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Remote sensing and mathematical modelling of Lake Vostok, East Antarctica: past, present and future research

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Abstract. The paper presents a review of the studies carried out in the area of the subglacial Lake Vostok (East Antarctica) to date. They include geophysical, glaciological, geodesic, and geological investigations. The most important geophysical investigations were carried out by the Polar Marine Geosurvey Expedition. They included reflection and refraction seismic, and also radio-echo sounding. The major contribution to the study of this region was made by American researchers, who in the 2000/01 field season performed a complex airborne geophysical survey on a regular network. Their work included magnetometric, gravimetric, and radio-echo sounding measurements. All the research conducted found that the water surface area is 15 790 km², and its altitudinal height changes from –600 to –150 m. The average depth of Lake Vostok is 400 m, and the maximum marks reach 1 200 m. The water body volume is estimated at 6 100 km³. There are 11 islands in the lake, and their total area is 365 km². In addition, 56 isolated subglacial water bodies were found around the lake. A special section is devoted to a review of mathematical models of heat and mass transfer processes in the glacier and water movement in Lake Vostok.

Keywords: Lake Vostok, glacier dynamics, multidisciplinary studies, review of mathematical models

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Introduction

The interest in the study of the subglacial Lake Vostok is related to the uniqueness of this natural object. Today, it has no analogues on our planet. The hypothesis of the existence of a large subglacial water body buried under an ice sheet to the north of the Vostok Station was suggested based on the analysis of satellite data published in the well-known article [1]. In addition to these data, the article discussed radio-echo sounding (RES) data, which allow detecting with a very high degree of probability the existence of water under an ice sheet [2]. Further geophysical studies made by Russian scientists confirmed the initial hypothesis. However, this issue was finally resolved by the first penetration of Lake Vostok. This momentous event took place on February 6, 2012, at 0:24 local time, which corresponds to February 5, 20:25 Moscow time [3].

In retrospect, it is clear that as early as the mid-1970s there was enough information to suggest that a large subglacial water body exists to the north of the Vostok Station. Even at the dawn of Antarctic studies, I.A. Zotikov suggested the existence of such objects. He attributed their formation to basal melting and the filling of the negative forms of subglacial relief with meltwater [4–6]. In general, one can say that this was the first large-scale study, which resulted in building a one-dimensional mathematical model based on an analytical solution of the thermal conductivity equation, taking into account the vertical movement of the ice sheet. This model was a development of an earlier and simpler version of the glacier heat transfer model [7]. Less than ten years after I.A. Zotikov's model was published, in December 1967, new data indicating the existence of a subglacial water body were obtained in conducting RES around the Sovetskaya Station [8]. Subsequent studies of Antarctica's interior led to the discovery of a large number of similar objects. At present, their revealed number is 675 [9], but Lake Vostok stands out among them for its truly grandiose size [10]. The first comprehensive review of Lake Vostok can be found in a monograph written by I.A. Zotikov [11]. It discusses many important issues, including the formation of the lake and the existence of life isolated from the rest of the world.

The present work is an attempt to summarize the main geophysical, glaciological, and geodesic results obtained in the years of study of the Lake Vostok region. The next step in the study, in the opinion of the authors, should be related to penetration into Lake Vostok with the aim of studying directly its water column and bottom sediments. This is the only proper way to get reliable data about the composition of the lake water, the processes taking place in the lake, the microorganisms living in the lake, etc., in other words, about the entire environment and its evolution. At the same time, mathematical modelling of processes in the lake is equally essential. For this reason, the authors have prepared an overview of the main results of modelling associated with Lake Vostok. The final part of the article describes how the authors see the next step in the study of this unique natural object, primarily in terms of remote sensing and mathematical modelling.

Main results of research before 1993

The first reliable geophysical data on the Lake Vostok area were obtained in 1958–1964 in the course of seismic sounding and gravimetric observations performed by A.P. Kapitsa and O.G. Sorokhtin [12–14]. However, in the process of data interpretation, the layer located directly under the ice sheet was mistakenly taken for a sedimentary cover. Subsequent works were mostly related to airborne RES. In particular, in the airborne RES of 1971–1978 reflections typical of water objects were registered to the north of the Vostok Station [2, 15]. In the 33rd Soviet Antarctic Expedition (SAE) field season on November 7 1987, Russian scientists made a regional flight from the Molodezhnaya Station to the Vostok Station, along the line of which complex airborne RES was performed. Reflections similar to those observed over ice shelves were registered in the area of the Vostok Station. However, this fact was not given due attention [16, 17]. Scientists returned to geophysical studies only after the publishing of the paper, in which the geographical name Lake Vostok first appeared [1].

In addition to several geophysical studies, meteorological, geomagnetic, ionospheric, glaciological, drilling works, and also observations of cosmic rays were carried out at the Vostok Station during this period. Meteorological observations started on December 16, 1957, on the day the station opened [18], and almost never stopped. The highest priority was probably given to glaciological studies. These also began in 1957 with the setting up of a snow profile and the first core drilling down to a depth of 12 metres. At that time, a wide range of measurements, including thermometry [18], was carried out in this borehole. Subsequently, the glaciological studies were significantly expanded and supplemented with observations at glaciological testing sites and in the ITASE traverses. In particular, during the 15th SAE (1970) along the route Komsomolskaya Station — Vostok Station snow stakes were installed every 3 km. In the same year deep drilling began at the Vostok Station, which continued 20 years later, on February 20, 1990 (the 35th SAE), when the borehole 5G was started [19], through which in the following years penetration into Lake Vostok was performed. The study of the ice core made it possible to form a reasonable hypothesis on how the climate of Antarctica has changed over the past nearly half a million years. In addition, the ice core data showed that the lower part of the ice sheet, starting from a depth of 3 538 m, consists of accreted ice formed as a result of lake water freezing [20]. This is very important information, especially for mathematical modelling of the heat-mass transfer processes both in the ice sheet and Lake Vostok. There is another important point: the upper part of the accretion layer in the depth range of 3 538–3 608 metres contains solid (mineral) unevenly distributed (from 2–3 to 25 particles per metre of the ice core) inclusions, 1–2 mm in size. They were probably captured by the glacier as it crossed the shallow coastal area of the lake. Thus, these particles may reflect the composition of the sediments, providing unique information on the geological structure of the subglacial environment [20, 21]. In addition to these works, geodesists from East Germany made measurements of the velocity of near-surface ice flow, which was estimated to be about 3 m/year [22]. These figures were subsequently refined by their colleagues [23].

Main results of research after 1993

The discovery of Lake Vostok and interest in this natural phenomenon resulted in the need for a thorough study of this area. For obvious reasons, Russian scientists were the first to step up their activities. In order to study the lake in detail by remote methods reflection seismic surveys were started around the Vostok station in 1995, and from 1998 they were complemented with ground-based RES. Specially for these purposes, the Polar Marine Geosurvey Expedition (PMGE) developed a unique ice-penetrating radar (RLS-60-98), which was subsequently modified (RLS-60-06) to have greater power and depth [16, 17]. At the initial stage, experimental and methodological works aimed at improving the research methodology and increasing its accuracy were performed. The latter was necessary for penetrating Lake Vostok, which became feasible as there was only about 130 metres left to drill, and the remaining ice thickness had to be calculated with maximum accuracy.

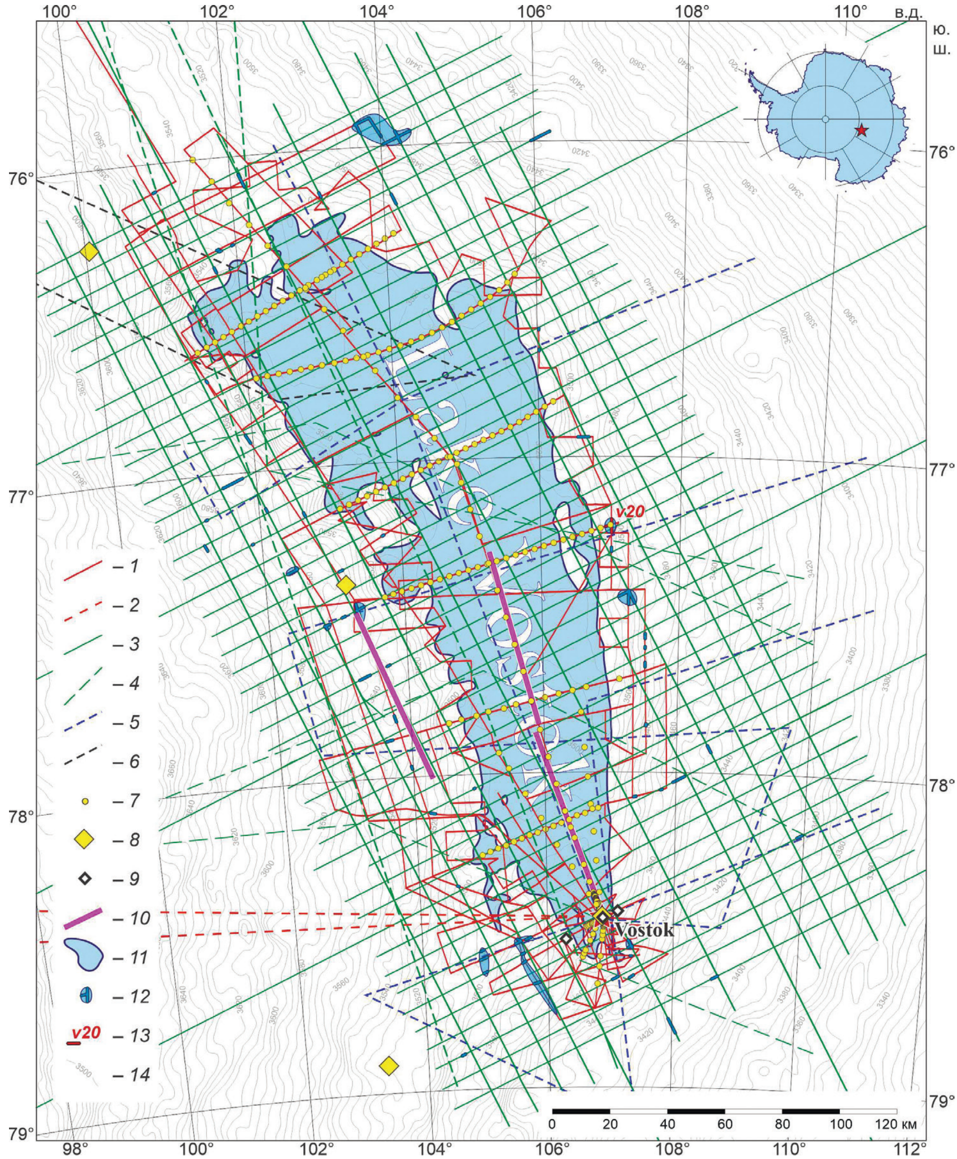
For this purpose, specialized seismic and RES works were carried out, which allowed the researchers to determine that directly at the point of drilling the average velocity of elastic wave propagation in the glacier body and in the pure atmospheric ice (the layer velocity) is 3 810 ± 20 m/s and 3 920 ± 20 m/s, respectively; the average electromagnetic wave propagation is 168.4 ± 0.5 m/μs [10]. On the basis of the data, the thickness of the ice sheet in this area was determined: the average value for both remote methods was 3,768 m, which is only a quarter of a percent less than the value 3 758.6 ± 3 m obtained from drilling after penetrating the lake [24]. The total length of the ground-based radar routes followed during the Russian surveys was 5.190 linear kilometres, and the total number of reflective seismic sounding points was 318 [16,17]. They are shown in Fig. 1.

Seismic and radio-echo sounding was completed in 2008. This research method was replaced by seismic refraction experiments, which were carried out between 2009 and 2013 to determine the bedrock velocities and crustal structure of Lake Vostok and its western coast. During these studies, two lines were acquired with direct and reversed observation using explosives as a source of seismic waves (Fig. 1) [25]. This survey shows that seismic velocities at the lake bottom are in the range of 6.0 to 6.2 km/s, and definitely correspond to the crystalline basement. The data obtained, however, do not exclude the presence of a thin (100 to 200 m) low-velocity (less than 3.8 km/s) layer representing the sedimentary cover. On the seismic profile on the western side of the lake, the velocity of elastic waves was 5.4–5.5 km/s, which corresponds to consolidated sedimentary rocks [25].

In the 1999/2000 season, Italian scientists made 12 separate geophysical survey flights over the water area of Lake Vostok [26]. In the 2015/16 season, three routes crossed the northern end of the lake during comprehensive airborne geophysical investigations by Chinese scientists [27–29]. However, the major contribution to the study of this region was made by American researchers, who in the 2000/01 field season performed a complex airborne geophysical survey on a regular network. Their work included magnetometric, gravimetric and RES measurements [30, 31]. The Russian and American data complemented each other well and made it possible to plot an integrated diagram of the ice sheet thickness and of the heights of the under-ice relief, and to map the shoreline of Lake Vostok with high accuracy (Fig. 1). The ice thickness above the Lake Vostok basin varies between 3 600 and 4 350 m. The ice sheet has a distinctive layered structure, correlating with the ice core data from the borehole 5G [32]. RES data analysis of the ice sheet stratification (isochrones) allowed drawing ice flow lines practically through its entire thickness: from 900 to 3 750 metres over three layers [33].

It was found that the water surface area is 15 790 km², and its altitudinal height changes from –600 to –150 m. The average depth of the lake is 400 m, and the maximum marks reach 1 200 m. The water body volume is estimated at 6 100 km³ [34]. There are 11 islands in the lake, and their total area is 365 km². In addition, 56 isolated subglacial water bodies were found around the lake [10], one of which (*v20*) is active (Fig. 1), i. e. the height of the ice sheet above it changes with time, which indicates a change in the volume of water, which, in turn, indirectly points to possible drainage [9, 35]. On the basis of the map of the natural relief a geomorphological analysis was done [10], whose results, when interpreted, helped to more precisely identify the features of the bedrock and to draw the first orographic diagram of the area [36].

The results of the US complex RES made it possible to substantiate the earlier assumption that the basin of Lake Vostok is a long-term rift graben filled with sediments of the Late Mesozoic to Cenozoic age [21, 37, 38]. These conclusions about the deep structure were confirmed by seismological earthquake converted-wave method observations made in the 2002/03 season along a 20.7 km profile passing through the Vostok station (the observation points are shown in Fig. 1). They showed that the western and eastern



sides of the Lake Vostok basin are divided by a distinct crustal-through rupture zone, the boundary of which is clearly traced up to 50 km. The crust thickness to the west and east of the Vostok basin is 34 km and 36 km, respectively. In addition, the data obtained indicate that an elevated geothermal flux may exist directly beneath the basin [39].

The conclusions about the tectonic nature of the Vostok basin and the neo-tectonic processes taking place in the region are also confirmed by biological studies. The thermophilic bacteria *Hydrogenophilus thermoluteolus* were found in the borehole G5 ice core at a depth of 3 607 m [40]. It is known that 50 °C is the optimal temperature for their growth and development. The hydrothermal activity may be caused by the rise of hot waters through the deep faults [21]. Moreover, these waters are probably mineralized and, therefore, the water mass may be stratified. This is extremely important for understanding the processes at the bottom of Lake Vostok and modelling the lake water circulation.

Important information for the mathematical modelling of heat-and-mass transfer in the ice and water mass/column has been obtained by geodetic methods. This work was carried out in ITASE traverses by researchers from the Institute of Planetary Geodesy of Dresden Technical University (Technische Universität Dresden — Institut für Planetare Geodäsie). In particular, the near-surface velocity of the ice flow above and beyond Lake Vostok was instrumentally determined to be 2.00 ± 0.01 m/year [41]. Another important result for mathematical modelling was the detection of tides in Lake Vostok and instrumental determination of variations in the ice surface heights associated with them. It was shown in [42, 43] that they are about 40 mm, and the resulting redistribution of the lake water from the tides forms an additional component of the general circulation. The geodetic data and modelling showed, among other things, that the water of Lake Vostok cannot flow out, it only can flow in, for example, as a result of drainage from the surrounding small water bodies [44].

Mathematical models of processes in Lake Vostok

The main results presented above do not in themselves answer the question of what processes occur in Lake Vostok and in the contact zone of its surface with the ice sheet, and how exactly these processes occur. Meanwhile, they are certainly important not only

Fig. 1. Location of geophysical investigations in the Lake Vostok area.

1 — Russian ground-based RES; *2* — Russian regional complex airborne geophysical survey route (1987); *3* — American complex airborne geophysical survey (magnetometric, gravimetric, RES, and laser altimetry, 2000/01); *4* — Italian complex airborne geophysical survey (magnetometric, gravimetric and RES, 1999/2000); *5* — Danish-American-British airborne RES; *6* — Chinese Airborne (CHINARE) studies (magnetometric, gravimetric and RES measurements, 2015/16); *7* — Russian reflection seismic (1995–2008); *8* — Russian reflection seismic (1950–1960s); *9* — Russian sounding by the earthquake converted-wave method; *10* — Russian refraction seismic; *11* — Lake Vostok coastal line; *12* — stable subglacial water bodies; *13* — active subglacial water body *v20*; *14* — ice surface elevation contours in metres

Рис. 1. Схема расположения геофизических работ в районе озера Восток.

1 — отечественные наземные радиолокационные исследования; *2* — региональные маршруты комплексной аэрогеофизической съёмки СССР (1987 г.); *3* — комплексные аэрогеофизические работы США (магнитометрические, гравиметрические и радиолокационные измерения, а также лазерная альтиметрия; 2000/01 г.); *4* — комплексные аэрогеофизические работы PNRA (магнитометрические, гравиметрические и радиолокационные измерения; 1999/2000 г.); *5* — аэрогеофизические маршруты комплексной датско-американо-британской аэрогеофизической съемки 1971, 1974–1975 гг.; *6* — работы CHINARE (магнитометрические, гравиметрические и радиолокационные измерения; 2015/16 г.); *7* — отечественные сейсмические зондирования МОВ (1995–2008 гг.); *8* — отечественные сейсмические зондирования МОВ (1950–1960-е гг.); 9 — отечественные зондирования МОВЗ; *10* — отечественные профили МПВ; *11* — береговая линия озера Восток; *12* — стабильные подледниковые водоемы; *13* — активный подледниковый водоем *v20*; *14* — изогипсы высот дневной поверхности в метрах from the theoretical point of view, but also from the applied perspective, e. g. prediction of probe behaviour in the process of sampling lake water or bottom sediments. But any remote sensing methods cannot answer this or other questions. Among the many theoretical and applied issues related to Lake Vostok, the moving of lake water is the most interesting and important. To some extent, it can only be resolved by mathematical modeling, which, of course, should be based on in situ data [45]. Despite the fact that Lake Vostok is covered by a thick ice sheet, currents may exist in it, as in other subglacial water bodies. Water circulation is a result of the indirect effects of endogenous and exogenous processes. The former lead to the vertical movement of water masses due to convection associated with the Earth's heat flow. The latter are related to the geomorphological and subglacial processes of freezing–melting, glacier movement, tides, water and glacial erosion, and a number of others. In addition, the drainage of subglacial water bodies [46, 47] is also an additional source of the inlake advection and turbulent diffusion.

Even small density gradients, which in turn depend on pressure, temperature and mineralization, can cause water circulation in isolated and unstable subglacial water bodies. The latter parameter is the most uncertain for these objects. As mentioned above, the water column of Lake Vostok may well be stratified: fresh at the top and mineralized at the bottom. The water pressure in a subglacial reservoir should be close to that of the ice sheet above it. In this case, if it exceeds 28.4 MPa (which corresponds to a thickness of 3 170 m), the maximum density of fresh water at its freezing temperature is reached. These conditions occur in Lake Vostok, which is under 3 700–4 300 m of ice [10]. Because the thickness of the ice sheet above the lake is not constant, but changes by a few hundred metres, there is a temperature gradient. For example, for Lake Vostok the difference in ice thickness between its northern and southern parts is 460 m. This creates a temperature difference of 0.31 °C, which, according to model estimates [48], results in the horizontal movement of the water at a rate from 0.3 to 0.6 mm/s (i. e. up to 20 km per year). The strength of this horizontal circulation will depend on the heat flow at the ice-water interface, the inclination of the lake surface, and the Coriolis force. Subsequently, similar calculations were made using a numerical 3D model of the ocean circulation, and the results confirmed that Lake Vostok has a weak circulation across the entire area with local variations in the velocity field determined by bathymetry [49].

One of the methods to study the specific features of water circulation in lakes is physical simulation in specially designed test apparatuses. Undoubtedly, this is the most obvious way to get an idea of the true course of natural processes, which, in turn, can help develop mathematical models. However, physical modelling has its drawbacks, which are primarily related to the impossibility to simulate the whole set of similarity parameters, such as the Reynolds, Rayleigh, Taylor, Rossby and Prandtl coefficients, characteristic of natural basins, in a laboratory environment. Nevertheless, a number of researchers have been able to obtain very interesting and promising results in their experiments [50, 51]. The authors of these works modelled the convection process in laboratory experiments with water put in rotating tanks. In particular, the study [50] provides a brief overview of vortex movements, their genesis, the evolution of vortex structures and their role in the ocean and atmosphere dynamics. Special attention was given to the influence of vortices upon small-scale turbulence and water circulation. On the whole, the paper presents general results of the laboratory and numerical modelling of phenomena associated with vortices in stratified and rotating liquids, as well as their values in convective flows.

Wells and Wettlaufer moved from more general questions to more specific ones and carried out laboratory experiments specifically to study the circulation in subglacial Lake Vostok [51]. Their experimental tank was made of transparent double-glazed units and had the following dimensions: length 91.4 cm, width 30.4 cm, and depth from 14.5 to 24.5 cm. In order to account for the effects of the boundary heat fluxes due to ice melting/freezing and the geothermal heat fluxes, a cooling element was connected to one half of the structure and a heating element to the other half. The near-bottom part also had constant heating, simulating the flow of geothermal heat. The entire cell was mounted on a precision-controlled rotating platform in order to account for the influence of the Coriolis force on the forming circulation currents. By performing a series of experiments under different initial and boundary conditions, the researchers obtained two fundamentally different results. The nature of the convective motions was largely dependent on whether the tank was rotating or not. In the non-rotating experiment, overturning circulation arose. When the horizontal scale of the eddies >1, a small stratified domain was formed under the roof, while the deeper region had an overturning circulation. When the horizontal scale of the eddies <1, a similar overturning circulation occurred, with sinking beneath the cold region, rising in the deep region, without the presence of a stratified domain. In the rotating experiment, columnar eddies dominated in the water body, transferring the heat directly from the base to the top. The horizontal movement of the particles 100 μm in size added to the water occurred predominantly in the thin top and bottom boundary layers. The action of the stronger rotation changed the flow dynamics dramatically so that the columnar vortices rapidly stirred passive tracers, but the exchange between the parts of the tank was weak. On this basis, it was concluded that the water exchange between the northern and southern parts of Lake Vostok might also be small, and thus their chemical and biological compositions would be different. According to the authors, in both the experiment and in Lake Vostok, rotation plays a dominant role in controlling the nature of the convective motions, and compensatory water exchange between the base and the roof of Lake Vostok takes about 20–30 days, with minimal lateral mixing.

In theoretical works [48, 52], to describe the water circulation in Lake Vostok, various balance ratios were used, which have a clear physical meaning and with some simplifications allow one to estimate this process. The advantage of this approach was that it made cumbersome calculations redundant; however, avoiding the equations of thermodynamics and hydrodynamics, it is often possible to answer only a small number of questions. In particular, Jean-Robert Petit formulated the concept of an empirical model of the water cycle and the energy balance of Lake Vostok and made the following simplified diagram of water circulation in it [52]. He did not take into account the Coriolis force deviation. The circulation consisted of two closed structures (loops) in the near-surface and deep parts of the water body. The currents formed at the surface were thermohaline structures in which the water temperature and mineralization changed. The cycle began with the formation of water as a result of melting of the lower edge of the ice cover and this melt water mixing with the lake water. The flow was directed from the melting area to the freezing area, where the ice condensed, and the salt, impurities and gases were expelled. Deeper than this layer was a warmer and more mineralized downward water loop with a temperature of –2.5 °C. The flow recirculated, returning to the melting area and mixing heat and salt with the lower layers. The lower water masses cooled, forcing the water to sink to the bottom of the lake. There it was heated again by geothermal heat and rose to the surface. This formed a second circulatory structure, the development of which was supported solely by the Earth's heat flow. Thus, according to [52], this circulation of water from deep layers probably generates additional heat, which increases the thermal flux to 170 mW/m² (compared to the geothermal flux of ~53 mW/m²), of which almost 2/3 is used for ice melt and 1/3 is released through the glacier/ice sheet. Similar conclusions were also presented in [48], which was used by Jean-Robert Petit and other researchers to further study the circulation in Lake Vostok [51, 53, 54].

An alternative and more relevant approach to studying water circulation in subglacial lakes is numerical modelling based on hydrodynamic equations. This approach was applied in two studies [49, 53], which used various modifications of the 3D hydrodynamic model originally developed for calculations of ocean circulation [55–57]. In the first research [49], two calculations were made using an adapted model, in one of which the depth of the lake was made constant, and in the other the author used what little information he had about the bathymetry and topography of the Lake Vostok basin and assumed the water mineralization to be equal to zero. Undoubtedly, those assumptions affected the modelling results. In the first case, he obtained the result that the horizontal circulation in the lake was predominantly barotropic and accompanied by a single vortex. In the second case, the horizontal circulation was baroclinic. In general, there was upwelling in the western part of the lake and downwelling in the eastern one, with vertical speeds of about 0.01 cm/s. There were also other difficulties caused by the lack of data for studying water circulation in Lake Vostok [48, 58]. However, the researchers who carried out later assessments no longer faced this kind of problems, as Lake Vostok had already been well studied by geophysical methods [10].

For instance, more recently, using the 3D Hydrodynamic model ROMBAX, Malte Thoma and co-authors concluded that a barocline circulation is dominant in Lake Vostok [53]. A weak counter-clockwise circulation was formed in the northern basin of the reservoir, while two more strong vortices (one clockwise and one counter-clockwise) were observed in the southern depression. Also, in the southern part of the lake, where the freezing area is located, an anticyclonic water circulation was observed closer to the surface, and a cyclonic circulation in the deeper layers. In general, the anticyclonic circulation was more dominant with respect to the overall mass transfer. The upwelling was concentrated in the east and the downwelling in the west. The only exception was the southern part, where freezing led to vertical stratification of the water column and upwelling concentrated in the western part. The researchers assumed that initially the lake was in stationary state, its water was fresh, and its temperature was –2.6 °C (the phase transition temperature at the pressure created by the ice column). The simulation time was chosen to be 150 years, this period was sufficient to reach a stationary state [53]. In 2010, Malte Thoma and co-authors complicated the problem and used both the RIMBAY ice-dynamics model and the ROMBAX circulation model, as well as their combination in the RIROCO model to assess the interaction of the two systems: the lake and the glacier [59].

Russian researchers have also attempted to characterize the circulation in the subglacial Lake Vostok. For instance, papers [60, 61] present a specially developed 3D non-hydrostatic model. The authors concluded that the previously used hydrodynamic models with hydrostatic approximation have their limitations. The reason for the insufficient adequacy of the hydrostatic approximation, in their opinion, is that the horizontal and vertical components of the water velocity moduli differ by only one order of magnitude in the estimates of Lake Vostok circulation parameters made in [48, 49, 52, 53, 62]. Publications [60, 61] present the results of calculations for the hydrodynamic model of convective circulation, which is based on 3D equations of hydrodynamics in the variables "vortex" — "vector potential" (Helmholtz equations) and the heat-balance equation. Refusal to use the hydrostatic approximation entailed limitations on time and computational resources. For this reason, during the calculations, the model equations were integrated in time for only two years, a period insufficient for reaching a stationary state of the circulation system, and due only to the limited computer resources available to the author's team. The temperature distribution in the water column of Lake Vostok and the zonal and meridional velocity of the currents in it were estimated based on the modelling results. Undoubtedly, the non-hydrostatic model has the advantage of allowing one to reproduce meso- and small-scale vertical vortex structures, however, that was not possible within the framework of this work.

Thus, numerical estimates and application of mathematical modelling methods [48, 49, 53, 54, 58, 63, 64] gave the first ideas about the currents both in Lake Vostok and other subglacial water bodies. In addition, an analysis of the influence of subglacial lakes on the overlying ice sheet was given [33, 65–70], which is important for further studies of subglacial hydrological and geomorphological processes in these unique natural objects.

Conclusion: plans for the future

Plans for further research of Lake Vostok, as well as any other site, are determined by the results achieved, which logically leads to setting new tasks. In the previous studies, a variety of data from different branches of science were obtained. However, there are important questions that remain unanswered. How, when, and why was Lake Vostok formed? Was it formed before or after the glaciation? In other words, is the lake water relic water that existed millions of years ago, or is the basin filled with melt glacial water? Of course, there are opinions on this issue. They are, in particular, outlined in [70], which suggest that Lake Vostok is a relic lake. This theory also appeals to the authors of this paper, but well-grounded answers to these questions can be obtained only based on the results of the next stage, which, as mentioned above, involves studying the lake itself as a water body and taking bottom samples. This will allow inferring how the lake was formed and how it developed. The next question concerns the deep structure of the Lake Vostok area. The already available geophysical data are still insufficient for unambiguous classification of the lake basin as rift graben. In the opinion of the authors, this issue requires further geophysical work, and, first and foremost, deep seismic sounding and earthquake converted-wave method profiling. These works will help to define the structural features of the Earth's crust and determine the Mohorovičić discontinuity. Besides, the important issue is the thickness and stratification of the lake bottom sediments. Unfortunately, the recent investigations described above cannot characterize it. This is a matter for future research, e. g. by high-resolution common-depth-point reflection profiling.

And finally, the third question. What is happening in the lake itself? What is happening in the area of its contact with the ice sheet? A separate issue concerns the behaviour of small subglacial water bodies surrounding the lake, and a particularly active water body *v20*, which seems to drain into Lake Vostok. Part of the answer to these questions may be a subsequent in situ study of the lake water and basal sediments. However, the borehole is not the whole lake, and without mathematical modelling it is impossible to build a correct, complete, and reasonable picture of these processes. Modelling will require, among other things, studies of the glacier dynamics, i. e. geodetic and glaciological studies over a large area of the lake and beyond, as well as systematic satellite observations. Geodetic measurements are important not only for modelling the moving of the lake water but also for better understanding of the glacier behaviour both inside and outside the lake. In addition, ground-based RES and satellite observations can certainly shed light on the processes taking place in the active subsurface water body *v20*. Particularly, a series of satellite altimeters, such as ICESat, CryoSat, and ICESat-2, CryoSat-2, could be used to see and show how the glacier surface over this small lake has changed in height from 2003 until now.

Thus, the authors see the new stage of research at the renovated station as large-scale multidisciplinary work based on the results of research in the borehole 5Г (including bottom sampling) [71], and its ultimate goal is to describe the deep structure and evolutionary stages of the region, as well as a mathematical model of heat-and-mass transfer processes in the glacier and lake water.

* * *

Study of Lake Vostok is an absolute priority of Russian research in Antarctica, which is stated in the “Strategy for the Development of Russia’s Activities in Antarctica until 2030” approved by the Government of the Russian Federation on 19.08.2020. The “Plan of Measures for the Implementation of the Strategy for the Development of the Activity of the Russian Federation in Antarctica until 2030”, approved by the Government of the Russian Federation 30.06.2021 No1767-р, contains Action 21 “Complex research of subglacial Lake Vostok and the Earth’s paleoclimate near the Russian Antarctic Station Vostok”, included in “Strategy…”. Large-scale construction of new buildings, including scientific ones, is currently under way at the Vostok Station. And the planned work follows the path of our country’s priority scientific objectives in Antarctica.

Competing interests. The authors have no conflicts of interest to declare.

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Дистанционные исследования и математическое моделирование озера Восток, Восточная Антарктида: прошлое, настоящее и будущее

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Расширенный реферат

В статье представлен обзор исследований, выполненный к настоящему времени в районе подледникового озера Восток (Восточная Антарктида). Они включают в себя геофизические, гляциологические, геодезические и геологические исследования. Наиболее важные геофизические исследования были проведены Полярной морской геологоразведочной экспедицией. Они включали в себя сейсмические исследования методом отраженных и преломленных волн, а также радиолокационное профилирование. Значительный вклад в изучение этого региона внесли американские исследователи, которые в ходе летнего полевого сезона 2000/01 г. провели комплексную аэрогеофизическую съемку по регулярной сети маршрутов. Она включала в себя магнитометрические, гравиметрические и радиолокационные измерения. В результате этих работ установлено, что площадь водной поверхности составляет 15 790 км^2, а ее высота над уровнем моря изменяется в пределах от –600 до –150 м. Средняя глубина озера Восток составляет 400 м, а максимальные отметки достигают 1200 м. Объем воды озера составляет 6100 км³. На его акватории насчитывается 11 островов, а их общая площадь составляет 365 км². Кроме того, вокруг озера было обнаружено 56 изолированных подледниковых водоемов, один из которых активный. На начальном этапе проводились специализированные работы, направленные на совершенствование методики исследований и повышения их точности. Они позволили установить, что непосредственно в пункте бурения скважины 5Г средняя скорость распространения упругих волн в теле ледника и в чистом атмосферном льду (пластовая скорость) составляет 3810 ± 20 м/с и 3920 ± 20 м/с соответственно; средняя скорость распространения электромагнитных волн составляет 168,4 ± 0,5 м/мкс. На основе этих данных была определена мощность ледника в этом районе, которая составила 3768 м. Специальный раздел посвящен обзору математических моделей, которые описывают процессы тепло- и массопереноса в леднике и движения воды в озере Восток. Новый этап исследований на обновленной станции видится авторам как масштабные мультидисциплинарные работы с опорой на результаты бурения скважины, включая донное опробование. Конечным результатом может стать описание глубинного строения и этапов развития региона, а также математическая модель процессов тепломассопереноса в леднике и озерной воде. Изучение озера Восток является безусловным приоритетом отечественных исследований в Антарктиде. Это нашло свое отражение в «Стратегии развития деятельности Российской Федерации в Антарктике до 2030 года», утвержденной Правительством РФ 19.08.2020. В этом основополагающем документе, регламентирующем все научные исследования в южной полярной области, имеется Мероприятие № 21 «Комплексные исследования подледникового озера Восток и палеоклимата Земли в районе российской антарктической станции Восток», и планируемые работы следуют в фарватере приоритетных научных задач нашей страны в Антарктике.

Ключевые слова: озеро Восток, динамика ледника, комплексные исследования, обзор математических моделей

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