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Development of the Black Sea Regional Forecasting System for its Easternmost Part with Inclusion of Oil Spill Transport Forecast

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(Presented by Academy Member Tamaz Chelidze)

ABSTRACT. A regional forecasting system of the Black Sea state has been developed to predict the dynamical and oil spill transportation processes in the easternmost part of the sea basin. The main components of the forecasting system are a 3-D baroclinic regional model of the Black Sea dynamics of M. Nodia Institute of Geophysics, I. Javakhishvili Tbilisi state University, based on a primitive equation system of ocean hydro and thermodynamics and a 2-D oil spill transport model based on nonstationary advection-diffusion equation for nonconservative admixture. The oil spill transport model uses surface nonstationary flow field received from the regional model of the sea dynamics with 1 km spacing, which is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (Sevastopol) with 5 km spacing. To solve the equations of both models the two-cycle splitting method is used: with respect to physical processes, coordinate planes and lines for the 3-D model and with respect to coordinate lines for the 2-D model. Some results of forecast of circulation and oil pollution spreading in the case of hypothetical accident are presented. *© 2014 Bull. Georg. Natl. Acad. Sci.*

Key words: *numerical simulation, advection-diffusion equation, nonstationary flow, turbulent diffusion.*

At present there is a special importance to estimate and forecast the state of the natural environment [1-3]. The topicality of an operational monitoring and forecasting system development for the Georgian Black Sea coastal zone is caused by its growing recreational and transport role, creation of new hydraulic engineering constructions (e. g., Anaklia port) and effective exploitation of the sea resources. In connection with strengthening of human economic activities the danger of pollution of coastal waters by oil and other toxic substances considerably grows. Among different polluting substances the oil and oil products are more dangerous and widespread in the Black Sea environment, which can cause significant negative changes in hydrobiosphere and to infringe natural mass exchange between the sea and the atmosphere. Operative forecast of the oil pollution spreading zones and its intensity allows to optimize

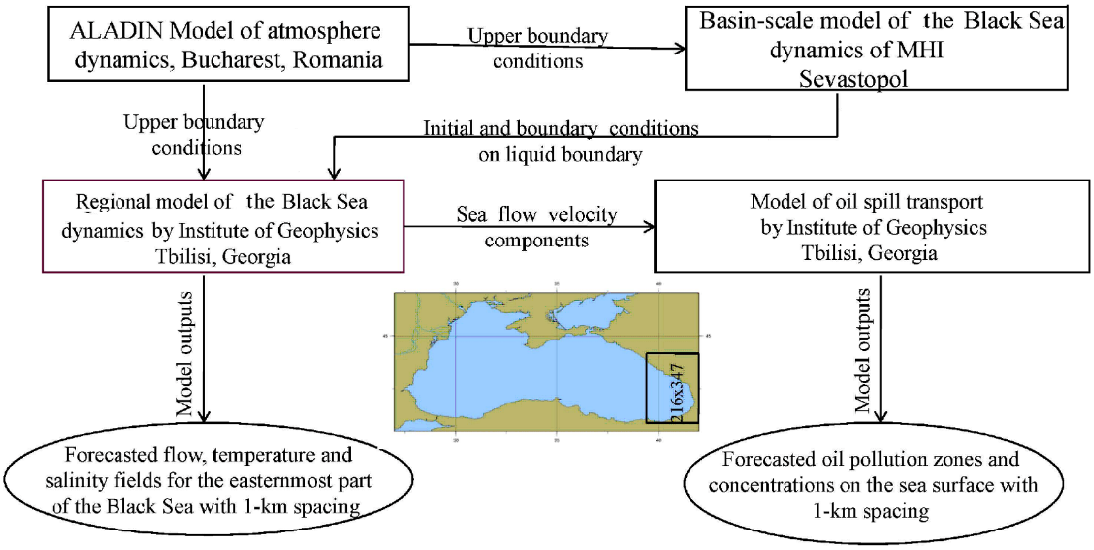

Fig. 1. Forecasting domain and the structure of the regional forecasting system.

and to take more effective measures for reduction of negative consequences.

The problem of simulation and forecast of oil distribution processes in the sea environment is a complex problem and requires knowledge of the sea circulation parameters, which may be defined by the mathematical models of sea dynamics. In recent years the regional Black Sea forecasting system is developed [4-6] within the context of EU projects ARENA and ECOOP at M. Nodia Institute of Geophysics, I. Javakhishvili Tbilisi state University. The regional forecasting system is one of the parts of the basin-scale Black Sea forecasting system providing 3-day forecast of 3-D fields of currents, temperature and salinity with 1 km spacing in the Easternmost part of the Black Sea. The regional area is limited to the Caucasian and Turkish shorelines and the western liquid boundary coinciding with meridian 39.08^{0}E. The results of operative forecasts are available on web-addresses: www.ig-geophysics.ge, www.oceandna.ge.

In the present paper the regional forecasting system is extended by an oil spill transport module and some results of simulation and forecast of circulation and oil spill transport processes if hypothetical accident is presented.

Description of the regional forecasting system

In Fig.1 the forecasting domain and the structure of the regional forecasting system are shown. The main components of the forecasting system are the 3-D baroclinic regional model of the Black Sea dynamics (M. Nodia Institute of Geophysics, I. Javakhishvili Tbilisi state University) and 2-D oil spill transport model.

The oil spill transport model uses surface nonstationary flow field received from the regional model of the sea dynamics. The regional model of the Black Sea dynamics with 1 km spacing is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol) with 5 km spacing [7]. All the required input data are provided from MHI in operative mode via the ftp site. The input data are as follows: 3-D initial fields of the current velocity components, temperature and salinity; 2-D fields of the same quantities on the liquid boundary and 2-D meteorological fields at the sea surface – heat fluxes, atmospheric precipitation, evaporation and wind stress. The conditions on the liquid boundary are values of hydrophysical parameters forecasted from the basin-scale model of MHI, the meteorological fields at the upper boundary are forecasted fields calculated from the ALADIN regional atmospheric dynamics model operated at the National Hydrometeorological Administration of Romania (Bucharest).

Inclusion of the oil spill transport model into the regional forecasting system will enable to predict operatively not only dynamic state of the Black Sea, but also oil pollution areas and concentrations of the sea environment in accidental situations.

Hydrodynamic module

The hydrodynamic module of the regional forecasting system – the regional model of the Black Sea dynamics is based on a primitive equation system of the ocean hydro and thermodynamics in z coordinates for deviations of thermodynamic values from the corresponding standard values [3]. The model takes into account the sea bottom relief, the configuration of the basin, atmospheric forcing, discharge of the rivers: Bzipi, Kodori, Erisckali, Enguri, Xobi, Rioni, Choroxi, the absorption of total solar radiation by the sea upper layer, the spatial-temporal variability of factors of horizontal and vertical turbulent viscosity and diffusion. To solve the model equation system the two-cycle splitting method is used with respect to physical processes, coordinate planes and lines [8, 9]

Oil spill transport module

We describe the oil pollution spreading on the sea surface by advection-diffusion equation for nonconservative substance, which is considered in a two-dimensional bounded area Ω with a lateral boundary S

$$\frac{\partial \varphi}{\partial t} + \frac{\partial \mathrm{u} \varphi}{\partial \mathrm{x}} + \frac{\partial \mathrm{v}\varphi}{\partial \mathrm{y}} + \sigma \varphi = = \frac{\partial}{\partial x} \mu \frac{\partial \varphi}{\partial x} + \frac{\partial}{\partial y} \mu \frac{\partial \varphi}{\partial y} + f \qquad (1)$$

with the following boundary and initial conditions

$$a\left(\mu \frac{\partial \varphi}{\partial n} - \beta \varphi \right) + bQ = 0 \quad \text{on} \quad S, \qquad (2)$$

$$\varphi = \varphi^0 \quad \text{at} \quad t = 0. \qquad (3)$$

Here φ is the volume concentration of a substance; μ is the coefficient of turbulent diffusion; n is the vector of the outer normal to S; $\sigma = \ln 2/ T_0$ is the parameter, which parametrically describes changeability of concentration because of physical and biochemical factors; T_0 represents time interval, during which the initial oil concentrations decrease two times; in general, f describes the space-temporal distribution of the source power, which in case of the point source can be given by the delta function

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

where x_0 and y_0 are coordinates of location of the source. a and b are the factors accepting values either unit or zero; β is the parameter of interaction of the oil with the appropriate lateral boundary. Q is power of oil emission from the point source.

The turbulent diffusion coefficient was calculated by the formula [10]

$$\mu = \gamma\, \Delta x \Delta y \times \times \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2}, \qquad (4)$$

where Δx and Δy are horizontal grid steps along x and y axes, respectively; γ is some constant.

For solving the problem (1)-(3) a two-cycle splitting method is used with respect to space coordinates [11].

Numerical experiments

The oil transport model is included in the forecasting system as a separate module allowing to calculate oil concentrations and pollution zones at emergency. With this purpose it is required to input the source parameters: coordinates of source location, amount of oil emission, duration of emission and the parameter σ in the calculated program written on algorithmic language "Fortran". The models of dynamics and oil spill transport use the calculated grid having 216x347 points on horizon with the grid step Δx = Δy = 1 km, the time step was equal to 0.5 h in the

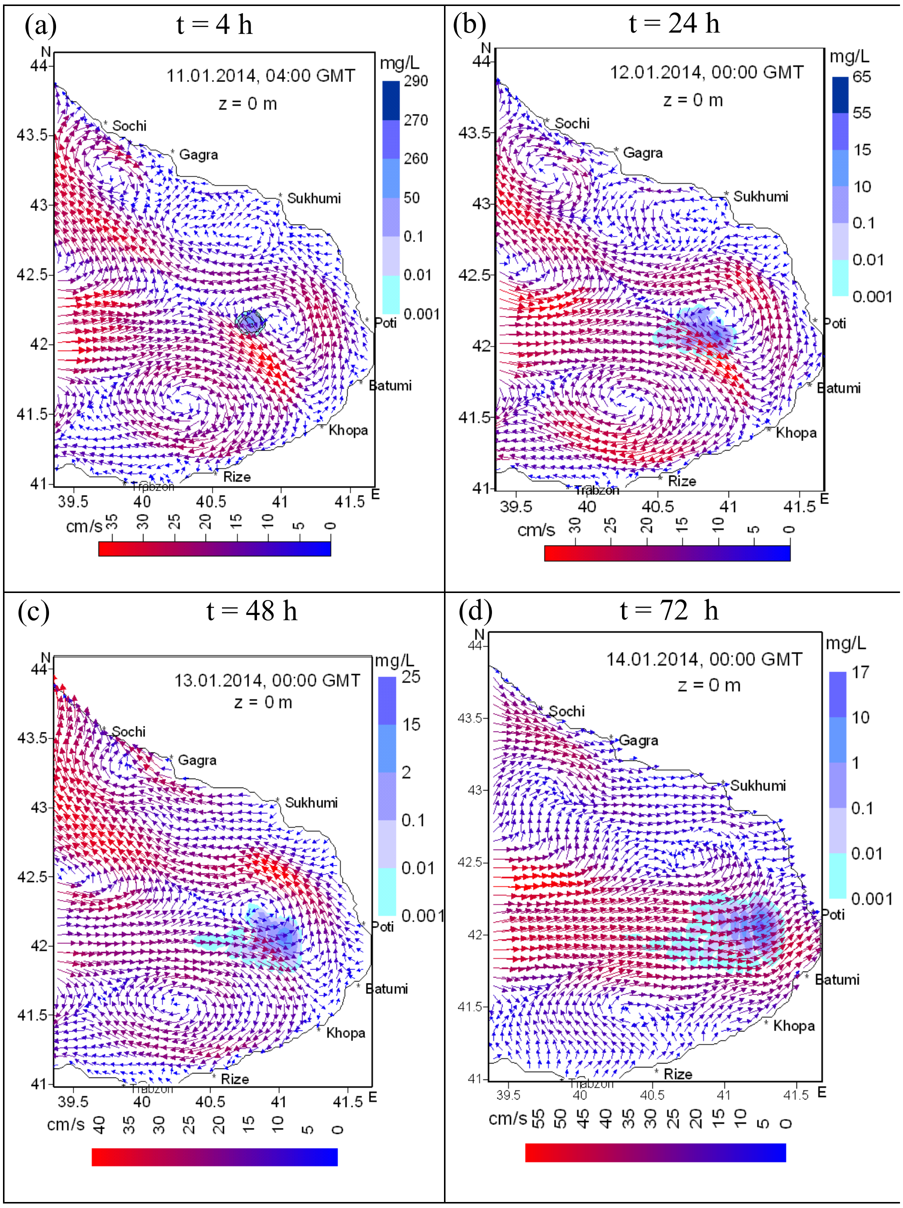

Fig. 2. Simulated surface current fields and oil spill transport corresponded to the following time moments after oil flood: (a) - 4h, (b) - 24 h, (c) - 48 h, (d) - 72 h; the forecasting period is: 00:00 GMT,11-14 January 2014.

3-D model of dynamics 32 calculated levels with irregular vertical steps were considered on a vertical [3]. In numerical experiments presented in this article it is accepted that a = 1, b = 0, β = 0, $\gamma = 0.1$.

The parameter of σ describing the change of oil concentrations due to physical and biochemical factors depends on the type of oil. These factors are evaporation, emulsification, dissolution, sinking/sedimentation*, etc*. At the beginning of the oil drift, there is an intensive evaporation of light fractions of oil, which is an initial process of removal of oil from the sea surface. Evaporation depends on oil composition and on atmospheric parameters - wind speed and air temperature [12]. It is estimated that from 1/3 to 2/3 oil mass during the period of time starting with several hours up to 24 hours might be lost [13]. Therefore, in case of short-range forecast of oil spill transport evaporation is the most important factor. Taking this fact into consideration, we accepted: $\sigma = 1.6.10^{-5}$ if $t \le 24$ h and $\sigma = 8.2.10^{-7}$, if t>24 h in most numeri-

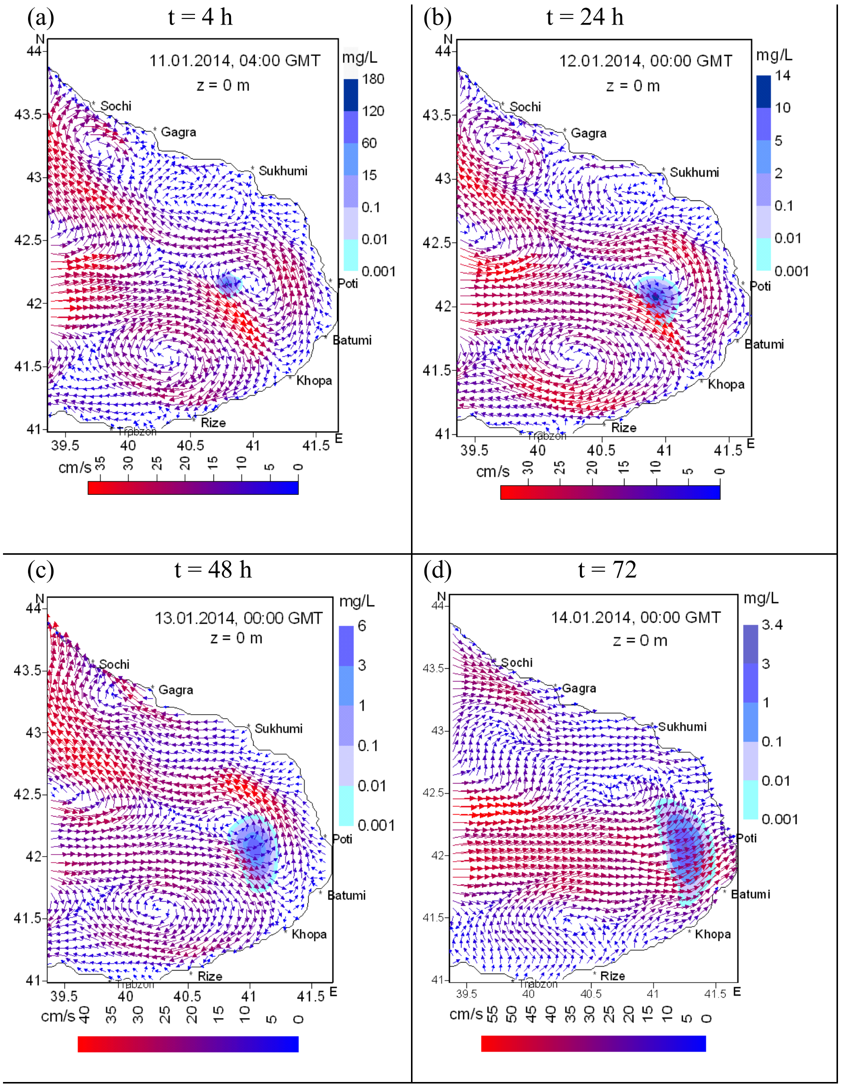

Fig. 3. The same as in Fig.2, but the coefficient of diffusion is constant.

cal experiments (though, with the purpose of researching dependence of oil distribution processes on this parameter other values were also considered) . The first value of parameter of σ corresponds to double reduction of concentrations for 12 hours, and the second one - to double reduction of concentrations during 10 days.

In performed numerical experiments accidental oil spill in the sea occurred within two hours in amount of 50 t or 10 t. The oil spill was considered as a point source , which was located in different points of the Georgian coastal zone in conditions of different circulation modes.

The performed numerical experiments showed that pollution concentration field is significantly sensitive to the parameter of non-conservativeness, i. e., to the kind of oil - at reduction of the parameter of non-conservativeness the growth of oil concentrations is observed and the oil spillage occupies more territory. Amount of spilled oil on the sea surface influences qualitatively on oil pollution distribution.

Fig. 2 illustrates forecasted regional circulation in the easternmost part of the Black Sea and drifting of oil slick in case when 50 t occurred on distance about 65 km from Poti shoreline in the point with coordinates of 140Δx and 132Δy (the forecasting period 00:00 GMT,11-14 January 2014). The variable diffusion coefficient was calculated by the formula (4). Fig. 2 shows that the surface circulation is essentially changeable for the considered forecasting period. At the initial period of oil flood the surface regional circulation is characterized by formation of vortical dipolar structure which occupies significant territory of the considered area (Fig.2a). Apart from this dipolar structure, some vortical formations of the smaller sizes are also observed. For three days the circulating mode is transformed and the different mode is formed (Fig. 2d). Such circulating reorganization is essentially reflected on of the oil spill motion. In the course of migration the oil slick gradually extends and is deformed. Simultaneously, the oil pollution concentration is reduced caused by diffusion expansion, evaporation and other physical and chemical factors, which are taken into account in the model indirectly. Under the influence of sea current the oil spillage gradually comes nearer to the coast of Georgia (Fig. 2d).

With the purpose of researching the sensitivity of oil spill transport process to turbulent diffusion there was performed the same numerical experiment, but with the constant coefficient of turbulent diffusion equal to $\mu = 8.10^5$ cm^2/s (Fig.3). From comparison of Fig. 2 and Fig.3 the distinctive features of distribution of oil pollution on the sea surface are well visible. This distinction has quantitative and qualitative character. In case of the constant diffusion coefficient the oil spillage is represented as a single formation, where the pollution concentration distribution has concentric character decreasing from the centre of the stain to peripheries in a radial direction (Fig.3). In case of more real diffusion coefficient with spatial - temporary variability, the oil spill deformation is of different character, the oil concentration distribution is broken and the concentration field is characterized by relatively high heterogeneity within the oil slick (Fig.2). Higher values of pollution concentrations are observed in case of the variable diffusion coefficient.

Conclusion

The paper presents a regional forecasting system for the easternmost Black Sea state allowing to forecast with 3-days forward not only 3-D dynamical fields – current, temperature and salinity with 1 km spacing, but also the oil pollution spreading zones and concentrations in case of accidental situations. The regional forecasting system is a part of the basin-scale nowcasting/forecasting system and all required input data are provided from MHI (Sevastopol) in operative mode via Internet.

The numerical experiments carried out in different location of hypothetical sources and real circulating modes, show a significant role of circulating processes in formation of spatial-temporary distribution of pollution. The oil spill transport is significantly sensitive to the turbulent diffusion coefficient and the type of oil.

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გეოფიზიკა

შავი ზღვის რეგიონული პროგნოზული სისტემის შემუშავება მისი აღმოსავლეთ ნაწილისათვის ნავთობის ლაქის გადატანის პროგნოზის გათვალისწინებით

ა. კორძაძე, დ. დემეტრაშვილი

ივ. ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტის მ. ნოდიას გეოფიზიკის ინსტიტუტი

(წარმოდგენილია აკადემიის წევრის თ. ჭელიძის მიერ)

შავი ზღვის აღმოსავლეთ ნაწილში დინამიკური და ნავთობის ლაქის გადატანის პროცესების პროგნოზის მიზნით შემუშავებულია შავი ზღვის მდგომარეობის რეგიონული პროგნოზული სისტემა. პროგნოზული სისტემის მთავარი კომპონენტებია ოკეანის ჰიდროთერმოდინამიკის განტოლებათა სრულ სისტემაზე დაფუძნებული ივ. ჯავახიშვილის სახელობის თბილისის სახელმწიფო უნივერსიტეტის მ. ნოდიას გეოფიზიკის ინსტიტუტის შავი ზღვის დინამიკის 3-განზომილებიანი ბაროკლინური რეგიონული მოდელი და არაკონსერვატიული მინარევის არასტაციონარულ ადვექცია-დიფუზიის განტოლებაზე დაფუძნებული ნავთობის ლაქის გადატანის 2-განზომილებიანი მოდელი. ნავთობის ლაქის გადატანის მოდელი იყენებს ზღვის დინამიკის რეგიონული მოდელიდან მიღებულ არასტაციონარულ ზედაპირული დინების ველს. 1 კმ გარჩევისუნარიანობის მქონე შავი ზღვის დინამიკის რეგიონული მოდელი ჩადგმულია ზღვის ჰიდროფიზიკის ინსტიტუტის (ქ. სევასტოპოლი) 5 კმ გარჩევისუნარიანობის მქონე შავი ზღვის დინამიკის დიდმასშტაბიან მოდელში. ორივე მოდელის განტოლებათა ამოსახსნელად გამოყენებულია გახლეჩის ორციკლიანი მეთოდი: ფიზიკური პროცესების, საკოორდინატო სიბრტყეებისა და წრფეების მიხედვით 3-განზომილებიანი მოდელისათვის, ხოლო საკოორდინატო წრფეების მიხედვით – 2-განზომილებიანი მოდელისათვის. წარმოდგენილია ცირკულაციისა და ნავთობით დაჭუჭყიანების გავრცელების პროგნოზის შედეგები ჰიპოთეზური ავარიის შემთხვევაში.

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