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Models of Climate, Geophysical Boundary Layers, and the Active Land Layer: In Memory of V. N. Lykosov

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Abstract—This paper is dedicated to the memory of Vasily Nikolaevich Lykosov, a prominent Russian scientist and a specialist in the field of mathematical modeling of the dynamics of the turbulent boundary layer and its interaction with large-scale atmospheric circulation, global and regional climatic processes, and the active layer of the land. His scientific activities are briefly described in the context of modern research, one characteristic feature of which is attention to the links between local and global physical phenomena and a combination of theoretical models and numerical experiments.

Keywords: mathematical modeling, climate, atmospheric turbulence, active land layer, V. N. Lykosov

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Fig. 1. Vasily Nikolaevich Lykosov (January 14, 1945–September 10, 2021).

1. INTRODUCTION

Vasily Nikolaevich Lykosov, a prominent Russian scientist in the field of mathematical modeling of atmospheric turbulence, atmospheric circulation, and environmental dynamics, was born in Karpinsk in the Sverdlovsk Region on January 14, 1945. In 1962, he graduated from school with a silver medal and participated in the same year in the First All-Siberian Physics and Mathematics Olympiad. Based on the results of the Olympiad, he was invited to the Novosibirsk Academgorodok, where he entered the Faculty of Mechanics and Mathematics at Novosibirsk State University (NSU). He graduated from Novosibirsk State University with a red diploma in the Mathematics specialty and was assigned to the Computing Center at the Siberian Branch of the USSR Academy of Sciences (CC SB AS). At the Computing Center at the Siberian Branch of the Academy of Sciences from 1968 to 1979 he advanced from a junior researcher to a senior researcher. In the period from 1979 to 1982, he was the head of the seasonal forecast laboratory at the West Siberian Regional Research Hydrometeorological Institute, the USSR Hydrometeorological Service. In 1982, he was invited by Academician G.I. Marchuk to work at the Department of Computational Mathematics, of the Presidium of the USSR Academy of Sciences (from 1991, of the Institute of Computational Mathematics of the Russian Academy of Sciences).

In 1972, he defended his dissertation for the degree of Candidate of Physical and Mathematical Sciences Some questions of the theory of the turbulent planetary layer of the Earth's atmosphere (specialty 01.04.12, geophysics, the supervisor was Prof. L.N. Gutman). In 1989, he defended his thesis for the degree of Doctor of Sciences in Physics and Mathematics Mathematical modeling of the interaction of the planetary boundary layer with the underlying surface and with large-scale atmospheric circulation (specialty 01.04.12: geophysics). On May 26, 2000, V.N. Lykosov was elected a Corresponding Member of the Russian Academy of Sciences with a degree in Atmospheric Physics. He went repeatedly on business trips abroad as a visiting scientist. The longest of them were to the European Center for Medium-Range Weather Forecasts (Reading, UK, November 1979–May 1981) and to the Max Planck Institute for Meteorology (Hamburg, Germany, July 1992–December 1993).

By Decree of the Presidium of the Supreme Soviet of USSR, V.N. Lykosov was awarded the For Labor Valor medal (1986). He is a laureate of the State Prize of Russia in the field of science and technology (2000) for the cycle of studies Models and Methods in Problems of Atmospheric and Oceanic Physics.

V.N. Lykosov taught as a professor from 2004 at the Department of Computational Technologies and Modeling, Faculty of Computational Mathematics and Cybernetics, Moscow State University, where he read the special educational courses Mathematical modeling of geophysical turbulence and Computational and information technologies in climate modeling. He authored the textbooks *Supercomputer Simulation in the Physics of the Climate System* [1] (the cover is shown below) and *Models and Methods in the Problem of the Interaction of the Atmosphere and the Hydrosphere* [2] (the cover is shown below).

At the Institute of Computational Mathematics (ICM) at the Russian Academy of Sciences, Lykosov worked from 1982, first as a senior researcher (1982–1990), then as a leading researcher (1990–2000), and as a chief researcher from 2000. Recently, he was the co-leader of the creative team on the Modeling the dynamics of the Earth system and environmental problems topic and the head of the Mathematical modeling of regional natural and climatic processes subtopic.

A significant part of his scientific activities took place at Moscow State University, where, working part-time, he headed the laboratory of supercomputer modeling of natural and climatic processes at the Research Computing center (2002–2019) and was the chief researcher from 2020. Here, with the leading role of Vasily Nikolaevich, the scientific and educational seminars Mathematical modeling of geophysical processes: direct and inverse problems and Supercomputer modeling of the Earth system (an interdisciplinary seminar jointly organized by Moscow State University, the Russian Academy of Sciences, and Roshydromet), were created, which he led from 2003 to 2021. The seminars became one of the main platforms in Russia for presenting the results of leading research teams at the intersection of computational mathematics, geophysical hydrodynamics, meteorology, and ecology.

V.N. Lykosov found a wonderful path in science. It is difficult to overestimate his contribution to the creation of the first model in the USSR of the joint general circulation of the atmosphere and the ocean. To implement this project, a group of young researchers, which included Vasily Nikolaevich and was headed by Academician G.I. Marchuk, was created at the Computing Center of the Siberian Branch of the USSR Academy of Sciences. The research results of this group were published in a series of papers in Soviet and foreign journals and in the Mathematical Modeling of the General Circulation of the Atmosphere and Ocean monograph [3] that was published in 1984.

If we consider the personal qualities of Vasily Nikolaevich, which are very important in teamwork, then one of these main qualities can be described in one word: reliability. One could always be sure that if he undertook some project that this work would be done and done well. This applies both to scientific work and to scientific and organizational activities related to holding schools for young scientists (the CITES series, jointly with the Institute for Monitoring Climatic and Ecological Systems (IMCES) of the


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Siberian Branch of the Russian Academy of Sciences), seminars and conferences (the ENVIROMIS series, jointly with IMCES SB RAS), work in editorial boards, etc. For many years, he was a member of the editorial board of the Proceedings of the Russian Academy of Sciences at the *Atmospheric and Oceanic Physics* journal.

Below are the results on the four main topics of his scientific research: modeling of the joint circulation of the atmosphere and the ocean, atmospheric turbulence, modeling of heat and moisture transfer processes in the active land layer, and parameterization of water bodies in the Earth system model.

2. MODELS OF THE GLOBAL CIRCULATION OF THE ATMOSPHERE AND OCEAN, CLIMATE, AND THE EARTH SYSTEM

In October 1973, at the initiative of Academician G.I. Marchuk, the Department of Oceanology, Atmospheric Physics, and Geography of the USSR Academy of Sciences decided to create mathematical climate models in the USSR based on the equations of the general circulation of the atmosphere and ocean. The climate model was supposed to describe the maximum possible range of large-scale movements in the global atmosphere and the World Ocean, including their interaction in the planetary boundary layer, and absorption and propagation of solar radiation. Numerical algorithms of the combined model were supposed to be based on promising methods of computational mathematics, which have an efficient implementation on a computer. The model required knowledge and an optimal combination of physics, fast algorithms and high-performance computers.

A special group was created at the Computing Center of the Siberian Branch of the USSR Academy of Sciences to solve these superproblems, the development of a model for the joint circulation of the atmosphere and the ocean. This group consisted of five people, including the young candidate of sciences V.N. Lykosov, who defended his dissertation in 1972 on the topic of Some questions of the turbulent planetary layer theory of the Earth's atmosphere. Each member of the group had a common task, a joint model, and their own module (or subtask): atmosphere, ocean, radiation, planetary boundary layer, and parameterization of mesometeorological processes. The main task for Lykosov, as a specialist in the field of atmospheric turbulence and mesometeorology, was to develop blocks for the interaction of planetary layers of the atmosphere and the World Ocean and global atmospheric dynamics.

This approach to solving the superproblem based on the organization of a special "shock" group was successful and a joint model was created in 1975 [4]. The next stage consisted in the implementation and verification of the model, with the involvement of one of the most powerful computers of that time, the Cray-1 (RAM is 1 mln words, the performance is 80 mln/s). The experiments were performed by Lykosov at the European Center for Medium-Range Weather Forecasts in Reading in the period from 1979 to 1981. The characteristics of the mid-January circulation of the global atmosphere, the World Ocean, and the combined system were calculated and analyzed [3, 5]. This was the first version of the model based on the numerical method of splitting into spatial processes and geometric coordinates. The spatial resolution of the model was relatively low: $5 \times 5°$ in latitude and longitude and 6–8 vertical levels.

The joint circulation model was significantly enriched in terms of physical processes, new parameterizations, and model blocks. Its spatial resolution increased significantly, while the duration of integration over time increased to hundreds of years. The current INM RAS model confidently reaches the level of the Earth system model. The results of model calculations of the Earth's climate, its own and anthropogenic climatic variability, as well as the prospects for further development of climate models on the way to creating models of the Earth system, were reflected in [6, 7].

3. SIMULATION OF ATMOSPHERIC TURBULENCE

Parameterization of turbulent transport processes in geophysical boundary layers is an integral and important part of large-scale numerical models of the atmosphere and ocean. Developers have access to an extensive set of in-situ measurement data and 3D turbulence modeling results with very high spatial resolution (using Direct Numerical Simulation or DNS and Large Eddy Simulation or LES models) for their construction and refinement. The abundance of data and the variety of methods for their analysis and generalization give rise to the illusion of continuous progress in locally one-dimensional models of boundary layers and schemes for calculating the turbulent exchange between the atmosphere and the surface. However, upon careful testing of such models, it often turns out [8, 9] that despite the apparent simplicity of the problem, the spread between them is unacceptably large while the results depend not only on the type of differential equations, but also on the imposed restrictions, variations of the constants, and applied numerical methods.

As a representative of the generation of the founders of boundary layer theory, Lykosov invariably followed a rigorous mathematical approach to constructing turbulence models. Beginning from his Ph.D. thesis, his work was primarily based on finding analytical solutions, revealing the properties of systems of nonlinear equations, and searching for asymptotic dependencies. For example, as first obtained by Lykosov et al. [10–12], solutions for katabatic slope currents were the only possible method for the mathematical description of the phenomenon at that time. With the advent of computer calculations, Lykosov became both one of the first developers of one-dimensional boundary layer models and one of the pioneers in introducing turbulence parameterizations into numerical models of global atmospheric circulation [3]. In this case, he invariably carefully and convincingly studied the mathematical properties of the proposed models and parametrizations [13, 14], in which he greatly anticipated later studies. Lykosov made a great contribution to the development of nonlocal closures and models of antigradient transport in the atmospheric boundary layer [15–19]. Despite his propensity for rigorous mathematical formulations of problems, there are also papers devoted to natural measurements of turbulence among his published studies, for example, [20], where the phenomenon of turbulence intermittency with strong stability was clearly and reasonably revealed. His work [21], in which solutions were obtained for the first time that generalize the Monin-Obukhov similarity theory to the case of a surface layer with a suspension of snow particles, was one of the objects of his scientific pride.

At the end of the last century, the power of computing systems reached the level where both direct (DNS) and eddy-resolving (LES) numerical simulation of turbulence approached measurements of turbulence in the natural environment and under laboratory conditions in terms of information content and reliability. Lykosov was a staunch supporter of the priority development of this direction and initiated the development of original LES and DNS models at the INM, RAS, and the Research and Development Center at Moscow State University [22, 23]. At the same time, from the very beginning, he focused on the need for the development and implementation of parallel supercomputer computing technologies.

Using powerful tools for data generation, which are three-dimensional nonstationary turbulence models, current researchers have the opportunity to return to the consideration of problems Lykosov and his contemporaries posed. Approaches and solutions he suggested have not lost their relevance, although they are subject to clarification and verification.

4. SIMULATION OF HEAT AND MOISTURE TRANSFER IN THE ACTIVE LAND LAYER

Vasily Nikolayevich's attention to the problem of mathematical modeling of heat and moisture transfer in the active land layer was attracted for the first time in 1975 during his participation in the summer student expedition of the Leningrad Hydrometeorological Institute in the Yamalo-Nenets Autonomous Okrug [24]. This had a fruitful effect on his further scientific activities, since it was necessary to understand and relate the physical process, its mathematical model, and observation data.

Vasily Nikolayevich was aware of the need for adequate modeling of energy, mass, and momentum flows on the surface of the active layer of land and ocean due to his work on the parametrization of the boundary layer in the combined model of the general circulation of the atmosphere and ocean,. He approached the problem as a mathematician by formulating the statement in the most general form as opposed to the "physical" approach, where small terms are often discarded under the assumption of nonextremal deviations of the physical system from the characteristic state. He already considered the problem of interrelated heat and moisture transfer with allowance for cross diffusion and thermal conductivity coefficients in his first studies [25, 26], as well as "water–ice" phase transitions. Thus, the nonisothermality of moisture transfer was taken into account [27], although the dependences of the cross coefficients on soil state variables were poorly studied at that time. The presence of an unfrozen part of water at a negative temperature due to a strong pressure drop in water menisci of high curvature in narrow pores was also taken into account. In [28, 29], this model was supplemented with snow cover, which considers heat transfer; the model was successfully tested on measurements under natural conditions and in soil monoliths. In the model, the soil freezing/thawing process is reproduced based on the Stefan approach, i.e., with the solution of the evolutionary equation for the depth of the freezing front. It should be noted that the inclusion of cross-diffusion coefficients is still a rarity for schemes of the active land layer in weather and climate models, although the inclusion of these effects in models of soil thermohydrodynamics became an accepted practice [30]. From the beginning of the 1980s significant progress was made in studies of the physical mechanisms of conjugate heat and moisture transfer; for example, moisture transfer due to a temperature gradient is associated with the dependence of the surface tension of moisture films on temperature, which makes it possible to analytically obtain expressions for the cross coefficient of thermal and moisture conductivity [31]. Thus, the problem formulation of heat and moisture transfer in his early studies was far ahead of its time and is still rare in most blocks of the active land layer. At the same time, significant progress in soil physics, including the specification of the coefficients of mutual heat and mass transfer, now makes it possible to approach the problem at a new level.

By the beginning of the 1980s the active land layer was represented by an integral (vertically averaged) model for temperature and soil moisture in the climate model of the Computing Center at the SB RAS/INM RAS [5]. In the late 1970s, developments made by Lykosov with his coauthors formed the basis of a one-dimensional (vertically) soil model, which was later used in the climate model. An important development of the scheme of the active land layer was associated with a study by E.M. Volodin, Vasily Nikolayevich's student [32, 33]. The normalized vertical coordinates in the soil were replaced with a z-coordinate with a grid that thickens to the soil surface (23 levels in the soil to a depth of 10 m and 4 levels in the snow cover) and an equation for water vapor diffusion and water evaporation/condensation in the pore space was added. To take water transpiration by plants, as well as surface and subsurface water runoff, into account parametrizations were borrowed from the ECHAM3 model [34]. These developments made it possible to noticeably improve the reproduction of air temperature at a height of 2 m, soil moisture, atmospheric precipitation, and the spread of permafrost by the model. It should be noted that the detailed resolution of the INM RAS model in the soil at that time was considered by many colleagues to be redundant. However, the subsequent development of soil models was also accompanied by an increase in the number of layers (see, for example, CLM5 models, https://escomp.github.io/ctsm-docs/versions/release-clm5.0/html/tech_note/index.html, ORCHIDEE, [35]), which confirmed the correctness of his approach.

The subsequent development of the scheme of the active land layer (in the INM RAS climate model) was the improvement of the snow cover model that was performed by the postgraduate student E.E. Machulskaya (Volodina) under his supervision [36, 37]. Adding an equation for liquid moisture to the model made it possible to reproduce the seepage of melt water through the snow cover at a finite rate, which improved the reproduction of the observed periods of snow cover melting and the onset of the spring flood peak. This version of the snow cover scheme also served as the basis [38] for a new version of the corresponding scheme in the COSMO model. In collaboration with E.E. Machulskaya, Vasily Nikolaevich also drew attention for the first time to the importance of the low thermal conductivity of a thin vegetation cover (mosses and lichens) in the permafrost zone for the formation of the thermal regime of the active layer [39]. Recently, with his support, studies on the development of parametrization of heat and moisture transfer in the moss-lichen cover were resumed [40].

5. PARAMETERIZATION OF INTERNAL LAND WATER BODIES FOR THE EARTH SYSTEM MODEL

In the early 2000s, Lykosov set the problem of creating a parametrization of inland water bodies for the Earth system model. In the developed LAKE model, by analogy with the early versions of the soil model [25, 26], normalized vertical coordinates [41] are used to describe heat and mass transfer in evolving layers of ice and water. Models previously developed by Lykosov and his students were used as blocks of soil and snow cover. An equation for salinity was introduced into the model, which makes it possible to reproduce the features of the thermodynamic regime of lakes stratified by temperature and salinity [42]. The parametrization of water bodies was supplemented with equations that describe the generation, transport, consumption, and emission of methane and carbon dioxide into the atmosphere for the first time [43, 44]. The LAKE water body model was tested using the measurement data of dozens of lakes and included in the INM RAS climate model [45]. With his participation, a scheme of thermohydrodynamics of rivers based on the equations of a diffusion wave was created and implemented in the INM RAS-MSU model of the active land layer [46] and was successfully tested using the observational data on the discharge of Northern Dvina, Kolyma, etc. rivers.

6. CONCLUSIONS

Considering the path Vasily Nikolaevich travelled, we note his work with young scientists, to which he attached great importance. He set problems that determined the direction of the scientific activities of students for decades. Among other things, this happened because his work often predicted future developments and was ahead of its time. He rarely praised students and was demanding; at the same time, he was correct and delicate in dealing with students. He instilled the habit of regularity in work in his students (most of all, he did not like it when people “disappeared”). He trained them to find an accurate answer to each seemingly particular question that arose in the course of performing the main task (“you cannot dismiss this question, you need to answer it”). He welcomed initiative, did not impose his ideas, and preferred not to criticize other people’s proposals, which were sometimes dubious, but offered to prove them. By his own example, he always demonstrated how any work must be done on time and with high quality. He rarely allowed himself to speak impolitely about anyone. He was very attentive to the quality of the scientific Russian language, both in oral discussions and in written papers and meticulously corrected the texts of his students. During his many years of scientific and pedagogical work Vasily Nikolayevich actually created a scientific school, although he did not take credit for it, and he liked to emphasize the continuity of generations of the Russian mathematical tradition, which he rightfully considered himself part of.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

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