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Some Results of Studies in the Area of Numerical Weather Prediction and Climate Theory in Siberia

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Abstract—The results of studies in the area of numerical weather prediction and climate theory are presented. These results were obtained by the team of researchers of the Siberian school of mathematical modeling of atmosphere and ocean dynamics established by academician G.I. Marchuk. Academician V.P. Dymnikov played an enormous role in the development of this school by enriching it with new approaches and ideas. His contribution to the Siberian school of mathematical modeling was most strongly pronounced concerning three problems: numerical weather prediction for the Siberian region, the modeling of the climate system dynamics, and the mathematics and theory of climate.

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1. INTRODUCTION

Physical and mathematical models are the main instrument for studying the general atmosphere and ocean circulation and climate change as well as for the weather prediction of various scales and lead times. The research areas provided by the Siberian school of mathematical modeling of atmosphere and ocean dynamics were founded by academician G.I. Marchuk. The following problems are considered: the creation, improvement, and analysis of mathematical models of atmosphere and ocean dynamics based on the modern methods of applied mathematics and theory of differential equations; the elaboration and development of schemes for the parameterization of physical processes (stochastic physics, turbulent diffusion, interaction with the underlying surface, condensation and convection, cloud formation and precipitation, radiation); the creation of data assimilation systems on various scales; ensemble prediction and predictability.

The significant contribution to the development of each of these areas was made by V.P. Dymnikov. His first papers dealt with the development of effective numerical methods and physical parameterizations for creating the weather prediction models which were implemented to the operational practice of the Hydrometeorological Service of Western Siberia and provided high-quality weather forecasting. These papers formed a base for the development and implementation of the next generation of the forecasting system with a higher resolution and with the more detailed description of physical processes in the atmosphere.

For many years, V.P. Dymnikov supported research works carried out in the Laboratory of Mathematical Modeling of Atmosphere and Hydrosphere Processes of the Institute of Computational Mathematics and Mathematical Geophysics (ICMMG) of Siberian Branch of Russian Academy of Sciences (SB RAS). In the early 2000s, he called attention of the laboratory specialists to a number of interesting scientific problems which arise due to the increasing role of polar-latitude processes in the terrestrial climate system. In particular, he recommended to consider the problems of the Arctic Ocean water and ice climatic variability modeling and of studying the propagation of freshwater of Siberian rivers in the global ocean circulation system. During the recent decades, international research teams have focused on these issues. The numerical model of ocean and sea ice developed in ICMMG has been actively used in the FAMOS/AOMIP international project (Forum for Arctic Modeling and Observational Synthesis, http://web.whoi.edu/famos/) whose objective is to elaborate the coordinated approach that combines numerical simulation, theoretical studies, and to analyze data characterizing climate processes in the Arctic.

The experience gained by the Siberian school allows the studies associated with the development and improvement of physical and mathematical models for investigating the physical mechanisms of multiscale processes of weather and climate formation.

2. NUMERICAL WEATHER PREDICTION FOR THE SIBERIAN REGION

Hydrodynamic models for short-range weather forecasting have been implemented to the operational practice of Western Siberian Administration of Hydrometeorological Service since 1962. When the use of simplified equations of atmospheric hydrothermodynamics ran its course, it became clear that the further progress in the area of numerical weather prediction was associated with the development of primitive equations of hydrothermodynamics describing atmospheric processes. In 1971, a new hydrodynamic weather forecasting model appeared in the Western Siberian Administration of Hydrometeorological Service [10, 12, 14, 15, 39]. It was created in the Computing Center of Siberian Branch of Academy of Sciences of the USSR and was implemented in the Western Siberian Regional Research Hydrometeorological Institute by the team of specialists led by the head of division V.P. Dymnikov. This model called DIABAT became a base for the operational system of calculation of the numerical forecast of meteorological parameters. It was succcesfully used in the Western Siberian Regional Hydrometcenter [14, 15], and its accuracy was not lower than for the best global schemes. This forecasting technology was developed further [24] due to the growth of computational resources and according to new requirements the most important of which were the improvement of quality of prediction of meteorological parameters and the extension of the range of predicted parameters. At the initiative of V.P. Dymnikov, a new regional model of atmospheric dynamics was developed by that time [17, 24, 26, 50]. This model provides the detailed description of physical processes in the high-resolution model for a specified region for its interaction with global models.

The initial system of differential equations of atmospheric hydrodynamics for the sigma coordinate system has some integral invariants: the conservation of total energy (in the absence of dissipation and heat influx), angular momentum (absolute angular momentum) in case of zonal transport, potential enstrophy (in the approximation of shallow water equations). As the regional model of atmospheric dynamics is also used for climatic studies, where the implementation of integral conservation laws is required, the numerical model of atmospheric dynamics is constructed proceeding from the requirement of fulfilment of finite-difference analogs of the above integral characteristics [28].

Papers [27, 29] provide the detailed description of this model which became a base for the technology of numerical weather prediction with the lead time of 2–3 days in the Western Siberian Administration for Hydrometeorology and Environmental Monitoring (Western Siberian AHEM). The forecasting scheme was implemented with the spatial resolution of 1.25   1.66 along the longitude and latitude, respectively, and with 15 vertical sigma levels (10 levels in the troposphere and 5 levels in the stratosphere). The integration is provided for the zone of 40 –80 N, 40 –145 E covering the territory of the Urals, Western and Eastern Siberia. The free-surface boundary condition is applied at the top, and the flow condition is applied at the base. The time integration step for the 48-hour forecast is 5 minutes. The results of forecasts obtained with the Exeter global model (Bracknell, Great Britain) coming to the Western Siberian regional computing center in the GRIB format on the 2.5   2.5 grid at 00:00 and 12:00 UTC were used as initial and boundary conditions (updated with the period of 6 hours). The scheme of multi-element three-dimensional numerical analysis of meteorological data for the Siberian region [22] was developed as well as the method of nonlinear initialization by normal modes for the regional atmosphere model which allows the effective suppression of the amplitude of gravity waves at the initial stage of integration [4, 5, 17, 18, 27].

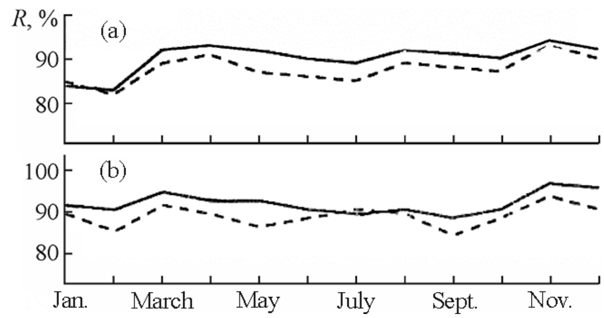

Fig. 1. The coefficient of correlation between the simulated and observed values of trends in (a) surface air pressure and (b) 500 hPa geopotential height for the forecasts for 24 (the solid line) and 48 (the dash line) hours in 1992.

To compute the numerical weather forecast, the automated maintenance system is also used which controls the completeness and quality of information coming from the global forecast model, the archiving, and the verification (for the zone of responsibility of the Western Siberian AHEM) of forecasts: both formal (statistical) and comparative (based on actual data). Figure 1 presents an example of coefficients of correlation between the trends in surface air pressure and 500 hPa geopotential height for the moment when the forecasting technology was introduced to the operational practice.

The detailed description of the operational technology of numerical weather prediction which was used in the Western Siberian AHEM till 2010 is presented in [4, 5, 18]. Based on the numerical prediction data, it was also shown that this model can be used to diagnose mesoscale events, for example, atmospheric fronts [1, 2].

3. SIMULATION OF CLIMATE SYSTEM DYNAMICS

The experience of mathematical modeling accumulated in the recent decades and based on the achievements of geophysical hydrodynamics and numerical mathematics allows creating powerful systems of assimilation of meteorological and oceanographic data with a high spatiotemporal resolution, developing high-quality operational technologies of numerical weather prediction, and conducting studies on the mathematical modeling of climate. Such studies concern the solutions to such problems as the creation of the mathematical apparatus for the numerical solution of the system of nonlinear three-dimensional equations of geophysical hydrodynamics; the investigation of physical mechanisms of multiscale processes of weather and climate formation; and the formulation of mathematical models of atmosphere and ocean dynamics. All these studies and the development of the software package have been carried out in accordance to the plans of research works of the Siberian Research Hydrometeorological Institute (SibRHMI) and Institute of Computational Mathematics and Mathematical Geophysics of SB RAS. The software package was developed by coupling the global model of atmospheric dynamics [28, 30, 31, 40, 45] and the regional climate model for the investigation of atmospheric dynamics sensitivity to the sea surface temperature anomalies [30, 31], for the exploration of atmosphere response to the moisture supply of continents [40], and for numerical experiments on the simulation of Siberian climate.

When describing the atmosphere–land surface interaction in the global climate model, special attention is paid to biophysical and biochemical processes [23, 32, 46, 49]. The successful simulation of sensible and latent heat fluxes on the surface is impossible without a detailed description of the biosphere state and without the consideration of biochemical factors which are utilized to describe these fluxes. At the same time, the modeling of primary production and emission of greenhouse gases needs the representative description of surface hydrology, surface layer dynamics, and thermal regime of soil. All these models (biospheric, hydrological, and atmospheric) describe the processes of various time scales in the climate system. The surface biosphere is the major component of the climate system from the point of view of climate change, water cycle, and global cycle of major greenhouse gases [24, 25]. Researchers pay special attention to feedbacks between the processes in the atmosphere and soil. The thermodynamic impact of soil is compared with the ocean effect at the middle and high latitudes. While the ocean accumulates solar energy in summer and gives the accumulated heat to the atmosphere in winter, soil accumulates precipitation in winter in order to provide the atmosphere with moisture in summer and to cool it. Thus, the effect of long-term memory with the scale of several months arises. The process that directly increases evapotranspiration or indirectly enhances (on the scales of several hundreds of kilometers) precipitation is of special interest [36].

It is generally accepted that the climate warming due to the increase in the concentration of greenhouse gases in the atmosphere is most strongly pronounced in the polar regions of the Northern Hemisphere. In particular, it is expected that under conditions of increasing concentration of greenhouse gases, the most significant changes will occur in temperature and precipitation, with the subsequent impact on the state of sea ice and permafrost which covers most of Russia. The threshold value of temperature equal to 0 C associated with phase transitions between water and ice is critical for northern regions, because the dramatic acceleration of already observed permafrost degradation should be expected under the conditions of significant climate warming. In turn, this may become a trigger for the erosion and subsidence of soil in these regions with unfavorable consequences both for the environmental system and for the human's economic activity. This warming may lead to increase in the thaw depth as it affects chemical and biological processes in the Arctic tundra. Most of Russia is located in the zone of permafrost; if its thawing is accompanied by the growing impact of anthropogenic factors, serious consequences come: the depreservation of less than 0.1% of organic carbon stored in the upper 100-m permafrost layer (about 10^4 Gt of carbon in the form of CH_4) may lead to the doubling of atmospheric concentration of methane whose radiation activity is by 20 times higher than for CO_2. This may lead to a still more significant warming and, hence, to the speedup of permafrost thaw (the mechanism of positive feedback is realized which can greatly enhance the global warming).

The above processes were taken into account in the climate system model worked out by the team of specialists from ICMMG SB RAS [23, 46, 49] and developed towards the account of biophysical and biochemical processes in the vegetation layer and in soil [24, 25]. It describes simple biochemical processes (for example, CO_2 fluxes resulting from the photosynthesis response or due to the processes of plant respiration within a certain biome) and methane emission from natural overmoistened surface areas [25, 36]. The distribution of five land surface types is specified in each grid cell: glaciers, lakes, bogs, bare surface, vegetation. Data on biome distribution on the surface [54], on soil types [57], and on the distribution of lakes and wetlands on the continents are assumed to be known.

During several recent decades, the general atmospheric circulation has changed due to climate change: its elements like the Hadley cell and storm tracks are displaced towards the pole, the tropopause height changes, etc. These processes became a subject of the joint study conducted by the specialists of ICMMG SB RAS and SibRHMI. The peculiarities of dynamics of the Hadley cell and tropopause height under the conditions of changing climate revealed during numerical experiments were investigated in [3, 38, 41, 53]. The results of numerical calculations of climate dynamics using the idealized model demonstrated that the trend towards the poleward displacement of storm tracks in the Northern Hemisphere will be kept under the conditions of climate warming (according to the RCP-8.5 scenario).

When searching for possible physical mechanisms which form a base for the dynamic interaction between the atmosphere in the northern and middle latitudes under conditions of the Arctic warming, special attention was paid to the dynamics of polar lows. For this purpose, the original computational technology was developed which included the global model of the climate system, the regional model of the Arctic atmosphere dynamics, and the Arctic Ocean model. The scenarios of numerical simulation were also developed to solve the problems stated [56].

The specialists of ICMMG worked out the system of three-dimensional numerical models intended for studying climate and its change in the Arctic Ocean, with the detailed description of hydrological processes in the areas of shelf seas [6, 33, 34, 47, 55]. This system includes the global ocean model and regional models of ocean and sea ice dynamics with various spatial resolution (50 to 5 km) with the possibility of specifying processes in the shelf zone and in the zone of river water inflow (the grid spacing is up to 400 m). The oceanic component of the model is supplemented with the model of the sedimentation layer with permafrost [37].

Based on the developed system of numerical models and NCEP/NCAR reanalysis atmosphere data [48], numerical experiments were conducted which simulated the past and present states of sea ice, thermohaline characteristics, and fields of currents for the Arctic Ocean (Fig. 2). The influence of variations in atmospheric circulation on ice drift and circulation in the upper ocean layer, on the thermohaline structure of waters, and on the ice cover thermodynamics is considered. The effect of Pacific and Atlantic waters on the distribution and thickness of Arctic ice was investigated [6, 7] as well as the role of river runoff in the formation of the thermohaline structure of shelf water and Arctic Ocean water. The system of model tracer-floats released from the mouths of Siberian rivers allows monitoring the spatiotemporal variability of river water trajectory during the certain period (Fig. 3) and revealing the specific features of river water

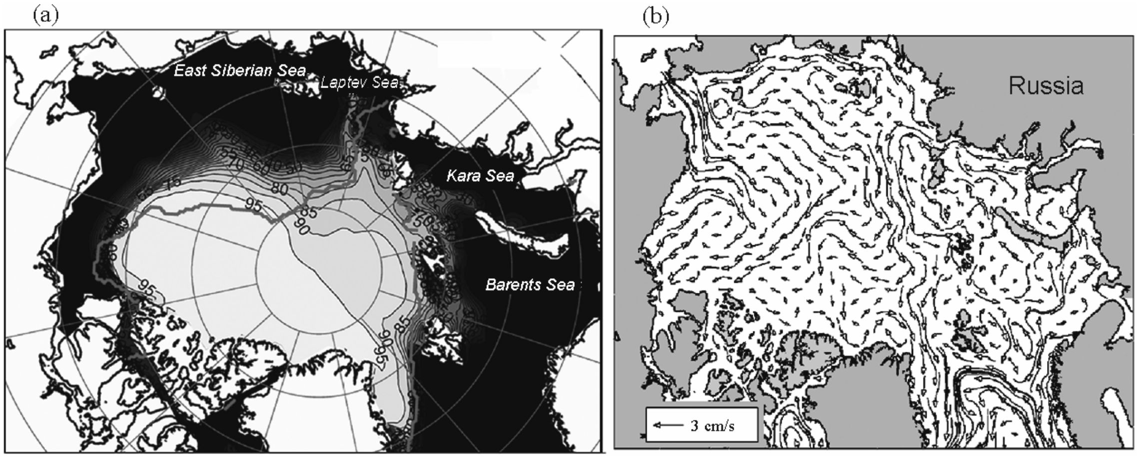

Fig. 2. The results of numerical simulation of the current state of the Arctic Ocean: (a) the ice concentration derived from data of numerical modeling (%) in September 2007 and from NSCIC data (the red line corresponds to the 15% concentration); (b) the field of model currents for the upper 150-m layer of the Arctic Ocean.

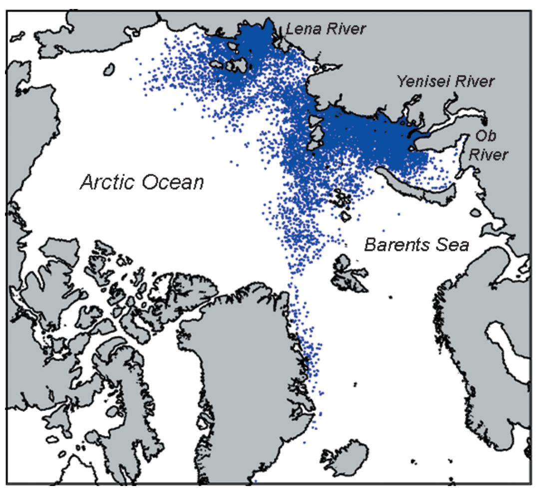

Fig. 3. The propagation of tracer-floats from the mouths of Siberian rivers during five years.

propagation. The analysis of float trajectories demonstrates that the tracers released from the Lena River branches are situated on the Laptev Sea shelf for several years and gradually move eastward to the East Siberian Sea and to the continental slope. The tracers belonging to the Yenisei and Ob rivers come to the Kara Sea shelf and are carried out through the Fram Strait.

The numerical experiments revealed the pattern of propagation of the salinity anomaly caused by the freshwater runoff from Siberian rivers [33–35]. The interannual variability of runoff of northern rivers considerably affects the distribution and propagation of freshwater in the Arctic Ocean and in the North Atlantic by accumulating the anomalies associated with the excess or deficiency of river water in some periods. These anomalies favor the strengthening or weakening of cyclonic circulation of subsurface waters in the Arctic Ocean; in the first case, the discharge of desalinated and cold Arctic waters through the Canadian straits increases with the respective growth of the volumes of salt and warm waters coming from the Atlantic Ocean. On the other hand, even slight changes in freshwater content against a background of significant salinity anomalies lead to significant deviations of the thermohaline structure from the normal in the upper ocean layer (they regulate its convective stability due to the stratification change).

The use of the system of nested models allows specifying the most interesting processes on the shelf of the Arctic seas. The possible reasons for water temperature rise in the Laptev Sea bottom layer are analyzed using the numerical modeling [43]. The results of model simulations [47] demonstrate the following: in summer, atmospheric dynamics is the key factor of the formation of water mass circulation in the shelf zone; the cyclonic circulation pattern with the prevalence of northwestern winds in summer may lead to the heat transfer to the bottom layer of shelf seas; the episodic emergence of warmer waters in the model sea bottom layer in the external part of the shelf bordering the continental slope (the depth is 50–150 m) is caused by the contact with warm and salt Atlantic water situated in the Arctic Ocean in the layer of 150–1000 m; the possible mechanism of temperature anomaly formation in the bottom layer in the shallow part of the Laptev Sea is the heat flow of rivers. The account of heat transfer from the bottom layer of Siberian seas to the sedimentation layer of the shelf characterized by the presence of permafrost allows assessing the current state and rate of degradation of subsea permafrost [37].

4. MATHEMATICS AND CLIMATE THEORY

The atmospheric transfer of heat and moisture from the equator to the poles is of fundamental importance for meteorology and climatology of the Earth. Baroclinic eddies are the main mechanism of this meridional transfer at the mid-latitudes. The mid-latitude transport of heat and moisture with baroclinic eddies plays a key role in the Earth energy budget and is of critical importance for the formation of sources of sensible and latent heating in the atmosphere. In this context, the important problem of studying the general atmospheric circulation is the formation of surface temperature gradient at mid-latitudes: it reaches the local maximum which, at the same time, is lower than it could be under the condition of radiation-convective equilibrium. However, there is no simple explanation why the temperature gradient takes this value.

The theoretical basis describing heat transfer in the mid-latitude atmosphere in the context of baroclinic waves and their stability is given in papers [42, 43]. However, these studies considered “dry” atmosphere, and the influence of humidity was not taken into account. Some problems are still unsolved, for example, those associated with the instability of large-scale perturbations in the humid atmosphere and caused by the consideration of mechanisms of nonadiabatic heating due to the condensation caused by these perturbations. Experimental and theoretical studies of the influence of condensation-induced heating on the intensity, size, structure, and dynamics of extratropical cyclones revealed that this influence can be significant. The account of the humidity effect in the framework of the theoretical study of dynamics of baroclinic waves attracted attention of researchers; one of the first of them was V.P. Dymnikov. He proposed an original approach to the account of interaction between the condensation-induced heating and baroclinic instability [8, 9, 11]. In general case, this is a very complex analytical problem with nonlinearities caused by phase transitions; this makes researchers pay attention to the more accurate description of the mechanism of latent heat release, because the amount of atmospheric water vapor considerably grows in case of the warming.

The forecast of weather and climate is characterized by uncertainties associated with the fact that initial conditions are never accurate, and the models are imperfect in terms of the description of physical laws forming their base. In view of this, the following questions arise: how can be the uncertainty of weather and climate forecasts assessed for the timescales from a day to a century, and what is needed to reduce the level of uncertainty? The answers to these questions are of critical importance for climate studies and require that, besides the physics of the climate system, the investigations consider the theory of nonlinear dynamic systems and the theory of stochastic processes.

The classic approaches to the determination of climate sensitivity are based on the concepts taken from the analysis of near-equilibrium dynamic systems; however, the more general point of view is needed. Climate is a complex dynamic system characterized by the variability within a wide range of spatial and temporal scales that takes places as a result of instability of different kinds acting as a negative feedback and setting equilibrium states. The authors of [13, 16] consider the fundamental problems of geophysical hydrodynamics and modern theory of weather prediction and climate change. Their main idea is to demonstrate how mathematics is used to study such complex nonlinear dynamic system as the terrestrial climate system. In [13], along with traditional approaches to the analysis of stability of the solution of equations of atmospheric dynamics based on the Lyapunov’s method, new approaches and methods are proposed which are related to the investigation of stability of attractors of dissipative dynamic systems including the Earth’s climate system.

The urgent problem of modern climate theory is a high sensitivity of the climate system to the external forcing. Following the ideas presented in the book by V.P. Dymnikov [13], the authors of [20] analyzed the correctness of the Cauchy problem for the Lorenz stochastic system [26, 51, 52] with the right-hand side perturbed by white noise. The theorem on the existence and uniqueness of the solution was proved, and the continuous dependence of this solution on the set of initial data and the right-hend side for the final time period was assessed.

Paper [13] also noted a need in studying the existence of a stationary measure for the systems of equations describing the atmospheric dynamics for the purpose of investigation of the climate predictability problem. This problem was considered in [19–21], where the existence of the only stationary measure was proved for the Lorenz stochastic system (under some additional restrictions for the parameters and the righ-hand side), and the rate of convergence of distributions of all solutions (from the certain class) of the mentioned system to the only stationary measure at t was assessed.

5. CONCLUSIONS

It is known that the forecast of the atmosphere state can be considered as an initial-boundary value problem of mathematical physics, where future weather is determined by the integration of partial differential equations starting from its current state. For this purpose, the system of nonlinear differential equations is daily integrated for the huge ($\sim 10^9$) number of grid points for the period from several hours to several months with account of dynamic, thermodynamic, radiation, and chemical processes. An indicator of understanding of observed processes and of the possibility of their numerical simulation is weather forecast accuracy and the ability to assess the predictability of specific synoptic conditions. The paradigm of determinism is rejected taking into account the uncertainties (random ones) resulting from the formulation of initial and boundary conditions and from the description of physical processes. This tendency was noted by V.P. Dymnikov as early as in the 1970s. The gradual transition to the application of nonlinear stochastic systems of differential equations for the description of weather and climate dynamics requires mathematical substantiation. V.P. Dymnikov, its colleags and followers made a huge contribution to this area and gave mathematical substantiation for new approaches and methods for the solution of the systems of equations of weather and climate dynamics. The further success in this area requires interdisciplinary studies and prospective supercomputer computing technologies. While requirements to the accurate and reliable weather and climate information are becoming increasingly topical, the resolution and complexity of physical processes in global numerical models should increase. On the other hand, the efficiency of computation and processing of the large volume of data impose restrictions on the complexity of these models whose calculations are conducted within the strict frameworks of operational technological process. This problem will be especially urgent for the run of global convection-resolving models with the grid spacing of about 1 km. The authors hope that the scientific achievements of the Siberian school of mathematical modeling of atmosphere and ocean dynamics will be further developed in the framework of modern global trends in the area of mathematical modeling of the Earth system dynamics.

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