Arctic Sea Ice Cover Sensitivity Analysis in Global Climate Model

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Abstract. Results of numerical of coupled numerical experiments with 3D atmospheric general circulation model, upper layer ocean model and sea ice evolution model are carried out and discussed for Arctic region. Model calculations to analyze sea ice cover evolution are carried out. Calculated sea ice cover distributions for different seasons are presented. Sea ice cover sensitivity analysis to base models parameters, determining atmosphere, ocean and ice interaction, sensible heat flux from sea ice and snow surface, heat flux from ocean to ice is presented. The spatial and seasonal structure of changes has rather complex non-uniform character, there are great areas of opposite changes. It is connected with nonlinear behavior of feedback and interactions in model system including an atmosphere, sea ice and ocean. The author was supported by the Russian Foundation for Basic Research (project no. №17-01-00693).

1. Introduction
There is ample evidence that the greenhouse effect will cause significant changes in climate and biotic processes in the Arctic region, as well as a restructuring of the hydrological regime of the Arctic Ocean [1-3]. These changes will have a wide variety of economic and environmental consequences and should cause an adequate response from humanity. This is all the more important in the light of the growing role of the Russian North as a source of raw materials (oil, natural gas, non-ferrous metals, wood), and the most important transport route West-East [4, 5]. In particular, these factors indicate the importance of studying the climate system of the Arctic region. Changes in the ice cover were observed in the past [6].

The paper presents and discusses the results of coupled calculations based on the atmospheric general circulation model (AGCM), the upper ocean layer model and sea ice evolution model for the Arctic region.

This formulation allows studying the interactive influence of atmospheric factors on the hydrological regime of the ocean. The surface temperature, snow fallout and melting are largely related to the stochastic nature of the calculated parameters in the AGCM. Thus, calculations using the coupled model make it possible to obtain new results when calculating the sea ice evolution.
2. Models description
The climate model of the Computer Centre of the Russian Academy of Sciences (CC RAS) includes a 5 level model of the AGCM [7, 8] and the ocean block [9, 10], which is the ocean active layer model with a given field of geostrophic currents. The interaction between the blocks is carried out online. A detailed description of the models is present in the references.

The system of three-dimensional differential equations of the atmospheric model [11], the so-called system of primitive equations, includes dynamic prognostic equations for horizontal velocity components, a thermodynamic energy conservation equation, an equation describing the hydrostatic approximation vertically, a prognostic equation describing the conservation law of dry air mass, prognostic equation for moisture balance in the atmosphere. Models describing the hydrological cycle [12], and the propagation processes of thermal and solar radiation are used to determine the water vapor and heat sources. The model also describes specific mechanisms describing the processes of cloud formation.

The atmospheric general circulation model of the CC RAS is actively used for calculations of atmospheric and climatic processes on Earth. The reliability of the model was investigated by the quality of its reproduction of the current climate in real seasonal mode [13]. This procedure allows to check the adequacy of the model for a large number of parameters of the climate system by comparing with observational data [14, 15].

The ocean block is an integral two-dimensional model of ocean active layer. The active layer thickness is assumed to be everywhere equal to 250 m. The system of equations of the model includes the heat conduction equation integrated within the seasonal thermocline, as well as the equation for the effective mixed layer thickness [10]. The thermodynamic part of the sea ice evolution model is based on the one proposed by Semptner [16], but contains some differences and improvements [7]. It is assumed that all the energy fluxes from the atmosphere, minus the reflected and absorbed short-wave radiation, are used to change the ice surface temperature and the snow-ice cover mass. The formation of internal cavities in the ice column is taken into account [17-19]. Heat fluxes, precipitation, etc. calculated in the atmospheric model.

3. Numerical experiments
The base case calculations, corresponding to the current climate, begin with the ice cover initial conditions, when ice thickness is equal 2 m everywhere, compactness (the cell fraction filled with thick ice) is 0.9 and there is no snow cover. The area and configuration of the Arctic sea ice cover correspond to observed climate data.

In the first stage of reaching the steady state, there is a summer rapid ice melting in the marginal areas, which leads to a decrease in the average ice thickness. The ice freezing and accumulation in the Arctic Basin central regions during the winter period is slow, therefore, transition to the stationary mode occurs gradually and takes about 15 years. The change in time of the average ice thickness in the Arctic Basin is shown in figure 1.

The bold line indicates the moving average of this value with an averaging period of 1 year. These results are confirmed by the analysis of the ice thickness change over time at selected characteristic points (figure 2). Note that in the steady state mode, there are significant interannual fluctuations in the ice cover in accordance with figure 1, 2.

The calculated ice cover thickness distribution in the Arctic for two months is shown in figures 3 and 4: March and September, respectively. These and subsequent similar figures show an Earth map the with contours of the coastline (Eurasia is down), viewed from the North Pole, which is located in the center of the map. Colored areas determine the sea ice distribution, the thickness of which is highlighted in different colors.
Figure 1. Changes in time of the average Arctic ice thickness. Calculation results.

Figure 2. Changes in time of the ice thickness in the cell near the North Pole. Calculation results.

The figure 5 data corresponds to the maximum ice cover during the year, and the figure 6 data - the minimum. The ice spatial distribution and thickness are consistent with observational data. These calculation results will be considered basic and the rest results will be compared with them.

Figure 3. Arctic ice thickness and distribution in March. Calculation results.

Figure 4. Arctic ice thickness and distribution in September. Calculation results.

A series of numerical calculations was carried out to determine the model sensitivity to some important parameters defining the ice cover. The initial conditions for all these calculations were the final distributions obtained in the basic calculation.

In the first numerical experiment, the sensible heat flux from ice to the atmosphere was reduced 10% by decreasing the corresponding coefficient in the Fourier law. This coefficient value is not exactly known and is chosen empirically. The calculation results are presented in figure 5. On average, there is an increase of the ice thickness, mostly within 50 cm. However, there is a decrease in the ice thickness up to 50 cm in some areas.
Figure 5. Ice thickness spatial changes in March (left) and September (right) with 10% sensible heat flux decrease. Calculation results.

The maximum increase of ice thickness occurs at the end of spring and summer (figure 5). Apparently, this is due to the maximum temperature difference air - ice in the warm period. The heat flux decreases to the greatest extent, which leads to a slowdown in the melting of snow and ice.

The sea ice albedo without snow was reduced by 0.05 compared to the base case in the following numerical experiment. This corresponds to possible surface contamination. The calculation results are presented in figure 6.

Figure 6. Ice thickness spatial changes in March (left) and September (right) with sea ice albedo decrease. Calculation results.

Analysis of the change in the average ice thickness over the seasons shows a decrease in this value in the range from 20 cm to 60 cm, with the maximum change occurring during the summer period of intensive thawing. At this time, there is not only an insolation maximum, but almost all snow has melted on the ice surface. The spatial distribution of ice thickness changes (figure 6) shows that ice thickness decreased by up to 100 cm over most of the Arctic area. However, as follows from the same figure, there is also an area of the increase in the ice layer mainly in the range up to 20 cm. It is localized in
the Beaufort Sea region. The calculations results are presented here for the steady state. It means that the long-term adaptation and different feedbacks of the ocean system to the new albedo are taken into account.

It is interesting to study the effect of albedo of the snow cover on the sea ice area and thickness. This is done in the following experiment. The snow albedo is reduced in comparison with the basic variant by 0.05. The calculation results are presented in figure 7.

![Figure 7. Ice thickness spatial changes in March (left) and September (right) with snow albedo decrease. Calculation results.](image)

In this case, the average ice thickness decreased by about 20 cm, and this value only slightly depends on the season. Changes in individual points are also not as large as in the previous case. Apparently, this is due to the fact that changes in the surface albedo in the polar regions are significant in the summer period, while at this time the snow melted over large areas of the ice cover and does not affect the absorption of solar radiation.

As can be seen from figure 7, the area of the ice thickness reduction is almost independent of the season and was formed under the influence of dynamic processes in the climate system. As in the previous case, there is a stable area of the increasing ice cover thickness and it is located at the same area. Perhaps this is due to changes in atmospheric circulation, cloudiness and precipitation.

4. Conclusion

The paper presents a set of models: atmospheric circulation, thermodynamics of the active layer of the ocean, evolution of the ice cover. A series of numerical experiments on the calculation of the Arctic Ocean ice cover was carried out, and the influence of various factors and parameters on the change in the ice cover in time and space was estimated. Considerable natural interannual variability of the ice cover has been established. The effect on the thickness, area, compactness, seasonal changes in the ice cover of climate system parameters as the sensible heat flux from the ice surface to the atmosphere, snow and ice albedo, and the heat flux from the ocean to the ice are analyzed.

The results of numerical experiments showed that the ice cover and its seasonal evolution depend strongly enough on the variable parameters. The spatial and seasonal structure of ice changes has a rather complex heterogeneous character; there are vast areas of opposite changes in sign. This is due to a complex system of feedbacks and interactions in the climate system, including the atmosphere, sea ice and the ocean.

Thus, a decrease in the albedo of snow and ice leads to a decrease in the average thickness, as was to be expected. However, there are areas where there is an increase of the ice cover thickness. The similar results are get with other parameters. Development of models, numerical methods and improvement of the spatial and temporal characteristics of the models are required to refine the results.
References
[1] Climate Change [Core Writing Team R K Pachauri and L A Meyer (eds.)] IPCC 2015 (Geneva, Switzerland) p 151
[2] Lindsay R W et al. 2009 Arctic sea ice retreat in 2007 follows thinning trend Journal of Climate 22 pp 165-175
[3] Manzhurov AV, Gupta N K 2017 Fundamentals of Continuous Growth Processes in Technology and Nature Procedia IUTAM 23 pp 1-12
[4] Sychev A M, Sukhorukova N A, Kholod D A 2017 Estimation of security of objects of informatization on the basis of mathematical simulation as an alternative to certification testing CEUR Workshop Proceedings 2081 pp 127-130
[5] Chursin A, Drogovoz P, Sadovskaya T, Shiboldenkov V A 2017 linear model of economic and technological shocks in science-intensive industries Journal of Applied Economic Sciences 12(6) pp 1567-1577
[6] Blaschek M, Renssen H 2013 The Holocene thermal maximum in the Nordic Seas: the impact of Greenland Ice Sheet melt and other forcings in a coupled atmosphere–sea–ice–ocean model Clim. Past 9 pp 1629-1643
[7] Parkhomenko V P, Tran Van Lang 2013 Improved computing performance and load balancing of atmospheric general circulation model Journal of Computer Science and Cybernetics 29(2) pp 138 – 148
[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 Informatics and its applications 11(2) pp 65-73
[9] Goldberg D N, Little C M, Sergienko O V, Gnanadesikan A, Hallberg R, Oppenheimer M 2012 Investigation of land ice-ocean interaction with a fully coupled ice-ocean model: 1. Model description and behavior J. of geophysical research 117 F02037
[10] Ganapolsky A V, Gusev A M, Nefedov N N 1987 Climatic integral model of the ocean active layer Oceanology 27(4) pp 573-578
[11] Tolstykh M A 2010 Variable resolution global semi-Lagrangian atmospheric model Russian Journal of Numerical Analysis and Mathematical Modelling 18 pp 347-361
[12] Varaksin A Y 2017 Air tornado-like vortices: Mathematical modeling (a review) High Temperature 55(2) pp 286-309
[13] Parkhomenko V P 2018 Modeling of global and regional climate response to solar radiation management J. Phys.: Conf. Ser. 1141 012057
[14] Shevchenko S Y, Melnik Y A, Smirnov A E, Htet W Y 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
[15] Uskov A, Serdyukova N A, Serdyukov V I, Heinemann C, Byerly 2016 Multi objective optimization of VPN design by linear programming with risks models International Journal of Knowledge-Based and Intelligent Engineering Systems 20(3) pp 175-188
[16] Semtner A J A numerical study of sea ice and ocean circulation in the Arctic. 1987 J. Phys.Oceanogr. 17(8) pp. 1077-1099
[17] Girard L, Weiss J, Molines J M, Barnier B, Bouillon S 2009 Evaluation of high-resolution sea ice models on the basis of statistical and scaling properties of arctic sea ice drift and deformation J. of Geophysical Research 114 C08015
[18] Konovalov Y V 2019 Ice-shelf vibrations modeled by a full 3-D elastic model Annals of Glaciology 10.1017/aog.2019.9
[19] Ovcharuk V, Solovev D B 2019 Features of Registration of Acoustic Signals in Multichannel Acoustic-Emission Systems 2019 International Science and Technology Conference "EastConf", International Conference on. pp. [Online]. Available: http://dx.doi.org/10.1109/EastConf.2019.8725383