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ОБНОВЛЁННЫЙ ПРОГРАММНЫЙ КОМПЛЕКС ДЛЯ МОДЕЛИРОВАНИЯ ВНУТРЕННИХ ВОЛН В МИРОВОМ ОКЕАНЕ С ПОДДЕРЖКОЙ ОБЛАЧНЫХ ВЫЧИСЛЕНИЙ

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В статье описан разработанный программный инструмент, объединяющий в себе численные модели, гидрологические данные, средства подготовки, анализ результатов и информацию о наблюдениях по тематике внутренних волн в Мировом океане. Предлагаемый подход направлен на повышение эффективности исследования путем автоматизации рутинных операций, повторяющихся при каждом численном эксперименте. Разработана новая версия программного комплекса (IGWResearch2). Структура комплекса была существенно переработана и дополнена новым функционалом с учетом анализа запросов пользователей. Были разработаны коммуникационные блоки для проведения облачных вычислений, интеграции исходных данных и результатов расчета в облачное хранилище. Такой подход позволяет перенести вычислительный процесс с рабочих станций на вычислительный сервер с более производительным аппаратным обеспечением. Облачное хранилище дает возможность обмениваться данными между пользователями и хранить результаты расчетов на сервере. Пользовательский интерфейс переработан, добавлена пошаговая система инициализации модели с автоматической корректировкой на основе теоретических оценок. Разработан блок интеграции с сервисами НИЛ МПиТК НГТУ им. Р. Е. Алексеева: авторизацией и онлайн базой данных наблюдений внутренних волн, позволяющий отображать информацию о типах, источниках и дате наблюдений на интерактивной карте. В статье рассматриваются особенности реализации комплекса, обзор используемых моделей, данных и численный эксперимент, выполненный при помощи комплекса.

Ключевые слова: внутренние волны, программный комплекс, слабонелинейная теория, облачные вычисления

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UPDATED SOFTWARE PACKAGE FOR INTERNAL WAVES MODELING IN THE WORLD OCEAN WITH CLOUD COMPUTING SUPPORT

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The development of a software package IGWResearch2 is considered in the paper. This package contains numerical models, hydrological data, data preparation tools, analysis tools and observations' information related to internal waves in the World Ocean. The proposed approach is pursuing a goal to increase research efficiency by automation of routine operations repeatable with every numerical computation run. A new version of the software package was developed. The software structure was changed significantly and extended based on users' requests. Communication modules for cloud computing and cloud storage were developed. This approach brings the possibility to transfer a computational process from workstations to a dedicated high-performance server. Cloud storage provides an ability for users to exchange numerical results and other data and store their data on the server. The graphical user interface was upgraded. A step-by-step configuration tool for the initialization of numeric models was added. This tool provides an ability to automatically correct user input based on weakly nonlinear theory estimations. New tools for the laboratory of modeling of natural and anthropogenic disasters of NNSTU n. a. R. E. Alekseev services access were developed. They extend the package with web-site based authorization

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and provide online access to the database of internal waves' observations. These tools provide information about internal waves' locations, their types, and dates on the interactive map. A numerical experiment using the software package is presented in the paper.

Key words: internal waves, software package, weak non-linear theory, cloud computing

1. Introduction

Similar to the surface waves that are on the border of water and air, the internal waves of the ocean prevail at the interface of water layers of different density. The presence of such layers is due to different temperatures and salinity of the liquid at different depths. Internal waves are a sub-mesoscale phenomenon both in time and in space. Typical wavelengths range from hundreds of meters to tens of kilometers, and typical periods range from a few minutes to several hours. Internal waves are very important because of their ability to transfer energy from one part of the ocean to another. As a result, they affect the marine ecosystem, impact the bottom topography, marine, and hydraulic structures [1].

The waves generate convergent and divergent flows on the surface and are visible in the images of radar and optical sensors [2]. Such observations were reported for many water bodies of the planet. Especially numerous observations are available for the South China Sea, where internal waves of large amplitudes are generated regularly [3].

Numerical modeling of the internal waves' propagation and transformation processes is one of the tools for studying such phenomena. For modeling, data are required to set the hydrological conditions. Such data can be obtained from open sources — international oceanographic atlases containing the distribution of temperature and salinity fields on a certain geographical grid [4]. As a rule, such atlases have different data formats and require preliminary processing.

Numerical models for describing the above processes based on the weakly nonlinear theory of long waves have been being developed for many years and have been proved efficient [5–9]. In the framework of this theory, the wavelength should significantly exceed the depth of the liquid. Wave dynamics is described by a one-dimensional evolutionary equation to a first approximation [10] (Korteweg — de Vries (KdV)). An updated model, considering corrections of the subsequent orders of smallness, is the KdV equation with combined nonlinearity (Gardner equation) [11, 12]. Models of this class may also address the rotation of the Earth and dissipative effects [13].

Thus, the creation of a tool that combines numerical models, hydrological data, training tools, data analysis and information about observations on the subject of internal waves could enhance the study of this phenomenon and automate routine operations repeated with each numerical experiment. The first attempt to create and combine some of these components in a single software tool was made in our previous project [14]. Based on the results obtained, user reviews and modern technologies, the software package was revised and extended. A description of new approaches and blocks is presented in this article.

2. A brief overview of the models used

The package contains the following calculation blocks: a calculation block of the density field of seawater [15], a calculation block for mathematical modeling of the internal waves propagation and transformation in a stratified fluid with a geometrically complex configuration (variable topography) in the field of gravity and Coriolis based on the equations by Korteweg-de-Vries, Gardner [11] and Gardner-Ostrovsky [12], calculation blocks for modeling wave propagation in a weakly inhomogeneous ocean in the framework of ray theory [16, 17], calculation block for particle transport in the field of internal waves [18].

In this article, we restrict ourselves to the description of the block related to the model of equations of the KdV family. The basis of the computational module is the extended nonlinear evolutionary Korteweg — de Vries equation with combined nonlinearity (Gardner equation):

$$\frac{\partial \eta}{\partial t} + (c + \alpha\eta + \alpha_1\eta^2)\frac{\partial \eta}{\partial x} + \beta\frac{\partial^3 \eta}{\partial x^3} = 0, \qquad (1)$$

where η is a displacem,ent of the isopycnic surface at the maximum of the vertical mode; c — s is the phase velocity; α — quadratic nonlinearity coefficient; α_1 — cubic nonlinearity coefficient; β — dispersion coefficient

(c, α, α_1, and β — are the characteristics of the internal waves obtained from the data on the stratification of the liquid). Equation (1) in the case of a horizontally inhomogeneous ocean along the section, considering the rotation of the Earth and friction in the near-bottom turbulent boundary layer, assumes the following form:

$$\frac{\partial\xi}{\partial X}+\left(\frac{\alpha(X)Q(X)}{c^2(X)}\xi+\frac{\alpha_1(X)Q^2(X)}{c^2(X)}\xi^2\right)\frac{\partial\xi}{\partial\tilde{s}}+\frac{\beta(X)}{c^4(X)}\frac{\partial^3\xi}{\partial\tilde{s}^3}+\frac{kc(X)Q(X)}{\hat{a}(X)}\xi|\xi|=\frac{f^2}{2c(X)}\int\xi d\tilde{s}, \qquad (2)$$

where $\xi(\tilde{s},X)=\eta(\tilde{s},X)/Q(X)$, $\tilde{s}=\int\frac{dx}{c(x)}-t$ — time in the corresponding reference system, X — coordinate along the wave propagation path, Q — linear gain coefficient found from the natural condition of flow energy conservation in an inhomogeneous medium, f — the Coriolis parameter, k — coefficient of friction, which is chosen phenomenologically.

3. Data

For hydrological conditions settings, three atlases with different resolution and territorial coverage are integrated into the package: WOA18 [19] (World Ocean Atlas), GDEMv3 [20] (Generalized Digital Environmental Model Database), and RCO [21] (Rossby Center Ocean). The coastline is set by the bathymetry atlas ETOPO1 [22] considering it contains a higher resolution of the topography and coastline in comparison with hydrological atlases. Atlas GDEMv3 contains arrays of monthly average climatic data, with a vertical distribution of temperature and salinity at 58 depth levels, as well as blocks of averaged data for January and July. Atlas WOA18 contains blocks of averaged data for months and seasons at 57 depth levels. The RCO Atlas comprises monthly averaged data obtained by the Rossby Centre Ocean Model, particularly, high-resolution temperature and salinity data for the Baltic Sea between 4’ longitude and 2’ latitude at 41 depth levels, with a 6 hours time step from 1961 to 2005. The other characteristics are presented in Table 1.

4. Overview of the software package features

Hydrological data is used to calculate density fields, buoyancy frequencies, and also the coefficients of the Gardner equation. Hydrological atlases are in different formats; therefore, a data import module was added to the package. Its main function is to convert the initial data into a format supported in the software package, as well as to associate atlas variables with the package variables. The NetCDF library format [23] was chosen as the primary as it offers several advantages. These include a compact binary storage system, the ability to include several physical parameters bound to an assigned coordinate grid, as well as tools for metadata handling. These tools enable writing parameter descriptions, measurement units, data sources, organizations, etc. to the data file. A user can import a data set and calculate the necessary fields or use the built-in data set that can be downloaded from the laboratory server using the package.

The new version of the package was transferred to the project-based system. Thus, all calculations, data, and other parameters can be combined into a single entity in the form of a project. Such a data set fully describes all the work done during the simulation and can be transferred between users via cloud data storage.

Table 1

Characteristics of the hydrology and bathymetry atlases

	ETOPO1	WOA18	RCO	GDEMv3
Data type	bathymetry	bathymetry, hydrology	bathymetry, hydrology	bathymetry, hydrology
Variables	depth	depth, temperature, salinity	depth, temperature, salinity	depth, temperature, salinity
Grid resolution	1/60 degrees	1/4 degrees	1/15, 1/30 degrees	1/6 degrees
Territorial coverage, latitude	90° S. — 90° N	89.875° S – 89.875°N	53.925° N — 65.825° N	78° S — 90° N
Territorial coverage, longitude	180° W — 180° E	179.875° W – 179.875° E	9.5167° W — 30.1834° E	180° W — 180° E
Bathymetry Limits	10421 m	1500 m	249 m	9999 m

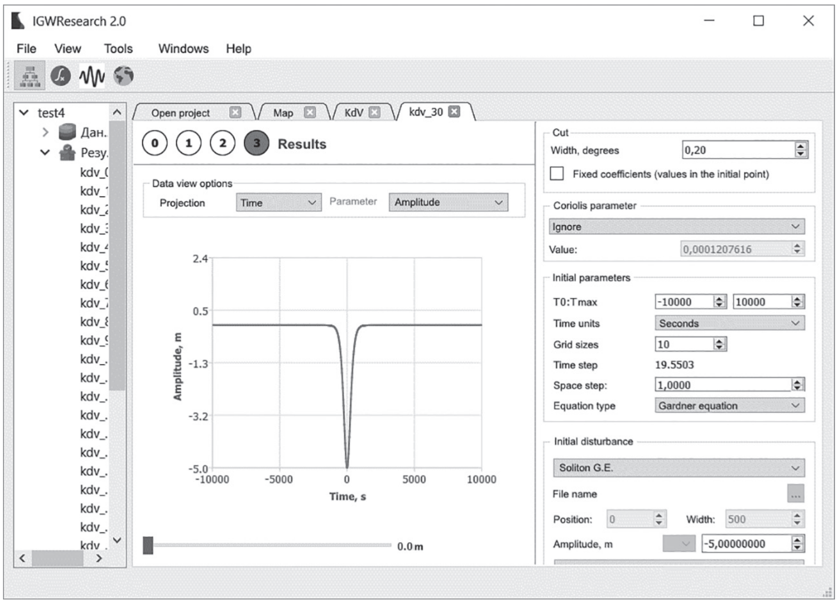

Fig. 1. Software interface.

The package includes visualization for several data types: two-dimensional visualization of the fields of internal waves' characteristics, regarding the geographical grid; display and editing of color maps; plotting graphs and histograms of density profiles, sections, displaying statistical data. The new user interface has been redesigned in accordance with the users' requests. It implements a step-by-step structure for initializing a numerical model, fig. 1.

Conditions checks at each step are carried out automatically using various algorithms. For example, for running a model based on the Gardner equation, it is possible to carry out analytical estimates of the initial perturbation limiting amplitudes automatically and check the given initial amplitude for physical correctness. Thus, the user receives recommendations related to physical limitations, depending on the data entered. Data sampling tools allow interactive selection of data area on the map, including cross-sections, for subsequent processing.

5. Software Cloud Mode

Numerical modeling suggests the fulfillment of several tasks associated with the data preparation, initialization of the model, the calculation initiation, and analysis of the results. Additionally, the numerical calculation can be performed outside the user's workstation on more productive hardware provided via the Internet on request.

The advantages of this approach are more powerful resources, the ability to run multiple calculations in a queue, efficient sharing of equipment, as well as shared cloud data storage.

This approach is implemented in the presented software package. The package system underwent disintegration into modules, during which several modules were allocated: working with data, calculation, and communication blocks. A calculation queue has been implemented that allows run calculations efficiently without overloading the server, fig. 2.

The first system's operation step implies authorization. Since each employee of the laboratory of modeling of natural and anthropogenic disasters of NNSTU n. a. R. E. Alekseev possesses a login and password for the site, thus authorization is performed through the site (http://lmnad.nntu.ru/) by requesting data by the computing server from the laboratory server site server of the laboratory.

The implementation of the remote access system is based on three components — an FTP file transfer server (vsftp), a MySQL database, and a communication unit implemented in C ++ using Qt libraries. The communication unit at the user's request performs authorization in the laboratory site infrastructure and carries out job scheduling, status monitoring, and calculation management through the database. The remaining components receive the tasks from the database and perform jobs according to priority and server load.

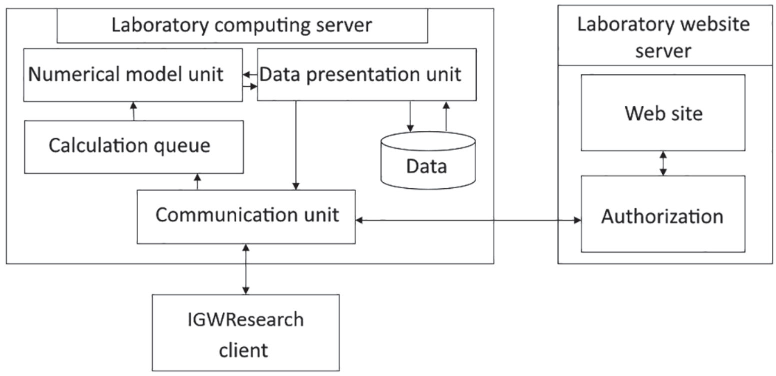

Fig. 2. Block diagram of the cloud computing implementation in the software package.

An additional advantage of the system is the ability to store data and calculation results on the server, as well as exchange these data between users through the system settings of the access rights. Any user of the system can provide access to individual calculations or data to another user.

All calculations are performed using the IGWResearch application, launched on the user's workstation. The interface provides source data download and view for the model initialization, a list of running and scheduled calculations, tools for managing the calculation and status information request, as well as instruments for visualization and download the results from the server.

6. Integration with an online database of internal waves' observations

A communication unit was added to the developed software package to access the online database of internal waves' observations in the oceans [24]. The base was created and maintained by the team of the LMNAD NNSTU n. a. R. E. Alekseev. An online version is also available on the laboratory website [25].

The database consists of brief information about the source of observation, the location coordinates of the recorded event, the date of the event, and the type of observation. At the moment, about 2300 events are recorded, systematized by the type of registration (satellite image, density profile, graph, etc.). The database is updated by scientific articles analysis and other open sources, for example [26].

The interaction with the database module allows visualization of the recorded observations on the map, and the brief information display for each observation in the preview mode, fig. 3.

When necessary, the user can switch to full viewing mode for the selected observation and additional information, including graphic and text data, that are available from the laboratory's website, which guarantees work with the current version of the database.

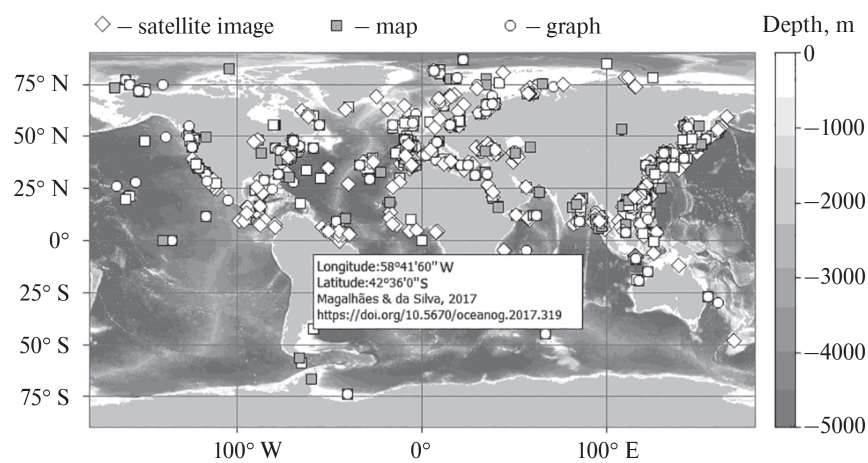

Fig. 3. View mode of the internal wave observations database.

Markers plotted on the map have differentiation according to the data recording type and presented in different shapes and colors. When necessary, built-in filters can be applied, allowing a view of a certain type of data only. Filtering data by type of registration, date, location of the water area is available. The presence of links to the data source allows access to the original site.

Statistics modes are also available, presented in the form of data sources distribution histograms over a geographical location and season or time interval, which can be useful in analyzing the water area and the frequency of occurring phenomena.

7. Example of numerical calculation

When studying the wave regime of the water area, it is advisable to study the existing recordings of wave activity. This information is available in the database of internal waves' observations. For example, consider the waters of the Baltic Sea. It is known that even in non-tidal seas, internal waves can be generated during various dynamic processes. The presence of markers on the map in the Baltic Sea, associated with recorded observations, is shown in fig. 4.

Parameters of the medium are set by designating a section, along with which the simulation is performed. The beginning and the end of the section are set on the interactive map, while the user obtains information about the coordinates of the endpoints and the distance between them, fig. 5.

Since the Baltic Sea is non-tidal, the direction of internal waves' propagation is almost entirely determined by the source of generation and the properties of the medium. In this example, we consider the internal wave soliton transformation southeast of

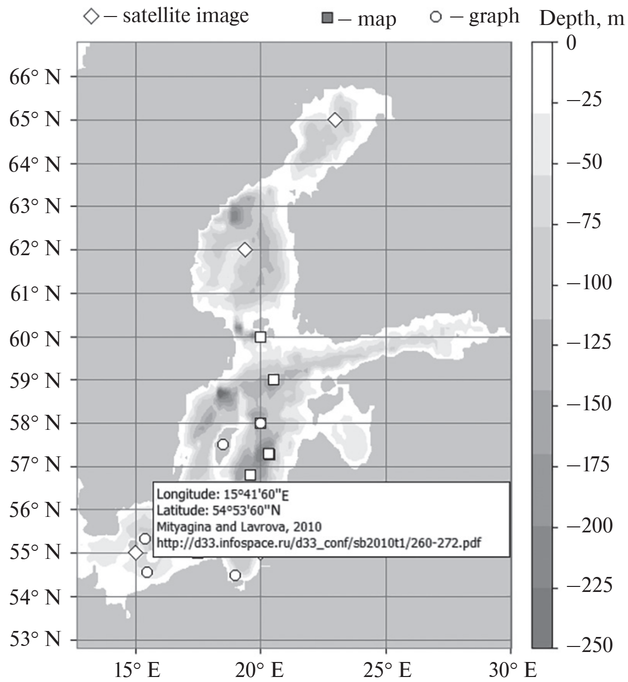

Fig. 4. In situ internal waves observations in the Baltic Sea.

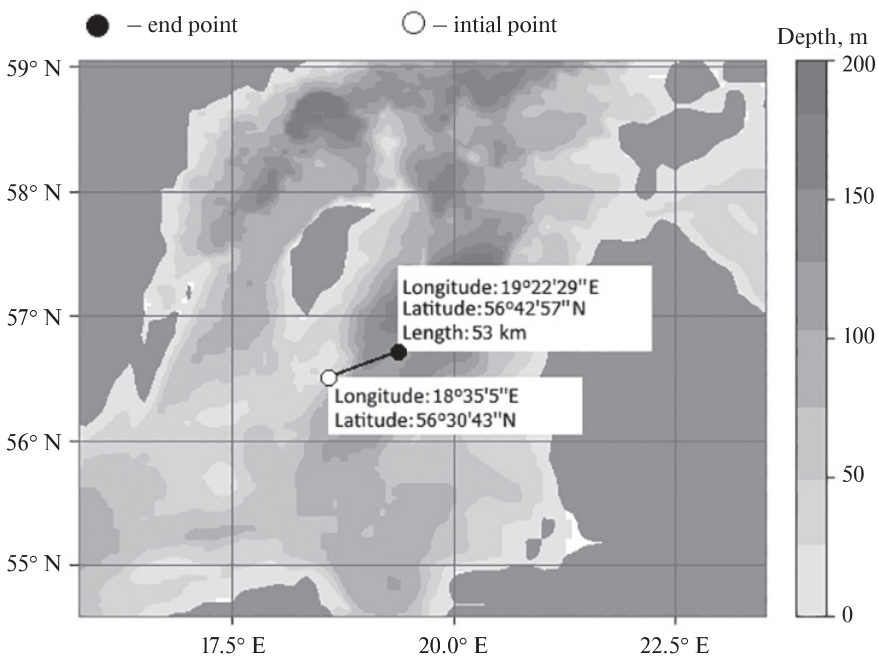

Fig. 5. Environment setting tool.

Gotland island, in the proximity of which there are satellite observations of surface manifestations of internal waves. The RCO atlas was chosen as the January initial data for the experiment. The length of the selected section was 53 km, the coordinates of the initial point of the section: 18° 35'5'' E, 56° 30'43'' N and the coordinates of the endpoint of the section: 19° 22'29'' E, 56° 42'57'' N. The density field along the section is shown in fig. 6. As an illustration, we used a simplified model based on the Gardner equation for an inhomogeneous medium (not considering the effects of Earth's rotation and dissipation) to focus on the features of wave transformation along a horizontally variable path. The values of the coefficients of the Gardner equation along the section are shown in fig. 7.

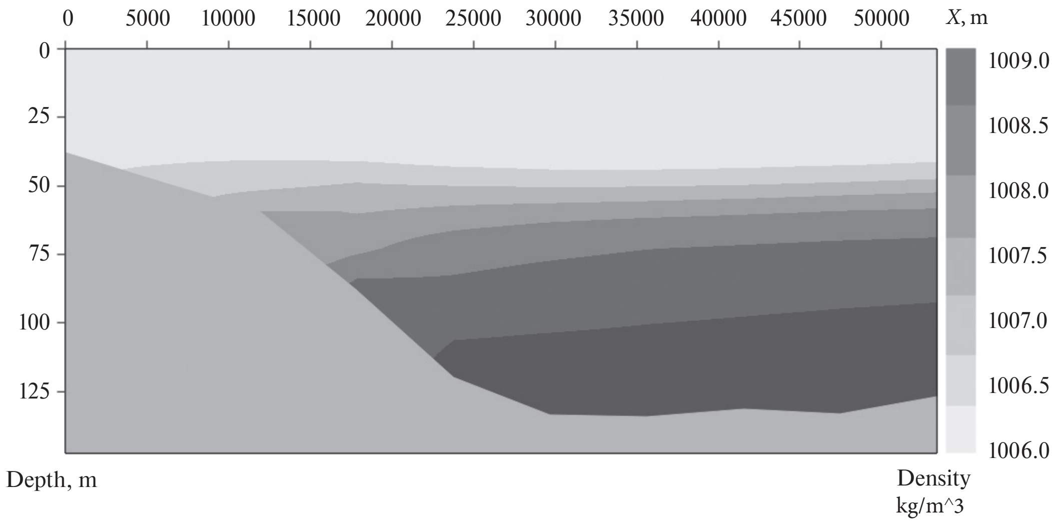

Fig. 6. Density field along the selected cross-section.

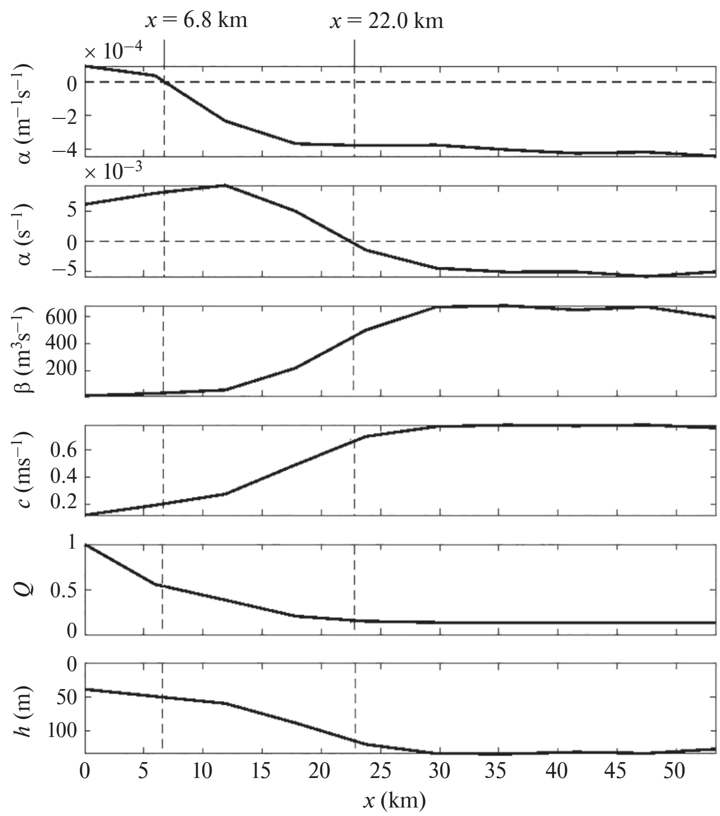

Fig. 7. Characteristics of internal waves and bathymetry along the cross-section and the positions of turning points where the parameters of the quadratic and cubic nonlinearity change signs (6.8 km and 22 km respectively).

At each section point, they are completely defined by the depth and density stratification (see, for example, [27]) and drive the wave regime of internal waves.

The initial perturbation is given in the form of the Gardner equation [11] soliton with a 10-meter amplitude with a positive polarity. Since the coefficient of quadratic nonlinearity (α) and the coefficient of cubic nonlinearity (α_1) are positive at the beginning of the section, the weakly non-linear theory predicts the existence of waves of both positive and negative polarity, but with amplitudes greater than the minimum critical value (amplitudes of an algebraic soliton; see fig. 8). The result of the propagation and transformation modeling of a soliton with an amplitude of 10 m is shown in fig. 9 as a diagram, where x is the coordinate along the section, $\tilde{s}$ — is the time coordinate in the moving coordinate system.

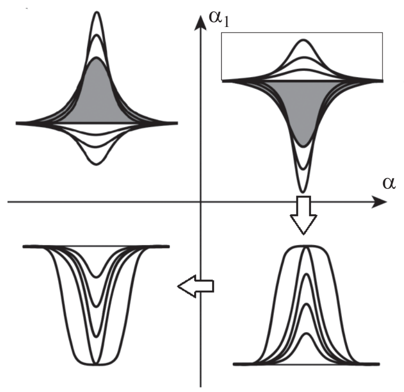

Fig. 8. Wave regimes estimate.

In 6.8 km from the section beginning, the coefficient of cubic nonlinearity changes sign, while the coefficient of quadratic nonlinearity remains positive and even increases. A change of cubic nonlinearity sign leads to a change in the wave regime resulting in only one family of soliton solutions of positive polarity only (since the coefficient α is positive) with a limited amplitude, defined as the ratio of the quadratic nonlinearity coefficient to the modulus of the cubic nonlinearity coefficient (fig. 8). In addition to changing wave modes in the second part of the section (from 6.8 km to 22 km, where the sign of the quadratic nonlinearity changes), there is a significant horizontal heterogeneity of the marine environment (in particular, the bottom depth changes significantly, as can be seen from fig. 7). It may explain the intense restructuring of the soliton. Starting from the middle of the second part of the section, the nonlinear correction to the wave velocity tends to zero, therefore transforming to a train of waves of comparable amplitude.

At a distance of 22 km from the start of the wave propagation, the quadratic nonlinearity coefficient changes sign (from positive to negative). Following the Gardner equation, negative polarity solitons only can exist in this case. In other words, in a transition to this zone, a soliton of positive polarity should cease to exist, which is

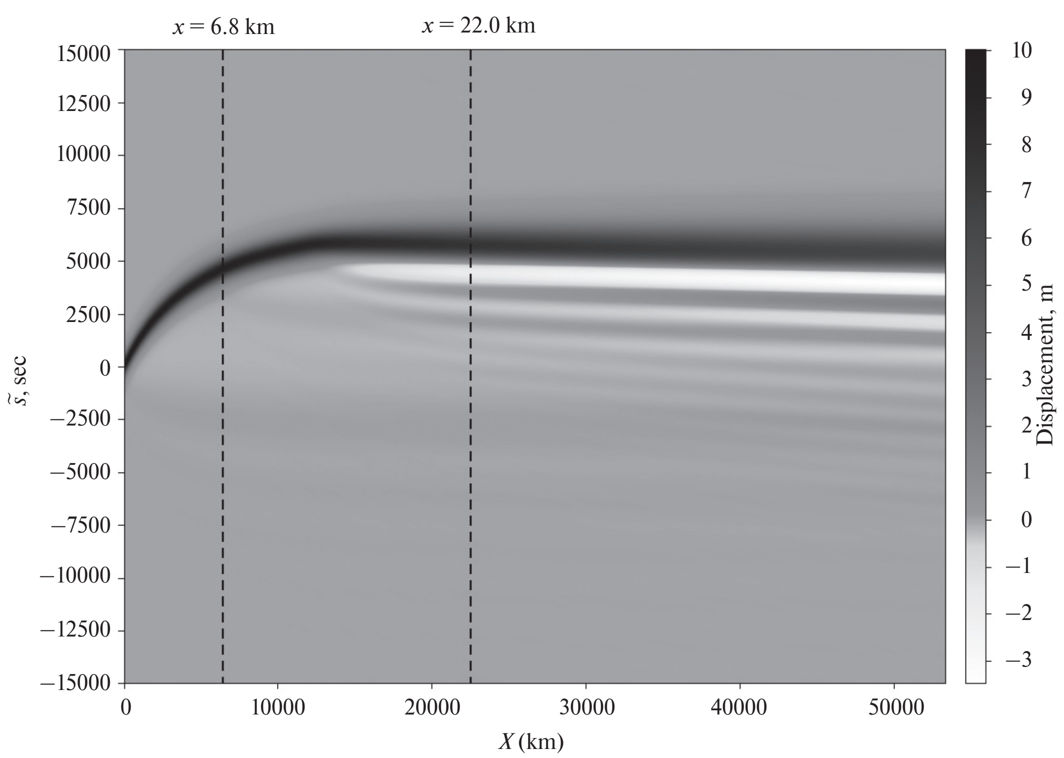

Fig. 9. Result of the soliton propagation and transformation modeling.

seen in the spatiotemporal diagram in the third part of the section. As can be seen from fig. 9, the amplitude of the wavefield decreases from 10 m at the start of the path to 4 m at the end, while the soliton is converted into a train of waves.

8. Conclusion

In this article, the authors presented the capabilities of the IGWResearch2 software package, examined some features of the software implementation, and provided an example of numerical simulation. The package supports internal waves modeling in a stratified fluid and contains a sufficient set of tools for numerical experiment setup, management, and analysis. It does not require an examination of the source code and is designed for a wide range of users.

The developed environment comprises a set of input data for initializing numerical models, several models on the subject of internal waves and tools for experiment control and results' analysis. It allows for efficient calculations, including usage of cloud technologies and cloud data storage. The proposed approach made it possible to increase the efficiency of numerical experiments by transferring the computational process from workstations to a more efficient multiprocessor server. The calculations' queueing enables computing resources' handling on the server. Cloud storage shared between users of the system provides flexible access to data, including experimental results exchange, as well as the sharing of raw data for numerical models' initialization. Integration of the Research Laboratory's of the LMNAD NNSTU n. a. R. E. Alekseev services and infrastructure (access to the observation database, authorization mechanism) into the software package made it possible to create a comprehensive tool for conducting numerical experiments.

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Литература

1. *Рувинская Е.А.*, *Куркина О.Е.*, *Куркин А.А.*, *Зайцев А.И.* Моделирование воздействия внутренних волн на морские платформы для гидрологических условий шельфовой зоны о. Сахалин // Фундаментальная и прикладная гидрофизика. 2017. Т. 10, № 4. С. 61–70.
2. *Alpers W.* Theory of radar imaging of internal waves // Nature. 1985. V. 314. P. 245–247.
3. *Liu A. K.*, *Chang Y.S.*, *Hsu M.-K.*, *Liang N.K.* Evolution of nonlinear internal waves in the East and South China Seas // *Journal of Geophysical Research*. 1998. V. 103. P. 7995–8008.
4. *Рувинская Е.А.*, *Тюгин Д.Ю.*, *Куркина О.Е.*, *Куркин А.А.* Зонирование по типам плотностной стратификации вод балтийского моря в контексте динамики внутренних гравитационных волн // Фундаментальная и прикладная гидрофизика. 2018. Т. 11, № 1. С. 46–51.
5. *Grimshaw R.*, *Pelinovsky E.*, *Talipova T.* The modified Korteweg-de Vries equation in the theory of large-amplitude internal waves // Nonlinear Processes in Geophysics. 1997. V. 4, N4. P. 237–350.
6. *Kurkina O.E.*, *Kurkin A.A.*, *Soomere T.*, *Pelinovsky E.N.*, *Rouvinskaya E.A.* Higher-order (2+4) Korteweg-de Vries — like equation for interfacial waves in a symmetric three-layer fluid // Physics of Fluids. 2011. V. 23, N11. P. 116602–1–13.21.
7. *Талипова Т.Г.*, *Пелиновский Е.Н.*, *Куркин А.А.*, *Куркина О.Е.* Моделирование динамики длинных внутренних волн на шельфе // Известия РАН. ФАО. 2014. Т. 50, № 6. С. 714–722.
8. *Талипова Т.Г.*, *Куркина О.Е.*, *Наумов А.А.*, *Куркин А.А.* Моделирование эволюции внутреннего бора в Печорском море // Фундаментальная и прикладная гидрофизика. 2015. Т. 8, № 3. С. 62–71.
9. *Талипова Т.Г.*, *Пелиновский Е.Н.* Моделирование распространяющихся длинных внутренних волн в неоднородном океане: теория и верификация // Фундаментальная и прикладная гидрофизика. 2013. Т. 6, № 2. С. 46–54.
10. *Полухина О.Е.* Поверхностные волны в стратифицированном океане со сдвигом скорости // Известия Академии инженерных наук РФ. 2001. Т. 2. С. 126–138.
11. *Pelinovsky E.*, *Polukhina O.*, *Slunyaev A.*, *Talipova T.* Internal solitary waves // Chapter 4 in the book "Solitary Waves in Fluids" (Editor R. Grimshaw). WIT Press. Southampton, Boston, 2007. P. 85–110.
12. *Grimshaw R.*, *Talipova T.*, *Pelinovsky E.*, *Kurkina O.* Internal solitary waves: propagation, deformation and disintegration // Nonlinear Processes in Geophysics. 2010. V. 17, N6. P. 633–649.
13. *Holloway P.*, *Pelinovsky E.*, *Talipova T.* A Generalized Korteweg — de Vries Model of Internal Tide Transformation in the Coastal Zone // J. Geophys. Res. 1999. V. 104, N C8. P. 18333–18350.
14. *Тюгин Д.Ю.*, *Куркина О.Е.*, *Куркин А.А.* Программный комплекс для численного моделирования внутренних гравитационных волн в Мировом океане // Фундаментальная и прикладная гидрофизика. 2011. Т. 4, № 2. С. 32–44.

15. *Fofonoff N.*, *Millard R. Jr.* Algorithms for computation of fundamental properties of seawater // UNESCO Technical Paper in Marine Science. 1983. V. 44. P. 15–25.
16. *Бреховских Л.М.*, *Годин О.А.* Акустика слоистых сред. М.: Наука, 1989. 416 с.
17. *Воронович А.Г.* Распространение внутренних и поверхностных гравитационных волн в приближении геометрической оптики // Известия АН СССР. Физика атмосферы и океана. 1976. Т. 12, № 8. С. 519–523.
18. *Куркина О.Е.*, *Рувинская Е.А.*, *Куркин А.А.*, *Гиниятуллин А.Р.*, *Рыбин А.В.* Вертикальная структура поля скорости жидких частиц при прохождении внутреннего солитона первой и второй моды в стратифицированной жидкости // XXIII международная научно-техническая конференция «Информационные системы и технологии» ИСТ-2017, Нижний Новгород, 12.04–15.04.2017. 2017. С. 971–972.
19. World Ocean Atlas. URL: https://www.nodc.noaa.gov/OC5/woa18 (дата обращения: 31.03.2019).
20. *Teague W.J.*, *Carron M.J.*, *Hogan P.J.* A Comparison between the Generalized Digital Environmental Model and Levitus Climatologies // J. Geophys. Res. 1990. V. 95. P. 7167–7183.
21. *Meier H. E.M.*, *Döscher R.*, *Coward A.C.*, *Nycander J.*, *Döös K.* RCO-Rossby Centre regional Ocean climate model: Model description (version 1.0) and first results from the hindcast period 1992/93 // Rep. Oceanogr. 26, Swed. Meteorol. Hydrol. Inst., Norrköping, Sweden, 1999. 102 p.
22. *Amante C.*, *Eakins B.W.* ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis // NOAA Technical Memorandum NESDIS NGDC-24, 2009. P. 19.
23. NetCDF. URL: http://www.unidata.ucar.edu/software/netcdf (дата обращения 31.03.2019).
24. *Рыбин А.В.*, *Куркин А.А.*, *Куркина О.Е.* Визуализация данных наблюдений внутренних волн в мировом океане // 28-я Всероссийская научно-практическая конференция по графическим информационным технологиям и системам, Нижний Новгород, 16.04–19.04.2018, 2018. С. 201–206.
25. IGWAtlas. URL: https://lmnad.nntu.ru/ru/igwatlas (дата обращения 31.03.2019).
26. *Jackson C.R.* An atlas of internal solitary-like waves and their properties // Second ed Global Ocean Associates, 2004, URL: http://www.internalwaveatlas.com (дата обращения 31.03.2019).
27. *Kurkina O.*, *Talipova T.*, *Pelinovsky E.*, *Soomere T.* Mapping the internal wave field in the Baltic Sea in the context of sediment transport in shallow water // Journal of Coastal Research. SI. 2011. V. 64. P. 2042–2047.

References

1. *Rouvinskaya E.*, *Kurkina O.*, *Kurkin A.*, *Zaytsev A.* Modeling of internal wave action on offshore platforms for hydrological conditions of the Sakhalin shelf zone. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2017, 10, 4, 61–70 (in Russian).
2. *Alpers W.* Theory of radar imaging of internal waves. *Nature*. 1985, 314, 245–247.
3. *Liu A.K.*, *Chang Y.S.*, *Hsu M.-K.*, *Liang N.K.* Evolution of nonlinear internal waves in the East and South China Seas. *Journal of Geophysical Research*. 1998, 103, 7995–8008.
4. *Rouvinskaya E.A.*, *Tyugin D.Y.*, *Kurkina O.E.*, *Kurkin A.A.* Mapping of the Baltic Sea by the types of density stratification in the context of dynamics of internal gravity waves. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2018, 11, 1, 46–51 (in Russian).
5. *Grimshaw R., Pelinovsky E., Talipova T.* The modified Korteweg-de Vries equation in the theory of large-amplitude internal waves. *Nonlinear Processes in Geophysics*. 1997, 4, 4, 237–350.
6. *Kurkina O.E.*, *Kurkin A.A.*, *Soomere T.*, *Pelinovsky E.N.*, *Rouvinskaya E.A.* Higher-order (2+4) Korteweg-de Vries — like equation for interfacial waves in a symmetric three-layer fluid. *Physics of Fluids*. 2011, 23, 11, 116602–1–13.21.
7. *Talipova T.G.*, *Pelinovsky E.N.*, *Kurkin A.A.*, *Kurkina O.E.* Modeling the dynamics of intense internal waves on the shelf. *Izvestiya*, *Atmospheric and Oceanic Physics*. 2014, 50, 6, 630–637 (in Russian).
8. *Talipova T.G.*, *Kurkina O.E.*, *Naumov A.A.*, *Kurkin A.A.* Modelling of the evolution of the internal boron in the Pechora sea. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2015, 8, 3, 62–71 (in Russian).
9. *Talipova T.G.*, *Pelinovsky E.N.* Modeling of propagating long internal waves in an inhomogeneous ocean: the theory and its verification. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2013, 6, 2, 46–54 (in Russian).
10. *Poloukhina O.E.* Surface waves in a stratified ocean with background shear flow. *Izvestiya of the Academy of Engineering Sciences of the Russian Federation*. 2001, 2, 126–138 (in Russian).
11. *Pelinovsky E., Polukhina O., Slunyaev A., Talipova T.* Internal solitary waves. *Chapter 4 in the book* "*Solitary Waves in Fluids*" (Editor R. Grimshaw). *WIT Press*, *Southampton*, *Boston*, 2007. P. 85–110.
12. *Grimshaw R.*, *Talipova T.*, *Pelinovsky E.*, *Kurkina O.* Internal solitary waves: propagation, deformation and disintegration. *Nonlinear Processes in Geophysics*. 2010, 17, 6, 633–649.
13. *Holloway P.*, *Pelinovsky E.*, *Talipova T.* A Generalized Korteweg — de Vries Model of Internal Tide Transformation in the Coastal Zone. *J. Geophys. Res*. 1999, 104, C8, 18333–18350.

14. *Tyugin D.Yu., Kurkina O.E., Kurkin A.A.* Software package for modeling of internal gravity waves in the world ocean. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2011, 4, 2, 32–44 (in Russian).
15. *Fofonoff N., Millard R.Jr.* Algorithms for computation of fundamental properties of seawater. *UNESCO Technical Paper in Marine Science*. 1983, 44, 15–25 (in Russian).
16. *Brekhovskikh L.M., Godin O.A.* Acoustics of layered media. *M., Nauka*, 1989. 416 p. (in Russian).
17. *Voronovich A.G.* Propagation of internal and surface gravity waves in the geometric optics approximation. *Izvestiya AN USSR. Fizika Atmosfery i Okeana*. 1976, 12, 8, 519–523 (in Russian).
18. *Kurkina O.E., Rouvinskaya E.A., Kurkin A.A., Giniyatullin A.R., Rybin A.V.* The vertical structure of the velocity field of fluid particles during the propagation of the first and second mode internal soliton in a stratified fluid. *XXIII International scientific and technical conference* "*Information Systems and Technologies*" IST-2017, *Nizhny Novgorod*, 12.04–15.04.2017, 2017. P. 971–972 (in Russian).
19. World Ocean Atlas. URL: https://www.nodc.noaa.gov/OC5/woa18 (date of access: 31.03.2019).
20. *Teague W.J., Carron M.J., Hogan P.J.* A Comparison between the Generalized Digital Environmental Model and Levitus Climatologies. *J. Geophys. Res*. 1990, 95, 7167–7183.
21. *Meier H. E.M., Döscher R., Coward A.C., Nycander J., Döös K.* RCO-Rossby Centre regional Ocean climate model: Model description (version 1.0) and first results from the hindcast period 1992/93. *Rep. Oceanogr. 26, Swed. Meteorol. Hydrol. Inst., Norrköping, Sweden*, 1999. 102 p.
22. *Amante C., Eakins B.W.* ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. *NOAA Technical Memorandum NESDIS NGDC-24*, 2009. 19 p.
23. NetCDF. URL: http://www.unidata.ucar.edu/software/netcdf (date of access: 31.03.2019).
24. *Rybin A.V., Kurkin A.A., Kurkina O.E.* Visualization of internal wave observation data in the world ocean. *28th All-Russian scientific and practical conference on graphic information technologies and systems, Nizhny Novgorod*, 16.04–19.04.2018, 2018. P. 201–206 (in Russian).
25. IGWAtlas. URL: https://lmnad.nntu.ru/ru/igwatlas (date of access: 31.03.2019).
26. *Jackson C.R.* An atlas of internal solitary-like waves and their properties. *Second ed Global Ocean Associates*, 2004, URL: http://www.internalwaveatlas.com (date of access: 31.03.2019).
27. *Kurkina O., Talipova T., Pelinovsky E., Soomere T.* Mapping the internal wave field in the Baltic Sea in the context of sediment transport in shallow water. *Journal of Coastal Research*. SI, 2011, 64, 2042–2047.