Numerical 3-d model experiments on global climate sensitivity to solar constant variations

V P Parkhomenko¹,²

¹ Bauman Moscow State Technical University ul. Baumanskaya 2-ya, 5/1, Moscow, 105005, Russia
² Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences (FRC CSC RAS), Moscow, 119333, Russia

E-mail: vparhom@yandex.ru

Abstract. The aim of the study is to show an important role of the solar radiation flux in positive feedback “temperature - surface albedo” during the transition to glaciation regimes observed in the history of the Earth. The study is based on a three-dimensional hydrodynamic global climate coupled model, including ocean model with real depths and continents configuration, sea ice evolution model and energy - moisture balance atmosphere model. A series of numerical experiments were carried out to assess the impact of changes in solar radiation flux on the global climate. It is assumed that the solar constant gradually decreases discretely compared to the current value and in each case is determined the steady climatic mode. Simulation period is about 2000 years. Gradual increase in the sea ice area and a catastrophic increase at the end of stage 3, when the oceans are completely covered with ice (so called “snow ball Earth”) are get. These results are naturally explained by the presence of the “temperature decrease - glaciation” positive feedback. The stage 3 maximum surface air temperature is ~30°C, the minimum -80°C. Strong temperature and ice cover changes lead to significant changes in the horizontal and vertical thermohaline ocean circulation. The vertical thermohaline circulation has the weakened horizontal velocities in the north direction in the ocean upper layers and increased in the direction of the equator in the deep layers (in contrast to the present situation). The author was supported by the Russian Foundation for Basic Research (project no. №17-01-00693).

1. Introduction

Classical calculations on simple zonal energy-balance models [1] show an important role in reducing the solar radiation flux of positive feedback “temperature - surface albedo” during the transition to glaciation regimes observed in Earth’s history. All hydrodynamic processes in the atmosphere and the ocean are parameterized in the energy-balance models of climate [2, 3]. They are based on the thermodynamic description of the climate system as a whole. This is a significant limitation in the climate sensitivity study.

To get more adequate results, it is necessary to consider the entire atmosphere, the ocean (with sea ice) and the active land layer (soil and vegetation) as interacting parts of the climate system. It is characterized by complex interactions and feedbacks of its elements. The joint study of global environmental changes and climate will give the ability of the transition to sustainable development.
The climate system has significant temporal and spatial variability. Cost-efficient, dynamical ocean models are necessary to perform millennial-scale simulations, to systematically assess uncertainties in the climate system in and to represent a wide range of tracers and processes in a coherent dynamical setting.

In this work, the numerical climate model of intermediate complexity is used. The study is based on a three-dimensional hydrodynamic global climate coupled model, including ocean model with real depths and continents configuration, sea ice evolution model and energy and moisture balance atmosphere model [6-8].

In numerical experiments to assess the effect of changes in solar radiation flux (solar constant) on the global climate, it is assumed that the solar constant gradually decreases discretely compared to the current value and in each case the stationary climate regime is determined.

2. Model description
The basic equations of the large-scale ocean currents are usually written in the Boussinesq approximation (constancy of density in horizontal equations of momentum and continuity, the presence of Coriolis force, vertical and horizontal turbulent viscosity) [9]. Vertically, the hydrostatic equation is assumed. The equations are supplemented by the equations of transport and turbulent diffusion of heat and salts, as well as the state equation for density, depending on temperature and salinity.

The depth-averaged equations for a stationary case with bottom friction term, proportional to the average depth explain the effect of western currents intensification, the influence of variable ocean depth and the wind effects [9]. It can be assumed that some of their generalization and further use as horizontal momentum equations may be suitable for describing the thermohaline circulation of the world ocean.

Taking these considerations into account, the system of the ocean model equations is considered in the geostrophic approximation with a friction term in the horizontal momentum equations. The temperature and salinity values satisfy the advection-diffusion equations, which allow one to describe the thermohaline circulation of the ocean. Convective processes are also taken into account in an approximate way.

The frictional geostrophic ocean model is three-dimensional, but significantly more efficient than extant 3-D global ocean models based on the primitive equations [7, 8, 10]. The model has eight depth levels and shares a sine(latitude)-longitude horizontal grid of 72x72 equal area grid cells (~2.5°x10°) with the other components of the coupled model. The sea-ice component is a dynamic and thermodynamic model based on [11, 12]. The dynamic equations are solved for ice capacity and for average ice thickness. The growth and melting of the ice in the model depends on the difference between the heat flux from the atmosphere to the sea ice and the heat flux from the ice to the ocean. The diagnostic equation is solved for the ice surface temperature.

The zero normal flow condition is required at all boundaries in the ocean model. The heat and salt normal components fluxes are also assumed to be zero at the continents borders. The ocean is exposed to the wind stress on the surface. Heat and salt fluxes at the bottom are assumed to be zero, and they are determined by interaction with the atmosphere on the surface. Heat fluxes between adjacent blocks can be modified by phase transitions at the boundaries (evaporation, melting, etc.). A procedure is proposed for determining the wind velocity field from the field of the atmospheric surface temperature based on the geostrophic approach, taking into account the thermal component of the wind and introducing a mechanism of underlying surface friction. This allows qualitatively correct description of the wind velocity field depending on the climate system state.

We use an energy and moisture balance model of the atmosphere, similar to that described in [13]. The prognostic variables are surface air temperature $T_a$ and surface specific humidity $q_a$, for which the governing equations can be written as
\begin{align*}
\rho_h h_T C_{pa} \left( \frac{\partial T_a}{\partial t} + \beta_T \nabla (u T_a) - \nabla (v \nabla T_a) \right) &= Q_{ua} \\
\rho_q h_q \left( \frac{\partial q_a}{\partial t} + \beta_q \nabla (u q_a) - \nabla (\kappa \nabla q_a) \right) &= \rho_0 (E - P),
\end{align*}

where \( h_T \) and \( h_q \) are the atmospheric boundary layer depths for heat and moisture, respectively, \( v \) and \( \kappa \) are the eddy diffusivities for heat and moisture respectively, \( u \) is the horizontal wind velocity, \( Q_{ua} \) is the total heat flux to atmosphere, \( E \) is the evaporation or sublimation rate, \( P \) is the precipitation rate, \( \rho_a \) is air density, and \( \rho_0 \) is the density of water. \( C_{pa} \) is the specific heat of air at constant pressure.

The parameters \( \beta_T, \beta_q \) allow for a linear scaling of the advective transport term. This may be necessary as a result of the overly simplistic, one-layer representation of the atmosphere, particularly if surface velocity data are used in place of vertically averaged data, as in our standard runs. We use the values \( \beta_T = 0, \beta_q = 0.4 \) \[8, 13, 14\]. In view of the convergence of the grid, winds in the two grid points nearest each pole are averaged zonally to give smoother results in these regions.

The initial state of the system is characterized by constant temperatures of the ocean, atmosphere and zero velocities of ocean currents. Numerical experiments show that the model goes to equilibrium over a period of about 2000 years.

### 3. Numerical experiments

In a numerical experiment to assess the impact of changes in solar radiation flux (solar constant) on the global climate, it is assumed that the solar constant gradually decreases compared with the current value and in each case the steady climate regime is determined \[4\]. The calculations were performed for three successively decreasing values of the solar constant: 0.950S, 0.925S and 0.8S, where S is the current value of the solar constant. In fig. 1 results corresponding to these solar constant values are denoted by numbers 1, 2 and 3.

![Figure 1](image)

**Figure 1.** The mean global air temperature (a) and the global sea ice area (b) evolution for the three stages of calculations

Fig. 1a shows the time variation of the mean global air temperature for these three stages. For stages 1 and 2, the temperature drops from 13.5°C to 5.8°C and to 1.1°C at the end of each stage,
respectively. For stage 3, a sharp temperature drop occurs over a period of less than 30 years, to a value of approximately -35°C. This strong air cooling is due to (or is accompanied by) complete glaciation of the ocean surface.

The global sea ice area evolution for the three stages of the calculations is shown in Fig. 1b. There is an increase in sea ice during stages 1-2 and a catastrophic increase of the sea ice area at the end of stage 3, when the oceans are completely covered with ice. These results are naturally explained by the presence of positive feedback “temperature decrease - glaciation”.

The maximum January air temperature at the end of stage 3 is -30°C, the minimum - about -80°C (Fig. 2). The distribution and thickness of sea ice for this case is shown in Fig. 3. Sea ice completely covers the ocean surface.

![Figure 2. Air temperature (°C) at the end of stage 3, July](image)

Such strong changes in temperature and ice cover lead to significant changes in the horizontal circulation and vertical thermohaline circulation (in Fig. 4 — for the Atlantic Ocean, averaging over longitude). From Fig. 4 it can be seen that the vertical thermohaline circulation has weakened horizontal velocities in the northern direction in the upper layers of the ocean and increased in the direction of the equator in the deep layers (in contrast to the current situation).

![Figure 3. Sea ice thickness (m) at the end of stage 3, July](image)
In addition, there is negative circulation (counterclockwise) in the north region of the Atlantic Ocean. Barotropic streamfunction (Sv) at the end of stage 3 is presented in Fig. 5. There is no strong horizontal circulation in the Northern Hemisphere, which is inherent in the current climate. This is connected with the state of the world ocean, completely covered with ice.

Figure 4. Meridional overturning streamfunction (Sv) in the Atlantic sector at the end of stage 3

Figure 5. Barotropic streamfunction (Sv) at the end of stage 3

4. Conclusions
A hydrodynamic three-dimensional global climate model is described, which includes atmospheric blocks, large-scale thermohaline circulation of the ocean and sea ice. Based on numerical experiments, the possibility of transition to the glaciation regime with a decrease in the solar constant has been established. It is sufficiently 20% decreasing of solar constant to get transition to full Earth glaciation period when the oceans are completely covered with ice (so called “snow ball Earth”). Strong temperature and ice cover changes lead to significant changes in the horizontal and vertical thermohaline ocean circulation. The vertical thermohaline circulation has the weakened horizontal velocities in the north direction in the ocean upper layers and increased in the direction of the equator in the deep layers (in contrast to the present situation).

References
[1] Stocker T F 2001 The Role of Simple Models in Understanding Climate Change. *Continuum Mechanics and Applications in Geophysics and the Environment*. B. Straugham, R. Greve,
H. Ehrentraut, Y. Wang (eds.) Springer Verlag p 337–367

[2] Varaksin A Y 2017 Air tornado-like vortices: Mathematical modeling (a review) *High Temperature* **55** (2) 286–309

[3] Shevchenko S Y, Melnik Y A, Smirnov A E, Htet W Y M 2017 Comparative evaluation of methods for the determination of heat transfer coefficients of liquid and gaseous quenching media *Mechanics and Industry* **18** (7) paper № 703

[4] Chursin A, Drogovo P, Sadovskaya T, Shiboldenkov V 2017 A linear model of economic and technological shocks in science-intensive industries *Journal of Applied Economic Sciences* **12** (6) 1567–77

[5] Manzhirov A V and Gupta N K 2017 Fundamentals of Continuous Growth Processes in Technology and Nature *Procedia IUTAM* **23** 1–12

[6] Marsh R, Edwards N R, Shepherd J G 2002 Development of a fast climate model (C-GOLDSTEIN) for Earth System Science SOC. No.83 p 54

[7] Parkhomenko V P 2018 Modeling of global and regional climate response to solar radiation management. *J. Phys.: Conf. Ser.* 1141 012057

[8] Parkhomenko V P 2017 Application of the quasi-random approach and ensemble calculations for the determination of optimal sets of values of the parameters of the climate model. *Informatika i ee Primeneniy* **11** no. 2 65–73 (in Russian)

[9] Pedlosky J 1992 *Geophysical Fluid Dynamics* Springer New York

[10] Edwards N R and Marsh R 2005 Uncertainties due to transport parameter sensitivity in an efficient 3-D ocean-climate model. *Clim Dyn* **24** 415–433.

[11] Semtner A J 1976 A model for the thermodynamic growth of sea ice in numerical investigations of climate. *J Phys Oceanogr* **6** 379–389

[12] Hibler W D 1979 A dynamic thermodynamic sea ice model. *J Phys Oceanogr* **9** 815–846

[13] Weaver A J, Eby M, Weibe E C, Bitz C M, Duffy P B, Ewen T L, Fanning A F, Holland M M, MacFadyen A, Matthews H D, Meissner K J, Saenko O, Schmittner A, Wang H, Yoshimori M 2001 The UVic earth system climate model: Model description, climatology, and applications to past, present and future climates. *Atmos-Ocean* **39**(4) 361–428

[14] Uskov A, Serdyukova N A, Serdyukov V I, Heinemann C, Byerly A. 2016 Multi objective optimization of VPN design by linear programming with risks models. *International Journal of Knowledge-Based and Intelligent Engineering Systems* **20** (3) 175–188