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Equilibrium State of the Greenland Ice Sheet in the Earth System Model

O. O. Rybak[a, b]*, E. M. Volodin[a], P. A. Morozova[a, c], and P. Huybrechts[d]

[a]*Institute of Numerical Mathematics, Russian Academy of Sciences, ul. Gubkina 8, Moscow, 119333 Russia*

[b]*Sochi Research Center, Russian Academy of Sciences, ul. Theatralnaya 8a, Sochi, 354000 Russia*

[c]*Institute of Geography, Russian Academy of Sciences, ul. Vavilova 77, Moscow, 117335 Russia*

[d]*Vrije Universiteit Brussel, Pleinlaan 2, Brussels, B-1050 Belgium*

**e-mail: o.o.rybak@gmail.com*

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Abstract—Currently, the Earth system models are widely used for studying present-day climate dynamics and for palaeoreconstructions. A full Earth system model should include dynamical ice sheet models of Greenland and Antarctica as subsystems. To couple the latters with the atmospheric and with the oceanic blocks, it is necessary to introduce a special procedure to sustain mutual data exchange between subsystems with different temporal and spatial scales. In this paper, we give a brief description of the blocks of the Earth system model developed in the Institute of Numerical Mathematics of RAS (INMCM). On the basis of the previous studies aimed at examination of sensitivity of the cryospheric block of the model to variations in the key model parameters, we carried out numerical experiments to prove stability of the model climate and to establish equilibration time of the Greenland ice sheet to the conventional pre-industrial climate. It was confirmed that our Earth System Model with the interactively and asynchronously coupled Greenland ice sheet model simulates stationary climate. Equilibration time of the Greenland ice sheet is nearly 20 thousand model years. It was demonstrated that the values of calculated surface mass balance and its components correspond to similar model results described in the literature.

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1. INTRODUCTION

Currently, the Earth system models (ESMs) are widely used to solve various problems of climatology, palaeoclimatology, oceanography and in other fields when it is necessary to study a number of interconnected and multiscale processes in the atmosphere, ocean, or in the planet biosphere or cryosphere. Though ice sheets have always been incorporated into climate models of diverse complexity [14, 20] in one or another way, computational facilities did not allow comprehensive description of their dynamics using coupled models. Present day computers allow not only taking into account the dynamic processes governing the evolution of ice sheets but also simulating the entire complex of direct and indirect links between ice sheets, on the one hand, and the atmosphere and the ocean, on the other hand. The key methodological problem to be solved while coupling a cryospheric block to a climate model is much greater inertia of ice sheets compared with the atmosphere and the ocean as well as the substantial difference in the spatial and temporal scales of integration of the equations of aforementioned model blocks [9]. The dynamic models of ice sheets are incorporated into ESMs in different ways. First of all, it is required to ensure the transfer of simulated climatic data from the atmospheric block to the ice sheet block. Dynamic downscaling is one of the commonly used methods for climatic data regionalization. The use of regional climatic models (RCMs) for downscaling climate modeling results provided by general circulation models of the atmospheric and the ocean (AOGCM) to a relatively small area is not a new method. However, RCMs, a sort of a simplified AOGCM version, require substantial computational costs and, therefore, are of limited use for the modeling of ice sheet evolution over long time periods, though they can be used in some other applications [18]. Paper [24] suggested to couple a Greenland ice sheet model (GrISM) to a model of intermediate complexity CLIMBER of small spatial resolution using a simple energy- and moisture-balance model. We used this approach to couple a GrISM to an AOGCM INMCM3.2 (Institute of Numerical Mathematics Climate Model, version 3.2) using our own buffer model EWBM-G [9, 11, 12]. Since the spatial resolution of the INMCM (4 5 in the atmospheric block) is significantly higher than in the CLIMBER (5 10), the method was revised and tested in a number of numerical experiments. Previously, we studied the sensitivity of the EWNM-G to key model parameters [11, 12]. Climatic fields calculated during long numerical experiments on the INMCM model have been used for this purpose. In this paper, we analyze the performance of the complete Earth system model with the Greenland ice sheet (GrIS) as its active component assimilating model-generated climate from the atmospheric block and returning back changes in surface topography as well as freshwater runoff changes into the oceanic block.

2. DESCRIPTION OF THE EARTH SYSTEM MODEL

2.1. General Structure

The model version used in this paper consists of three blocks (see Fig. 1 in [12]): AOGCM INMCM, the climatic core; EWBM-G, the buffer model; and the dynamic model of Greenland ice sheet (GrISM). All of them, in turn, have hierarchical architecture and consist of smaller structural units that are also referred to as blocks for convenience. Since the present paper focuses on the Greenland ice sheet, the Antarctic ice sheet is incorporated in the model as a passive not-evolving component with fixed topography.

2.2. INMCM Model

Formal pre-industrial climatic conditions are reproduced in the INMCM3.2 model version. A detailed description of the model one can find in papers [4, 8]. The model consists of two main blocks: atmospheric and oceanic.

The atmospheric block is a modified version of model [1]. The short-wave part of incoming radiation spectrum is split into 18 spectral intervals, and the long-wave part, into 10 spectral intervals [6]. Radiation absorption by water vapor, clouds, oxygen, ozone, carbon dioxide, methane, nitrogen monoxide, and aerosols is taken into account. The amount of clouds at vertical levels is calculated diagnostically on the basis of relative humidity and vertical air temperature gradient values. The distributions of other radiation active components are represented as given functions. The parameterizations of deep and shallow convections are developed according to schemes from [17]. The model also accounts for orographic [23] and non-orographic [21] gravitational wave resistance.

The description of convection and condensation takes into account the formation of large-scale precipitation, falling snow melting, falling precipitation evaporation, dry convective adaptation, and convective friction for the cases of deep and shallow convection. Heat, moisture, and momentum fluxes on the surface are calculated using bulk aerodynamic formulae. Turbulence in the boundary layer of the atmosphere is parameterized through vertical diffusion. The diffusion coefficient depends on the Richardson number. Heat and moisture fluxes from land surface as well as heat-and-moisture exchange processes in soil are calculated according to the methodology described in [5]. The maximum possible proportion values of different vegetation types in each cell as well as leaf index values are used as input data in the vegetation block. Then the actual values of the leaf index and the cell cover ratio by a certain type of vegetation are calculated with moisture content and soil temperature taken into account. Evaporation and water absorption from soil by roots are calculated according to stomatal resistance. The latter depends on the vegetation type and weather conditions. Falling rain drops captured by leaves and their further evaporation are estimated. Carbon and methane fluxes between plants, soil, and the atmosphere resulting from photosynthesis, respiration, and the decomposition of organic matter are calculated in the carbon cycle block.

Dynamic equations are solved on the C-type Arakawa grid [15]. Dynamic processes are calculated using the 12-minute time step. Radiation is calculated every 3 hours, the other physical processes are parameterized every hour. Near the poles (from the 69 latitude), the Fourier filtration of high frequency harmonics is applied along the latitudinal circle to all prognostic variables.

Spatial resolution in the atmospheric block is 5 4 in longitude and latitude, respectively, with 21 sigma-levels in the vertical (from the Earth surface up to 10 hPa).

The oceanic block. The ocean general circulation model is based on primitive ocean equations in the Boussinesque approximations, hydrostatics and "hard cover" approximations expressed in a spherical sigma-coordinate system [2, 3, 7]. The model includes the block responsible for the dynamics and thermodynamics of sea ice [13]. River runoff is evaluated taking into account the drainage area and atmospheric precipitation. Fresh water conventionally inflows into the ocean with no delay.

The model domain covers the entire World Ocean (excluding the point corresponding to the North Pole). The ocean block resolution is 2.5 2 with 33 vertical levels. The parallel implementation of the ocean dynamics model code is described in [25]. Prognostic equations for all model variables in the current model version are solved using explicit schemes.

2.3. The Buffer Model EWBM-G

EWBM-G consists of two blocks, the climatic and mass balance ones (see Fig. 1 in [12]).

The climatic block. Diffusion equations for surface air temperature T and surface specific humidity q are solved in the climatic block. The equations are formulated for unit atmospheric columns and simulate synoptic processes in a simplified way:

$$c_{\mathrm{p}} \quad {}_{\mathrm{a}} h_{\mathrm{a}} \frac{T}{t} \qquad {}^{2}(D_T T) \quad Q, \tag{1}$$

$$ {}_{\mathrm{a}} h_{\mathrm{e}} \frac{q}{t} \qquad {}^{2}(D_q q) \quad P. \tag{2}$$

Here c_{p} is the specific heat capacity of the surface air; ${}_{\mathrm{a}}$ is surface air density; h_{a} is the conventional height of the atmospheric column; h_{e} is the conventional height of the wet atmospheric column; radiation sources and heat sinks are collected in summand Q; D_T and D_q are the coefficients of large-scale diffusion of heat and moisture linearly dependent on latitude and absolute elevation [12]. Equations (1) and (2) are solved by the finite-difference method in the internal grid points of the domain which includes GrIS (see Section 2.4). EWBM-G assimilates the boundary conditions calculated in the INMCM and takes into account the topographic features which certainly cannot be resolved by the INMCM. As a result, the stationary daily fields of T and q are obtained. Note that the initial version of the EWBM-G [9, 11] was modified in such a way that equations (1) and (2) were formulated in the Cartesian coordinate system and solved in a rectangular domain instead of a sphere sector [12].

The adjustment of T to the absolute height of the site (the calculation of daily average surface air temperature $\overline{T}_{\mathrm{A}}$ at z altitude) is performed using empirically established gradients for Greenland [19]. Precipitation sum P on the right-hand side of equation (2) depends on q; on the total cloud cover n; on , the typical water exchange period in the atmosphere; and on the surface gradient z [24]:

$$P \quad (1 \quad k| \quad z|)\frac{nq}{} \tag{3}$$

where k is a tuning parameter.

The ratio between solid (PS) and liquid (PL) precipitation in the total precipitation sum varies as a sinusoid function of surface air temperature $\overline{T}_{\mathrm{A}}$ in the range from –7 C to 7 C. It is assumed that only snowfall occurs when $\overline{T}_{\mathrm{A}}$ –7 C and only rainfall, when $\overline{T}_{\mathrm{A}}$ 7 C [24].

The mass balance block. P and $\overline{T}_{\mathrm{A}}$ calculated in the climatic block are used as input variables for mass balance calculation on the ice sheet surface (SMB). SMB is assumed as a difference between accumulation (AC) and runoff (RO):

$$SMB \quad \overset{365}{\underset{1}{}}[AC \quad RO] \quad \overset{365}{\underset{1}{}}[(PS \quad PL \quad SU) \quad (M \quad PL \quad RF)]. \tag{4}$$

Sublimation SU is proportional to the hidden heat flux value (LE). The amount of refrozen water (RF) is calculated according to the Oerlemans method [12] which has been adapted for incorporation in EWBM-G. The amount of meltwater M is proportional to the available energy and is determined from the energy balance on infinitesimally thin surface layer [10]. Liquid precipitations are indicated both on the left-hand side and on the right-hand side of equation (4). It means that only frozen liquid precipitations contribute to the mass balance. SMB is estimated every hour. For this purpose daily mean surface air temperature $\overline{T}_{\mathrm{A}}$ is converted into hourly mean:

$$T_{\mathrm{A}} \quad \overline{T}_{\mathrm{A}} \quad \widetilde{T}_{\mathrm{A}} \cos 2 \frac{t}{24} \tag{5}$$

where $\widetilde{T}_A$ is the daily amplitude, $t = 0,\ldots, 23$ are day hours. The analysis of the long-term hourly measurements of surface air temperature at 21 GC-Net automatic weather stations enabled us to construct the linear dependence of $\widetilde{T}_A$ on absolute elevation and harmonic dependence of $\widetilde{T}_A$ on time [12]:

$$\widetilde{T}_A \quad t_0 \quad (a_0 \quad a_1 z)\sin[4 \; m/365 \quad (b_0 \quad b_1 z)] \quad (f_0 \quad f_1 z) \tag{6}$$

where $m = 1,\ldots, 365$ is a day of the standard year, z is absolute elevation, t_0 is a tuning parameter. The values of the rest parameters are given in [12].

The total mass loss of GrIS consists of three components: surface runoff (*RO* in equation (4)), basal runoff resulting from the ice sheet melting at the ice sheet base, and ice discharge because of caving at GrIS marine boundaries. The last two variables are calculated in the block of the ice sheet model (GrISM).

2.4. GrISM Model of the Greenland Ice Sheet

The standard architecture of the mathematical model of the Greenland ice sheet is described in detail in [22]. The model is based on the laws of conservation of mass, momentum, and energy. Ice is considered as viscous, incompressible, non-Newtonian, heat-conductive fluid. The dynamics of ice is considered within the frameworks of the shallow ice approximation with a limited set of stress gradients. The response of underlying rocks to the changing load is estimated within the ELRA model, where lithosphere is accepted as a plate bending under ice sheet mass and “floating” on the surface of the viscous asthenosphere. The geothermal heat flux field is based on reconstructions and corrected according to basal temperature measurements in deep ice cores [10]. The model equations are solved by the finite-difference method on the grid with 20-km horizontal resolution in the domain 2800 1640 km (141 83 grid points) and 51 layers in the vertical with the thickness decreasing exponentially with depth. The model calculates the changes of ice thickness in response to the forcing generated in EWBM-G in accordance with INMCM boundary conditions. Average annual surface air temperature is applied as an upper boundary condition to calculate temperature inside the ice sheet body, and *SMB* from equation (4) is applied to estimate the updated values of ice thickness in each point of the spatial grid filled with ice.

3. ORGANIZING DATA EXCHANGE BETWEEN THE EARTH SYSTEM MODEL BLOCKS

Data exchange between the atmospheric and oceanic blocks occurs every 2 model hours. Sensible and latent heat fluxes, fresh water flux, momentum flux, cumulative (incoming and outgoing) flows of long-wave and short-wave radiation are transferred from the atmospheric to the oceanic block, while sea surface temperature (SST) and the sea ice area are transferred from the oceanic to the atmospheric block. The flows are not corrected. Linear interpolation is applied to recalculate atmospheric fields to the oceanic spatial grid. In order to recalculate SST to the atmospheric grid, a procedure of spatial weighted averaging is applied. For calculation of ocean surface fluxes in the atmospheric model, temperature of the uppermost calculated level in the oceanic model is accepted as the surface temperature. Salinity in the estuaries of the biggest 48 rivers is calculated taking into account fresh water fluxes from these rivers evaluated in the atmospheric model. Meltwater from the ice sheets is considered in the salinity field calculations.

Average daily values of variables calculated in INMCM (T is surface air temperature at sea level, q is specific humidity, p is sea level pressure, v is wind speed modulus, n is the total cloud cover), are accumulated, daily averaged, and transferred into EWBM-G in the end of each model year. T and q values after rescaling and interpolation from the 4 5 grid to a regular spatial grid of 20 20 km are assigned to the boundary grid points of a 1600 2800 km domain, including Greenland. The values of the rest variables used in parameterization expressions are assigned to all the grid points of the domain. The updated topography of the sheet calculated at each annual time step is assimilated in the atmospheric block of the INMCM, and the updated total runoff is assimilated in the oceanic block.

4. DESCRIPTION OF NUMERICAL EXPERIMENTS

In a series of preliminary numerical experiments we tested performance of separate model blocks and of the fully coupled ESM [11, 12]. Basing on the results, several insignificant corrections have been made into the oceanic block of the INMCM to improve stability of the model-generated climate. Once this had been done, it was necessary to test performance of the fully coupled ESM in order:

—to confirm stability of climatic conditions generated by a coupled INMCM–EWBM-G model and absence of variable drift;

—to assess the time scale of GrIS adaptation to the model-generated pre-industrial climate;

—to evaluate the differences of the model-generated equilibrium surface elevation from the observed one;

—to determine dependence of modeled ice volume of GrIS on tuning parameter t_0, which is responsible for melting rate.

The model blocks were asynchronously coupled in numerical experiments: every time step in the INMCM–EWBM-G integration corresponded to 100 model years of GrISM integration. Asynchronous coupling enables substantial reduction of computational time, because the time step in GrISM integration is 1 year, but the adaptation of the ice sheet to updated climatic conditions is a rather slow process due to thermal inertia. Asynchronous coupling is the only possible way for performance of long-term numerical experiments. As initial conditions for GrIS, surface and bedrock elevation, ice thickness and ice temperatures fields generated with minimum deviations of modeled data from the present-day observed ones [16] were used. Selected initial state was obtained after GrISM integration during 225 thousand model years. This time period covered two glacial-interglacial cycles [10]. Thus, new experiments can be considered as a continuation of what has already been done. This substantially reduces computational time required for the evolution of the model topography from the observed one to the topography which is in the quasi-equilibrium with the modeled pre-industrial climate.

The extremely high computational cost for integration of a fully coupled ESM, puts natural limits on the number of possible numerical experiments and on their duration. Altogether, we carried out four numerical experiments of 25 thousand model years (for the GrISM) duration each (250 steps of the INMCM). In these experiments, a tuning parameter t_0 in equation (6) was varied, which controls the melting area spread from the coast into internal area of the ice sheet: $t_0 = 0$ C (experiment 1), $t_0 = 0.2$ C (experiment 2), $t_0 = 0.4$ C (experiment 3), $t_0 = 0.6$ C (experiment 4) varied in the experiments. The variability of the model-generated daily amplitude of surface air temperature is lower than the variability of observed amplitude. This explains the t_0 application. A critical reasonable value for conventional pre-industrial climate generated by the INMCM, is likely to be t_0 1.0 C [12].

5. DISCUSSION AND SUMMARY

In the numerical experiments, GrIS surface elevation was gradually adapted to the model-generated climatic conditions. In order to evaluate the difference of the model height from the observed [16], we calculated mean square errors only in the area currently covered with ice in accordance with observations ($_S$). In other words, in the areas where model ice is present, but real ice is absent, are not taken into account. In order to account for the fact that conventionally equilibrium state was used as the initial condition obtained in the numerical experiment [10], $_S$ series was normalized by $_S$ in the first year of its integration.

The most significant changes in the ice sheet topography occur during the first 5 thousand model years, when the growth of $_{S\,rel}$ is 7–10% depending on the experiment (Fig. 1a). During the following 15 thousand model years $_{S\,rel}$ increases at a slower rate by about 5%. After that, its growth stops. Therefore, the process of GrIS full adaptation to conventional pre-industrial climate lasts approximately 20 thousand model years. The sheet volume (also normalized by a value in the first year of integration) after initial growth by 0.5–1.2% during the first 2 thousand years, later on gradually decreases to 98.5–99.5% of the present-day level and stabilizes at this level after about 15 thousand model years (Fig. 1b). Generally speaking, the stabilization time is almost the same in all experiments.

Asynchronous coupling means that there may be a possibility that interannual variability of temperature and water content generated in the climatic block and transferred to the ice sheet model would transform into centannial positive and negative anomalies of the ice sheet volume and area or is capable to result in non-zero linear trends of these characteristics. The latter, however, does not occur, and the average values of surface mass balance and its components are in practice stable during the whole time of integration (Figure 2a designed for experiment 4). The resulting slight drift within 1% can be attributed to the process of GrIS adaptation to the model climate. Note that at first GrIS quickly expands almost to the margins of the island in all four experiments. This leads the growth of the ice loss through the marine boundary of the ice sheet compared with the real ice loss (dynamic discharge). In present-day climatic conditions, GrIS mass loss is partitioned approximately equally between surface runoff and dynamic discharge [26]. In the numerical experiments, dynamic discharge is approximately by 20% higher than surface runoff (Fig. 2b). The

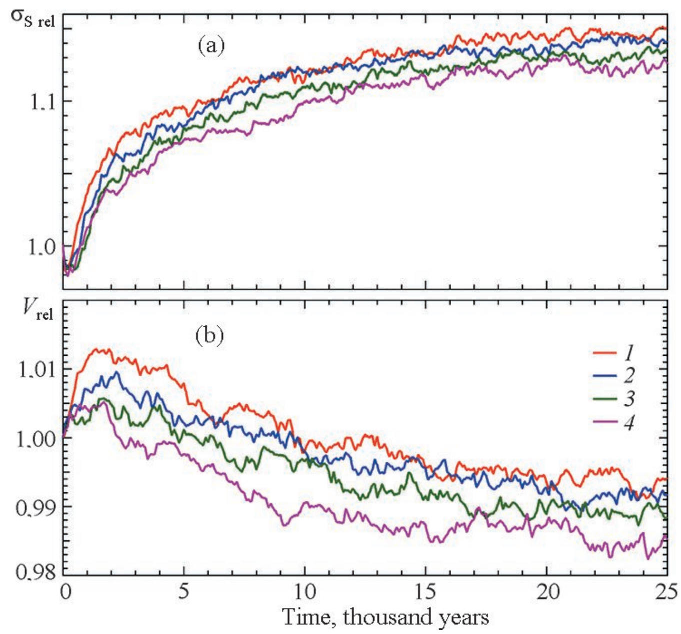

Fig. 1. Changes in root-mean-square ($_S$) deviations of the modeled surface elevation (a) and volume V of the Greenland ice sheet (b) from the observed ones in four numerical experiments (curves *1–4*, respectively). $_S$ and volume are shown in relative values, i.e., after normalization on the value in the first year of integration.

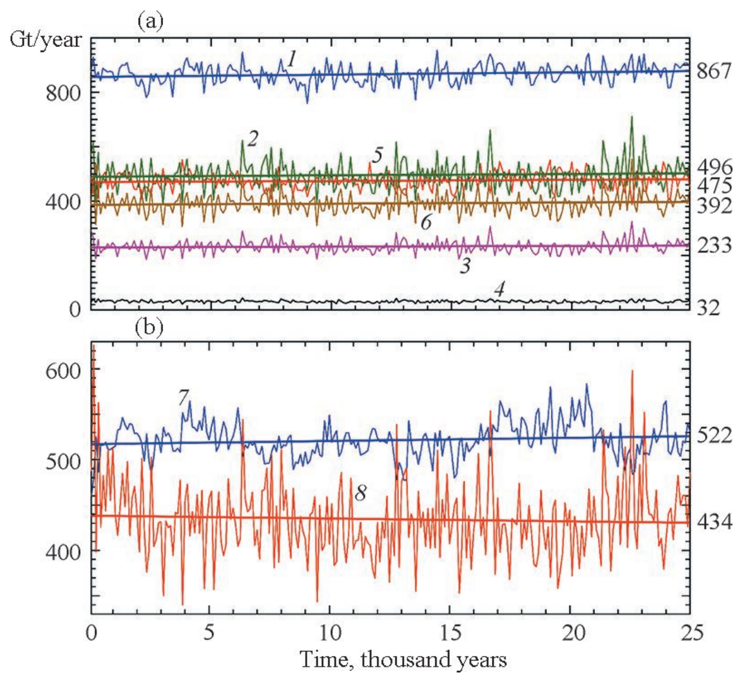

Fig. 2. Changes in surface mass balance and its components (a), and runoff (b) in experiment 4: (*1*) accumulation; (*2*) melting; (*3*) refreezing; (*4*) sublimation; (*5*) mass balance; (*6*) surface runoff; (*7*) ice calving (discharge through the marine boundaries of the ice sheet); (*8*) sum of surface and basal runoff. The horizontal lines and figures on the right-hand scale indicate average meanings.

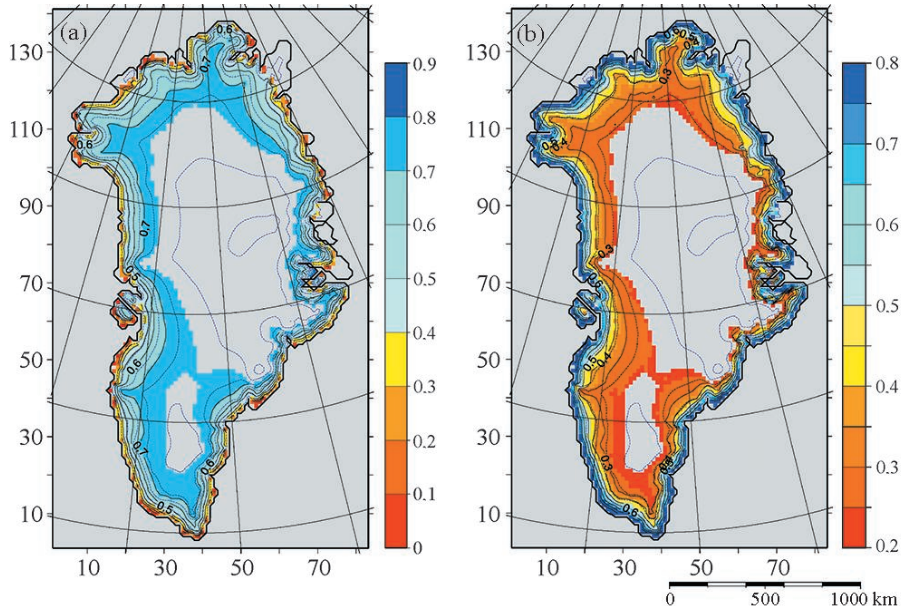

Fig. 3. Ratio of (a) refrozen water to melting and (b) surface runoff to melting in experiment 4. The isolines of surface elevation in the last year of integration are indicated every 500 m (the thin dashed line). The figures on the margins correspond to numbers of points of 20 20 km spatial grid.

Model components of surface mass balance of the Greenland ice sheet (km^3/year or Gt/year) for the period 1958–2007 (Polar MM5 until the year 2006) [18] and according to the numerical experiment

Model	*PS*	*PL*	*AC*	*SU*	*RO*	*M*	*RF*	*SMB*	*RO/M*	*RF/M*
RACMO2/GR	696	46	716*	26	248	404	202	469 ± 41	0.614	0.500
MAR	578	22	595*	5	307	580	295	288	0.529	0.509
Polar MM5	678	18	588	108	232	249	35	365	0.932	0.141
ERA-40	582	28	572*	38	285	341	84	287	0.836	0.246
Experiment 4	738	129	867	32	392	496	233	475	0.790	0.470

Note: * is calculated as *PS* + *PL* – *SU*; the other explanations are given in the text.

model ice sheet expansion to the margins of the island (mostly apparent in the south-western part) is typical of many models [24].

The process of meltwater refreezing plays a prominent role in GrIS mass balance. It varies from 0.05 on the margins to 0.75 at the elevation exceeding 2500 m (Fig. 3a). The average ratio of the refrozen water is 0.47. This value is rather close the results obtained with MAR and RACMO2/GR models (approximately 0.5, see the table) and slightly less than the conventional proportion of refrozen water (0.6), used in simplified calculation schemes [24]. The ratio of runoff in meltwater falls from the value 0.8 on the margins to 0.2 and less in the interior of GrIS (Fig. 3b). An average ratio (0.79) is intermediate among four models shown in the table. Note that in order to correctly compare absolute values of surface mass balance components, it is important to keep in mind that they are dependent on the area of the ice sheet. In particular, in experiment 4 the area of the model sheet is approximately by 15% higher than the observed one which is used in the models listed in the table.

In general, the numerical experiments proved that the climatic block of the Earth system model generated stable climatic conditions. It took approximately 20 thousands model years for the Greenland ice sheet to adapt to them irrespectively of the intensity of melting on the external margins.

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REFERENCES

1. V. A. Alekseev, E. M. Volodin, V. Ya. Galin, et al., *The Modeling of Present-day Climate Using Atmospheric Model of INM RAS*, Preprint of INM No. 2086-B98 (INM, Moscow, 1998) [in Russian].
2. V. V. Alekseev and V. B. Zalesny, "The Numerical Model of the Large Scale Dynamics of the Ocean," in *Computational Processes and Systems*, Ed. by G. I. Marchuk (Nauka, Moscow, 1984), No. 10.
3. A. V. Bagno, R. V. Garaschyuk, and V. B. Zalesny, "A Model of the Large-scale Ocean Circulation and Sea Ice Evolution," Okeanologiya, No. 2, **36** (1996) [Oceanology, No. 2, **36** (1996)].
4. E. M. Volodin and N. A. Diansky, "Responce of a Coupled Atmosphere–Ocean General Circulation Model to Increased Carbon Dioxide," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 2, **39** (2003) [Izv. Atmos. Ocean. Phys., No. 2, **39** (2003)].
5. E. M. Volodin and V. H. Lykossov, "Parameterization of Heat and Moisture Transfer in a Soil-vegetation System for Use in Atmospheric General Circulation Models. 1. Formulation and Simulations Based on Local Observational Data," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 4, **34** (1998) [Izv. Atmos. Ocean. Phys., No. 4, **34** (1998)].
6. V. Ya. Galin, "Parameterization of Radiative Processes in the DNM Atmospheric Model of INM," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 3, **34** (1998) [Izv. Atmos. Ocean. Phys., No. 3, **34** (1998)].
7. N. A. Diansky, A. V. Bagno, and V. B. Zalesny, "Sigma-model of Global Ocean Circulation and Its Sensitivity to Variations in Wind Stress," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 4, **38** (2002) [Izv. Atmos. Ocean. Phys., No. 4, **38** (2002].
8. N. A. Diansky and E. A. Volodin, "Simulation of Present-day Climate with a Coupled Atmosphere–Ocean General Circulation Model," Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 6, **38** (2002) [Izv. Atmos. Ocean. Phys., No. 6, **38** (2002].
9. O. O. Rybak and E. M. Volodin, "Applying the Energy- and Water Balance Model for Incorporation of the Cryospheric Component into a Climate Model. Part I. Description of the Model and Computed Climatic Fields of Surface Air Temperature and Precipitation Rate," Meteorol. Gidrol., No. 11 (2015) [Russ. Meteorol. Hydrol., No. 11, **40** (2015)].
10. O. O. Rybak, E. M. Volodin, and A. P. Nevecherja, "Geothermal Heat Flux in Greenland and Its Influence upon the Model Ice Sheet Topography," Led i Sneg, No. 4, **55** (2015) [in Russian].
11. O. O. Rybak, E. M. Volodin, A. P. Nevecherja, and P. A. Morozova, "Applying the Energy- and Water Balance Model for Incorporation of the Cryospheric Component into a Climate Model. Part II. Modeled Mass Balance on the Greenland Ice Sheet Surface," Meteorol. Gidrol., No. 6, **41** (2016) [Russ. Meteorol. Hydrol., No. 6, **41** (2016)].
12. O. O. Rybak, E. M. Volodin, A. P. Nevecherja, et al., "Calculation of Mass Discharge of the Greenland Ice Sheet in the Earth System Model," Led i Sneg, No. 3, **56** (2016) [in Russian].
13. N. G. Yakovlev, "Coupled Model of Ocean General Circulation and Sea Ice Evolution," Izv. Akad Nauk, Fiz. Atmos. Okeana, No. 3, **39** (2003) [Izv. Atmos. and Oceanic Physics, No. 3, **39** (2003)].
14. J. Adem, "Numerical Simulation of the Annual Cycle of Climate during the Ice Ages," J. Geophys. Res., **86** (1981).
15. A. Arakawa and V. Lamb, "Computational Design of the Basic Dynamical Processes of the UCLA General Circulation Model," in *Methods in Computational Physics*, Ed. by J. Chang, Vol. 17 (Academic Press, San Francisco, 1977).
16. J. L. Bamber, S. Ekholm, and W. B. Krabill, "A New, High Resolution Digital Elevation Model of Greenland Fully Validated with Airborne Laser Altimeter Data," J. Geophys. Res., **106** (2001).
17. A. K. Betts, "A New Convective Adjustment Scheme. Part I. Observational and Theoretical Basis," Quart. J. Roy. Meteorol. Soc., **112** (1986).
18. J. Ettema, M. R. van den Broeke, E. van Meijgaard, and W. J. van de Berg, "Climate of the Greenland Ice Sheet using a High-resolution Climate Model. Part 2: Near Surface Climate and Energy Balance," The Cryosphere, **4** (2010).
19. R. S. Fausto, A. P. Ahlstrom, D. van As, et al., "A New Present-day Temperature Parameterization for Greenland," J. Glaciology, **55** (2009).

20. W. L. Gates, "The Numerical Simulation of Ice-age Climate with a Global General Circulation Model," J. Atmos. Sci., **33** (1976).
21. C. O. Hines, "Doppler Spread Parameterization of Gravity Wave Momentum Deposition in the Middle Atmosphere, Part 2: Broad and Quasimonochromatic Spectra, and Implementation," J. Atmos. and Solar-Terrestrial Phys., **59** (1997).
22. P. Huybrechts, "Sea-level Changes at the LGM from Ice-dynamic Reconstructions of the Greenland and Antarctic Ice Sheets during the Glacial Cycles," Quart. Sci. Rev., **21** (2002).
23. T. N. Palmer, G. J. Shutts, and R. Swinbank, "Alleviation of a Systematic Westerly Bias in General Circulation and Numerical Weather Prediction Models through an Orographic Gravity Wave Drag Parameterization," Quart. J. Roy. Meteorol. Soc., **112** (1986).
24. A. Robinson, R. Calov, and A. Ganopolski, "An Efficient Regional Energy-moisture Balance Model for Simulation of the Greenland Ice Sheet Response to Climate Change," The Cryosphere, **4** (2010).
25. K. M. Terekhov, E. M. Volodin, and A. V. Gusev, "Methods and Efficiency Estimation of Parallel Implementation of the -model of General Ocean Circulation," Russ. J. Numer. Analysis and Mathematical Modelling, No. 2, **26** (2011).
26. M. van den Broeke, J. Bamber, J. Ettema, et al., "Partitioning Recent Greenland Mass Loss," Science, **326** (2009).