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Pollution of the Black Sea and its study by methods of mathematical modeling

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Abstract

In this study, the articles devoted to simulation of dispersion processes of different substances in the seas and oceans are reviewed. The basic attention is focused on the diffusion mathematical models on spreading of substances of anthropogenic origin in the Black Sea. Numerical models developed at M. Nodia Institute of Geophysics (Tbilisi, Georgia) concerning distribution of different admixtures (oil, Strontium-90, Rioni River alluvium) in the Back Sea basin are described in more details. These models are based on nonstationary 2D and 3D transfer-diffusion equations using annual mean climatic flow field calculated by the barotropic and baroclinic models of the Black Sea dynamics. A theoretical method of determining the pollution source location in a water basin on known pollution concentrations in some points of the upper layer of the sea is also considered. The method is based on a conjugate transfer-diffusion equation. For solution of both the models of dynamics and admixture's dispersion the two-cycle splitting methods, offered by G. I. Marchuk for solution of problems of atmosphere and ocean dynamics are used.

1. Introduction

Among varieties of anthropogenic impact, contamination of an environment (atmosphere, hydrosphere, soil) by the different toxic and radioactive impurities accepts especially dangerous scales. Basic sources of pollution are transport, industrial, power, and rural-economic objects. According to the data of 1980s, all wastes discharged in biosphere were 600 million tone annually, which contained 7 million different chemical substances [1]. Because of growing man-made impact American geophysicists as far back as 1957 have noticed that the humanity makes "large-scale geophysical experiment", it makes not to laboratories or on the computer, but on own planet [2].

Pollution of the hydrosphere especially threatens the humanity. It is obvious that finally the huge part of waste gets in the seas and oceans which perniciously influences sea flora and fauna. Oil and oil products are one of the most dangerous ingredients. Besides that they can cause a serious damage to the live world of the world ocean, they can break a natural hydrological cycle and, consequently, cause anthropogenic climate changes. If on the big square of the ocean surface oil and oil products in a considerable quantity are poured, they will promote reduction of evaporation and simultaneously will decrease salt fluxes in the atmosphere (as decreases wind waves and splashes). As it is known, salt particles play a role of the centers of condensation and consequently their deficiency will block processes of cloud's formation.

All above mentioned concerns first of all the Black Sea, level of pollution of which progresses [3-5]. Note that the Black Sea is a closed water body vulnerable to anthropogenic impact. The sources of the Black Sea's problems are myriad. The rivers that drain into the Black Sea bring with them heavy metals, synthetic organic compounds, oil, nutrients, untreated sewage, and radionuclides from Chernobyl [5]. In the document prepared by the Executive Secretariat of the European and Mediterranean Major Hazards Agreement (2008) is noted that the Danube River alone discharges up to 280 tones of cadmium, 60 tones of mercury, 900 tones of copper, 4500 tones of lead, 6000 tones of zinc, 1000 tones of chromium and 50000 tones of hydrocarbons annually. The other main rivers that flow into the Black Sea deposit another 87 tones of cadmium, 1500 tones of copper, 825 tones of lead and 2600 tones of zinc annually. These rivers are also the source of huge amounts of nitrates and phosphorus, which cause increased algal and plankton blooms, a reduction of dissolved oxygen concentrations and severe reductions in fish stocks, leading to changes in the food chain. Seaside cities are an additional source of untreated sewage, while their ports are a large source of both oil pollution and the importation of non-native species [5].

Studying of regularities of migration processes of different substances in the seas and their forecast is one of the most actual problems of modern operative oceanography. Besides experimental methods of researches, successful solution of these problems demands wide attraction of mathematical methods for the purpose of creation of adequate models of distribution of admixtures in water basins. It is well known that hydrodynamic factors – transport and dispersion of impurities by currents and turbulent eddies play an important role in change of concentrations along with other physical and chemical-biological factors. Therefore, modeling and forecast of distribution of different substances in the seas is a complex problem, which needs coupling of transport models with models of sea dynamics.

Models of distribution of impurity (transport models) coupled with models of dynamics should become a basis for operative forecasting system which will provide information about current and future state of the sea environment. Such operative information gives possibility to optimize and make more effective the actions carrying out for the purpose of minimizing of negative consequences.

In some cases, the finding of a pollution source, when its location is not known, may be also an important environmental problem. It is well-known that the Black Sea (as well as some closed seas) sometimes was a place of a burial place of strongly toxic substances (see, the newspaper "Izvestia ", 22 December 1998, Russia). Such burial places which are in deep layers of the sea, are "delayed-action bomb". In due course, as a result of corrosion of tightness of the cases containing these substances, they can become the reason of considerable accident – poisonings of the most part of water area of the sea. In certain cases location of such burial places it is not known. The finding of such sources for the purpose of their neutralization is connected with carrying out of expensive experimental works. Therefore, working out of theoretical methods of definition of source location will allow to avoid the big financial expenses.

Important problem for coastal zones of the seas is also studying of distribution of river alluvium deposits which play important role in processes of formation beaches and coastal lines [6-8].

In this study, papers devoted to simulation of dispersion processes of different substances in the seas and oceans are reviewed. The basic attention is focused on the diffusion mathematical models on spreading of substances of anthropogenic origin in the Black Sea. 2D and 3D numerical models developed at M. Nodia Institute of Geophysics (Tbilisi, Georgia) concerning distribution of different admixtures (oil, Strontium-90, Rioni River alluvium) in the Back Sea basin are described in more details. A theoretical method of determining the pollution source location in a water basin (on example of the Black Sea) on known pollution concentrations in some points of the upper layer of the sea is also considered.

2. State of studying of pollution of the Black Sea and other regions of the World ocean

Several last decades, distribution of impurity of anthropogenic and natural origin in the seas and oceans and related problems of turbulent diffusion are studying intensively with use of experimental and theoretical methods. Well-known monographies [9-13] are devoted to these problems. Experimental researches which have been based on direct measurements of turbulent pulsations of current speeds, have begun in the 1940s [14-16]. It is obvious that application of only experimental methods is not able to study complex migration processes of different substances in the World ocean completely.

At present, methods of mathematical modeling are an effective tool for studying of non-stationary diffusive processes in the natural environment. In this article we will concern for the most part the works which are based on a transfer-diffusion equation of a substance. This equation considers hydrodynamic factors – advection and turbulent diffusion. Change of concentration of an impurity because of physical and chemical factors may be taken into account with including of a special term in the equation.

Among diffusion models on simulation of dispersion of different substances in the seas and oceans stationary one-dimensional models are the most simple, where distribution of substances (oxygen, radiocarbon, et al) on a vertical is considered [17, 18]. In these models the vertical speed and the factor of diffusion were constant and the equations were solved for Pacific and Atlantic oceans. Comparison of the observed and calculated values has given to authors the chance to define values of vertical speed and turbulence factor. It is obvious that we can not expect from such simplified models to describe real processes with good accuracy.

Nonstationary one-dimensional models on a vertical have found wide application in studying of contamination of the ocean by radioactive impurity. Such researches became very actual from the end 1950s and the beginnings of 1960s, when the nuclear weapon tests have intensively begun. Artificial isotopes have appeared in the nature since 1945, when Uranium nuclear fission was carried out for the first time. Since this moment there is an environment pollution by radioactive impurity continuously. At the beginning, the basic source of pollution was the nuclear weapon testing in different objects of environment [19]. After the contract of 1963 on prohibition of nuclear tests the contribution of this source in nature pollution was sharply reduced, but this contract could not stop growth of radioactive danger [20]. The role of atomic power stations, nuclear reactors, and manufactures of processing of nuclear fuel grows in environment pollution. Unprecedented source of radioactive isotopes became the failure occurring on April, 26th, 1986 on the Chernobyl atomic power station when within several hours per atmosphere the radioactive substance in number of 50 million Curie has been thrown out.

It is necessary to notice that contamination of the ocean by radioactive products occurs on two ways: in the form of aerosols under the influence of gravitational forces (dry sedimentation) and atmospheric precipitation (wet sedimentation). The radioactive analysis has shown that concentrations of radioactive impurity of the internal seas of Europe, including the Black Sea, considerably surpass concentrations in the ocean [13]. Some authors explain this fact by "effect of the limited layer". It means that radioactive substance does not extend in deep layers because of shallow reservoir and a weak vertical turbulent exchange.

Experimental and theoretical studying of radioactive pollution of the Black Sea has begun since 1959 [13, 19-26]. A radioisotope strontium-90 (Sr^{90}) was taken as the indicator of radioactive infection which always accompanies an artificial radioactivity and his half-life is 28 years. For the first time the intensity of distribution of strontium-90 from a surface of the Black Sea in deep waters has been calculated in [22] on the basis of the nonstationary one-dimensional equation of turbulent diffusion. On the Black Sea surface the flux of Sr^{90} has been presented as the sum of two components: the first component was a flux from atmosphere, and the second one – the flux caused by flowing into the sea by the big rivers Sr^{90} and its redistribution across on the Sea surface by turbulent diffusion. Comparison of the calculated profiles of strontium-90 with the observed data has shown good coincidence, especially below depth of 100 m. The one-dimensional non-stationary equation of diffusion was used also for simulation of distribution of Sr^{90} in ocean in [23, 24].

In [25, 26] solutions of one-dimensional turbulent diffusion (vertical velocity was not considered) are given in cases, when on a surface the flux of radioactive isotope was a periodic function of time [25] and exponentially decreased on time [26]. In the first case by means of the upper boundary condition sedimentation of cosmogonies radioisotopes on the sea surface was simulated (it is characteristic by sharply expressed periodicity) and in the second one - reduction of global sedimentation of artificial radioisotopes after the Moscow contract of 1963 was simulated.

In a number of works [27-30] equation of turbulent diffusion was used for the purpose of modelling of biogenic elements and natural impurity – oxygen and carbonic gas. Modelling of these substances is connected with considerable difficulties because chemical and biological processes play big role in changing of their concentrations.

Development of computer facilities and numerical methods of solution of nonstationary 3D differential equations has allowed to consider more perfect models [10, 31-37]. In [35] a 3D numerical model of non-conservative contaminant, coming from permanently acting source in the near-shore zone of a deep-basin is proposed. It was assumed that density and temperature was horizontally homogeneous, the Coriolis parameter and wind stress being constant. Computations carried out by this model have shown that it is necessary to take account of basis orography, space variability of flows and turbulence characteristics in the near-shore zone in calculation of problems of basin contamination.

It is necessary to notice that last decades intensively occurs pollution of the World ocean (including the Black Sea) by oil and oil products. For the Black Sea oil hydrocarbons – the most widespread and dangerous pollutant. These chemical compounds are highly toxic substances and perniciously influence on the organic world of the seas and oceans. Therefore working out of methods of the forecast of distribution and intensity poured in the sea of oil products is one of the most important questions of applied oceanology. The basic mechanisms of distribution of oil in sea basins are described in details in [38-41]. Advective and turbulent transfer, oil evaporation, dispersing, emulsification, photo-oxidation, biodegradation, dissolution, sedimentation on a sea bottom, and formation of pitch balls concern to main physical and biochemical processes. The articles [3, 40-54] are devoted to simulation of oil spill in the Black and other seas. One of paragraphs of the monography [3] is devoted to modelling of distribution of oil hydrocarbons in gulf of Burgos. Model calculations had the purpose to allocate a zone of the greatest oil concentration in water area at concrete hydro-weather conditions. Evolution of concentrations of oil pollution was described by the two-dimensional equation of turbulent diffusion, and the current field turned out on the basis of the model of shallow water. In the model of oil's distribution evaporation, sedimentation and destruction under the influence of biochemical factors were considered. Numerical integration proceeded 25 days to an establishment of a stationary mode. The model is a component of a modelling network of system Argos. Three numerical experiments with the various data on pollution dump have been performed at the currents corresponding to prevailing types of winds in gulf of Burgos (western, southeast, northeast winds).

In [48] the modeling system for weather, currents, wind waves coupled with oil slick transport and fate model is developed. The local area weather forecasting model MM5 is used for operational forecasts in the Black Sea region [55]. It is coupled with a 3D hydrodynamics and sediment transport model, and with the third –generation wave model WAVEWATCH III [56]. The hydrodynamics is simulated on the basis of the 3D primitive equation POM model [57]. This set of models supplies information on currents, waves and sediment concentration to the 3D Lagrangian model of oil slick transport and fate, OILTOX. The oil spill model describes the most important processes of oil transport and weathering. The modeling system was adapted to the Black Sea basin. Examples of application to the North-western shelf of the Black Sea and Dnipro-Boog Estuary were given.

In [40] a 3D coupled flow/transport model has been developed to predict the dynamics of the Black Sea and dispersal of pollution. The transport module of the model used Lagrangian tracking to predict the motion of individual particles. Currents used in the model have been generated by high resolution, low-dissipative numerical circulation model, DiaCAST [58], implemented for the Black Sea. The basic processes affecting the fate of oil are taken into account and parameterized in the transport model.

In [41, 43, 44] A 3D hybrid flow/transport model is developed to predict the dispersal of oil pollution in coastal waters. The model is realized for the Caspian Sea and very important results are received. Currents and turbulent diffusivities used in the model are generated by a numerical ocean circulation model (POM) implemented for the Caspian Sea. Oil slick movement and risk of coastline contamination by beaching of offshore oil spills are illustrated for different wind conditions. As in [40], the model predicts drift and dispersion processes at sea applying the Lagrangian dispersion formulation.

Danish Meteorological Institute (DMI) has developed an improved version of oil drift model based on a 3D current field (the old version was based on a 2D depth integrated current field). The new model calculates the oil transport, drift, and fate at sea surface and at the deeper water depths [47]. The new model is a 3D oil drift and fate model based on a 3D ocean circulation model developed by BSH in Germany. An oil spill is treated as a release of a number of "particles". Each particle is assigned mass, volume and composition. Turbulent motion is described by the Monte Carlo method. It is interested to note that DMI has experienced successful oil drift and fate predictions by the use of the 3D oil drift and fate model- for the two oil spill accidents in the Danish waters: the Fu Shan Hai and Baltic Carrier.

Météo-France has developed an oil spill response model (MOTHY), designed to simulate the transport of oil in three dimensions [49-54]. A hydrodynamic ocean model is linked to an oil spill model including current shear, vertical movements and fate of the oil. The oil slick is modelled as a distribution of independent droplets that move in response to current shear, turbulence, and buoyancy. The model was calibrated on a few well documented pollution incidents such as Torrey Canyon (1967), Amoco Cadiz (1978), Tanio (1980), Gulf War (1991), Aegean Sea (1992). A collaboration between the National Meteorological Services of Bulgaria (National Institute of Meteorology and Hydrology : NIMH) and France (Meteo-France) led to an oil spill response system for the Black Sea. The Météo-France oil spill model MOTHY has been configured and adapted for the specific conditions of the Black Sea area by NIMH. The model is now included in the operational system for numerical marine forecasts of NIMH and can be used in case of an accident, for contingency planning and risk assessment.

The 2D and 3D models of the Black Sea dynamics developed at M. Nodia Institute of Geophysics [59-61] have made possible to consider a number of problems connected with simulation of spreading of different impurities in the Black Sea. Next paragraphs of the present study are devoted to 2D and 3D problems connected with simulation of pollution processes of the Black Sea.

3. Simulation of The Black Sea pollution by the models developed at M. Nodia Institute of Geophysics

Developed 2D and 3D models of the Black Sea dynamics [59-61] enabled to consider the problems of distribution of different substances (oil, Strontiun-90, river alluvium) in the Black Sea on known location and power of the pollution sources and determination of location of the pollution source on known concentrations in some points of the upper layer of the sea. Mean annual climatic flow calculated by models of dynamics were used in the ecological problems. For solving of model equation systems in [59-61], we used the two cycle splitting methods, which was proposed by G. I. Marchuk for solving of nonstationary problems of atmosphere and ocean dynamics [62, 63]. This method substantially simplifies the implementation of complex numerical models.

3.1. Simulation of emergency oil spill in the Black Sea

For simulation of oil distribution on the Black Sea surface as a result of emergency emission into the open part of the basin the two-dimensional transfer-diffusion equation was considered in two-dimensional bounded area Ω with a lateral surface S

$$\frac{\partial \varphi}{\partial t}+\frac{\partial u \varphi}{\partial x}+\frac{\partial v\varphi}{\partial y}+\sigma \varphi=\frac{\partial}{\partial x}\mu_{\varphi}\frac{\partial \varphi}{\partial x}+\frac{\partial}{\partial y}\mu_{\varphi}\frac{\partial \varphi}{\partial y}+f \qquad (3.1.1)$$

with the following boundary and initial conditions:

$$\frac{\partial \varphi}{\partial n} = 0 \quad \text{on} \quad S, \tag{3.1.2}$$

$$\varphi = \varphi^0 \quad \text{at} \quad t = 0. \tag{3.1.3}$$

It is supposed that the continuity equation is executed

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

and

$$u_n = 0 \quad \text{on} \quad S.$$

Here φ is the volume concentration of a substance; u and v are the components of the current velocity vector along axes x and y respectively (x is directed eastward, y – northward); μ_φ is the turbulent diffusion coefficient; n is the vector of the outer normal to S; $\sigma = ln2/T_0$ is the parameter of non-conservatively, where T_0 represents a time interval, during which intensity of pollution is decreased two times in comparison with the initial intensity owing to physical–chemical and biological transformation (evaporation, sedimentation, microbiological decomposition, etc.). f describes the distribution of a source power, which in case of the point source may be represent by the delta function

$$f = Q\,\delta(x - x_0)\,\delta(y - y_0),$$

where x_0 and y_0 are coordinates of a location of the source.

The turbulent diffusion coefficient was calculated by the formula [64]

$$\mu_\varphi = \mu / c_\varphi, \qquad \mu = \Delta x\, \Delta y \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2},$$

where Δx and Δy are horizontal grid steps along x and y axes respectively; μ is the coefficient of turbulent viscosity; c_φ is some constant.

For solving of the problem (3.1.1) - (3.1.3) a two-cycle splitting method is used with respect to space coordinates [10]. Parameters of the task had the following values: grid step $\Delta x = \Delta y = 37$ km. time step τ= 1 h, c_φ=10, T_0=180 days. Oil getting into the sea was considered as a point source.

In Fig.1 annual mean surface current in the Black Sea calculated by the 2D barotropic model [59] is presented. It is visible that a conventional current pattern is obtained: the Rim current, which covers the sea basin and cyclonic rotations in the western and eastern parts of the basin. This current field was used in numerical experiments on spreading of the poured oil in a considerable quantity on the sea surface as a result of failures.

Numerical experiments were carried out at different location of a point source. It was assumed that the oil was emitted on the sea surface in quantity of 10000 or 100000 tons of oil.
In one of these experiments the oil in quantity 100000 t was falling into the sea basin in a point with geographical coordinates $44^o 11'$ N and $31^o 02' E$ during 10 h. This point was located in the north-western branch of the Rim current, where the flow was directed to south-west.

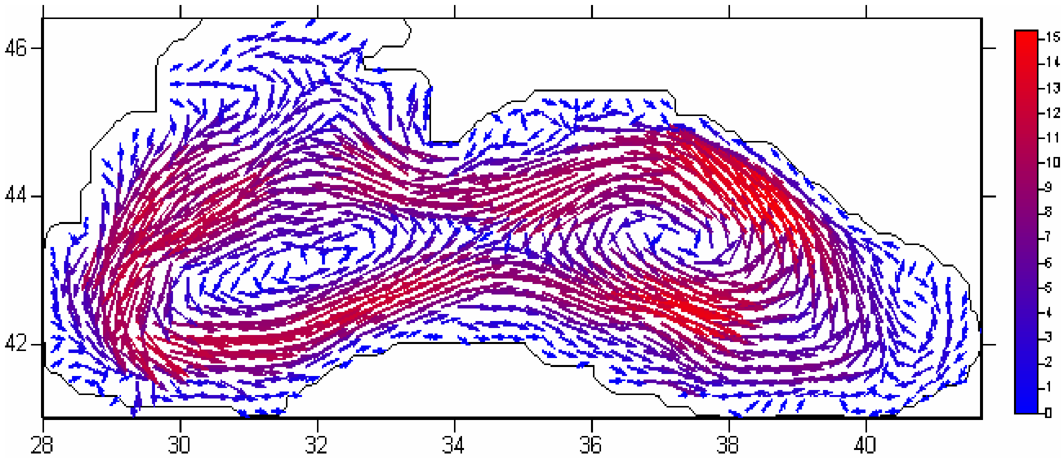

Fig.1.Annual mean climatic circulation (barotropic model).

Fig.2 illustrates a process of distribution of oil pollution in this case. From Figure is visible that a formed oil stain, for the first days under the influence of the Rim current approaches to coasts of Bulgaria and Romania, being expanded simultaneously under influence of the turbulent diffusion. After 15 days the zone of increased concentration ($c_{max} = 2.19$ mg/l) can be observed near Varna. The character of deformation of the oil stain well corresponds to features of circulation of the Black Sea: under influence of the Rim current isolines of oil concentration in a middle of the stain become concave, and spreading of the south part of the stain in east direction is observed (Fig. 2c and 2d). The analysis of results showed that the zone of high concentration drifted to the east direction and after 120 days reached Georgian coast, but with decreasing concentrations. The oil concentrations decreased as a result of diffusion expansion and physical-biochemical transformation.

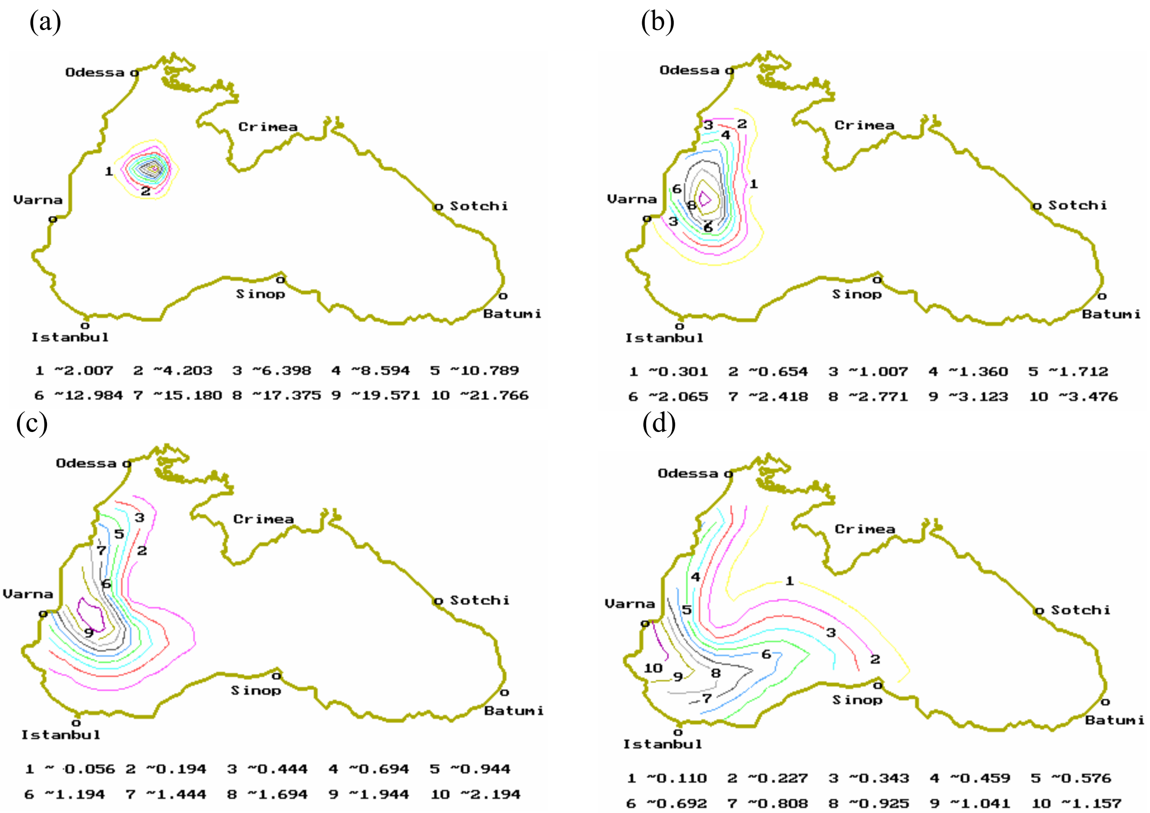

Fig.2. Isolines of the oil concentrations in the first numerical experiment (in unites of mg/l) at different moments after emergency oil emission: (a) – 2 days, (b) – 10 days, (c) – 15 days, (d)- 30 days.

In the other numerical experiment the source was located in a point, lying outside of the Rim current, about in a middle of the basin with geographical coordinates $43^0 11'$ N and $34^0 33'$ E. The oil in quantity 100000 t was falling into the sea basin. In this part of the basin current is more weak, than within the Rim current current. Isolines of computed oil concentrations are shown in Fig.3. From this Figure it is visible that in this case the process of oil pollution distribution differs from observable in the previous experiment at least in the first month after emergency emission. For this period deformation of the oil stain is reduced to its expansion in north-western and south-eastern directions.

The Rim current predetermines character of distribution of the oil pollution. The northern branch of the main Black Sea current brings away pollution for west, and the southern one - for east. Thus, as a result of an advection already during a month after emergency incoming of oil into the sea, almost whole basin of the Black Sea appears polluted by the oil. It should be noted, that in the previous experiment to this moment the pollution took much small territory. This fact specifies that scale and character of pollution of the Black Sea as a result of emergency oil emission largely depends on a region, where there was an emergency. Hereinafter the process of distribution of oil contamination has almost such character, as in the first experiment: the pollution takes the whole water area with decreasing concentrations and simultaneously process of their constant alignment goes. In addition, a zone of high concentration constantly drifts in cyclonal direction under the influence of the Rim current. Numerical experiments conducted at a source with getting the oil in quantity 10000 t have shown that qualitatively the process of the oil contamination dispersion does not practically differ from that oil distribution patterns, which are showed in the present paper.

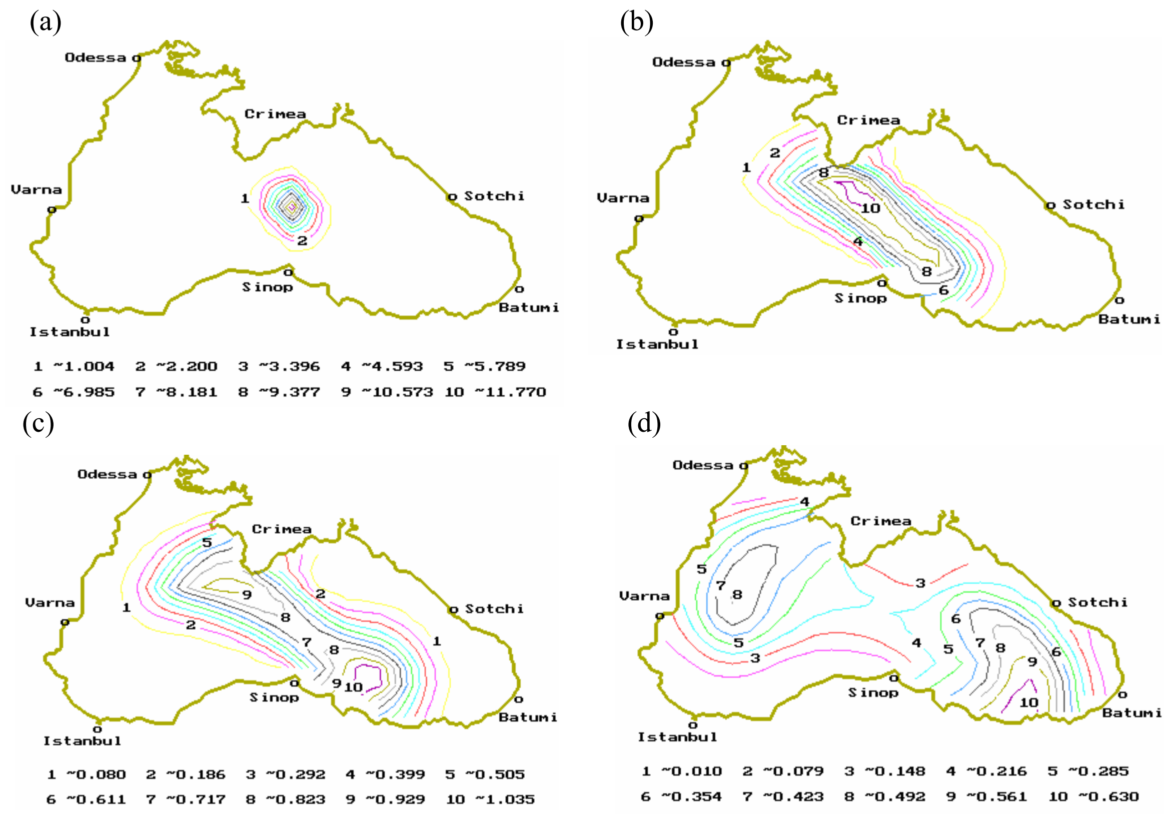

Fig.3. The same as in Fig. 2, but the oil emission was in point with coordinates $43^0 11'$ N and $34^0 33'$ E.

On the basis of the analysis of results of conducted numerical experiments is possible to conclude, that at single falling of a plenty of an oil into open part of the Black Sea following properties of process of oil distribution are found out:

a) The Rim current having cyclonic character predetermines principal features of the oil pollution distribution.
b) For several ten days after emergency emission, character and scale of oil pollution largely depend on that fact in which region of water area there was an emergency.
c) On expiration of a certain time (about 1.5 - 2 months) after failure, the process of distribution of oil concentrations practically does not depend on a location of the oil pollution source. Pollution is distributed on all water area of the Black Sea and tendency to alignment of concentrations is noticed.

3.2. Simulation of 3D distribution of non-conservative impurity from the deep source

3D problem of distribution of non-conservative impurity from the point source lying in deep layers of the Black Sea is considered on the basis of the nonstationary transfer-diffusion equation.. Let $\varphi(x,y,z,t)$ is a function describing volume concentration of a polluting substance in the sea basin, which represents a three-dimensional area Ω with a lateral surface Σ and depth H. In the area Ω we shall consider the transfer-diffusion equation (z is directed from a sea surface vertically downward):

$$\frac{\partial \varphi}{\partial t}+\frac{\partial u\varphi}{\partial x}+\frac{\partial \mathrm{v}\varphi}{\partial y}+\frac{\partial w\varphi}{\partial \mathrm{z}}+\sigma\varphi=\nabla\mu_\varphi\nabla\varphi+\frac{\partial}{\partial \mathrm{z}}\nu_\varphi\frac{\partial\varphi}{\partial \mathrm{z}}+\mathrm{f}, \qquad (3.2.1)$$

where

$$\nabla\mu_\varphi\nabla\varphi=\frac{\partial}{\partial \mathrm{x}}\mu_\varphi\frac{\partial\varphi}{\partial \mathrm{x}}+\frac{\partial}{\partial \mathrm{y}}\mu_\varphi\frac{\partial\varphi}{\partial \mathrm{y}};$$

Here ν_φ is the vertical turbulent diffusion coefficients; $\sigma = ln\,2/T_0$ in case of a radioactive contamination describes reduction of concentration because of radioactive decay (T_0 - decay period).

As boundary and initial conditions we shell accept

$$\begin{array}{llll} \varphi=0 \quad \text{или } \partial\varphi/\partial \mathrm{z}=0 & \text{at} & \mathrm{z}=0, & \\ \partial\varphi/\partial \mathrm{z}=\alpha\varphi & \text{at} & \mathrm{z}=\mathrm{H}, & \\ \partial\varphi/\partial \mathrm{n}=0 & \text{on} & \Gamma, & (3.2.2) \\ \varphi=\varphi^0 & \text{at} & \mathrm{t}=0, & \end{array}$$

where φ^0 is the function describing initial distribution of concentrations; n is the outer normal to the surface Γ, and α - some parameter describing interaction of an admixture with bottom. We assume that velocity components u, v and w satisfy the continuity equation and velocity vector's normal component to the surfaces limited the area Ω, is equal to zero.

Now we shall assume that from a vicinity of a point $\vec{r}_0\,(x_{o,}\,y_o, z_0)$, located in the bottom layers of the basin, in unit of time the quantity of substance Q enters into the sea environment, which subsequently is transferred by water masses and diffused under influence of a small-scale turbulence. In this case, the function f, describing a stationary source of a continuous action may be presented by the delta function

$$f(\vec{r})=Q\,\delta(\vec{r}-\vec{r}_o).$$

Let us integrate the equation (3.2.1) on all volume. Then, using (3.2.2) in case of a homogeneous Neumann boundary conditions we shall receive a mass balance equality

$$\frac{\partial M}{\partial t}=Q-P\ , \qquad (3.2.3)$$

where

$$M=\iiint\limits_{\Omega}\varphi\, d\vec{r}\ ,\ P=\sigma M\ .$$

From (3.2.3) it is visible, that through a certain time after inclusion of a stationary source dynamic balance ($Q=P$) will be established.

The model is realized with space step $\Delta x=\Delta y=37km$. On a vertical the non-uniform grid with the minimal step equal to 1 m near the sea surface was used. Lower than depth 205 m a step was constant, equal to 100m. In total was considered 32 calculating levels. Other parameters had the following values: $\mu_\varphi=2.10^7\,cm^2/s$, $\nu_\varphi=30\,cm^2/s$, $\alpha=0$, $\tau=6\,h$, $T_0=28$ years. Such value of decay period T_0 corresponds to radioisotope strontium-90 (Sr^{90}), which is always accompanied at artificial radioactive transformations. The homogeneous Neiman conditions on all bounders of area Ω were used. It was assumed that at the initial moment contamination of the Black Sea basin was absence.

Three numerical experiments were carried out which differed by depth and coordinates of location of a stationary point source of continuous action. It was supposed, that from a hypothetical source an isotope Sr^{90} by power 2000 Ci/ $year$ constantly enters into the sea. In concrete calculations the sources placed on different depths of 2205, 1205 and 805 m in points with coordinates $43^o11'$ N and $34^o07'$ E, $44^o11'$ N and $32^o47'$ E, $44^o11'$ N and $36^o19'$ E, Respectively. In addition, in the first case the source was in the central part of the sea, and in other cases - near Sevastopol and Novorosiisk.. In all numerical experiments the equation (3.2.1) was integrated up to achievement of dynamical balance. If the gain of polluting substance in the basin for one year did not surpass 200 Ci, was considered, that the equilibrium condition is achieved.

The change in time of activity of Sr^{90}, when the source was located near Sevastopol is shown in Fig.4. The similar picture was observed also in other numerical experiments. It is visible, that approximately after 39 years from the beginning of action of the source Sr^{90} grows slightly in the sea basin.

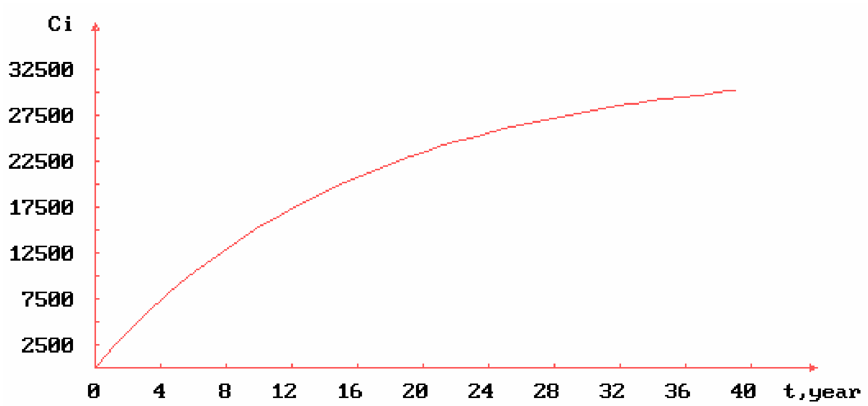

Fig. 4. Change in a time of activity of isotope Sr^{90} in the Black Sea, when the source was located on depth of 1205 m.

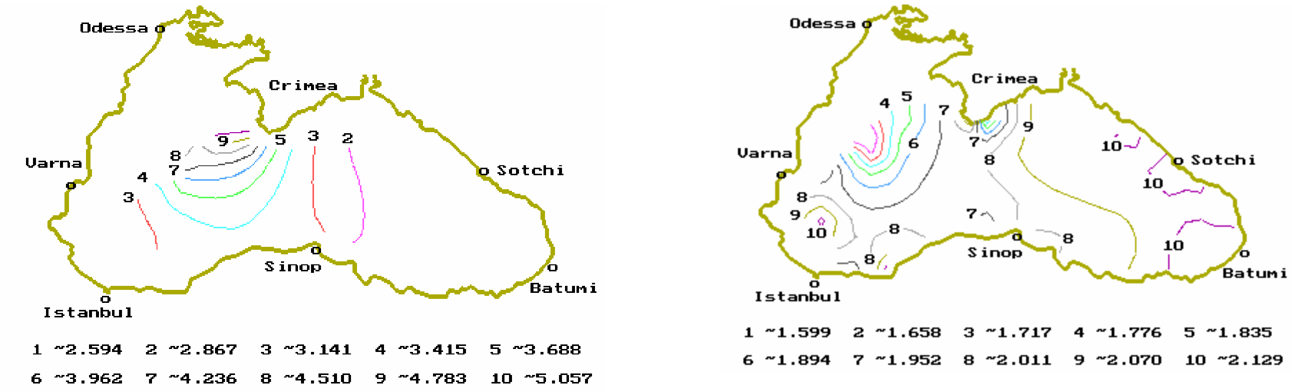

Fig. 5. Isolines of concentration of Sr^{90} (in unites of Bq/m3, the depth of the source location – 1205 m) on horizons: (a) – 1105 m, (b) – 85 m.

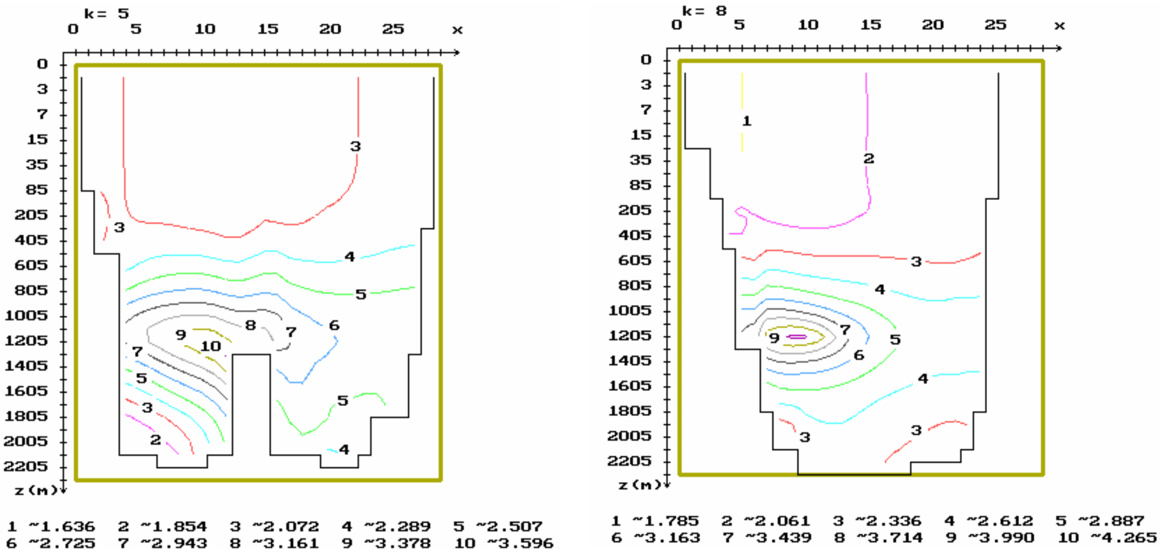

Fig. 6. Isolines of concentration of Sr^{90} (in unites of Bq/m3, the depth of the source location – 1205 m) on vertical sections zx.

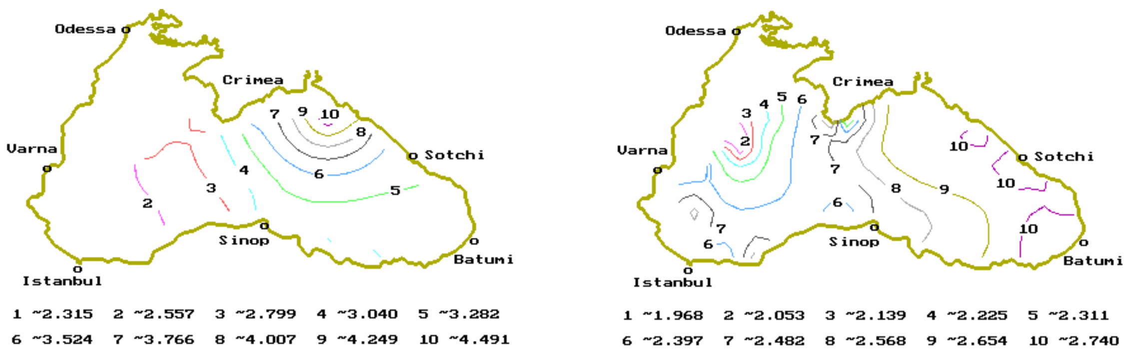

Fig. 7. The same as in Fig.5, but the source was located on depth of 805 m.

In Figs. 5-8 distributions of concentrations after 39 model years after the pollution source located at depths of 1205m and 805 m begun action are illustrated on some horizontal and vertical planes.

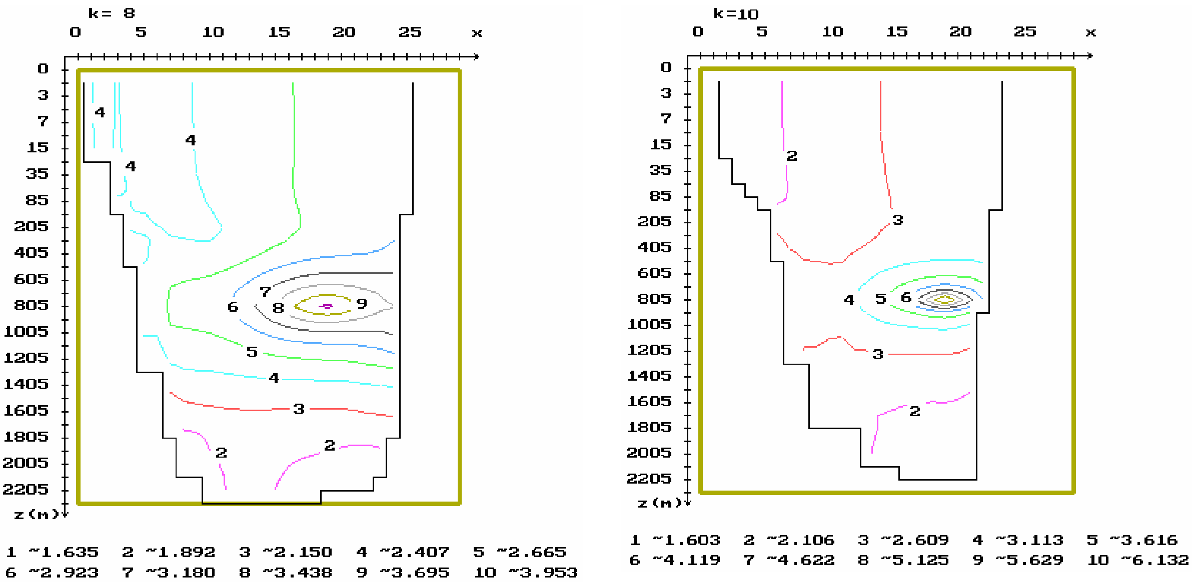

Fig. 8. The same as in Fig.6, but the source was located on depth of 805 m.

Analyzing obtained results it is possible to note the following features of concentration fields: The polluting substance under the influence of advective and diffusive processes is transferred from a source in both the horizontal and vertical directions. The considerable concentrations of an impurity (more than 10 % of concentration in a point source arrangements) can extend to the uppermost layers of the sea even from the source located in the deepest layers. Therefore, the use of a bottom of the Black Sea as a burial place of toxic substances it is inadmissible. Distribution of concentrations of Sr^{90} approximately in the upper 100 metre layer practically does not depend on location of the deep pollution source.

3.3. Simulation of dispersion and sedimentation processes of Rioni River alluvium in the Black Sea water area near Poti city.

Inner-annual variability of processes of transfer – diffusion of Rioni River alluvium and its sedimentation in the Georgian coastal zone of the Black Sea (water area of Poti sity) using the complex circulation/transfer model is simulated. Researches of such processes are very important for water area of Poti city, as it is well-known from experimental researches and historical sources that Rioni River always played a significant role in formation of a coastal line and beach both in the far past, and in the current period [6-8].

The non-stationary 3D complex model consists of hydrodynamic and transfer - diffusion modules. The hydrodynamic module in turn contains the 3D basin scale model of dynamics of the Black Sea [59, 60] and the nested grid model with high resolution. The structure of complex model is shown in Fig. 9.

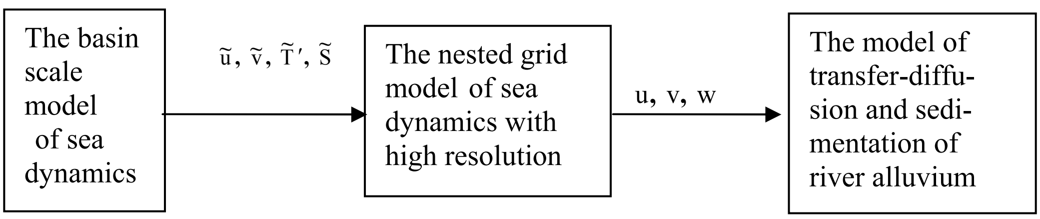

Fig.9. The structure of the complex model

Considered area in a vicinity of Poti (5.9 x 11.9 km) is separated by liquid boundary from other water area of the Black Sea. Information on the liquid boundary about current velocity components $\tilde{u}$, $\tilde{v}$, deviations of temperature $\tilde{T}'$ and salinity $\tilde{S}'$ is obtained as a result of realization of basin –scale dynamic model. The current components u, v and w along axes x, y and z, respectively calculated on the basis of the nested grid regional model of sea dynamics of a coastal zone are used in the model of transfer-diffusion and sedimentation.

The diffusion and sedimentation model of river alluvium is based on the 3D transfer-diffusion equation:

$$\frac{\partial \varphi}{\partial t}+\frac{\partial u\varphi}{\partial x}+\frac{\partial v\varphi}{\partial y}+\frac{\partial (w+w_G)\varphi}{\partial z}=\frac{\partial}{\partial x}\mu_\varphi\frac{\partial \varphi}{\partial x}+\frac{\partial}{\partial y}\mu_\varphi\frac{\partial \varphi}{\partial y}+\frac{\partial}{\partial z}\nu_\varphi\frac{\partial \varphi}{\partial z}, \qquad (3.3.1)$$

where φ is a volumetric concentration of sandy particles, μ_φ and ν_φ - horizontal and vertical diffusion factors, w_G - speed of gravitational sedimentation of particles,. that could be determined by Stock's formula:

$$w_G=\frac{2\rho_p g}{9\rho\,\nu}r_p^{\;2},$$

where r_p is particle's radius; ρ - water density; ρ_p - particles' density; ν -coefficient of kinematic viscosity of the sea water.

(3.3.1) is solved in area Ω with a lateral surface Γ using the following boundary and initial conditions:

$$\frac{\partial \varphi}{\partial z}=0 \text{ at } z=0;\ \nu_\varphi\frac{\partial \varphi}{\partial z}=\beta\varphi \text{ at } z=H;\text{ or } \varphi=0 \text{ on } \Gamma;\ \varphi=\varphi^0 \text{ at } t=0\ ,$$

where β is a parameter which characterizes interaction of substance with a bottom.

The vertical flux of sediments can be presented as the sum of two terms

$$p=-\nu_\varphi\frac{\partial\varphi}{\partial z}+\varphi w_G, \qquad (3.3.2)$$

where the first term represents a turbulent flux of sediments, and the second one - the flux caused by the own gravitational speed of particles. By calculation functions p on lowermost horizons, distribution of intensity of sedimentation on unit square was estimated. Integrating (2) on horizontal area D, we shall receive a total flux of sandy particles

$$p_c=-\iint\limits_D \nu_\varphi\frac{\partial\varphi}{\partial z}dxdy+w_G\iint\limits_D \varphi\,dxdy\,.$$

With the purpose of estimation of a sea-bottom deformation, thickness of sedimentary layer was calculated under the formula

$$h=\gamma\frac{p_t}{\rho_П}, \qquad p_t=\int_0^T p\,dt, \qquad (3.3.3)$$

where p_t represents alluvium passing through the unit square during time T and γ is the empirical coefficient.

Calculations were carried out with 100 m spacing. Own gravitational vertical speed of particles was accepted equal 0,003 cm /s which according to Stock's formula corresponds to particles with radius 0.0031 mm. The time step $\Delta t = 1h$, μ_φ=6.10^{3}cm^2/s, ν_φ = 5 cm^2/s. At t = 0 concentration of particles was absent in the sea and the numerical experiment on seasonal variability was carried out for one modelling year. The beginning of the account corresponded January.

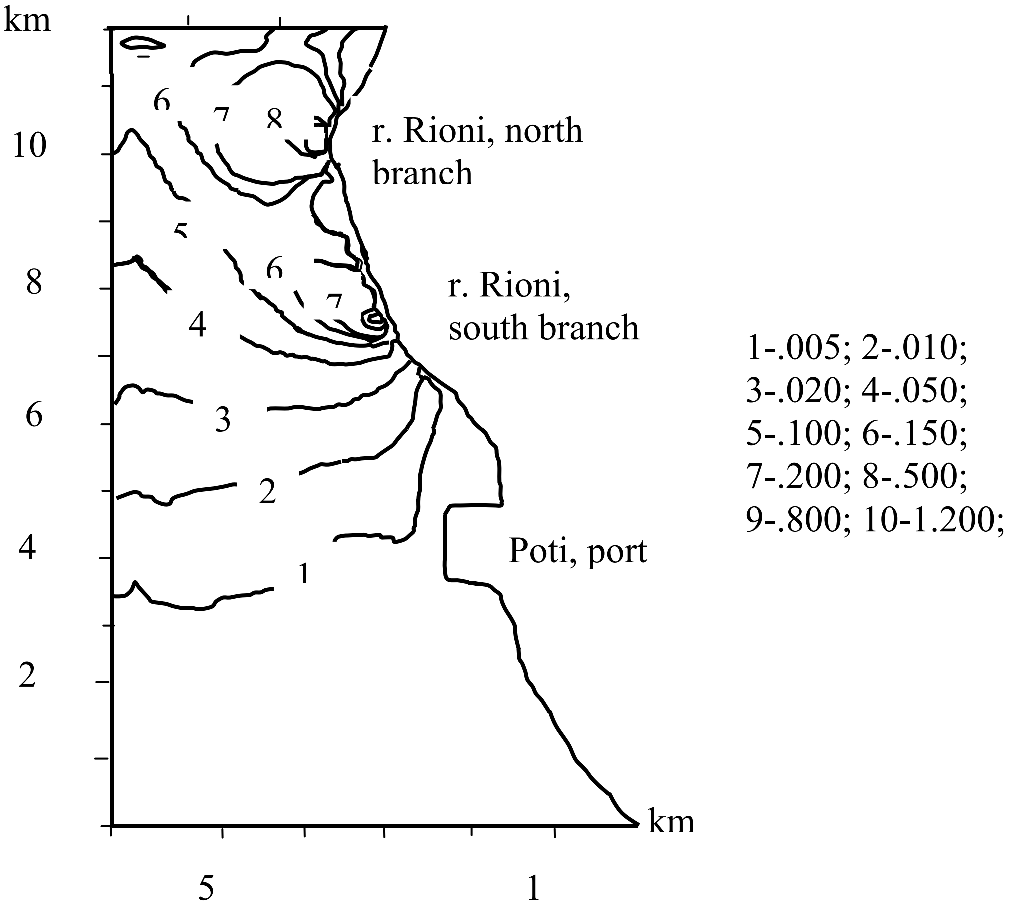

Fig. 10. Isolines of concentration of the Rioni alluvium ($w_{G=}$ 0.003cm/s) on depths of 1 m (in units kg/m^3, February)

In Fig. 10 the results of modeling of spreading of light fraction of alluvium (w_G = 0.003 cm/s) in coastal zone in February at depth of 1 m is presented. This Figure and other results obtained by us show that the pictures of concentration distribution during the year are similar by their quality, and differ from each other mainly by their quantity. The value of concentration in different periods of the year depends mainly on the seasonal changes of discharge of the Rioni River alluvium. The maximum concentration is observed in May, but minimum – in September. The specific peculiarities of the distribution of concentration is that high concentration zones on the upper levels are localized in the mouth regions of the south and north branches of the Rioni River. As it was expected, the marine flow having the north-west and the north directions in surface layer during the year provides the alluvium's transfer to the north, therefore, the alluvium in smaller quantity are spreading to the port side –in the south direction their concentrations gradually diminish. Diminishing of concentration by depth is observed during all periods of the year.

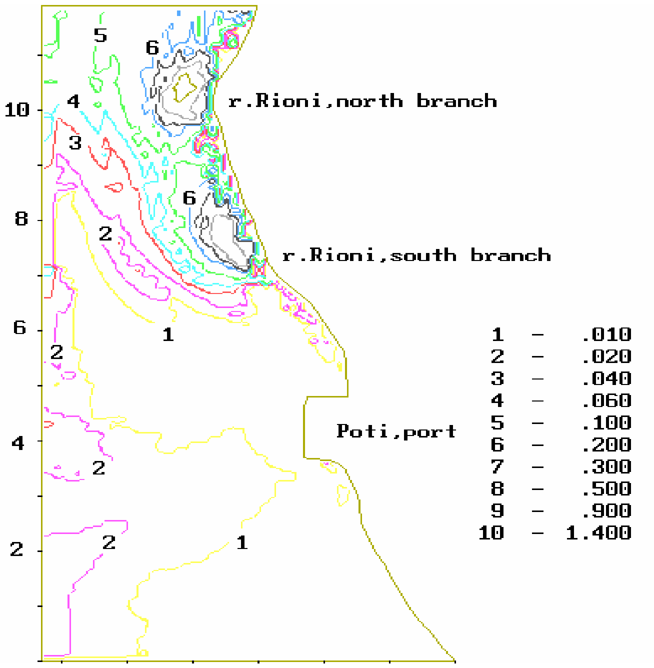

Fig.11. Calculated deformation of the sea bottom (in metres) caused by deposition of solid particles ($w_G = 0.003$ cm/s) during one year.

The precipitated alluvium on the sea bottom may considerably deform sea-bottom. For estimation of this effect we calculated thickness of precipitated mass within one year in each grid point by formula (3.3.3). With the help of coefficient γ in this formula correction of calculated thickness was made in view of that thickness of a sedimentary layer did not exceed 1/5 from depth in the given point. Calculations show that the Rioni River alluvium may significantly deform a sea-bottom (Fig.11).

4. Determination of the pollution source location on the basis of the conjugate equations theory

In [10] was proposed to apply a conjugate transfer-diffusion equation for solution of an important ecological problem of optimum accommodation of the industrial enterprises. The area of an arrangement of new industrial object was determined so that the pollution of atmosphere for all ecological important zones did not exceed the extreme allowable magnitude. This theory can be also used for other important ecological problem – for determination of the location of the pollution source in water basin on known concentrations of a polluting substance in some points of the basin. The method is based on solution of non-stationary conjugate transfer-diffusion equation and the principle of duality. According to this principle, functionals can be calculated as by solving of a basic problem of transfer-diffusion, also by solving of its conjugate problem.

Let's describe briefly essence of the method (in [65, 66] the method is described in details). We will assume, that the concentration field in a water are Ω with lateral boundary Σ and depth H is generated as a result of action of the stationary point source by power Q, location of which is unknown and as a result of observations pollution concentrations are known in some points $\vec{\xi}_i \in \Omega$ ($i=1,2,..,N$) of the upper layer of the sea during time interval (0, T). Our problem consists in determination of the domain $\omega \subset \Omega$, where the source is located.

The source in the vicinity of the point $\vec{r}_0(x_0, y_0, z_0)$ may be presented by the delta function

$$\delta(\vec{r}) = Q\,\delta(\vec{r}-\vec{r}_0)\,,$$

where $\vec{r}$ is any point with coordinates x, y, and z.

For definition $\omega \subset \Omega$ we are solving the conjugate transfer-diffusion equation N times with corresponding right part p_i

$$-\frac{\partial \varphi_i{}^*}{\partial t} - u\frac{\partial \varphi_i^*}{\partial x} - v\frac{\partial \varphi_i^*}{\partial y} - w\frac{\partial \varphi_i^*}{\partial z} + \sigma\,\varphi_i^* = D\,\varphi_i^* + P_i\,,\quad i = 1, 2 \ldots N \qquad (4.1)$$

With following boundary and initial conditions

$$\varphi_i^* = 0 \ \text{ или } \ \frac{\partial \varphi_i^*}{\partial \mathrm{z}} = 0 \ \text{ при } \ \mathrm{z} = 0 \qquad (4.2)$$

$$\begin{aligned} \frac{\partial \varphi_i^*}{\partial \mathrm{z}} &= \alpha\,\varphi_i^* && \text{при} && \mathrm{z} = \mathrm{H}\,, \\ \frac{\partial \varphi_i^*}{\partial \mathrm{n}} &= 0 && \text{на} && \Sigma \end{aligned} \qquad (4.3)$$

$$\varphi_i^* = 0 \qquad \text{при} \qquad \mathrm{t} = \mathrm{T}\,, \qquad (4.4)$$

p_i we will defined by delta-function

$$P_i(\,\vec{\mathrm{r}}, \mathrm{t}) = \delta\left(\vec{r} - \vec{\xi}_i\right)$$

The conjugate problem is solved with decreasing t in the interval $T \geq t \geq 0$. for every selected point in the upper layer of the sea.

It is possible to show that following equality takes place [10]

$$J_{P_i} = \int_0^T dt \iiint_\Omega P_i\,\varphi\, d\Omega = \int_0^T dt \iiint_\Omega \varphi_i^*\, f\, d\Omega \qquad (4.5)$$

This equality expresses a principle of duality of functional J_{P_i}. It means, that functional J_{P_i} can be calculated both by solving of basic problem and conjugate problem (4.1-4.4). If p_i and f we will express by delta-function, then (4.5) may be written as follows:

$$J_{p_I} = \int_0^T \varphi\left(\vec{\xi}_i, t\right) dt \ = Q\int_0^T \varphi_i^*\left(\vec{r}_0, t\right) dt \qquad (4.6)$$

location of the pollution source will be determined by the following way: for each selected points (where concentrations are known) $\vec{\xi}_i \in \Omega$ ($i=1,2,..,N$) the conjugate problem (5.1.1)-(5.1.4) will be solved and will be calculated corresponding functional $Q\int_0^T \varphi_i^*\left(\vec{r}_k, t\right)\mathrm{dt}$. The subset of possible points of location of the source ω_i (i = 1, 2,…, N) for each selected point will be defined from principle of duality (4.6).

The area of the location of the source is defined as intersection of subsets ω_i.In general, this area Can contain also other points, except a real point $\vec{r}_0$. It is obvious That than less points contains the area ω, the source site is especially precisely defined.

Test numerical experiments were following: as a result of solution of a direct transfer-diffusion problem in time interval (0, T) on known power and coordinates of pollution source, we received calculated field of pollution concentrations for the Black Sea basin. After that we "forget" coordinates of the source and aimed to determine the source location on the basis of the introduced theoretical method.

The method was tested for the Black Sea basin in two cases:

- The pollution source was allocated in deep layers of the sea (3D problem).
- The pollution source was allocated on the sea surface (a case of oil dispersion on the sea surface, 2D problem).

Sensitivity of the method to changes of values of parameters of a problem has been investigated.

Fig.12 illustrates determination of a location of the pollution source in that case, when the pollution source was at depth of 805 m. As a result of solution of the direct transfer-diffusion problem, (i. e. finding pollution concentration field on know location and power of the source) pollution concentration field after modelling 10 years has been received. After that we selected any 5 points in the surface layer. In this Figure subsets ω_i (i =1,2,…5) determine the areas of possible location of the source. Intersection of these subsets indicates the location of the pollution source (last picture in the Figure).

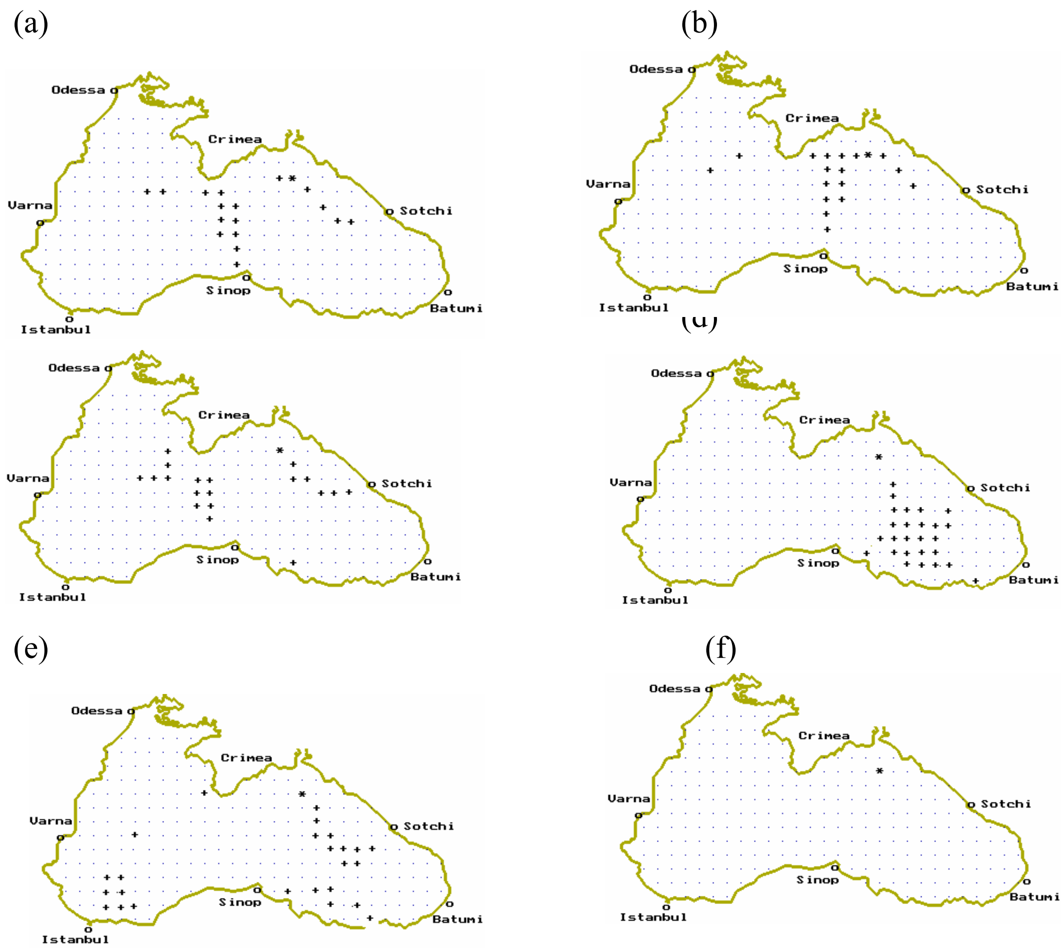

Fig. 12. Subsets of possible points of the source on the horizon 805 m: (a) – ω_1; (b) –ω_2; (c) – ω_3 ; (d) – ω_4; (e) – ω_5 ; (f) -w. .

Results of numerical experiments have shown that:

- the method is more exact in that case when the source is on a sea surface. In this case accuracy of a method depends on time which has expired from the moment of oil flood. The less time has passed, the source site is more precisely defined. The method is steady enough to changes of key parameters of a problem and can be used in practice.
- In case of a source arrangement in deep layers of the sea, the method the more precisely, than

on smaller depth is a source. When the source is in very deep layers (~ 2000 m) the method defines depth and area of an arrangement of a source, but this area is rather expanded. Errors of measurement influence accuracy of the method a little, but the error admitted at definition of a power of the source, is considerably reflected in accuracy of the method. Despite it, in this case method application in practice considerably will facilitate carrying out of experimental works on search of pollution source detection.

5. Summary

We provided an overview of mathematical models on simulation of different substances in oceans and seas. Our attention is focused on pollution of the Black Sea and its simulation using numerical methods, but there are also considered operative models of oil spill drift (the models of DMI and METEO-FRANCE), that are applied for other seas. On the basis of 2D and 3D turbulent diffusion equations we developed numerical models of

- oil spreading on the Black Sea surface as a result of emergency emission into the open part,
- 3D distribution of nonconservative, dynamically passive admixture from a deep point source (on an example of Sr^{90}),
- diffusion and sedimentation processes of Rioni River alluvium in the Black Sea water area of Poti port with high 100 m spacing.

Besides, a mathematical method of determining the pollution source location in water basin on the basis of a conjugate transfer-diffusion equation of substance is presented, which is tested for the Black Sea basin.

All the above mentioned models use mean annual current fields calculated from 2D barotropic and 3D baroclinic models developed at M. Nodia Institute of Geophysics (Tbilisi/Georgia). For solution of model equations two-cycle splitting methods, offered by Marchuk for solution of environmental problems are used [10, 62, 63]. These models are considered as necessary base for the development of forecasting system of the Black Sea pollution state in the Georgian Sector of the basin.

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Загрязнение Чёрного моря и его изучение методами математического моделирования

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Резюме

В статье даётся обзор работ, посвящённых математическому моделированию дисперсионных процессов разных веществ в морях и океанах. При этом основное внимание фокусируется на распространение в Чёрном море веществ антропогенного происхождения и его изучение с помощью диффузионных математических моделей. В работе более детально описаны математические модели, разработанные в Итституте геофизики им. М. Нодиа Тбилисского государственного университета им. И. Джавахишвили, касающиеся распределения разных примесей (нефть, Стронций-90, твёрдые наносы рек) в бассейне Чёрного моря. Эти модели основаны на двумерных и трёхмерных уравнениях переноса-диффузии с использованием среднегодового климатического поля течения, рассчитанного посредством баротропной и бароклинной моделей динамики Чёрного моря. Рассматривается

также теоретический метод определения местоположения источника загрязнения в морском бассейне по известным концентрациям примеси в некоторых точках верхнего слоя моря. Метод основан на сопряжённом уравнении переноса-диффузии. Как в моделях динамики, так и в моделях распространения примеси для решения уравнений используется предложенный Марчуком для решения сложных нестационарных задач динамики атмосферы и океана двуциклический метод расщепления.

შავი ზღვის დაჭუჭყიანება და მისი შესწავლა მათემატიკური მოდელირების მეთოდებით

ავთანდილ ა. კორძაძე, დემური ი. დემეტრაშვილი

რეზიუმე

სტატიაში მოცემულია ზღვებსა და ოკეანეებში სხვადასხვა ნივთიერებათა დისპერსიული პროცესების მათემატიკური მოდელირებისადმი მიძღვნილი შრომათა მიმოხილვა. ძირითადი ყურადღება ფოკუსირებულია შავ ზღვაში ანთროპოგენური წარმოშობის ნივთიერებათა გავრცელებასთან და მის შესწავლასთან დიფუზიური მათემატიკური მოდელების საშუალებით. სტატიაში უფრო დეტალურადაა აღწერილი ივ. ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტის მ. მოდიას გეოფიზიკის ინსტიტუტში შემუშავებული მათემატიკური მოდელები, რომლებიც შეეხება სხვადასხვა მინარევების (ნავთობი, სტრონციუმ-90, მდინარის მყარი ნატანი) გავრცელებას შავი ზღვის აუზში. ეს მოდელები ეფუძნება ორ და სამგანზომილებიან გადატანა-დიფუზიის განტოლებებს, რომლებშიც გამოყენებულია შავი ზღვის დინამიკის ბაროტროპული და ბაროკლინური მოდელების საშუალებით გამოთვლილი საშუალოწლიური კლიმატური დინების ველები. განიხილება აგრეთვე ზღვის აუზში დაჭუჭყიანების წყაროს მდებარეობის განსაზღვრის თეორიული მეთოდი ზღვის ზედა ფენის ზოგიერთ წერტილებში მინარევის ცნობილი კონცენტრაციების მიხედვით. მეთოდი დაფუძნებულია შეუღლებული გადატანა-დიფუზიის განტოლებაზე. როგორც დინამიკის, ასევე მინარევების გავრცელების მოდელებში განტოლებათა ამოხსნისათვის გამოყენებულია გ. ი. მარჩუკის მიერ შემოთავაზებული გახლეჩის ორციკლიანი მეთოდი. ატმოსფეროსა და ოკეანის დინამიკის რთულ არასტაციონარულ ამოცანათა ამოსახსნელად.