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Numerical experiments on paleoclimate modeling

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Numerical experiments on paleoclimate modeling

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Abstract. The influence of climatic parameters (values of CO_2 concentration in the atmosphere, solar constant), the configuration of continents, as well as the distribution of the depths of the World Ocean, characteristic of the time periods under consideration, on the climate is investigated. A global climate model is used, including a model of three-dimensional thermohaline circulation of the ocean, an energy-moisture balance model of the atmosphere and a model of the sea ice evolution. Numerical experiments have been carried out to model the climate corresponding to the periods 120.4 million years ago and 200 million years ago with sharply different parameters. The first interval was characterized by high CO_2 concentrations and a continent lying in meridional direction. During the second interval a super continent was located in the Northern polar region extending to the South but not reaching the South Pole. Calculations show that the average global climatic characteristics achieve to a stationary regime during about 1500-2000 years. The main global and spatial climatic characteristics for the atmosphere, ocean, and sea ice are obtained. The estimated average global atmospheric temperature falls within the limits reconstructed from observations. The features of ocean circulation for the corresponding periods are studied.

1. Introduction

Geological data indicate that in the Earth history [1], supercontinents have repeatedly appeared in different epochs, divided into separate continents that drifted apart from each other, and associated into new supercontinents [2, 3].

In this paper, the influence of climatic parameters (the atmosphere CO_2 concentration, the solar constant), as well as the continents configuration and the ocean depths distribution is investigated for the time periods under consideration on the climate.

The relatively late stages of evolution are considered so that more or less accurate data of the solar constant, the CO_2 concentration and continents configuration could be used [4, 5]. Two time intervals of the Earth's evolution with the most different structure of continents and oceans were selected for climate assessment calculations. The first interval, 120.4 million years ago, was characterized by high CO_2 concentrations and a continent lying in meridional direction [6]. During the second interval, 200 million years ago, a super continent was located in the Northern polar region extending to the South but not reaching the South Pole. At the same time, the continent is located on the site of the modern Arctic Ocean, and the ocean is located on the site of Antarctica [6]. This situation should lead to the formation of a climate and oceanic circulation significantly different from modern ones. The data used is given on the website https://www.odsn.de/odsn/services/paleomap/paleomap.html.

The study is based on the 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 [7, 8].

2. The climate model description and results of modelling

The system of the ocean model equations is considered in the geostrophic approximation with a frictional term in the horizontal momentum equations [8 - 10]. The values of temperature and salinity satisfy advection-diffusion equations, which makes it possible to describe the thermohaline circulation of the ocean. The convective adjustment procedure is also taken into account.

The zero normal flow condition is required at all solid boundaries. At the borders of continents, the normal components of heat and salt fluxes are also assumed to be zero. The ocean is exposed to the friction stress of the wind at the surface. The fluxes of heat and salinity at the bottom are assumed to be zero, and on the surface are determined by interaction with the atmosphere.

The equations are discretized on the Arakawa grid [11] using simple central space differences for diffusion and a scheme with upstream weights for advection. At each time step, the velocity field is determined diagnostically from the density field. Mathematical and numerical modeling is a powerful tool for studying the climate system and predicting climate change. Modern modeling is carried out using powerful software tools, including domestic ones, for example, to solve the problems of unsteady gas dynamics of multicomponent gas by various numerical methods [12 - 14].

The model vertical levels are uniformly spaced in the logarithmic coordinate so that the upper layers are thinner. The horizontal grid is uniform in longitude and in sine of latitude (giving boxes of equal area in physical space). There are 8 density vertical levels on a logarithmically stretched grid with vertical spacing increasing with depth from 140 m to 1120.4 m. The maximum depth is set to 5000 m.

The energy - and moisture-balance model is used to describe the processes occurring in the atmosphere. Prognostic variables are air temperature and specific humidity near the surface. The vertically integrated equation for air temperature, which determines the balance of incoming and outgoing radiation fluxes, explicit (turbulent) exchanges of heat flows with the surface, the release of latent heat due to precipitation and simple single-layer parameterization of horizontal transfer processes is solved in the model [15]. The sources in the transport equation for specific humidity are determined by precipitation, evaporation and sublimation from the underlying surface.

Dynamic equations for sea ice compactness and average ice thickness are solved in the sea ice evolution model [6, 10, 14, 15]. To determine the temperature of the ice surface, a diagnostic equation is used taking into account heat flows. The growth and melting of sea ice in the model depend only on the difference between the heat flow from the atmosphere to the sea ice and the heat flow from the ice to the ocean.

The rate of sea ice growth in the part of the ocean covered by ice is determined from the difference in heat flows to sea ice and back, minus latent heat losses due to sublimation. Snow formation is not considered in the model, all precipitation over the ocean or sea ice is added directly to the surface layer of the ocean, but the presence of snow on land is taken into account by changing the albedo of the surface.

The following variants of numerical experiments were carried out using the model described above:

1) for modern climatic conditions,
2) for the period 120.4 million years ago,
3) for the period 200 million years ago.

The values of the main parameters (CO_2 concentration and solar constant) in the simulation are presented in table 1, based on the reconstruction results of the values of climatic and astronomical factors (www.geocraft.com). Note that for a period of 120.4 million years, two calculation options are considered: with a CO_2 concentration of 3000 ppm (which corresponds to that period) and a modern CO_2 concentration of 350 ppm to assess the effect of increased CO_2 concentration.

Table 1. Values of the main parameters during modeling.

	Modern conditions	120.4 million years ago	120.4 million years ago (CO_2=1)	200 million years ago
CO_2 concentration (ppm)	350	3000	350	1225
Solar constant (W)	1368	1140	1368	1330

Calculations are carried out from the initial state of the climate system, characterized by homogeneous values of temperature, humidity, salinity and zero current velocities in the ocean. The output to the stationary mode is considered.

Calculations show that the average global climatic characteristics achieve a stationary regime during about 1500-2000 years. The average global atmosphere temperature and sea ice thickness for different calculation options are shown in figure 1.

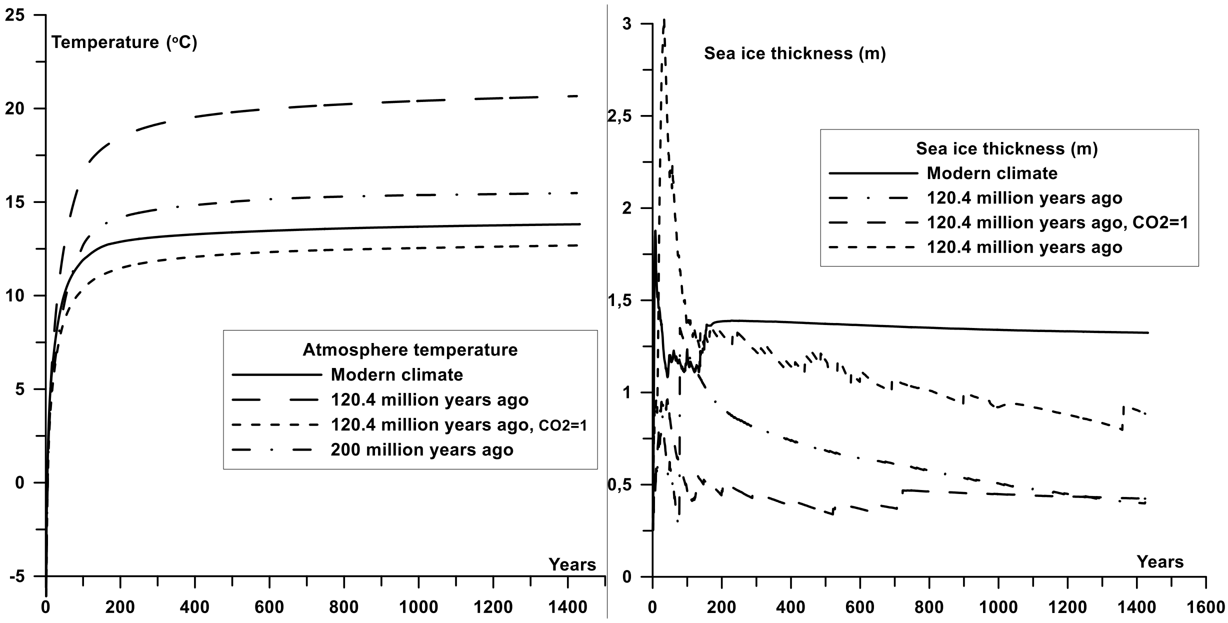

Figure 1. Average global atmosphere temperature (°C) and global sea ice thickness (m) for different calculation options emissions.

Some calculated global average climatic characteristics of a stationary regime are given in table 2.

Table 2. Global averages of some calculated climatic characteristics.

	Modern conditions	120.4 million years ago	120.4 million years ago (CO_2=1)	200 million years ago
Atmospheric temperature (°C)	13.4	20.7	12.7	15.5
Atmospheric humidity (g/kg)	0.011	0.016	0/010	0.011
Sea ice thickness (m)	1.32	0.11	0.19	0.88
Sea ice area (number of mesh cells)	45	1	6	11

We note a significant increase in global temperature (by 7.3°C), an increase in atmospheric humidity by 50% and the almost complete disappearance of sea ice for the variant 120.4 million years ago compared to the current state of the climate system. Of course, this is due to the increased concentration of carbon dioxide. The results show high July temperatures in the northern polar regions (15-25 ^{o}C) for variants 120.4 million and 200 million years ago. This is connected with both the presence of the continent up to the North Pole and the increased CO_2 concentration. Table 3 shows a satisfactory agreement of the global calculation results with the observations data and reconstruction of paleoclimate characteristics for the corresponding periods (www.geocraft.com). There are no more detailed geographical characteristics of the climate for remote periods of history, or they give a large range of values.

Table 3. Global average atmospheric temperature (^{o}C).

	Modern conditions	120.4 million years ago	200 million years ago
Calculation results	13.4	20.7	15.5
Experimental (reconstructed) data	13.8	22	17

The original procedure for determining the wind velocities field from the atmosphere temperature field, based on the geostrophic approach, taking into account the thermal component of the wind, and introducing the mechanism of friction on the underlying surface is used. This method allows in general describe the wind speeds field depending on the state of the climate system.

The atmosphere temperature distribution near the surface and the barotropic (i.e. depth-averaged) stream function are shown further on the world maps for different calculation options. Continents are highlighted in uniform gray. The atmosphere temperature distribution near the surface are shown for the month of January in figures 2, 3.

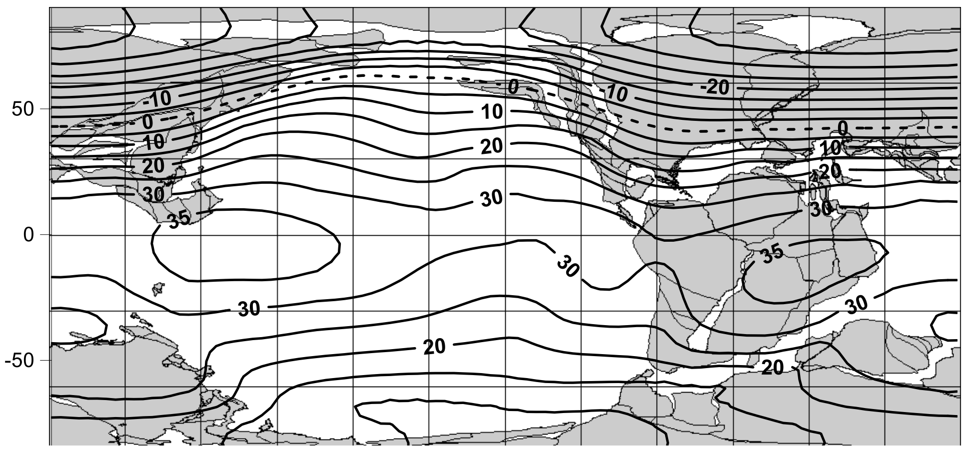

Figure 2. Atmosphere temperature distribution (^{o}C) (120.4 million years ago), January.

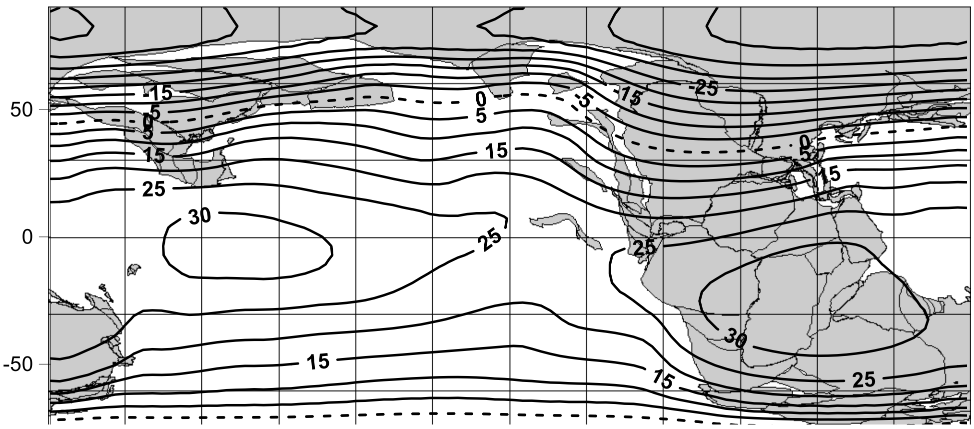

Figure 3. Atmosphere temperature distribution (°C) (200 million years ago), January.

We can highlight the strong influence of the increased CO_2 concentration for the 120.4 million year ago case – the temperature increase in the equatorial region of the ocean reaches 8 °C. The barotropic stream function in Sv (1 Sv =10^6 m^3) is shown in figures 4, 5 for various calculation options for the month of July.

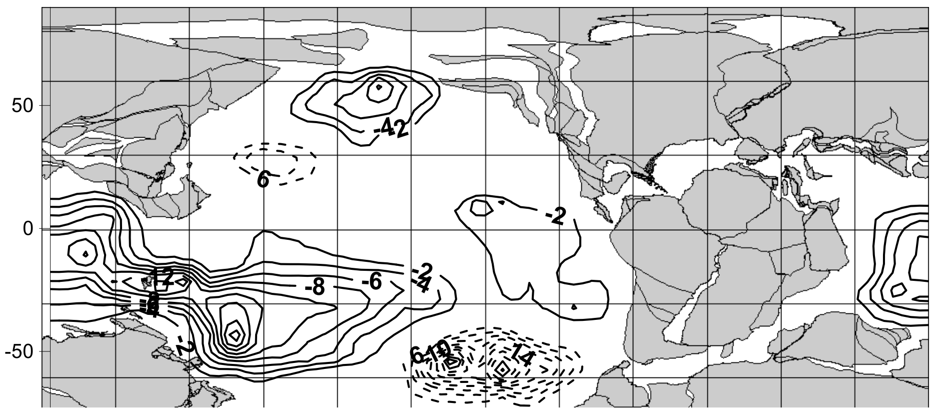

Figure 4. Barotropic stream function (120.4 million years ago), July.

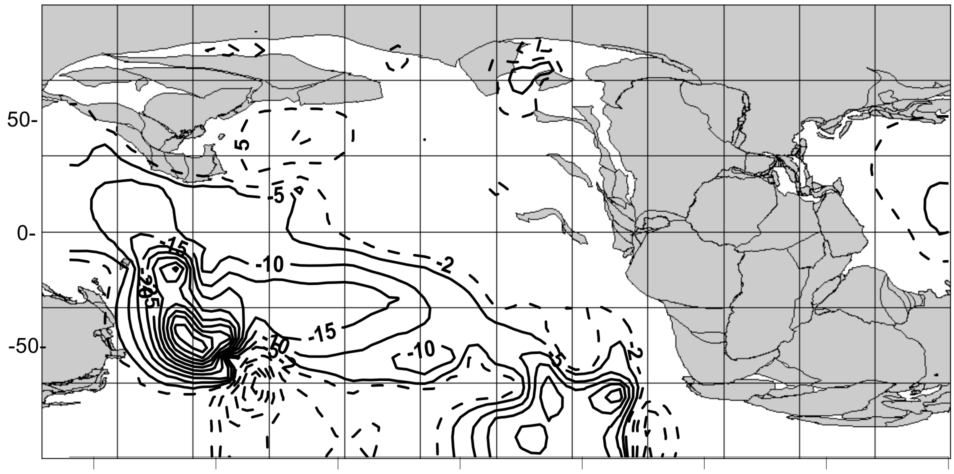

Figure 5. Barotropic stream function (200 million years ago), July.

Very strong differences in ocean circulation are observed for all three main calculation options. This is due to completely different configurations of continents and the distribution of ocean depths. There is a strong positive circulation in the southern hemisphere in the area of the southern mainland and an extended negative circulation in the western part of the ocean for the 120.4 million year ago variant. Circulation in the northern part is rather weak. Suppressed circulation is observed in the northern region of the World Ocean and a rather complex picture in the southern region for the 200 million year ago variant.

The meridional stream function is presented for various calculation options in figures 6 and 7. The vertical section of the World Ocean along the corresponding meridians is shown in these figures. The vertical scale corresponds to the numbers of the ocean grid points, and horizontally to the latitude of the grid points from the South Pole to the north. The variants 200 million years ago and 120.4 million years ago show a similar pattern of meridional global circulation, but more intense circulation near the south pole is manifested in the variant 200 million years ago in the absence of the southern continent.

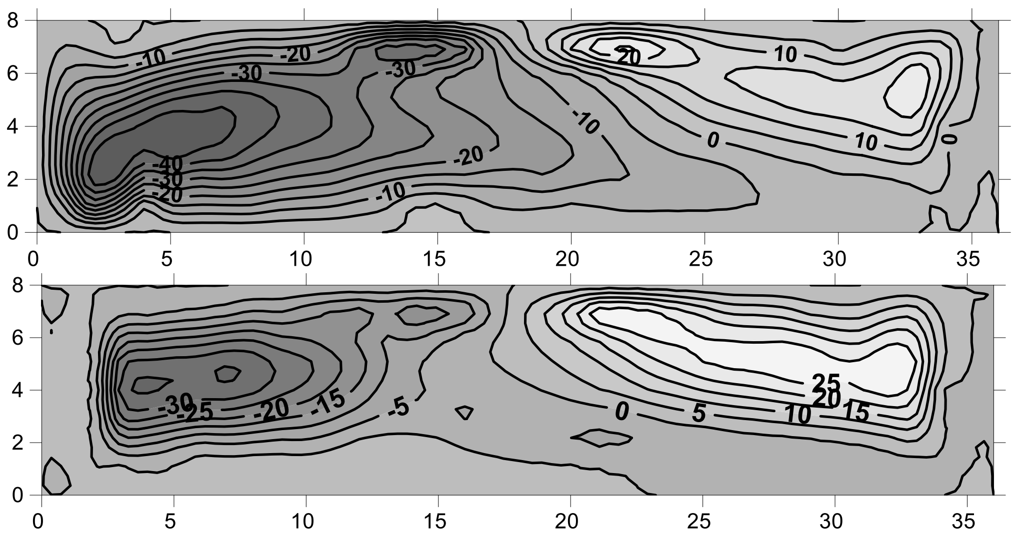

Figure 6. Meridional global stream function: 200 million years ago (top), and 124 million years ago (bottom), July.

Analysis of the season influence on the meridional global stream function for the variant 200 million years ago shows that the difference in January and July flows reaches 8 Sv in low latitudes.

The water area of the World Ocean, located in isolation in its western parts (the western ocean), occupies a zonally limited area at low latitudes (figure 7), therefore, the meridional circulation there is poorly developed. It is mostly positive for the variant 200 million years ago and negative for the variant 120.4 million years ago. This is explained by the predominant location of the ocean in the northern hemisphere in the first case and in the southern hemisphere in the second.

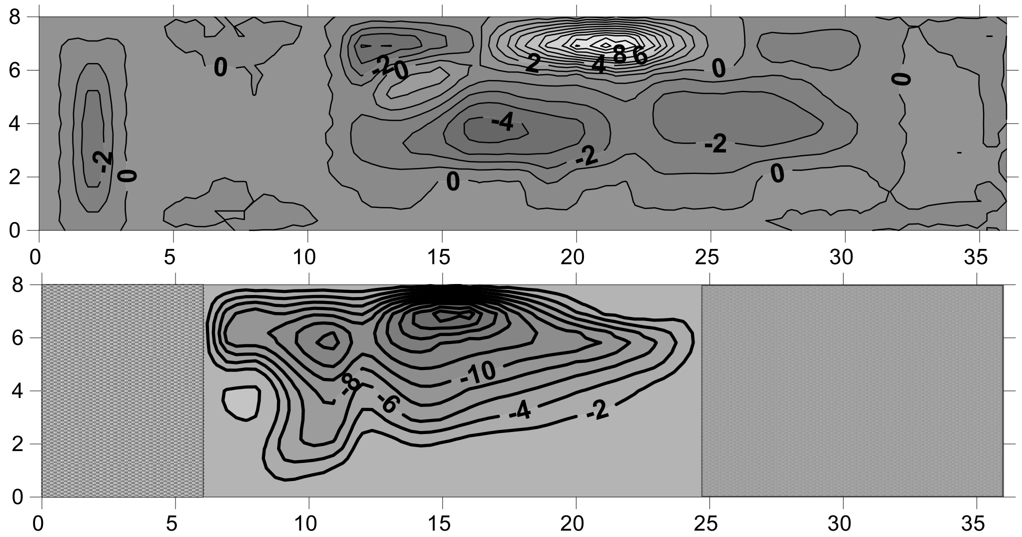

Figure 7. Meridional global stream function: 200 million years ago (top), and 124 million years ago (bottom). Western Ocean, July.

3. Conclusions

A modification of the global climate model has been implemented, including a model of three-dimensional thermohaline circulation of the ocean, an energy-moisture balance model of the atmosphere and a model of the evolution of sea ice for calculations on modeling the paleoclimate corresponding to the periods 120.4 million years ago and 200 million years ago. Studies have been carried out to determine the main parameters of the climate system for these periods.

Numerical experiments were carried out to simulate the climate 120.4 million years ago and 200 million years ago. Calculations show that the average global climatic characteristics achieve a stationary regime during about 1500-2000 years. Global and spatial characteristics, the main climatic features for the atmosphere, ocean, and sea ice are obtained. The estimated average global atmospheric temperature falls within the limits reconstructed from observations. The features of ocean circulation for the corresponding periods are studied.

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