Combined atmosphere–biosphere–soil–ocean model to study climate of Siberia

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Climate changes caused by natural and anthropogenic factors are the result of complicated nonlinear relations of physical, chemical, and biological processes in the atmosphere, ocean, and the Earth surface. Since the investigation of a climate system is in seeking explanations of the climate variation over a period from one year to centuries, the main attention is given to the study of mechanisms of interaction between the above pointed subsystems of a climate system. In this paper we describe a concept of the development of a climate system model to investigate global climate and climate in Siberia based on the results obtained recently in the Department of Mathematical Simulation in Atmospheric Physics, Ocean, and Environmental Problems of the Institute of Computational Mathematics and Mathematical Geophysics SB RAS.

Introduction

The problem on estimating the effect of climate changes on the development of the biosphere and humankind is, on the whole, the primary problem of modern science. Importance of solution of this problem is determined by the necessity of choosing a strategy for the further development while preventing global and regional climate and ecological catastrophes.

Among most essential regional manifestations of the global climate changes in Siberia we can point out the following:

- transformation of the hydrological cycle in the region including the variation of the run-off for great Siberian rivers and the conditions of Large Vasyugan marshes;
- variation of permafrost zones and, as a result, the growth of methane emission into the atmosphere;
- raise of the ocean level and possible disastrous consequences for the region which are connected with this event;
- variation of ice content of the Arctic seas and variation, in this connection, of the global cycle of fresh water.

Investigations that are carried out at the Institute of Computational Mathematics and Mathematical Geophysics SB RAS are aimed at the study of climate changes on the global and regional scales, which can occur in Siberia. Vast experience in solving complicated problems of geophysical hydrodynamics, to which the problems of study of the Earth's climate change relate, has been compiled at the Institute. Numerical models of circulation for the atmosphere and ocean which describe adequately the complicated nonlinear dynamics of atmospheric and oceanic processes and the methods for adoption of observation data and verification of models have been developed.

The basic purposes of investigations can be formulated as two problems:

- determination and estimation of regional manifestations of the global climate changes in Siberian region;
- selection and estimation of possible effects of the regional peculiarities on the global climate.

Current investigations are based on mathematical models, including the combined model of circulations in the atmosphere, ocean, and land, the boundary layer model, the models of transfer and transformation of impurities in the atmosphere and ocean, and also the class of models giving the estimations of the effect of climate changes on different components of ecological system in Siberia.

At present there is a sufficiently wide class of combined climate models that are used in practice. The most known models are the model of the USA National Center for Atmospheric Research,[1] model of the Max Planck Institute for Meteorology and the University of Hamburg,[2] and also the model of the Institute of Computational Mathematics of RAS[3] and the Main Geophysical Observatory.[4]

Global models of circulation are used for simulating the climate, as well as to investigate the effect of the external factors on climate changes on different time scales, to study an inverse effect on the atmosphere from the underlying surface covered with ice, vegetation, etc. Nevertheless, they have a number of restrictions of their applicability, which are connected with the insufficient resolution of regional peculiarities. One of the approaches, which allow one to overcome these difficulties, is the simulation of regional climate. Spatial resolution in regional models of a climate is increased so that it is possible to describe explicitly the mesoscale phenomena, which are caused by the mesoscale peculiarities of the underlying surface of a region. At the side boundaries the results of global analysis of observations or the data of numerical simulation of the general circulation of the atmosphere are used to formulate the boundary conditions. The use of data of the global analysis is preferable, since in this case the large-scale errors of simulation will be eliminated. The idea of the regional simulation has been developed[5] and has found its application to investigations of the regional climate in Europe[6] and Arctic region.[7]

1. Model of climate system

The climate changes, which are natural or caused by the anthropogenic factors, are the result of complicated nonlinear relations of physical, chemical, and biological processes in the atmosphere, ocean, and the Earth's surface. Since the investigation of a climate system is in seeking explanations of the climate variation over a period from one year to centuries, the main attention at present should be given to the study of mechanisms of interaction between physical, chemical, and biological subsystems.

1.1. Model of the atmosphere

At present, an attempt is undertaken to develop a global combined model based on the model of the atmosphere developed at the Institute of Computational Mathematics (ICM) of RAS and the model of biosphere of the Earth's surface developed at ICM&MG SB RAS. In this case, the main attention is given to a parameterization of the physical processes on the subgrid scales. The first results of realization of this project have been presented in Ref. 8. Description of the model of the general circulation of the atmosphere of the ICM RAS and the results of simulation of the global climate in 1979–1995 under the Atmospheric Model Intercomparison Project AMIP-II, the model has participated in, are represented in Ref. 3. To simulate the global climate the data on the ocean surface temperature and the distribution of marine ice for the same period are used. The diurnal and seasonal motion of the Sun is taken into account. The concentration of greenhouse gases in the atmosphere is fixed.

1.2. Models of biosphere on the Earth's surface

Models of biosphere on the Earth's surface are one of the basic components of a climate system. At present the models of the exchange between the atmosphere and the Earth's surface such as in Refs. 9, 10, 11 are widely known. The models of the Earth's surface provide the surface fluxes of latent heat, heat, momentum, shortwave and infrared radiation for the model of the general circulation of the atmosphere. The flows of CO_2 near the Earth's surface, which have well pronounced diurnal and seasonal cycles, are the component of the global CO_2 cycle and, therefore, the part of climate system.

1.3. Models of the ocean

Models of the ocean are the key items in developing a basic model of the climate. Ocean is an important factor affecting the climate of the Earth on time scales longer than one year. Therefore, the interannual variability that manifests itself in the rise of El-Niño phenomenon essentially depends on the wave processes of tropical ocean. Periods of interactions of the order of centuries are connected with the variations in thermodynamic structure of the World Ocean. The regional tendencies in the research propose the northern part of the Pacific Ocean and the Arctic Ocean as the water areas demanding special attention.

Ocean also is one of the basic regulators of greenhouse gases, since the hydrophysical and biochemical processes make it both the source and the sink. Thus, the ocean and its hydrochemical systems play a significant role in climate changes. Owing to this fact, the development of the models of a carbon cycle in ocean, the models of the spread of the accompanying biogeneous elements, and the models of transfer and transformation of methane are needed.

Based on all the above considerations the development of ocean models is being carried out in two research areas:

- simulation of circulation in the World Ocean and its parts;
- simulation of hydrochemical processes in the ocean.

1.4. Models of marine ice

Marine ice is an important part of a climate system. The ice of polar oceans attracts attention of climatologists for two reasons. First, the global cycle of fresh water is controlled by the processes of formation of bottom waters in the north and south Atlantics. Carrying out of ice to the low latitudes plays a basic role in this cycle. Secondly, the scenario experiments to study the response of the climate system to the increase of CO_2 show the essential warming in polar regions. The variations in the processes of ice-formation and in the hydrological cycle connected with it are to be studied in a more detail. Models of ice are presented as a two-dimensional continuum described by such variables as the thickness of ice, and snow, entirety of ice and velocity of its drift.[12] It is also important to record the internal strength in a mass of ice.

1.5. Methods of processing the data of observations and verification of models

Simulation of climate characteristics is connected with the necessity of using large arrays of observational data. In fact, the mathematical simulation in the climate problems is connected with the development of interacting model–data complexes integrated by special algorithms based on the dynamic-stochastic and variational approaches.

1.6. Organization of the climate system model (CSM)

The CSM is the system consisting of separate interacting components with the especial program block – the unitor of the combined model. The unitor organizes a versatile control over the data exchange between submodels of the atmosphere, biosphere, ice, and ocean. Such a program allows us to carry out climate studies, in parallel, calculating separate components of the system on different processors (using, for example, MPI system).

2. Simulation of the climate system components

In the present section some results of simulation for separate components of the climate system as prerequisites for the development of a combined model of a climate are presented.

2.1. Global model of the atmosphere

Description of the general circulation of the atmosphere of the ICM RAS with the results of simulation of the contemporary climate is given in Ref. 3. Its basic features and typical components are as follows:

- generalized vertical coordinate system,
- semi-implicit scheme of integration over time,
- fulfillment of the laws of conservation,
- horizontal finite-difference approximation of the system of equations,
- semi-implicit schemes of solution of equations,
- semi-Lagrangian scheme of the passive admixtures transport,
- friction by the interior gravitational waves,
- large-scale condensation,
- convection,
- radiation,
- planetary boundary layer.

2.2. Model of the Earth's surface

Biosphere models are used to estimate the effect of climate changes on ecological systems. Global system of vegetation can be divided into a set of structure types called biomes, every biome being characterized by the presence of one or several functionally dominating types. Conditions of the environment control their geographical distribution. For example, in the zone of moderate climate the duration of warm summer period and severity of winter effect on the competition between evergreen and deciduous forests. The global system of biomes together with the atmosphere and ocean is one of the most important and active components of a climate system. By certain estimations during a period of global biochemical cycle of photosynthesis during one year about 100 million tons of carbon is consumed and, approximately, the same quantity is given off due to the vegetation decay. Therefore, it is important to be able to simulate CO_2 flows to understand their influence on the greenhouse effect in the atmosphere. Except the explicit effect on the carbon cycle, a not less important effect of biochemical processes on the hydrological cycle exists.

The model is a combination of the standard model of the processes on the surface allowing for the vegetation and simple biochemical model simulating CO_2 flows inside certain biome. The global distribution of five types of surface is given: the land surface, the over-moistened parts of land, lakes and rivers, the parts covered by ice, and ocean. The data on types of the surface bioms,[13] the data on types of soil,[9] and the data on the distribution of lakes and marshland parts on continents[14] are considered as known.

2.3. Biochemical flows

Gas exchange of CO_2 between leaves and the atmosphere is the result of photosynthesis and breathing. The model of CO_2 exchange between a surface covered with vegetation and the atmosphere reproduces a natural cycle of CO_2 in the atmosphere and surface biomes. Basic processes of this cycle are the photosynthesis when the plants assimilate CO_2 coming from the atmosphere and the breathing of plants when CO_2 is emitted into the atmosphere.

To illustrate we consider the monthly average CO_2 flows (μmole/$m^2 \cdot s$) obtained using the combined model by the photosynthesis in January (1981–82) in Fig. 1*a* and in July (1981–82) in Fig. 1*b*. These figures show as the "gardening" of continents of the northern hemisphere from winter to summer occurs.

Experiments have shown a possibility of successfully simulating the CO_2 flows on the Earth's surface with the diurnal and seasonal fluctuations, which are the result of modeled interactions of the atmosphere and biosphere of the Earth's surface. In the biosphere model a set of restrictions is accepted connected with deficient data on the dynamics of vegetation cover structure and on the content of nutritious substances in soil. All this limits its applicability to the periods up to several decades. To make simulation for periods up to several centuries and more, it is necessary to include the block of dynamics of biomes allowing for the biochemical flows inside a biome and among the biomes.

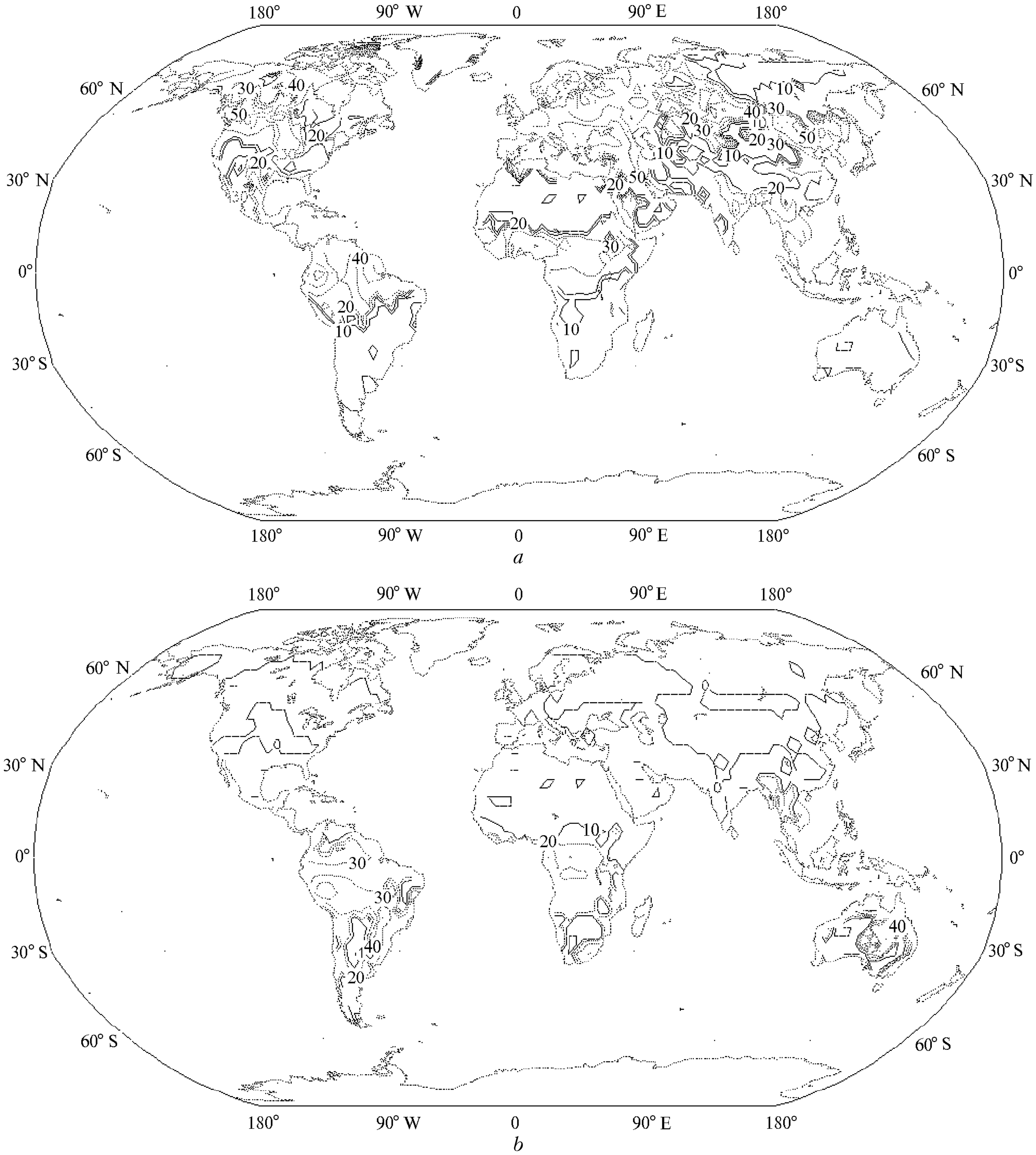

Fig. 1. Flows of CO_2 at the Earth's surface. Photosynthesis: January 1982 (*a*); July 1982 (*b*).

Methane (CH_4) is the third important atmospheric component after a water vapor and carbon dioxide, which affects the processes yielding the greenhouse effect. Systematic global observations of the atmospheric methane have shown that the global average concentration of methane in 1992 has made about 1710 ppbv and during the period from 1983 to 1992 it increased at an average rate of 0.8% per year.[15] Since CH_4 plays a significant role in the radiation transfer and photochemical reactions in the atmosphere, the increase of methane content in the atmosphere can cause intensification of the greenhouse effect.

To predict the varied levels of the concentration of atmospheric methane the qualitative and quantitative understanding is needed of its global cycle on the Earth's surface and the nature of natural and anthropogenic sources/sinks of methane. The first step in solving this problem has been a numerical simulation of the global atmospheric cycle of methane and its seasonal variability. Based on the three-dimensional transport model developed at the Laboratory of Climate Dynamics of ICM&MG SB RAS,[16] the data on methane concentration for the ground-based network of stations,[15] and the large-scale tropospheric fields of OH radical,[17] the simulation of global distribution and seasonal variability of CH_4 concentration has been carried out.

The main result of the experiment is that the given transport model allows us to interpolate sufficiently rare ground observations from stations that are distant from the continental sources and outflows of methane.

Simulation of the global distribution of methane in the atmosphere has shown that the specific peculiarity of methane distribution is the inter-latitudinal gradient directed from the north to the south with the maximum concentration of methane in the northern hemisphere. The existence of planetary gradient is an evidence of the fact that the northern peat-bog ecosystems are one of the most powerful natural sources of atmospheric methane. According to the results obtained in simulating the inter-latitudinal gradient is, on the whole, caused by the atmospheric transfer. Effect of the OH hydroxyl becomes a dominant in the lower and upper troposphere in the region of tropics.

Seasonal cycle in the model for northern hemisphere manifests itself in a doubled fall-winter maximum. Emissions from peat-bog ecosystems, which attain their maximum in September cause the first maximum in October. The oxidation of methane by the hydroxyl of OH attains a minimum during the winter months. Therefore, the doubled maximum in seasonal fluctuations of methane is caused, on the one hand, by the increase of emission during the fall and, on the other hand, by the decrease of its outflow during winter.

2.4. Simulation of regional climate in Siberia

Regional model of the atmosphere is a component of the global climate model ECSib developed at the Laboratory of Climate Dynamics of the ICM&MG SB RAS.[18] The mathematical simulation of a climate based on the global model allows us, on the whole, to obtain the qualitatively valid picture of the distribution of the basic atmospheric properties. However, the horizontal spatial resolution in the global model does not allow the fine structure of regional peculiarities to be studied in detail. In this connection, the regional model of the atmospheric dynamics that provides for better spatial resolution has been developed. On the whole, the mathematical realization of the regional model does not differ from the global one. Its specific feature is the necessity of formulating boundary conditions at the region sides providing for its sewing with the global model. The values of the evolutionary variables at the boundaries of the region under study, which are obtained from the global model with the interpolation to a more smaller-sized grid, are taken as the side-boundary conditions. The side-boundary conditions in the present version of the model present the one-sided interaction, i.e., the information from the large-scale model goes in the regional one, and the situation is not considered when the large-scale model additionally takes into account information from the regional model.

In the model of an active layer the vegetation cover, the presence of snow, and the processes in the upper soil layer are taken into account. Processes of thawing, decrease of moisture on the surface by its filtration deep into soil, the process of outflow of moisture to the surface, the inflow of moisture due to large-scale and convective precipitation and snow, the interception of precipitation by vegetation cover are also taken into account. Temperature of the surface of soil, temperature of four soil strata, turbulent heat flow from the surface, flow of heat deep into the soil, humidity of the surface of soil, moisture content in the surface layer, and the flow of moisture from surface are calculated.[19]

Experiments on studying sensitivity of the regional model of the atmosphere to an increase in the resolution and new parameterization of the interaction with the underlying surface have been carried out in the following way. Quasi-equilibrium climatic state of the atmosphere has been obtained in the beginning based on integration of the global model over a 10-year interval with the allowance for an annual variation of solar radiation.

Based on the obtained state during the last year of integration the calculation by the regional model has been done in parallel with the global model. Spatial distribution of the calculated characteristics such as surface temperature, near-ground pressure, and precipitation shows that the increase of spatial resolution and the use of improved parameterization of the processes of interaction between the atmosphere and the underlying surface allows us to obtain a more detailed picture where the regional peculiarities show more explicitly. In particular, in the regional model the islands of heat above water surfaces during the winter months (Baikal, Balkhash, and Aral) are well seen. It is not observed in the global model, since these formations are not described on the spatial resolution scale used in it (Fig. 2). It is natural, that it had an effect on the near-ground pressure, which has decreased above the areas where the regional water basins are located. In due course, it has caused a change of the overall picture of distribution of the near-ground pressure.

During summer months the picture is completely different since the contrast between the temperature of water surface and land practically vanishes. In this case the difference in reconstruction of the near-ground pressure is caused, on the whole, by dynamic factors. The use of the regional model has allowed us to reveal a more fine structure in the distribution of precipitation, humidity of soil, heat, and latent heat fluxes on the surface that is impossible within the global model. It is correspondingly reflected in the dynamics of near-ground characteristics, which demonstrate growth of mesoscale circulation.[20]

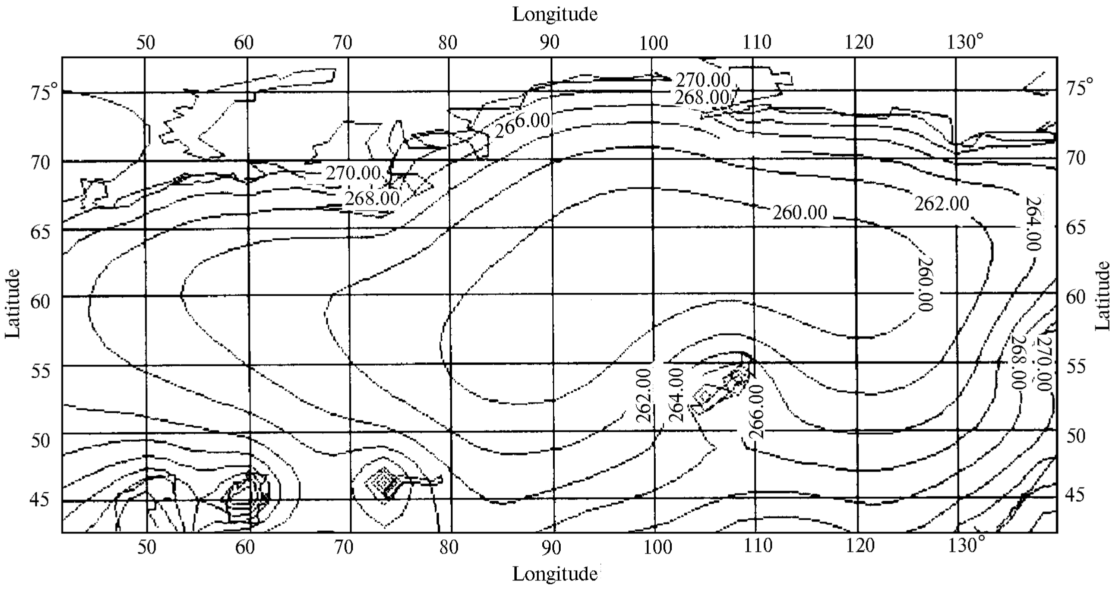

Fig. 2. Average February distribution of the surface temperature (K) calculated by the regional model.

2.5. Simulation of climate of the World Ocean and its parts

Simulation of thermodynamic processes in the ocean is a necessary component of a climate study. Regional orientation of the investigations has proposed as the basins of a particular significance the tropics of the Pacific Ocean, northern part of the Pacific Ocean, Arctic Ocean, and World Ocean as a whole. Every model can be a component of a combined climate model and will allow us to investigate the problems connected with the interaction of such climate components as the tropics of the Pacific Ocean and the global atmosphere, the World Ocean and the global atmosphere, and the Arctic Ocean and Siberian regional elements of circulation.

Basic features of the models of ocean dynamics, which have been developed at the Laboratory of Mathematical Simulation of Hydrosphere at the ICM&MG SB RAS are[21]:

- use of shifted grids for spatial variables;
- natural and reduced coordinate systems along the vertical;
- separation of barotropic and baroclinic components of motion;
- transformation of advective components of the model to a special form;
- decomposition of the equations by physical processes;
- finite-element digitization over space with the conservation of basic integrated invariants;
- coordinate-by-coordinate decomposition;
- use of implicit and semi-implicit algorithms for approximation over time;
- recording the processes in the upper quasi-homogeneous stratum.[22]

2.5.1. Simulation of circulation processes in the Pacific Ocean

The Pacific Ocean is the important component of a climate system affecting not only the adjacent regions of America and Asia, but also the global climate. One of the strongest signals of the short-periodic climate variability El-Niño–Southern Oscillation (ENSO) revealed every 3–5 years is connected with the tropics of the Pacific Ocean. Destructive atmospheric consequences of this phenomenon are: downpours, floods, and droughts.

Simulating the processes connected with the El-Niño phenomenon and the interdecade climate variability in the Pacific Ocean especial attention is given to the quality of numerical models of the ocean circulation.[23,24]

To investigate a climate of the Pacific Ocean and its variability a three-dimensional model of circulation in the northern part of the Pacific Ocean including tropical zone has been developed.[25]

Based on the model the diagnostics and short-period prognostic calculations to determine the climatic circulation of the Pacific Ocean have been carried out. The results obtained confirm the correctness of the description by the model of basic circulation systems and their fluctuations in a climatic annual variation.

At the same time, the study of the climate variability connected with the processes in the Pacific Ocean requires the models to provide for correct description of wave tropical dynamics and sensitivity of circulation in the extra-tropical zones. The purpose of further experiments is in estimation of the adequacy of a response of the model to the actual atmospheric events corresponding to the period of El-Niño. During the experiment, the data of reanalysis of European Center for Medium-Range Weather Forecasts (ECMWF) have been used. The calculated results show that in 1982 warm temperature anomaly formed during the El-Niño phenomenon in the ocean under the effect of atmospheric actions in the equatorial zone; it was transported at the level of thermocline to the east periphery of the Pacific Ocean reaching the near-surface layers in November–December 1982 that corresponds in observations to the maximum phase of El-Niño.

Figure 3 presents the experimental results showing the adequacy of the model description of the tropical dynamics of the Pacific Ocean.

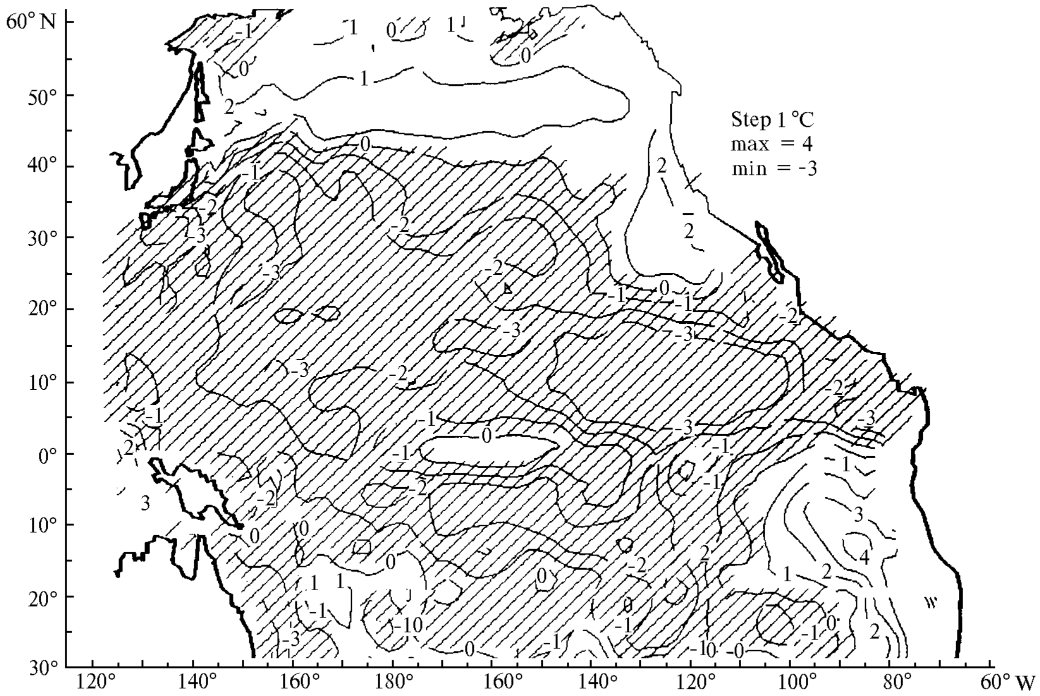

Fig. 3. Temperature of the surface of the Pacific Ocean (°C) calculated by the model. December 1982.

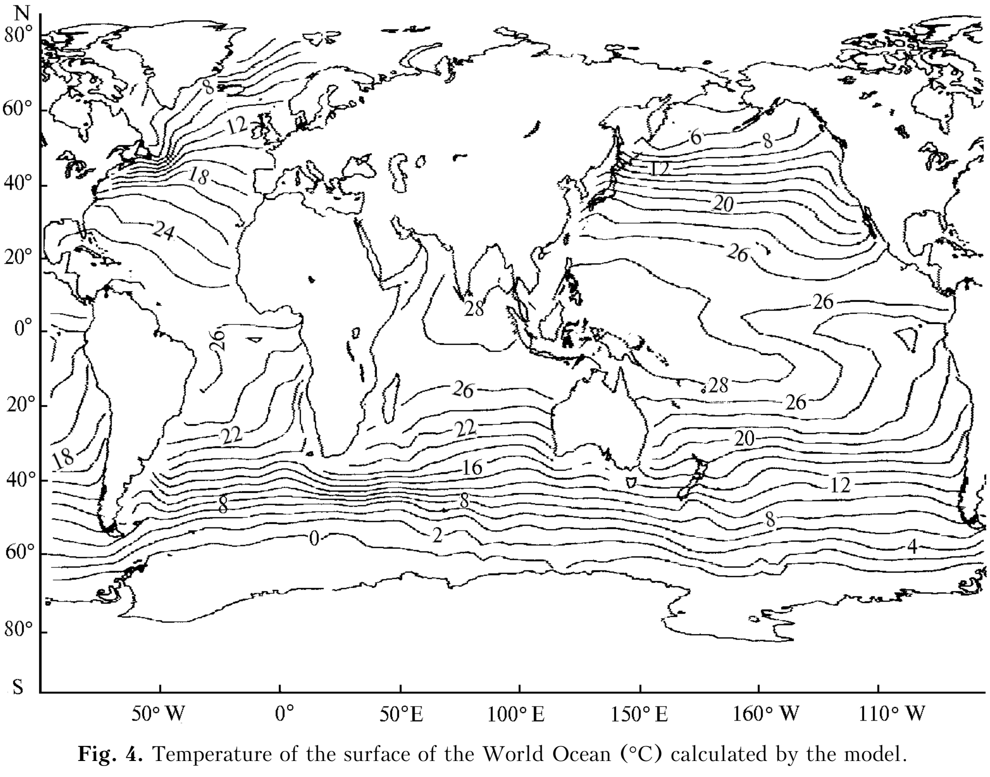

Fig. 4. Temperature of the surface of the World Ocean (°C) calculated by the model.

2.5.2. Simulation of climate for the World Ocean

Investigation of circulation of the World Ocean based on the global models and improvement of the monitoring of ocean need for understanding the climate variability. In the investigations presented the model of dynamics of the World Ocean developed at the Laboratory of Mathematical Simulation of Hydrosphere at the ICM&MG SB RAS has been used.

The purpose of the experiment was to obtain the climatic thermodynamic structure of the World Ocean. As an external action on the ocean surface the seasonal variation of climate characteristics has been taken. Based on the model the numerical experiments have been carried out for 3000 years of model time starting from a quiescent state at a constant temperature and salinity. In analyzing the results, special attention has been given to the quality of reconstruction by the model of the surface temperature and salinity, total structure of intermediate and depth water masses and circulation of the ocean waters. The obtained distribution of hydrophysical fields is typical for the large-scale models and reflects the basic characteristics of the dynamics of the World Ocean (Fig. 4). This conclusion is confirmed by a detailed comparison with results that have been the calculated based on the model developed at the Geophysical Fluid Dynamics Laboratory of Princeton University under the identical input conditions and integration time.

2.5.3. Simulation of hydrochemical processes in the World Ocean

As was pointed earlier, the hydrochemical processes in the World Ocean can essentially affect gas composition of the atmosphere. One of the gases intensifying the greenhouse effect is methane. As the investigations of recent decades have shown large reserves of methane as gas hydrates are concentrated in the World Ocean. Variation of the thermal state of ocean can cause destabilization of the methane hydrates with a consequent output of CH_4 into the atmosphere.

In connection with this problem, a model of propagation of the dissolved gases in the World Ocean has been developed at the ICM&MG. This model in a combination with the circulation model has allowed us to carry out the scenario experiments for the probable emission of gas hydrates from shelf into the atmosphere.

Based on the model the numerical experiment on simulation of the response of the World Ocean to the warming of surface waters was carried out. The short-term increase of surface temperature with the period of 100 years creates conditions for possible decomposition of methane hydrates. If the methane hydrates are present in a sufficient amount at the surface of the continental slopes and bottom, their decomposition can start practically simultaneously with the beginning of warming.

Increase of the surface temperature causes the long, on a period more than 1200 years, saturation of waters of the World Ocean with the dissolved methane. Methane hydrates of Greenland Sea, Newfoundland banks, western continental slope of Southern America, and Antarctic continental slope at the longitude of Australia undergo the strongest thermal action that is connected with the peculiarities of ocean streams.

Conclusion

Siberian region described by the large spatial scales is the climatic zone with the continental and strong continental climate in its central part. A consequence of this peculiarity can be the fact that the Earth's climate change on the global scale will manifest themselves in a certain manner in the given region, causing the changes of typical regional components of climatic cycle. On the other hand, an active use of resources of Siberia, Far East, and Arctic region including the Siberian shelf with the accompanying processes of deforestation, drainage of bogs over vast areas, and pollution of air and coastal waters of the Pacific and Arctic oceans can manifest themselves in the global variations of a climate system.

Basic causes of the global climate change are determined by the annual balance of heat received by the planet, its distribution in space, and seasonal distribution of this balance.

All factors acting on the climate are interconnected and their complicated nonlinear interaction can only be estimated based on the complex simulation with the use of combined climate models.

In this paper the concept of the development of a climate system atmosphere–biosphere–soil–ocean and some results of mathematical simulation of thermodynamic and biochemical processes in components of the system are presented. Results of the simulations, which have been carried out for every component of a climate system, allow us to draw a conclusion on the adequacy of the description of the characteristics simulated. This fact creates prerequisites for further integration of blocks of the combined climate model to study the climate of Siberia.

Acknowledgments

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