQL and have return direction in the DL. The vertically uniform atmosphere is divided into same zones as ocean. Variable quantities of the model are the molar concentration of the non-organic carbon in each ocean isolated block and carbon content in the form of CO_2 in each atmospheric zone. Model time step is one month.

2. Master Equations

The seasonal dynamics of global carbon cycle in the system of "atmosphere-ocean" is described with system of 112 non-linear common differential equations (see Nefedova and Tarko, 1995):

$$\frac{d}{dt}C_i^1 h_i - \left(\frac{dh_i}{dt} \pm V_i\right) C_i^1 = F_i^{ao} - Q_{h_i - o} + L_i^1 - B_i^p + B_i^{1d} \tag{1}$$

$$\frac{d}{dt}C_i^2 \left(H - h_i\right) + \left(\frac{dh_i}{dt} \pm V_i\right) C_i^2 = Q_{h_i - o} + Q_i^T + B_i^{2d} \tag{2}$$

$$\frac{d}{dt}C_i^3 \left(D - H\right) \pm V_i C_i^3 = -Q_i^T + L_i^3 + B_i^{3d} \tag{3}$$

$$\frac{dM_i^a}{dt} = -F_i^{ao} ss_i^{0.012} + \left(F_i - F_1\right) V_i^a \tag{4}$$

where i = 1, 2, …, 28 is the index showing the belonging to the zone; C_i^1, C_i^2, C_i^3 are the molar concentration of non-organic carbon in UQL, thermocline and DL, respectively; M_i^a is the carbon mass as CO_2 in the atmosphere; h_i is the UQL depth depending on season; V_i is the rate of upwelling or downwelling depending on season; H is the depth of the thermocline's lower boundary; D is the mean depth of ocean; ss_i is the surface area of oceanic zone. The carbon flux on the atmosphere-ocean interface is proportional to a difference of the CO_2 partial pressure in air P_i^a and water P_i^o at the sea level:

$$F_i^{ao} = k\left(u_i\right)\left(P_i^a - P_i^o\right) \tag{5}$$

where $k(u_i)$ is the proportionality coefficient depending on the wind velocity. According to Bacastow (1990), the CO_2 partial pressure in air is defined as

$$P_i^a = \frac{k_a M_i^a R T_i^a}{s_i \mu} \tag{6}$$

where M_i^a is the mass of CO_2 in the atmosphere; s_i is the Earth's surface area falling at the i-th atmospheric zone; T_i^a is the air temperature at the ocean level; μ is the CO_2 molecular weight; R is the gas constant; k_a is the value of mass fraction of 100-meter air column in the mass of 10-kilometer air column.

For accounting the CO_2 greenhouse property, the dependence of the temperatures of air and water at the see level from the CO_2 content in the atmosphere is inserted into model as follows

$$T_i^a = T_i^{as} + \Delta T_i^a \quad \text{and} \quad T_i^o = T_i^{os} + \Delta T_i^o$$

where T_i^{as} and T_i^{os} are the seasonal components, and ΔT_i^a and ΔT_i^o are the temperature variations associated with increase of atmospheric CO_2 content, at that $\Delta T_i^a = \Delta T_i^o$. The increment ΔT_i^a is the function of the average annual total atmospheric CO_2 content.

Approach used by Nefedova and Tarko (1995) is applied for description of the turbulent carbon flux at liquid UQL – thermocline interface. It is assumed, the turbulent fluxes at lower boundary of the UQL (Q_{h_i-o}) are the result of an entrapment of liquid from seasonal thermocline when the UQL deepens and are zeroes for inverse case:

$$Q_{h_i-o} = \begin{cases} \left(C_i^1 - C_i^2\right)\left(\dfrac{dh_i}{dt} \pm V_i\right) & \text{for } \dfrac{dh_i}{dt} \pm V_i > 0 \\ 0 & \text{for } \dfrac{dh_i}{dt} \pm V_i \le 0 \end{cases} \tag{7}$$

The turbulent carbon fluxes at the upper boundary of thermocline (Q_{h_i+o}) are equal to

$$Q_{h_i+o} = \begin{cases} 0 & \text{for } \dfrac{dh_i}{dt} \pm V_i > 0 \\ -\left(C_i^1 - C_i^2\right)\left(\dfrac{dh_i}{dt} \pm V_i\right) & \text{for } \dfrac{dh_i}{dt} \pm V_i \le 0 \end{cases} \tag{8}$$

The turbulent carbon fluxes at the thermocline-DL interface are supposed to be proportional to the differences of carbon concentration in these layers with time-independent proportionality coefficient (K^T):

$$Q_i^T = K^T\left(C_i^3 - C_i^2\right) \tag{9}$$

Model considers also the activity of sea biota (about importance of this carbon source/sink see, for example, study of Rivkin and Legendre (2001)). In the system (1)-(4), the flux B_i^p is the rate of organic substance production in the UQL, and B_i^{1d}, B_i^{2d}, B_i^{3d} are the rate of organic substance decaying in the UQL, thermocline and DL, respectively. Procedure described by Bacastow and Maier-Reimer (1990), modified on the model zonal scale and extended for two hemispheres is used for description of seasonal variability of these fluxes. It is also supposed, the carbon exchange between neighbor atmospheric zones occurs at the expense of advection F_i^d:

$$F_i = F_i^a + F_i^d \tag{10}$$

Magnitude of the advective carbon flux between separated atmospheric zones is proportional to the difference of carbon concentration in these zones:

$$F_i^a = \left(C_i^a - C_{i+1}^a\right)2\pi\cos\left(\varphi_i\right)h_a V_i^* \tag{11}$$

where $C_i^a = M_i^a / V_i^a$ is the atmospheric carbon concentration, M_i^a is the atmospheric carbon mass, V_i^a is the atmospheric volume, h_a is the height of atmosphere, and V_i^* is the mean velocity of atmospheric meridional transfer.

3. Results and Discussion

The dynamics of carbon cycle in the system "atmosphere-ocean" was investigated without CO_2 industrial emissions into atmosphere. The periodical solution of system (1)-(4) was found. For this purpose, the system (1)-(4) was numerically integrated using the four-order Runger-Cutt method with prescribed initial conditions till output of solution on periodic regime.

Fig. 1 shows the annual variations of the partial pressure of dissolved CO_2 for some latitudinal belts (preliminary results). As for concentration of non-organic carbon, analysis of a fluctuation amplitude for this characteristic during year detects connection with oscillations of the UQL thickness. At the same time, the presence of two

maximums in tropical and middle latitudes for this parameter points out the influence of seasonal variations for phytoplankton content onto the partial pressure of dissolved CO_2. Largest amplitude for seasonal fluctuations of the partial pressure of dissolved CO_2 was obtained latitudinal belt between 40 N and 50 N and have magnitude 85 microatmospheres (cf. with 72 microatmospheres in model of Nefedova and Tarko (1995)). For considered solution, the average annual concentration of atmospheric carbon dioxide is 290.3 ppmv.

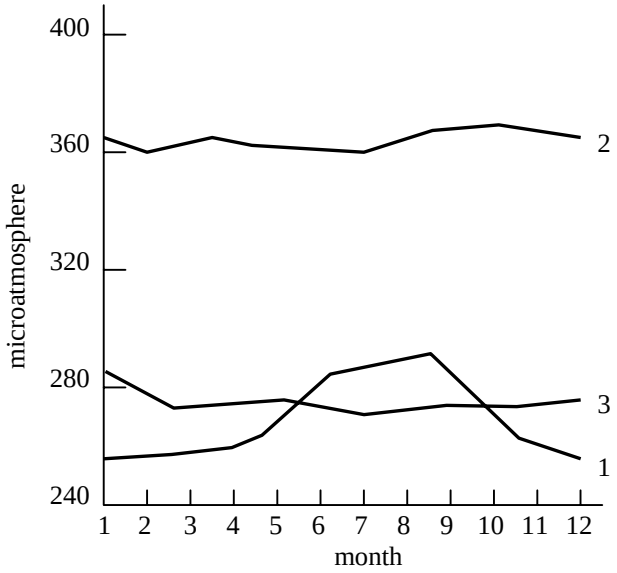

Fig. 1 Annual variations of partial pressure of CO2 dissolved in the UQL
1 – 60÷70 N, 2 – 10÷20 N, 3 – 60÷65 N.

Distribution of the CO_2 exchange at the atmosphere-ocean interface is shown in Fig. 2. As this graph shows,

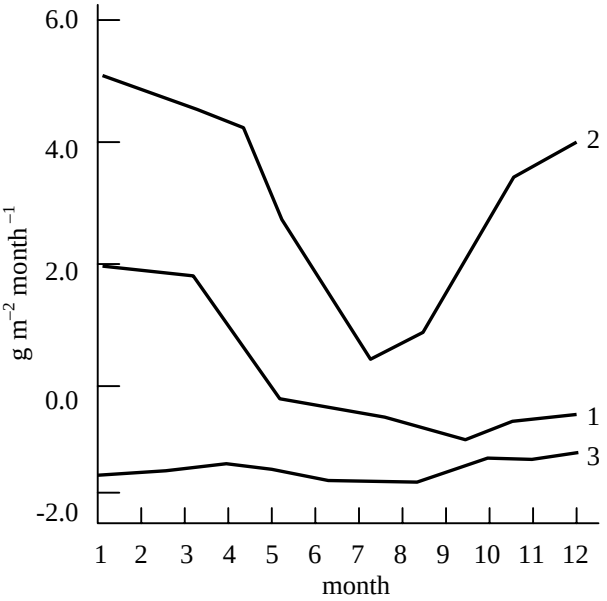

Fig. 2 Annual variations of the carbon exchange at atmosphere ocean interface
1 – 60÷70 N, 2 – 10÷20 N, 3 – 60÷65 N.

the tropical ocean is the CO_2 source but high-latitude one is the CO_2 sink. The ocean of middle latitudes (35÷60 N) during winter and beginning of spring absorbs carbon from atmosphere and during rest of year is the source for atmospheric carbon dioxide.

Also, an examination for sensitivity of model solutions to the variations of some parameters (upwelling rate and exchange coefficient between thermocline and DL) was carried out.The increase of upwelling rate by $1.0 \cdot 10^{-7}$ m s^{-1} results the decrease for the average annual concentration of atmospheric CO_2 by 5.4 ppmv, but the one's diminution to $3.0 \cdot 10^{-7}$ m s^{-1} leads to the increase of the CO_2 atmospheric concentration by 8.4 ppmv. For increase of exchange coefficient between thermocline and DL to $3.5 \cdot 10^{-7}$ m s^{-1} the average annual CO_2 atmospheric concentration rises to 308 ppmv; the decrease of above coefficient to $2.5 \cdot 10^{-7}$ m s^{-1} leads to the decrease of CO_2 concentration to 265 ppmv. Note, the variations of the carbon dioxide exchange rate not results the qualitative variations for spatial-temporal distribution of carbon content and CO_2 partial pressure in the system 'atmosphere-ocean'. Especially interesting situation could be realized, when the possible chaotic phenomenon is realized in the system 'atmosphere-ocean' that may have environmental consequences, including an impact on climate changing.
The possible scenario is analyzed on the basis earlier developed new methods (Oort and Peixoto, 1983; Glushkov et al., 1999) of monitoring the low-frequency climate processes (with using some summated contributions of low frequency oscillation for geophysical factors).

4. Conclusion

Numerical experiments with climatic models show that decreasing of the CO_2 concentration in the global system not only leads to the variations of atmospheric temperature but significantly influences global hydrological cycle. Present study represents the experimental results with model of the carbon cycle dynamics in the atmosphere-ocean system. These results show role of the oceanic branch in variations of the CO_2 atmospheric concentration. At that, it is examine the influence of such ocean characteristic as the UQL thickness, the upwelling rate and the carbon exchange coefficient at the thermocline-DL interface. Advantage of present model is relative simplicity, which, nevertheless, allows considering most of mechanisms affecting the global carbon cycle using common workstations for calculations. Subsequent experiments with model should be carried out with further determination of the chaotic phenomenon in the atmosphere-ocean system and its influence on global carbon cycle.

References

Bacastow, R. and Maier-Reimer, E. (1990). Ocean circulation model of the carbon cycle. Climate Dynamics. 4(2), 95-125.

Baes, C.F. Jr. (1982). Effects of ocean chemistry and biology on atmospheric carbon dioxide. Oxford Univ. Press.

Bates, N.R. and Merlivat, L. (2001). The influence of short-term wind variability on air-sea CO_2 exchange. Geophysical Research Letters. 28(17), 3281-3284.

Caldeira, K., Hoffert, M.I and Jain, A. (2000) Simple ocean carbon cycle models. In: "The carbon cycle" edited by T.M.L.Wigley and D.S. Schimel. Cambridge Univ. Press.

Enting, I.G. (1999). Characterising the temporal variability of the global carbon cycle. CSIRO Atmospheric Research.

Glushkov, A.V., Ambrosov, S.V. and Khokhlov, V.N. (1999). Atmospheric waveguides, teleconnection, Hadley cells and angular momentum balance. Meteorology, Climatology and Hydrology. 38, 42-46. (in russian)

Jin, X. and Shi, G. (2001). A simulation of CO_2 uptake in a three dimensional ocean carbon cycle model. Acta Meteorologica Sinica. 15(1), 29-39.

Nefedova, Ye.I. and Tarko, A.M. (1995). The global carbon cycle in terms of the zonal model in the atmosphere-ocean system. Transactions (Doklady) of the Russian Academy of Sciences. 335(2), 14-18.

Oort, A.H. and Peixoto, J.P. (1983). Global angular momentum and energy balance requirements from observations. Advances in Geophysics. 25, 355-490.

Parkinson, S. and Young, P. (1998). Uncertainty and sensitivity in global carbon cycle modeling. Climate Research. 9(3), 157-174.

Plattner, G-K., Joos, F., Stocker, T.F. and Marchal, O. (2001). Feedback mechanisms and sensitivities of ocean carbon uptake under global warming. Tellus. 53B(5), 564-592.

Rivkin, R.B. and Legendre, L. (2001). Biogenic carbon cycling in the upper ocean: effects of microbial respiration. Science. 291(5512), 2398-2400.

Stephens, B.B., Keeling, R.F., Heimann, M., Six, K.D., Murnane, R. and Caldeira, K. (1998). Testing global ocean carbon cycle models using measurements of atmospheric O_2 and CO_2 concentration. Global Biogeochemical

Cycles. 12(2), 213-230.
Xu, Y. and Wang, M. (1998). A two-dimensional zonally averaged ocean carbon cycle model. Advances in Atmospheric Sciences. 15(3), 370-379.
Zeebe, R.E. and Wolf-Gladrow, D. (2001). CO_2 in Seawater: Equilibrium, Kinetics, Isotopes. Elsevier Science.