Modeling of global and regional climate response to solar radiation management

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Abstract. Global warming climate changes are observed in recent decades. These changes largely associated with anthropogenic increases in greenhouse gases in the atmosphere. The problem and opportunity of the global climate stabilization at a current level by means of geoengineering methods are investigated. 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. The climate prediction calculations up to the year 2100, using different CO\textsubscript{2} growth scenario are carried out on the first stage. A series of numerical experiments were carried out to assess the possibility of climate stabilization at the level of the year 2010 by controlling emissions into the stratosphere of aerosol, reflecting a part of the incoming solar radiation. Evolution and sedimentation equation for sulphur aerosol mass calculation is considered. A uniform and zonal stratospheric aerosol space distribution was investigated. It is shown that by this way it is impossible to achieve the space and seasonal uniform approximation to the existing climate, although it is possible significantly reduce the greenhouse warming effect. The Pareto optimal frontier was investigated and visualized for two parameters - atmospheric temperature MSD for the winter and summer seasons. The author was supported by the Russian Foundation for Basic Research (projects no. №16-01-0466, №17-01-00693).

1. Introduction

Global warming climate changes are observed in recent decades. These changes largely associated with anthropogenic increases in atmosphere greenhouse gases [1]. Unprecedented, so is not the absolute magnitude of future changes, but their rate of growth [2, 3]. The joint study of global environmental changes and climate will give the ability of the transition to sustainable development [4].

Climate change has led to increasingly serious consideration of the potential role of geoengineering as a potential means to prevent an “extreme climatic situations” [5], as rapid melting of the Greenland and Antarctic ice sheets, or as a stopgap measure to gain time for effective emissions mitigation responses. The general purpose of climate geoengineering approaches is to intervene in the climate system by deliberately modifying the Earth’s energy balance to reduce potential temperature increases and ultimately stabilize temperatures at levels lower than currently projected.
Perhaps the most widely discussed climate geoengineering option is an increase of planetary albedo (surface reflectivity of solar radiation) using stratospheric sulfate aerosols [6]. The genesis of this approach was a suggestion by Russian climatologist Mikhail Budyko in 1974 [7]. Sulfate aerosols are an important component of the troposphere and stratosphere, and can substantially reduce the incoming solar radiation reaching the Earth’s system during powerful volcanic eruptions. A study [8] concluded that the sulfur emissions amount required to compensate for projected warming by 2050 would be between 5-16 TgS/year, increasing to 10-30 TgS/year by the end of the century.

The problem and opportunity of the global climate stabilization at a current level by means of geoengineering methods are investigated in this work. The numerical global climate model of intermediate complexity is used.

2. Model description
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 [9 - 12].

The system of the ocean model equations in the local Descartes coordinates (x,y,z) considered in the geostrophic approximation with the frictional term in the horizontal momentum equations:

\[-lu + \lambda u = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial (k_x \tau_x)}{\partial z} \]

\[lu + \lambda v = - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{1}{\rho} \frac{\partial (k_y \tau_y)}{\partial z} \]

\[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0; \frac{\partial p}{\partial z} = -\rho g; \rho = \rho(S,T) \]

\[\frac{d}{dt} X = k_h \nabla^2 X + \frac{\partial}{\partial z} (k_v \frac{\partial X}{\partial z}) + C,\]

where \((u, v)\) are the horizontal velocity components, \(w\) - the vertical velocity, \(\lambda\) is the drag coefficient, which varies in space, increasing close to lateral boundaries and the equator, \(T, S, p, -\) water temperature, salinity and pressure, respectively, \(\rho\) – water density, \(l\) is a Coriolis parameter, \(g\) - acceleration of gravity, \(k_v, k_h\) - the horizontal and vertical diffusion coefficients of ocean tracers \(X=(T,S)\), respectively, \(C\) – heat or moisture sources term.

The energy and moisture balance model is used to describe the atmosphere processes. The prognostic variables are the surface air temperature and surface specific humidity of the air. Energy balance equation determines the balance of incoming and outgoing radiation fluxes, explicit (turbulent) exchanges of heat fluxes with the underlying surface, release of latent heat due to precipitation and simple single-layer parameterization of horizontal transport processes. Sources in the specific humidity equation are determined by precipitation, evaporation and sublimation from the underlying surface.

Dynamic equations of the sea-ice model are solved for the fraction of the ocean surface covered by sea ice and for the average ice thickness. The growth and melting of ice depend only on the difference between the heat flux from the atmosphere in the sea ice and the heat flux from the ice to the ocean. The diagnostic equation is solved for the ice surface temperature.

All model components are coupled by the exchange of momentum, heat and water. The exchange of momentum consists only in the use of the velocity of the upper layer of the ocean for the advection of sea ice. Heat fluxes between adjacent blocks [13, 14] can be modified by phase transitions at the boundaries (evaporation, melting, etc.).

The fresh water fluxes into the atmosphere are determined taking into account evaporation from the surface and sea ice sublimation. It is assumed that precipitation falls directly into the ocean, without taking into account the presence of ice, and evaporated or sublimated water is removed from the ocean or ice, respectively. In the formulation of the ocean model in the "rigid lid" approximation used here,
the model represents the ocean as an infinite source of fresh water for the sea ice and the atmosphere. Fresh water is strictly conserved in the sea-ice and atmospheric components but converted to salinity at the ocean surface.

The model uses a uniformly longitude and sine of latitude finite-difference grid of $72 \times 72$ cells. The resolution of the model in longitude is $5^\circ$, and in latitude it varies from approximately $1.5^\circ$ at the equator to $10^\circ$ at the poles [12]. The depth of the ocean is represented as an eight-level logarithmic scale up to 5000 m.

3. Numerical experiments

According to this model, in the first stage, climate prediction calculations up to year 2100 have been made using CO$_2$ growth scenarios called RCP8.5 (concentration 860 ppm in 2100) and RCP4.5 (concentration 560 ppm in 2100) proposed by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1] and corresponding the differing forecasts of the world energy development. They give an increase in the average annual global surface temperature of the atmosphere by 2.2 °C for RCP8.5 and 1.3 °C for RCP4.5. Further for these scenarios, a series of calculations were performed to assess the possibility of climate stabilizing the at the 2010 level by controlling emissions to the stratosphere of the aerosol that reflects part of the incoming solar radiation.

Optical thickness of scattering stratospheric aerosols in the model depends linearly on their extinction coefficient and aerosol mass per unit. In turn, instantaneous radiative forcing at the top of the atmosphere is proportional to optical thickness with coefficient that is based on measurements performed for the aerosol loading after the Mt. Pinatubo eruption (1991). In the numerical experiments with geoengineering mitigation, global mass of the stratospheric aerosols is modeled via balance between stratospheric sulphur emission and falling per annum. Residence time of stratospheric sulphates is varied from 2 to 3 years. Based on fast mixing of volcanic aerosol clouds in zonal direction, zonal distribution of resulting stratospheric sulphates is assumed to be homogeneous.

Aerosol concentration from the year 2010 to 2100 is calculated as a controlling parameter to stabilize mean year surface air temperature. It is shown that by this way it is impossible to achieve the space and seasonal uniform approximation to the existing climate, although it is possible significantly reduce the greenhouse warming effect (Fig. 1). Assumption of a uniform stratospheric aerosol space distribution can stabilize the mean atmosphere global temperature, but climate will be colder at 0.1-0.2 °C in the low and mid-latitudes and at high latitudes it will be warmer at 0.2-1.2 °C.

**Figure 1.** Deviation of the atmosphere temperature of the stabilized climate (2100) from the current one. Scenario RCP8.5. January
In addition, these differences have strong seasonal changes - they increase in the winter. The situation is improved to some extent by the formulation of the problem, in which the latitude dependence of the aerosol concentration is allowed. Results demonstrate, that the concentration decreases in the low and middle latitudes and increases in the high. However, an increase in the aerosol concentration in the Polar regions has a weak effect, since the solar radiation influence is small there, while the greenhouse effect is present everywhere.

Dependence of the mean square deviation (MSD) of atmospheric temperature separately for winter and summer seasons is investigated for optimization purpose. Averaging of results separately in the northern hemisphere, the southern hemisphere and throughout the world for July and January with different values of the aerosol emissions was carried out. On the basis of calculations it is assumed that sulfur emissions from the 2010 year to 2100 year vary linearly.

The Pareto frontier [15], which determines the range of optimum aerosol masses in the stratosphere is investigated and visualized for two parameters - atmospheric temperature MSD for the winter and summer seasons (Fig. 2). The Pareto optimal amount of sulfur emissions for RCP8.5 would be between 19.2 and 21.9 TgS/year for the northern hemisphere. Similar calculations for the southern hemisphere gave the following best value range: 19.2 -19.9 TgS/year, and for the whole globe corresponding range: 19.9 – 20.9 TgS/year.

Thus, the optimal general emission value would be about 19.9 TgS/year. At the same time, the average humidity will decrease by 8.2%, the thickness of sea ice - by 4.1%, sulfur emissions will be 9.97 TgS/year for RCP8.5. The values mentioned for RCP4.5 are 4.5%, 2.0% and 4.98 TgS/year, respectively.

If geoengineering emissions are stopped after several decades of implementation, their climatic effect is removed within a few decades. In this period, surface air temperature may grow with a rate of several Kelvins per decade.

![Figure 2](image.png)

**Figure 2.** Two criteria optimality. Pareto frontier visualization. Dependence of atmospheric temperature MSD for July and January months on the mass of stratospheric aerosol in 2100. RCP8.5 scenario
4. Conclusions
The aerosol concentration from 2010 to 2100 is calculated as a control parameter for stabilizing the mean annual surface air temperature of the earth. The changes in aerosol concentration from 2010 to 2100 have been calculated, which allow to stabilize the mean annual temperature of the near-surface layer of the atmosphere. It is shown that in this way it is impossible to achieve a uniform proximity of the climate to the existing one, although it is possible to weaken significantly the effect of climate greenhouse warming.

References
[1] Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
[2] Manzhurov, A.V., Gupta, N.K. Fundamentals of Continuous Growth Processes in Technology and Nature (2017) Procedia IUTAM, 23, pp. 1-12.
[3] Sychev, A.M., Sukhorukova, N.A., Kholod, D.A. Estimation of security of objects of informatization on the basis of mathematical simulation as an alternative to certification testing (2017) CEUR Workshop Proceedings, 2081, pp. 127-130.
[4] Chursin, A., Drogovoz, P., Sadovskaya, T., Shiboldenkov, V. A linear model of economic and technological shocks in science-intensive industries (2017) Journal of Applied Economic Sciences, 12 (6), pp. 1567-1577.
[5] Caldeira K., Keith D. “The Need for Climate Engineering Research”, Issues in Science and Technology Studies. 27(1), p. 52-57 (2010).
[6] Lin A. C. “Balancing the Risks: Managing Technology and Dangerous Climate Change”, Issues In Legal Scholarship, 8(3), art. 2 (2009).
[7] Budyko M.I. “Climate changes”. American Geophysical Union, Washington, D.C., 244 p. (1977).
[8] Eliseev A.V., Mokhov I.I., Karpenko A.A. “Global warming mitigation by means of controlled aerosol emissions of sulphate aerosols into the stratosphere: global and regional peculiarities of temperature response as estimated in IAP RAS CM simulations”. Atmos. Ocean Opt. 22, p. 388–395 (2009).
[9] Marsh R., Edwards N.R., Shepherd J.G.. “Development of a fast climate model (C-GOLDSTEIN) for Earth System Science.” SOC, 2002, No.83. 54 p.
[10] Parkhomenko V.P. “Numerical experiments on global hydrodynamic model to assess the sensitivity and climate sustainability.” Vestnik MGTU im. Bauman. Issue Mathematical Modelling, p. 134-145 (2012) (in Russian).
[11] Parkhomenko V.P. Application of the quasi-random approach and ensemble calculations for the determination of optimal sets of values of the parameters of the climate model. Informatics and its applications. 2017, Vol. 11, no. 2, p. 65-74 (in Russian).
[12] Parkhomenko V.P. “Climate model with consideration World ocean deep circulation,” Vestnik MGTU im. Bauman. Issue Mathematical Modelling, p. 186-200 (2011) (in Russian).
[13] Varaksin, A.Y. Air tornado-like vortices: Mathematical modeling (a review) (2017) High Temperature, 55 (2), pp. 286-309.
[14] Shevchenko, S.Y., Melnik, Y.A., Smirnov, A.E., Htet, W.Y.M. Comparative evaluation of methods for the determination of heat transfer coefficients of liquid and gaseous quenching media (2017) Mechanics and Industry, 18 (7), paper № 703.
[15] Uskov, A., Serduyukova, N.A., Serduyuk, V.I., Heinemann, C., Byerly, A. Multi objective optimization of VPN design by linear programming with risks models (2016) International Journal of Knowledge-Based and Intelligent Engineering Systems, 20 (3), pp. 175-188.