Springer Proceedings in Earth and Environmental Sciences

Vladimir Karev *Editor*

Proceedings of the 9th International Conference on Physical and Mathematical Modelling of Earth and Environmental Processes

Springer

Springer Proceedings in Earth and Environmental Sciences

The series Springer Proceedings in Earth and Environmental Sciences publishes proceedings from scholarly meetings and workshops on all topics related to Environmental and Earth Sciences and related sciences. This series constitutes a comprehensive up-to-date source of reference on a field or subfield of relevance in Earth and Environmental Sciences. In addition to an overall evaluation of the interest, scientific quality, and timeliness of each proposal at the hands of the publisher, individual contributions are all refereed to the high quality standards of leading journals in the field. Thus, this series provides the research community with well-edited, authoritative reports on developments in the most exciting areas of environmental sciences, earth sciences and related fields.

Vladimir Karev
Editor

Proceedings of the 9th International Conference on Physical and Mathematical Modelling of Earth and Environmental Processes

Springer

Editor
Vladimir Karev
Fontanars dels Alforins, Valencia, Spain

ISSN 2524-342X ISSN 2524-3438 (electronic)
Springer Proceedings in Earth and Environmental Sciences
ISBN 978-3-031-54588-7 ISBN 978-3-031-54589-4 (eBook)
https://doi.org/10.1007/978-3-031-54589-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Development of the Structure of a Unified Hydrobiological and Hydrochemical Database for the Information and Analytical System "Lake Onego and Its Cathment"

V. N. Baklagin

Abstract The work is devoted to the creation of the structure of the database of hydrobiological and hydrochemical characteristics of Lake Onego, obtained as a result of field observations for the period 1960–2022. This database will be used as a full-scale basis for the information and analytical system "Lake Onego and its catchment", which is being actively developed within the framework of the Russian Science Foundation project No. 22-17-00193. This is a necessary tool for the calibration and verification of Lake Onego ecosystem models. The paper presents an algorithm and methodology for the formation of a single network of sampling stations, for the possibility of integrating the results of hydrobiological and hydrochemical measurements. The technique takes into account the spatial and temporal heterogeneity of the available data.

Keywords Database · Lake Onego · Information and analytical system

The intensification of the use of large lakes—important sources for the development of the regional economy (for water supply, sanitation, bio resources, water transport, energy, tourism, and aquaculture) should be accompanied by the improvement of systems for monitoring the state of lakes, systems for managing their resources. These systems should provide management decision-making with information to correct existing and justify future economic projects. Decision support systems are based on mathematical models, the calibration and verification of which is carried out according to observational data obtained both on the Agency on Hydrometeorology and Environmental Monitoring network and according to experiments performed by academic organizations.

V. N. Baklagin (✉)
Northern Water Problems Institute Karelian Research Centre Russian Academy of Sciences, Petrozavodsk, Republic Karelia, Russia
e-mail: slava.baklagin@mail.ru

V. Karev (ed.), *Proceedings of the 9th International Conference on Physical and Mathematical Modelling of Earth and Environmental Processes*, Springer Proceedings in Earth and Environmental Sciences, https://doi.org/10.1007/978-3-031-54589-4_1

The Agency on Hydrometeorology and Environmental Monitoring ensures the monitoring of the state and pollution of the environment, the assessment of changes occurring in it, as well as forecasting the development of the environment. However, the existing system of state monitoring of water bodies is insufficient both in terms of the composition of controlled substances and in terms of the location of observation points, and in terms of sampling frequency [1]. In addition, there was not enough observational data on the state of lake ecosystems obtained by academic organizations.

Now, there is extensive experience in creating databases of hydrometeorological observations both here and abroad. The WMO (World Meteorological Organization) International Data Center (www.hydrolare.net) has created a database of hydrometeorological observations. This database contains data on long-term observations at lake stations and posts, including monthly average data on the water level, water surface temperature (SST), maximum ice thickness per year, and other characteristics of the ice cover. This database contains data on 420 lakes and 170 reservoirs in Russia and the countries of the former USSR.

There is a base of hydrometeorological data of Russian Hydro Meteorological Data Research Institute in Obninsk. At the Institute of Lake Science of the Russian Academy of Sciences, the information system «Lakes of Russia» is being developed, which contains information about various parameters (location, morphometric and hydrological characteristics, as well as indicators water quality) of more than 300 lakes in Russia (http://www.limno.org.ru/win/rlake.php). A database was created for the Great American Lakes (GAL) in the USA and Canada based on NOAA (http://www.lre.usace.army.mil/Portals/). Using this database, a modern system for forecasting seasonal fluctuations in water levels, currents, temperature, ice, and bottom sediments of the Great American Lakes—"Great Lakes Coastal Forecasting System—GLCFS" has been developed. It is used to ensure the tasks of water transport and energy. There is also the Great Lakes Advanced Hydrological Prediction System (AHPS), which is a semi-automated system that combines observational data with mathematical models. With the help of this system, the water level and other hydrological characteristics of Great American Lakes are predicted. The Northern Water Problems Institute Karelian Research Centre Russian Academy of Sciences has developed a database and GIS "Lakes of Karelia", which includes data on long-term observations of the chemical-biological, morphometric and hydrological characteristics of lakes [2].

In addition, within the framework of the RSF project No. 14-17-00740, a database was created that made it possible to structure and summarize information on the long-term dynamics of the hydrological characteristics of the largest lakes in Russia [3]. The database contains information about Onego and Ladoga lakes, as well as climatic characteristics in the watersheds of these lakes for a period of more than 100 years. The database has functionality implemented in the C# programming language, which includes several blocks. A block for calculating regression coefficients and other statistical characteristics (determination coefficient, standard error of regression, etc.), integrated into the structure of the database on the hydrological characteristics of lakes, which allows the user to perform data analysis without using third-party tools. Visualization of the given sections of the lake basin. A block for calculating various bathymetric indicators (area at a selected depth, volumes of parts of the basin of the lake under consideration, and others) necessary for modeling thermohydrodynamic processes in the lake. The results of the analysis by the tools included in the developed information system can be used to modeling thermohydrodynamics and lake ecosystems, lake models and Lake Ecosystem models in text, binary and XML formats.

Also, within the framework of the RSF project No. 14-17-00740; an information system [4] was developed for working with data. In the information system, it is possible to obtain the calculated characteristics necessary for performing research. For example, to calculate heat fluxes through the surface of lakes, average monthly solar radiation, etc.

However, the created databases do not allow providing the developed information and analytical systems with full data and solving the tasks set—using them for calibration and verification of the created ecosystem models [5]. Difficulties in creating a unified database for the complex of hydrological, chemical and biological parameters of Lake Onego are due to the failure to comply with the basic principles of organizing and conducting observations to solve problems related to assessing the state and changes in lake ecosystems: according to hydrophysical, hydrochemical, hydrological, hydrobiological indicators, as well as in bottom sediments; consistency of the timing of their implementation with the characteristic phases of the hydrological regime of water bodies; determination of chemical and biological parameters of water by comparable methods.

In this regard, the purpose of this work is to form a method and structure of a common unified database of chemical and biological observations of Lake Onego in order to use it as a natural basis for calibrating and verifying ecosystem models.

For the purposes of integration of field and model data, the information and analytical system (IAS) "Lake Onego and its catchment" is being actively developed within the framework of the RSF project No. 22-17-00193 [5]. The IAS functionality provides spatio-temporal visualization of both direct modeling results and field measurement data linked to the electronic basis of Lake Onego, as well as products of their individual and joint analysis of various levels of generalization (statistics, integration, statistical analysis, etc.). An important function of the IAS is the possibility of automated comparison of natural and calculated data (hydrological, hydrochemical characteristics) used in the project of the mathematical model of the ecosystem of Lake Onego [6, 7].

To create a single database within the framework of the developed information-analytical system "Lake Onego and its catchment", both data from long-term observations of the chemical-biological, morphometric and hydrological characteristics of Lake Onego, obtained on the Agency on Hydrometeorology and Environmental Monitoring network from 1984 to 2022, as well as data collected by the Northern Water Problems Institute of Karelian Research Centre of the Russian Academy of Sciences starting from the second half of the twentieth century.

Long-term data were used, which are presented in the database and publications: chlorophyll-a [8, 9], benthos [10], phytoplankton [11], zooplankton [12] and primary production for the period 1960–2022, and by chemical indicators using comparable methods for the period 1992–2022 [13–15]. The functional blocks of the database and information system were used, created within the framework of the RSF project No. 14-17-00740, described in the work [4].

After 1991, data collection was dictated by the conditions for carrying out various kinds of private research tasks on state assignments, projects and grants, carried out by various research teams, which, unfortunately, did not have a comprehensive (interdisciplinary) and systematic character. In addition, different equipment for sample analysis was used in different periods of time, some methods for determining a number of parameters, for example, nutrients, primary production of phytoplankton, etc., changed, which led to the problem of comparability of results. The implementation of unrelated programs influenced the formation of networks of stations on the lake. Therefore, within the framework of this work, the task was set, which consisted in the generalization and unification of data for the possibility of integrating field data in an information-analytical system "Lake Onego and its catchment".

Works on the generalization of existing databases were carried out in the following points: formation of a single network of stations with their geographical reference; bringing data to a single format of dimensions; search and correction of errors; definition of data arrays, according to comparable methods; software implementation of the database manager system and its placement on the server of the Northern Water Problems Institute of Karelian Research Center of the Russian Academy of Sciences.

One of the most important and complex tasks is the formation of a unified network of stations. To solve this problem, the following operations were carried out, which required both manual and automated actions:

- A reliable (reference) station group has been identified based on peer review.
- An algorithm has been developed to classify the rest of the stations and records found in the databases of hydrobiological and hydrochemical observations based on the updated list of stations.

Figure 1 shows a block diagram that implements the algorithm for generating a single list of stations and updating the geodata of hydrobiological and hydrochemical data base records in a single database. The result of the algorithm (implemented as an application in the python programming language) made it possible to obtain a single list of stations (412 names—shown in Fig. 2) that have a geographic reference on the ground, as well as relational links with records of measurements in the databases developed by the Northern Water Problems Institute.

On the ground, the stations were grouped according to the limnic regions of Lake Onego, according to the description presented in Ref. [15] to enable comparison of the modeling results with the data of field observations within a separate region of Lake Onego. Figure 2 shows the location of sampling stations on Lake Onego for 1960–2022 (a fragment of a web application that implements the information and analytical system "Lake Onego and its catchment" is given).

Identification and elimination of gross errors in the values of hydrobiological and hydrochemical characteristics was carried out according to the "three sigma" criterion described in Sergeev [16]. Found records that did not meet the criterion

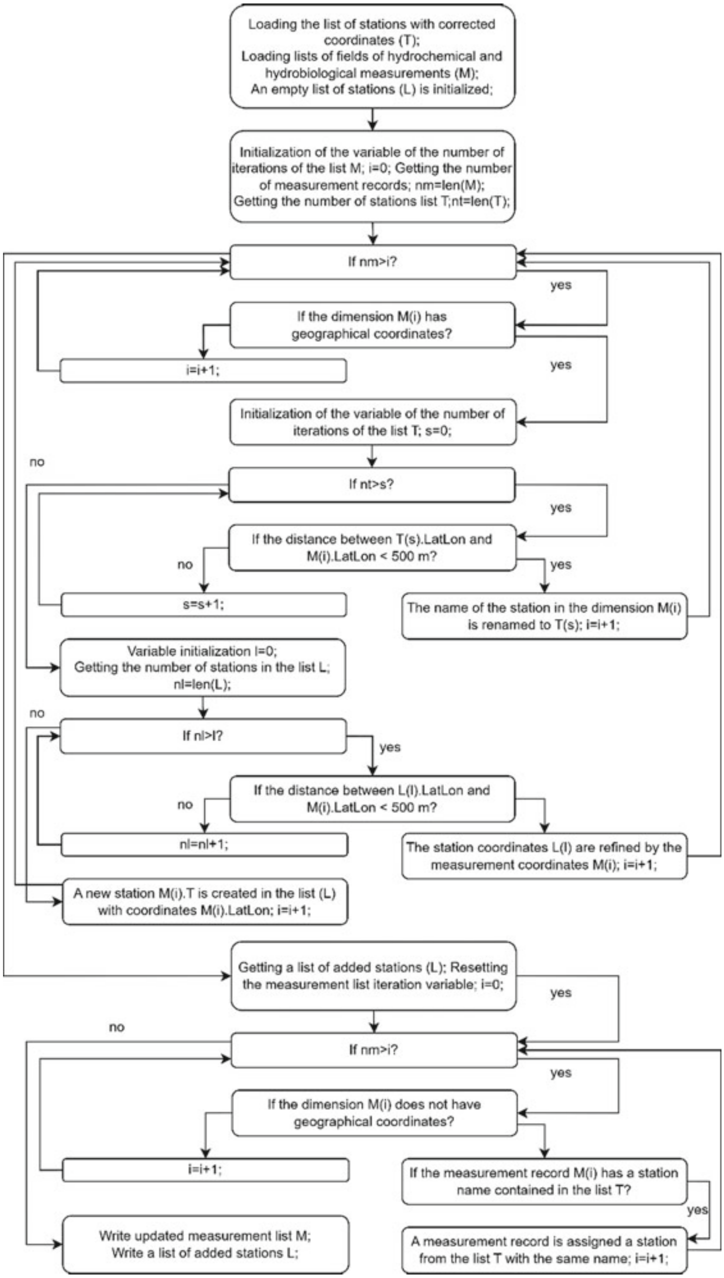

Fig. 1 Block diagram that implements the algorithm for generating a single list of stations and updating the geodata of records in hydrobiological and hydrochemical databases

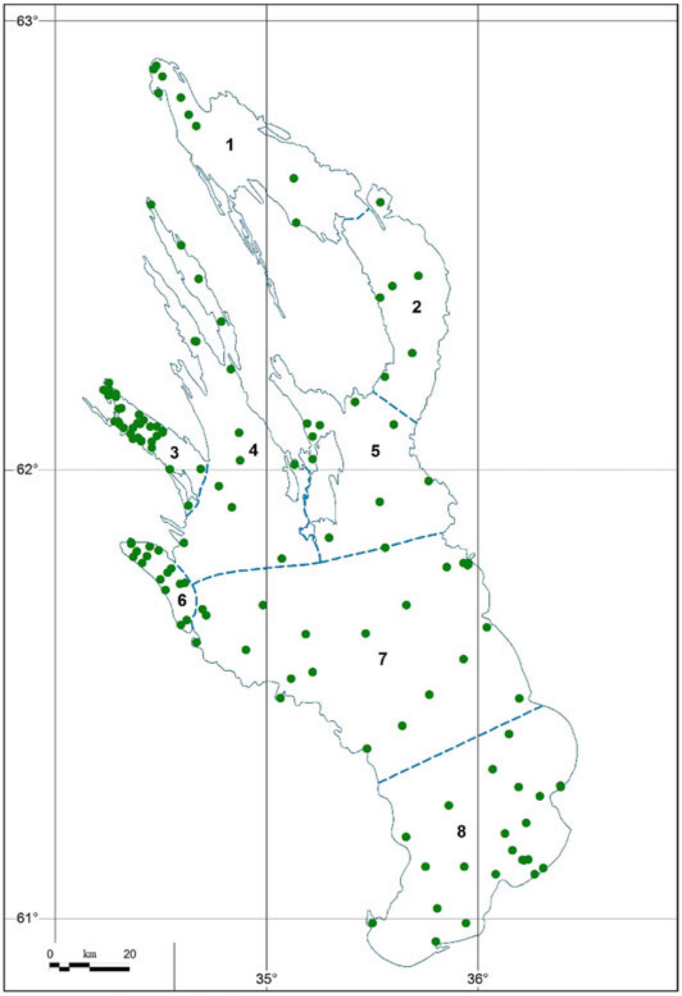

Fig. 2 Location of sampling stations on Lake Onego for 1960–2022: 1—Poveneckij bay, 2—Zaonezhskij bay, 3—Kondopozhskaya bay, 4—Bol'shoe Onego, 5—Maloe Onego, 6—Petrozavodskaya bay, 7—Central'noe Onego, 8—Yuzhnoe Onego

of "three sigma" were submitted for peer review by experts in the relevant field for adequacy. According to the "three sigma" criterion, it is considered that with a probability of P = 0.9973 and a significance of α = 0.0027, the occurrence of even one random error greater than an unlikely event and it can be considered a gross error if:

$$x_i > 3S_x,$$

where S_x is the estimate of the standard deviation of the measurements.

The values of S_x are calculated without taking into account the extreme values of x_i.

The three sigma method used the following procedure:

1. The doubtful value of the measured value was revealed—the largest or the smallest.
2. The arithmetic mean value of the sample was calculated without taking into account the doubtful value of the measured value.
3. The S_x values of the sample were determined without taking into account the doubtful value of the measured value.
4. The difference between the arithmetic mean and the doubtful value of the measured value was calculated and a comparison was made.

If the inequality is true:

$$|x_i - \overline{x}| > 3S_x,$$

that doubtful value was subjected to peer review, otherwise, the value was left in the series.

Extremely high and low, experts for adequacy further analyzed values of the parameters. For example, despite the very high detected values of chlorophyll-a concentration (57.99 mg/l) in the area of the Kondopoga Bay on August 22, 2007 station K27 (62.179167°N, 34.252222°E) (Fig. 3), experts confirmed (proved) the reliability of these data in scientific works [9, 17, 18].

As a result of processing the measurements, the results were structured in the form of relational (two-dimensional) tables for each of the sections. To convert data into SQL format, a software module has been developed built into the web application that implements the information and analytical system, which allows you to generate SQL tables from CSV files (field observation data, as a rule, consist of files represented by office formats.doc,.xls,.csv), this makes it possible to carry out operational and technological updating of the database, due to this, the generalization and reduction to a single format of the accumulated field measurements and the results of expeditionary research, as well as the integration of data into a single database.

In addition, an important and necessary functionality of the information and analytical system “Lake Onego and its catchment” is the ability to compare simulation results with field data. In this regard, the problem of processing field data unevenly distributed in space was solved in order to compare these data with the results of modeling on a model grid (with a horizontal step of 1 km). The solution of this problem was carried out by applying the interpolation method—the method of inverse weighted distances (IWR). The essence of this method lies in the fact that the points that are closer to those at which the characteristics are evaluated (in this case, hydrophysical, hydrobiological, hydrochemical)—reference points, have a greater influence than remote points. The value of the characteristic at the desired point (node of the model grid) will be most similar to the property values at nearby control

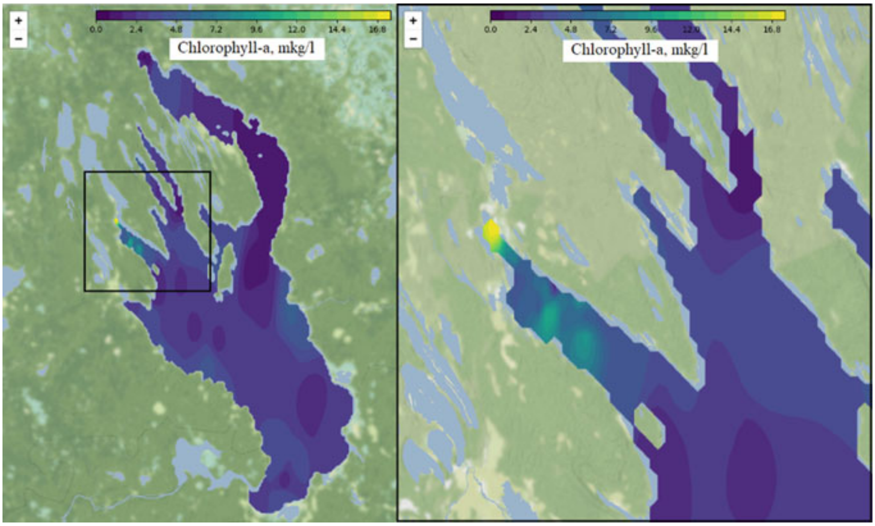

Fig. 3 Distribution of chlorophyll-a concentration (mg/l) on the surface of Lake Onego for the period 1992–2020 (averaged values for August) according to field observations [8, 9] (a fragment of a web application that implements the information and analytical system "Lake Onego and its catchment" is presented)

points, and less similar to the values at remote control points. The share of "participation" of the value of the characteristic in the reference point in the calculation of the desired value is expressed as a weighting factor ω. The weighting coefficients are calculated as inversely proportional to the distance to the power of p. The value of the characteristic in the node of the model grid is calculated by the formula:

$$Z(x_0, y_0) = \sum_{i=1}^{N} \omega_i \cdot Z(x_i, y_i),$$

where $Z(x_i, y_i)$ is the value of the characteristic at the i-th reference point; ω_i is the weight coefficient of the i-th reference point; N is the number of reference points.

The above calculation algorithm is implemented in the python programming language and embedded in the developed information and analytical system. Further work is aimed at solving the problems associated with the development of a methodology for checking the adequacy of model calculations in the conditions of a limited spatio-temporal series of available field data, since standard statistical methods cannot be applied due to the small volume of reference values.

Thus, the structure of a unified database of hydrochemical and hydrological parameters of Lake Onego has been developed, which will allow monitoring the state of the Lake Onego ecosystem, but also being a natural basis for calibrating and verifying mathematical models of the lake ecosystem.

Acknowledgements The work was supported by the RSF project No. 22-17-00193.

References

1. *Rumyantsev V.A., Filatov N.N. & Kondratiev S.A.*, 2021. Current state and improvement of the monitoring system of Lake Ladoga/Current state and problems of anthropogenic transformation of the ecosystem of Lake Ladoga in a changing climate. M: RAS: 540–558 (in Russian).
2. Lakes of Karelia, 2013. Handbook/ed. *N.N. Filatov & V.I. Kukharev*. Petrozavodsk: Karelian Scientific Center of the Russian Academy of Sciences: 463 (in Russian).
3. *Filatov N.N., Baklagin V.N., Bogdanova M.S. & Balagansky A.F.*, 2018. Hydrological characteristics of lakes in Russia/Certificate of state registration of the database No. 2018621718 dated 02.11.2018 (in Russian).
4. Diagnosis and forecast of thermohydrodynamics and ecosystems of the great lakes of Russia, 2020/ed. *N. N. Filatov*. Petrozavodsk: Karelian Scientific Center of the Russian Academy of Sciences: 255 (in Russian).
5. *Filatov N.N., Baklagin V.N., Isaev A.V., Kondratiev S.A. & Savchuk O.P.*, 2022. Developing a "lake-catchment" information analysis system as a method for basic research and a tool for decision-making (Lake Onego case Study). *Transactions of Karelian Research Center of Russian Academy of Science: Limnology and Oceanology*. 6: 161–172. https://doi.org/10.17076/lim1683 (in Russian).
6. *Isaev A., Vladimirova O., Eremina T., Ryabchenko V. & Savchuk* O., 2020. Accounting for Dissolved Organic Nutrients in an SPBEM-2 Model: Validation and Verification. *Water*. 12: 1307. https://doi.org/10.3390/w12051307.
7. *Savchuk O. P., Isaev A. V. & Filatov N. N.* 2020. Three-dimensional hindcast of nitrogen and phosphorus biogeochemical dynamics in Lake Onego Ecosystem, 1985–2015. Part II: seasonal dynamics and spatial features; integral fluxes. *Fundamental and applied hydrophysics.* 15(2): 98–109. https://doi.org/10.48612/fpg/9mg5-run6-4zr8.
8. *Sabylina A.V., Tekanova E.V. & Kalinkina N.M.*, 2018. Chlorophyll-a in the water of Lake Onego/Certificate of state registration of the database No. 2018621068 dated 06/13/2018 (in Russian).
9. *Kalinkina N. M. & Tekanova E. V.*, 2022. The Dependence of Chlorophyll a Concentration on Total Phosphorus in Water Bodies with Increasing Water Color. *Inland Water Biology*, 15(5): 539–542. https://doi.org/10.1134/S1995082922050108.
10. *Polyakova T. N.*, 2012. Macrozoobenthos of Lake Onego/Certificate of state registration of the database No. 2012620882 dated 08.31.2012.
11. *Chekryzheva T.A.*, 2018 Resource potential of the food base of Lake Onego: phytoplankton of Lake Onego/Certificate of state registration of the database No. 2018621090 dated 07/16/2018 (in Russian).
12. *Syarki M. T. & Kulikova T. P.*, 2012. Zooplankton of Lake Onego/Certificate of state registration of the database No. 2012621150 dated 9.11.2012 (in Russian).
13. *Galakhina N., Zobkov M. & Zobkova M.*, 2022. Current chemistry of Lake Onego and its spatial and temporal changes for the last three decades with special reference to nutrient concentrations. *Environmental Nanotechnology, Monitoring & Management*. 17: 100619. https://doi.org/10.1016/j.enmm.2021.100619.
14. *Zobkov M., Zobkova M., Galakhina N., Efremova T., Efremenko N. & Kulik N.*, 2022. Data on the chemical composition of Lake Onego water in 2019-2021. *Data in Brief*. 42: 108079. https://doi.org/10.1016/j.dib.2022.108079.
15. The largest lakes-reservoirs of the North-West of the European territory of Russia: the current state and changes in ecosystems under climatic and anthropogenic impacts, 2015/ed. *N.N. Filatov*. Petrozavodsk: Karelian Scientific Center of the Russian Academy of Sciences: 375.

16. *Sergeev A. G.*, 2005. Metrology: Textbook.—M.: Logos: 272.
17. *Kalinkina N.M., Tekanova E.V., Efremova T.V., Palshin N.I., Nazarova L.E., Baklagin V.N., Zdorovennov R.E. & Smirnova V.S*, 2021. Response of Lake Onego Ecosystem in the Spring–Summer Period to Anomaly High Air Temperature in Winter 2019/2020. *Izvestiya Rossiiskoi Akademii Nauk. Seriya Geograficheskaya.* 85(6): 888–899 (In Russian). https://doi.org/10.31857/S2587556621060078.
18. *Tekanova E. V., Kalinkina N. M., Zdorovennov R. E. & Makarova E. M.*, 2018. Results of the study of Lake Onego Ecosystem in the period of summer stratification based on measured data from a 2017 expedition//*Transactions of Karelian Research Center of Russian Academy of Science: Limnology and Oceanology*. 9: 44–53. https://doi.org/10.17076/lim753.

Analysis of Current Fields and Beryllium-7 Concentration in the Shore Area of the Southern Coast of Crimea in the Summer of 2016 According to the Modeling Results

Natalia Evstigneeva and Olga Dymova

Abstract Based on the hydrodynamic model of the MHI, adapted to the conditions of the Black Sea coastal area with open boundaries, a numerical experiment was carried out to reconstruct the fields of currents and beryllium concentration with the assimilation of hydrological data and satellite sea surface temperature in the summer of 2016. We used a high spatial resolution (horizontal grid ~500 × 500 m). A higher spatial resolution allowed to reconstruct a submesoscale structure of the current fields in the upper and deep layers and to obtain quantitative and qualitative characteristics of the eddies and currents more accurately compared to calculations on a ~1.6 km grid. An increased radionuclide content was reproduced in the field of beryllium-7 concentration in the coastal zone of Yalta and in the Feodosiya Bay, associated in the first case with atmospheric precipitation, and in the second case with submesoscale dynamics. Reduced values were detected at the periphery of the Rim Current and near Cape Sarych. At the same time, it was possible to reconstruct the decrease in beryllium content near the southern tip of the Crimea, recorded by in-situ measurements, only with the help of the model with a resolution of ~500 m. The decrease in the concentration of beryllium-7 was associated with the formation of coastal upwelling, not reproduced by the model with a resolution of ~1.6 km.

Keywords Black Sea · Numerical modeling · High spatial resolution · Assimilation of observational data · Submesoscale eddies · Beryllium-7

N. Evstigneeva (✉) · O. Dymova
Marine Hydrophysical Institute RAS, Sevastopol, Russian Federation
e-mail: naevstigneeva@yandex.ru

V. Karev (ed.), *Proceedings of the 9th International Conference on Physical and Mathematical Modelling of Earth and Environmental Processes*, Springer Proceedings in Earth and Environmental Sciences, https://doi.org/10.1007/978-3-031-54589-4_2

1 Introduction

Radioactive isotopes, such as beryllium-7 (^{7}Be), are informative tracers of the processes that determine the supply and transport of substances in the active layer of seas and oceans on various time scales. Since numerical modeling makes it possible to reconstruct and analyze the evolution of the radionuclide concentration field, the models of their transfer are of great interest and are used, in particular, to assess the state and predict changes in the ecosystem [1]. A necessary condition for the correct simulation of the radionuclide field evolution is the exact reconstruction of hydrodynamic fields close to observed.

A number of investigations for the Black Sea have been carried out on the numerical assessment of the transport of various impurities in the coastal zone, including the influence of fast submesoscale eddies. A three-dimensional model of beryllium-7 transport in the marine environment with a resolution of 5 km was proposed in Kremenchutskii et al. [2]. Validation of the calculation results was carried out according to the data from the stationary oceanographic platform in the urban-type settlement Katsiveli (Southern Coast of Crimea). Using the results of field observations, it was shown that the model allowed to correctly reproduce the evolution of the field of $^7\mathrm{Be}$ concentration in the surface water layer.

Preliminary estimates of the transfer of passive impurities in 2016 and comparison with measurement data in the upper layer were made in Dymova and Demyshev [3] on the basis of the model developed at the Marine Hydrophysical Institute (MHI) for carrying out calculations with a spatial resolution of ~1.6 km. The analysis showed that the modeling errors exceeded the measurement error for stations close to the shore, while for deep-sea stations a good agreement was observed (less measurement error). This result makes it necessary to increase the model resolution on the shelf.

Eddy structures of different scales, regularly recorded on satellite radar images, make a significant contribution to the circulation of the coastal zone and are an effective mechanism for the transfer of various kinds of impurities of natural and anthropogenic origin. The studies [4–7], done to date on modeling, forecasting and observation of hydrophysical fields with high spatial resolution, contain new results on meso- and submesoscale features of the Black Sea circulation.

Calculations of the distribution of pollutants in the coastal zone of the Adler-Sochi region were presented in Diansky et al. [4], based on the INMOM hydrodynamic model, implemented in two versions (with a uniform spatial resolution of ~4 km and uneven, with a step reduction of up to 50 m). It was shown that the version of the model with a higher spatial resolution reproduced the eddy circulation more adequately.

Hydrophysical fields were calculated with a high spatial resolution (horizontal grid ~350 $\times$ 350 m and 38 vertical horizons) in the period from 1 to 31 October 2006 in Demyshev and Evstigneeva [5], based on the hydrodynamic model of MHI in the coastal region of the South Coast of Crimea (between 44.25 and 44.72° N and 33.95 and 34.55° E) with open boundaries. The fields of currents, level, temperature and salinity on the northwestern shelf of the Black Sea were reconstructed with a spatial resolution of 500 m in the autumn period of 2007, also based on the MHI model, in Demyshev and Evstigneeva [6]. Due to the finer grid step in Demyshev and Evstigneeva [5, 6], it was possible to reconstruct the meso- and submesoscale structure of hydrophysical fields in the upper and deep layers and obtain quantitative and qualitative characteristics of eddies and jets more accurately compared to previous calculations.

Data on the evolution of the dynamic and thermohaline structure of submesoscale cyclonic eddies, attached to the Batumi anticyclone, were obtained in Bogdanov et al. [7], on the basis of the results of numerical modeling using the NEMO model for 2008–2009 and the algorithm for automatic identification of eddies.

Our study is a continuation of the development of a three-dimensional model of beryllium-7 transport in the waters of the Black Sea, developed earlier in Kremenchutskii et al. [2] and Dymova and Demyshev [3], in order to more correctly describe the spatial and temporal variability of the radionuclide concentration in the coastal zone. The reconstruction of the current fields and the beryllium-7 concentration in the area of the Crimean shelf was performed with ultra-high spatial resolution (horizontal grid ~500 × 500 m) and assimilation into the model of available observational data (in-situ temperature and salinity measurements, satellite sea surface temperature), based on the experience of previous works [5, 6, 8]. The expediency of using a finer grid step, when reconstructing the meso- and submesoscale features of the coastal circulation and radionuclide distribution, was shown by comparing with fields, obtained with a coarser grid step (~1.6 km).

2 Parameters of the Numerical Model and Description of Experiments

We used a z-coordinate three–dimensional nonlinear model of the Black Sea [9], based on the complete equations of ocean thermohydrodynamics in the Boussinesq approximation, hydrostatics and incompressibility of seawater in the form of Gromeka-Lamb, which was developed at the MHI. The model was supplemented with a block for calculating passive impurity transfer and assimilation of observational data. Wind friction stresses, heat, moisture and matter (radionuclide) fluxes from the atmosphere were set as boundary conditions on the free surface. Friction on the bottom was not taken into account; conditions for the absence of normal momentum, heat and matter fluxes on the solid boundary were set. The choice of conditions on open boundaries was determined by the type of experiment: for the entire basin or a limited area of the sea. The basin bathymetry was constructed with the help of the depths array by EMODnet (EMODnet Digital Bathymetry (DTM 2020)-Tile D3. https://emodnet.ec.europa.eu/geonetwork). The fields of sea surface height, temperature, salinity, radionuclide concentration and horizontal velocity were set at the initial time. Finite-difference discretization of the model equations, initial and boundary conditions was carried out on the C grid.

To set the fields of tangential wind friction stress, heat fluxes, short-wave radiation, precipitation and evaporation, we used ERA5 atmospheric reanalysis data with a resolution of (1/4)º (Copernicus Climate Change Service, Climate Data Store, (2023): ERA5 hourly data on single levels from 1940 to present doi: https://doi.org/10.24381/cds.adbb2d47). To assimilate the sea surface temperature (SST), satellite data from the Copernicus Marine Research Center (Black Sea product—High Resolution and Ultra High Resolution L3S Sea Surface Temperature https://doi.org/10.48670/moi-00158) were used.

The boundary conditions describing the total (dry plus wet deposition) flux of beryllium-7 from the atmosphere were constructed using a one-dimensional model [10]. The model also took into account the deposition of the radionuclide on particulate matter. The particulate matter concentration fields were calculated using the uplink brightness data measured by the MODIS satellites and the regional algorithm [11].

Two numerical experiments on modeling the circulation and transport of beryllium-7 were carried out in the work for the period June–July 2016: for the Crimean section of the shelf and for the entire basin. The choice of the interval was due to the fact that 87th cruise of the R/V "Professor Vodyanitsky" was held at that time in the area of the Southern Coast of Crimea [12] and direct measurements were carried out not only of hydrological characteristics, but also of the concentration of $^{7}\mathrm{Be}$.

Experiment 1 was carried out for the area, located between 33.37–36.46°E and 43.99–45.15°E and covering a section of the shelf from Cape Chersonesus to the tip of the Kerch Peninsula. The spatial resolution was 0.00696° in longitude and 0.005° in latitude (~560 m). We used 27 vertical z-horizons with depths 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 62.5, 75, 87.5, 100, 112.5, 150, 200, then every 100 m to 500, then after 200 m to 1700, 2100 m.

Dirichlet conditions were implemented for the equations of motion on the open part of the lateral boundaries (velocity components were specified, using a model with a coarser resolution for each calculated moment of time). From the analysis of the influence of various types of boundary conditions (Dirichlet conditions, free flow and mixed type) for temperature and salinity at the liquid boundary on the formation of thermohaline fields, those conditions were selected that provided a more accurate reproduction of temperature and salinity near open boundaries. For the border sections, where water flowed into the region, temperature and salinity were set (Dirichlet conditions); for the border sections, where water flowed out of the region, Orlansky conditions were set to determine T and S on the open border [13]. The discretization of those conditions was carried out using a central explicit numerical scheme [14] to calculate the disturbance transfer rate.

The coefficients of turbulent viscosity and horizontal diffusion were chosen $\nu^H = 5 \cdot 10^5$ cm^2/s, $\kappa^H = 3 \cdot 10^5$cm^2/s. The coefficients of turbulent momentum exchange and vertical diffusion were calculated in accordance with the Pakanovski-Philander approximation [15].

To assimilate the hydrological survey data, a four-dimensional analysis procedure was used [8], based on the method of sequential optimal interpolation. Covariance functions of thermohaline fields were approximated by an exponential type function $\exp\left(-\lambda\left[(x - x\prime)^2 + (y - y\prime)^2\right]\right)$, where λ was a dimensional parameter (equal to $0.023 \cdot (\Delta x)^{-2}$) corresponding to value of the correlation function of 0.1. The data of the hydrological survey of the 87th cruise of the R/V "Professor Vodyanitsky" were taken from the Bank of Oceanographic Data of the MHI.

The stations from the area under consideration were grouped by days and assimilation was carried out once a day: July 6–6 stations, July 8–3 stations, July 9–2 stations, July 10–6 stations, July 11–8 stations, July 12–4 stations, July 14–9 stations, July 15–5 stations, July 16–7 stations.

Experiment 2 was carried out for the entire Black Sea on a grid with a resolution of 0.020° and 0.015° in longitude and latitude, respectively (~1.6 km), the vertical resolution was similar to experiment 1. The open boundaries in the calculation were river mouths and straits where Dirichlet conditions were set. Vertical turbulent exchange was parametrized by the Mellor-Yamada closure model, horizontal diffusion and viscosity were defined with the help of the biharmonic Laplace operator with constant coefficients equal to 10^{16} cm^4/s. Satellite surface temperature was assimilated once a day. Assimilation of contact temperature and salinity profiles was carried out similarly to experiment 1. Due to the peculiarities of the implementation of the four-dimensional analysis procedure, the data were assimilated if at least two measurement stations on a specific date were located at a distance of less than 20 km from the model grid node.

When performing calculations, all initial and boundary fields were interpolated to the corresponding grid. The total time of integration of the model equations in experiment 1 was 26 days (06/26/2016–07/21/2016), in experiment 2—one year (01.01.2016–12.31.2016). The output data of both models were daily three-dimensional fields of thermohydrodynamic characteristics and beryllium-7 concentrations. The analysis was carried out for the area bounded by 33.37–36.46° E and 43.99–45.15° N.

3 Analysis of Current Fields, Reconstructed with Ultra-High Resolution

The initial field of currents was mainly characterized by westward flows with a maximum velocity 44 cm/s at the upper horizons; an anticyclonic eddy was observed in the 10–30 m layer in the Yalta Bay (between 34 and 34.4°E), anticyclonic eddy formations below 30 m—between 34.2 and 35.2° E. Figure 1 illustrates the fields of surface currents for 29th of June, 4th, 11 and 16th of July, 2016.

The Rim Current jet was observed along the Crimean coast, the maximum velocity could reach 50 cm/s at the upper horizons. During the considered summer period

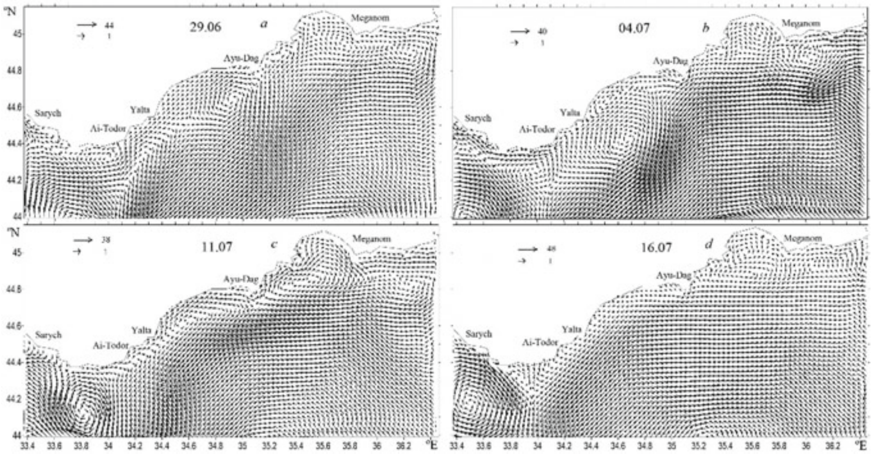

Fig. 1 Fields of currents (cm/s), calculated in experiment 1, at the depth of 3 m on 29th of June 29 (**a**), 4th of July (**b**), 11 of July (**c**) and 16th of July (**d**), 2016

meso- and submesoscale eddies were formed and developed in the upper layer between the coastline and the Rim Current.

An anticyclonic eddy with a radius of about 20 km was generated and moved along the direction of the movement of the Rim Current in the upper 30-m layer between Yalta and Cape Ayu-Dag from 27th of June to 15th of July (for example, Fig. 1a, b and c). An anticyclonic vorticity in the field of currents was observed in the Yalta Bay (between 34 and 34.4° E) (Fig. 1a) from 26th of June to 30th of June, a cyclonic eddy—near Cape Ai-Todor.

Chains of eddies of different scales and signs of vorticity were formed during the entire calculation period between Cape Ayu-Dag and Cape Meganom, when the Rim Current flowed around the uneven coastline (for example, Fig. 1). An anticyclonic eddy with a radius of about 20 km was observed from 9 to 18th of July between 33.4 and 33.9 ºE in the upper 30-m layer.

Changes with depth in the fields of currents were also analyzed. The fields of currents at the depth of 3, 10, 30 and 100 m on 27th of June and 12ve of July, 2016 are presented on Fig. 2.

An intense jet of Rim Current along the Crimean coast was noted at all horizons. Anticyclonic and cyclonic eddies were reconstructed in the upper 10-m layer west of Yalta on 27th of June, an anticyclonic vorticity was formed below 10 m between the Rim Current and the shore. An anticyclonic eddy between Cape Sarych and Cape Ai-Todor was obtained on 12th of July in the upper 30-m layer. Anticyclonic eddies were generated along the coast between Yalta and Cape Meganom.

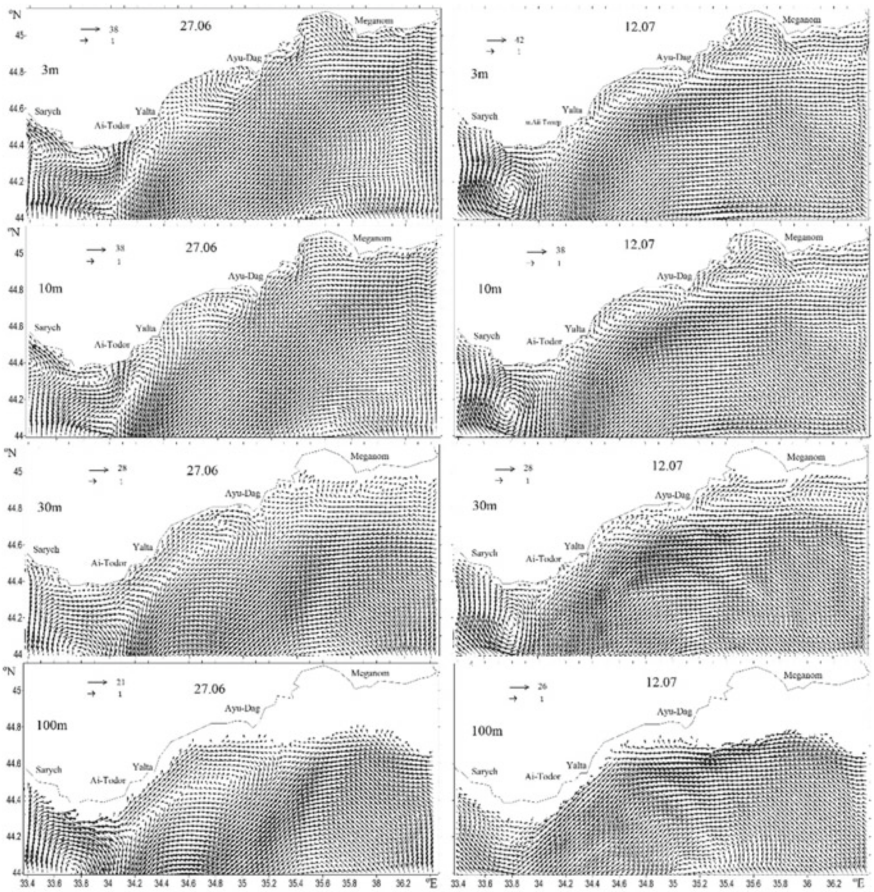

Fig. 2 Fields of currents (cm/s), calculated in experiment 1, at the depth of 3, 10, 30 and 100 m on 27th of June and 12th of July, 2016 (every fifth arrow was shown)

4 Comparison of the Results of Two Experiments (With a Resolution of ~500 m and ~1.6 km)

Fields of currents. Some qualitative differences were detected in the structure of the fields, when analyzing the fields of currents, calculated in two experiments. A number of eddy formations in the experiment with a lower resolution were absent or were less pronounced. It was possible to reproduce the circulation along the coast on the upper horizons in more detail in the experiment with a higher resolution. As an illustration, we present the fields on 29th of June, 2016.

Figure 3a and b show the fields of currents, calculated by the model with a resolution of ~500 m at 3 and 30 m levels (every sixth arrow is shown); Fig. 3c and d—the fields of currents, calculated by the model with a resolution of ~1.6 km at the depth

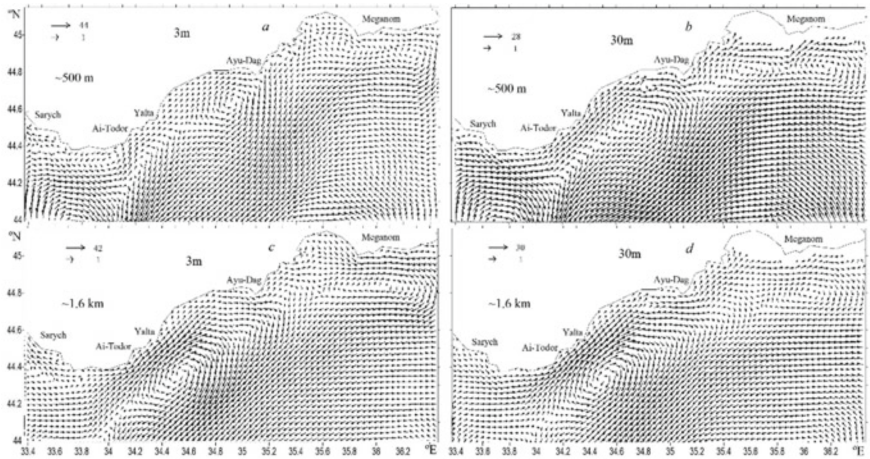

Fig. 3 Fields of currents (cm/s), calculated in experiments 1 and 2, at the depth of at 3 and 30 m on 29th of June, 2016

of 3 and 30 m horizons (the second arrow is shown). A qualitative agreement was obtained when comparing the fields of currents, presented on Fig. 3, however, due to a finer grid step, it was possible to specify the structure of the fields. An anticyclonic eddy formation in the Yalta Bay, a cyclonic eddy near Cape Ai-Todor and two anticyclonic eddies near Cape Meganom were reconstructed on the upper horizon (Fig. 3a). An anticyclonic eddy formation between 33.4 and 34° E was more clearly observed (Fig. 3c) at the deep horizon (30 m).

The field of beryllium-7 concentration. A comparison of the fields of concentration, based on the results of two calculations, showed that both models provided qualitatively similar data: increased concentrations of ^{7}Be, due to the advective transport of Rim Current, were observed in the southeastern part of the polygon. The values of concentration were lower at the periphery of the Rim Current, and the greatest differences were observed in the coastal zone. Figure 4 shows the fields of beryllium-7 concentration on 19th of July, 2016. The elevated concentrations of ^{7}Be in the area of urban-type settlement Gurzuf and Partenit, were apparently associated with atmospheric precipitation (Fig. 4c), while in the Feodosiya Bay, the concentration field was formed by submesoscale processes (Fig. 3a). Significant differences in the coastal zone were found in the area of Cape Sarych. According to the data of experiment 1 (Fig. 4b), the concentration here was approximately 1.5 times lower than in experiment 2 (Fig. 4a).

Comparison of the simulation results with observational data showed that both experiments gave similar values of concentration in the seaward part that fell within the measurement error themselves, and experiment 1 gave more accurate data near the shore. As can be seen from the Fig. 5, the ^{7}Be concentration, reconstructed in experiment 1, lied within the measurement error for the station, performed on 19th of July, 2016 at the point (33.55° E, 44.43° N), while it exceeded both data observations