Simulation and forecast of oil spill transport processes in the Georgian Black Sea coastal zone using the regional forecasting system

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Abstract

In the paper with the purpose of modeling and forecasting of oil spill transport in the Georgian Black Sea coastal zone the 2-D oil dispersion model is included in the regional forecasting system of the Black Sea state as a separate module. The model is based on solution of advection-diffusion equation for nonconservative admixture by using of the two-cycle splitting method with respect to spatial coordinates. The numerical experiments showed the essential contribution of advection and turbulent diffusion to peculiarities of spatial-temporal distribution of oil concentrations.

1. Introduction

Every year the recreational and transport role of the Georgian Black Sea coastal zone considerably grows, the projects on new hydraulic engineering constructions (e. g., Anaklia port) are developed. it is expected that strengthening of anthropogenous loading on the Georgian coastal zone will promote growth of pollution of coastal waters by different toxic substances, among which oil and oil products are more dangerous and widespread components for the sea environment [1-3]. The emergencies at which is possible the oil floods and pollution of extensive sea water areas are rather probable. In this connection creation of the operative control system of the coastal waters state is very important for the Georgian water area of the Black Sea as for other regions of the world ocean.

It should be noted that the transport and evolution processes of the oil and other substances in the sea environment are closely connected to dynamical processes (circulation, turbulence). Therefore forecast of spreading of the substances is a complex problem and it includes first of all forecast of sea dynamical processes.

Considerable amount of the publications are devoted to modelling of oil spill transport in the Black and other seas (for example, [1, 4-16]). In [1] a 3-D 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 implemented for the Black Sea [17]. In [4, 6, 7] the same

flow/transport model is used to predict the transport and dispersal of oil spill in coastal waters of the Caspian Sea, but currents and turbulent diffusivities used in the model are generated by the Princeton Ocean Model (POM) implemented for the Caspian Sea [18].

Danish Meteorological Institute (DMI) has developed an improved version of oil drift model based on a 3-D current field. The new model calculates the oil transport, drift, and fate at sea surface and at the deeper water depths [11]. The model is a 3-D oil drift and fate model based on a 3-D ocean circulation model. 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 3-D oil drift and fate model- for the two oil spill accidents in the Danish waters.

In [12] the integrated modeling system for weather, currents, wind waves coupled with oil slick transport is developed. The local area weather forecasting model MM5 is used for operational forecasts in the Black Sea region [19], which is coupled with a 3-D hydrodynamics and sediment transport model, and with the third –generation wave model WAVEWATCH III [20]. The hydrodynamics is simulated on the basis of POM [18]. The modeling system was implemented to the Black Sea basin.

Météo-France has developed an oil spill response model (MOTHY), designed to simulate the transport of oil in three dimensions [13, 14]. 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), *etc*. MOTHY has been configured and adapted for the specific conditions of the Black Sea area by National Institute of Meteorology and Hydrology of Bulgaria (NIMH) [15]. 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.

In [16] on the basis of 2-D advection-diffusion equation the distribution of the oil pollution on the Black Sea surface getting as a result of emergency emission into the open part of the water area is simulated. The current field is determined by using of barotropic sea dynamics model [21]. The problem is solved numerically on the basis of a two-cycle splitting method with respect to spatial variables.

Creation of the regional forecasting system of the Black Sea dynamics for the easternmost part of the Black Sea, which is one of the parts of the basin-scale Black Sea nowcasting/forecasting system [22-25], gives us the real possibility to develop the coupled forecasting system of oil spill transport in the Georgian Black Sea coastal area. Nowadays, the regional forecasting system is functioning in the near-real time. Results of calculated marine forecast for the easternmost part of the Black Sea – 3-D fields of the current, temperature and salinity are available in internet on addresses: www.iggeophysics.ge and www.oceandna.ge.

The main goal of the present paper is inclusion of the oil spill transport model in the regional forecasting system as a separate module and to investigate numerically features of hypothetical oil spill transport in conditions of the real circulation modes in the Georgian Black Sea water area.

2. Regional forecasting system

A 2-D model of oil spill transport is included in the regional forecasting system as a separate module. The forecasting domain and the structure of the new version of the regional forecasting system is shown in Fig.1. The regional area is limited to the Caucasus and Turkish shorelines and the western liquid boundary coinciding with a meridian 39.08^0E. The main components of the forecasting system are a 3-D baroclinic regional model of Black Sea dynamics of M. Nodia Institute of Geophysics of 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 sea dynamics.
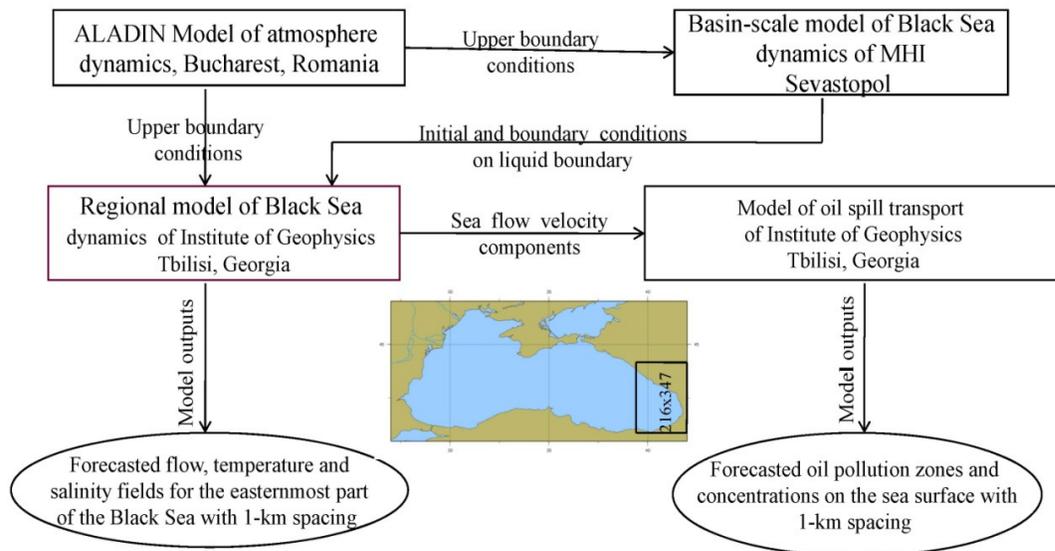

Fig. 1. Forecasting domain and the structure of the regional forecasting system.

The basic aspects of functioning of the regional forecasting system are described in details in [22-24]. Here we only note that the regional model of Black Sea dynamics with 1 km spacing is nested in the basin-scale model of Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol) with 5 km spacing [26]. All the required input data are provided from MHI in operative mode via the ftp site.

Inclusion of the oil spill transport model into the regional forecasting system enables to predict with 3-days forward operatively not only dynamic state of the Black Sea, also oil pollution areas and concentrations of the Georgian Black Sea coastal zone with space resolution 1 km in accidental situations.

3. Oil spill transport module

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

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

with the following boundary and initial conditions

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

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

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; $\sigma = ln2/T_0$ is the parameter of non-conservatively, which parametrically describes changeability of concentration because of physical and biochemical factors; T_0 represents the time interval, during which the initial oil concentrations decrease two times; in general, f describes the space-temporal distribution of a specific 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. 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 [27]

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

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 spatial coordinates [28].

4. Numerical experiments

The oil transport model is included in the forecasting system as a separate module and enables to calculate oil concentrations and pollution zones at emergency. With this purpose it is required to input in the calculated program written on the algorithmic language "Fortran" the following parameters: coordinates of source location, amount of oil emission, duration of

emission and the parameter of non-conservatively. The both models of dynamics and oil spill transport use the calculated grid having 216x347 points on horizon with the grid step $\Delta x = \Delta y =$ 1 km, the time step was equal to 0.5 h. in the 3-D model of dynamics 32 calculated levels with irregular vertical steps were considered on a vertical. In numerical experiments presented in this article were accepted: a = 1, b = 0, $\beta = 0$, $\gamma = 1$.

The parameter of non-conservatively 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 [1, 5]. There is estimated that during the period of time from several till 24 hours, probably, from 1/3 to 2/3 oil mass is lost [5]. Therefore, in case of short-range forecast of oil spill transport evaporation is most important factor. Taking into consideration this fact, we accepted $\sigma = 1{,}6.10^{-5}$ if $t \le 24$ h and $\sigma = 8{,}2.10^{-7}$ if t >24 h in most numerical experiments (though, with the purpose of researching dependence of oil distribution processes on this parameter other values were also considered) . The first value of σ corresponds to reduction of concentrations two times during 12 hours, and the second one - to reduction of concentration two times 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 concentrations are significantly sensitive to the parameter of non-conservatively, i. e. to the type of oil; at reduction of this parameter 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.
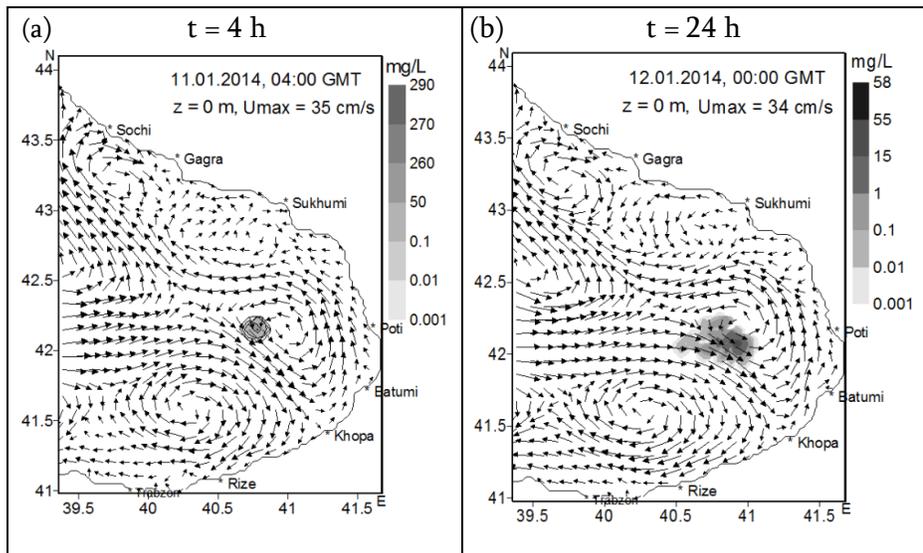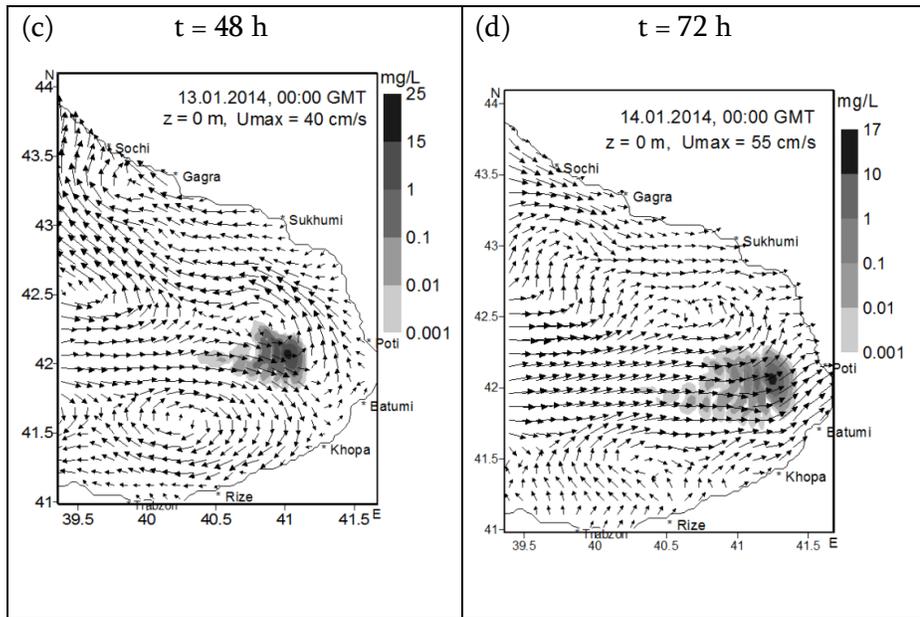
Fig.2. Simulated surface current field and oil spill transport corresponded to the following time moments after oil flood: (a) - 4h, (b) - 24 h, (c) - (48), (d) - (72). The forecasting interval is 00:00 GMT,11-14 January 2014. The source coordinates were: 140Δx, 132Δy.

Some results of numerical experiments are illustrated in Figs. 2-4. Fig. 2 illustrates forecasted regional circulation in the easternmost part of the Black Sea and drifting of oil slick in case when 50 t was occurred on distance about 65 km from Poti shoreline in the point with coordinates 140Δx and 132Δy (the forecasting period 00:00 GMT,11-14 January 2014). The diffusion coefficient was variable calculated by the formula (4). From Fig. 2 is well visible 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). Except for this dipolar structure, some vortical formations of the smaller sizes are also observed. For three days the circulating mode is transformed and the different circulation mode is formed shown in Fig. 2d. Such circulating reorganization
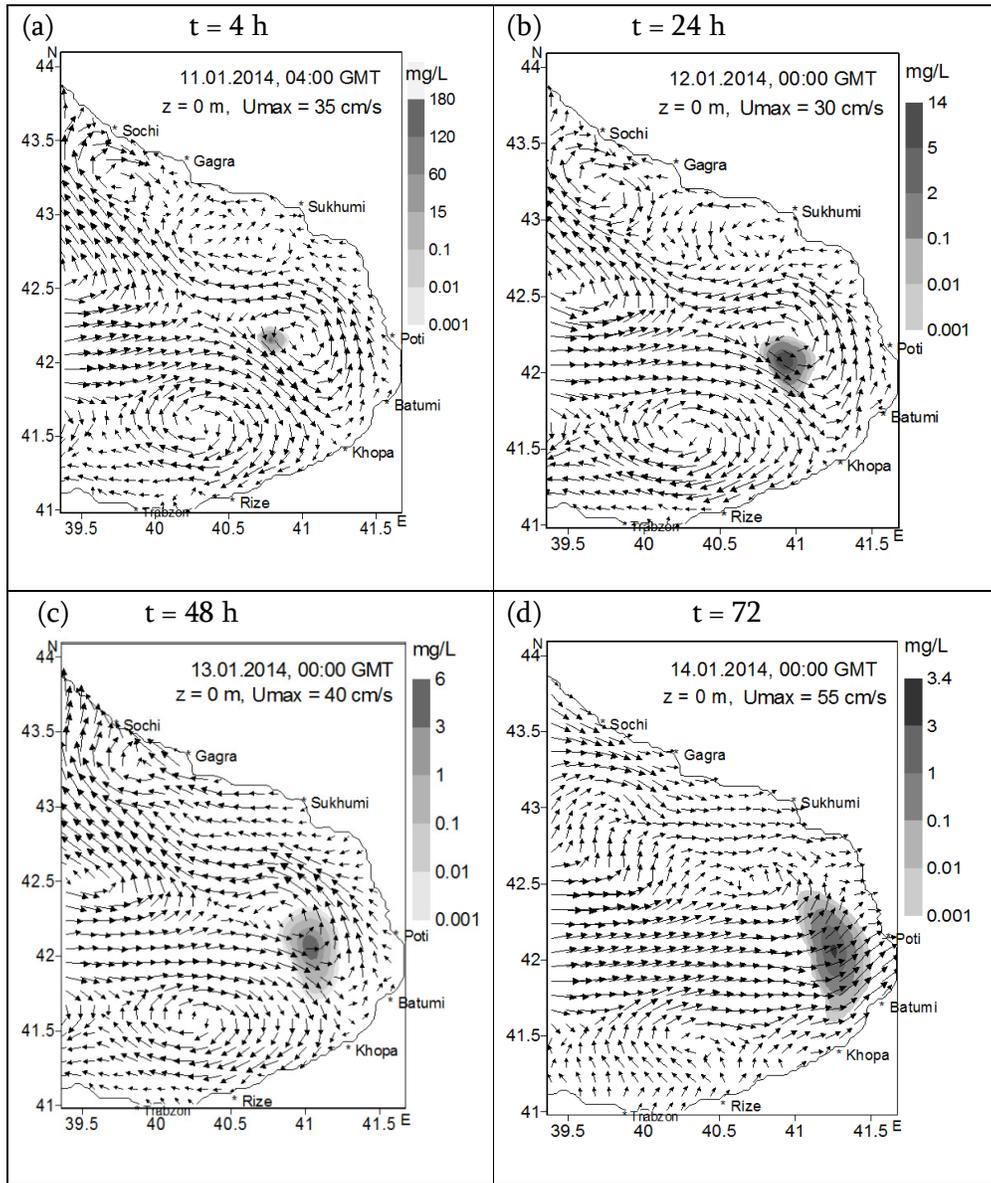
Fig.3. The same as in the Fig.2, but the coefficient of diffusion was constant.

is essentially reflected on moving of the oil spill. In the course of migration the oil slick extends gradually and deformed. Simultaneously   reduction of oil pollution concentrations is observed that is caused by diffusion expansion, evaporation and other physical and chemical factors, which are taken into account in the model indirectly. Under influence of the 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 the 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 Figs. 2

and 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 distribution of pollution concentration has concentric character and it decreases 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, character of oil spill deformation is different, concentric distribution of oil concentrations is broken and the concentration field is characterized with relatively high heterogeneity within the oil slick (Fig. 2). Higher values of pollution concentrations are observed in case of the variable diffusion coefficient.

In the next numerical experiment all parameters including source coordinates were the same as in the first numerical experiment illustrated by Fig. 2, but in this case the surface current structure was transformed within the forecasting time interval: 00:00 GMT, 1-4 March 2014, as it is shown in Fig. 4. From this Figure is well visible that in the east part of the considered water area the triplet structure consisting from two anticyclonic vortexes and one middle cyclonic vortex is formed at time moment 04:00 GMT, 1 March 2014 (Fig. 4a). During the forecasting interval the current is essentially transformed - the triplet structure gradually breaks up and the current directed to the north-west is formed, but there are also formed some vortexes with relatively small sizes (Fig.4c and 4d). Under influence of the current the character of deformation and moving of the oil slick essentially differs from the previous case with circulation during interval: 10-14 January 2014 (see, Fig. 2).

Conclusion

This paper presents the development of the regional forecasting system of the easternmost Black Sea state with inclusion of oil spill transport module. This module is based on a 2-D advection-diffusion equation for nonconservative admixture. The forecasting system enables to forecast with 3-days forward not only 3-D dynamical fields – current, temperature and salinity with 1 km spacing, also spreading of oil pollution 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 carrying out in case of 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. Thus, our researches have shown that the reliable forecast of oil pollution transport in the sea requires to reproduce in accuracy sea circulation and processes of turbulent mixing, also to take into account adequately physical-chemical properties of the oil.
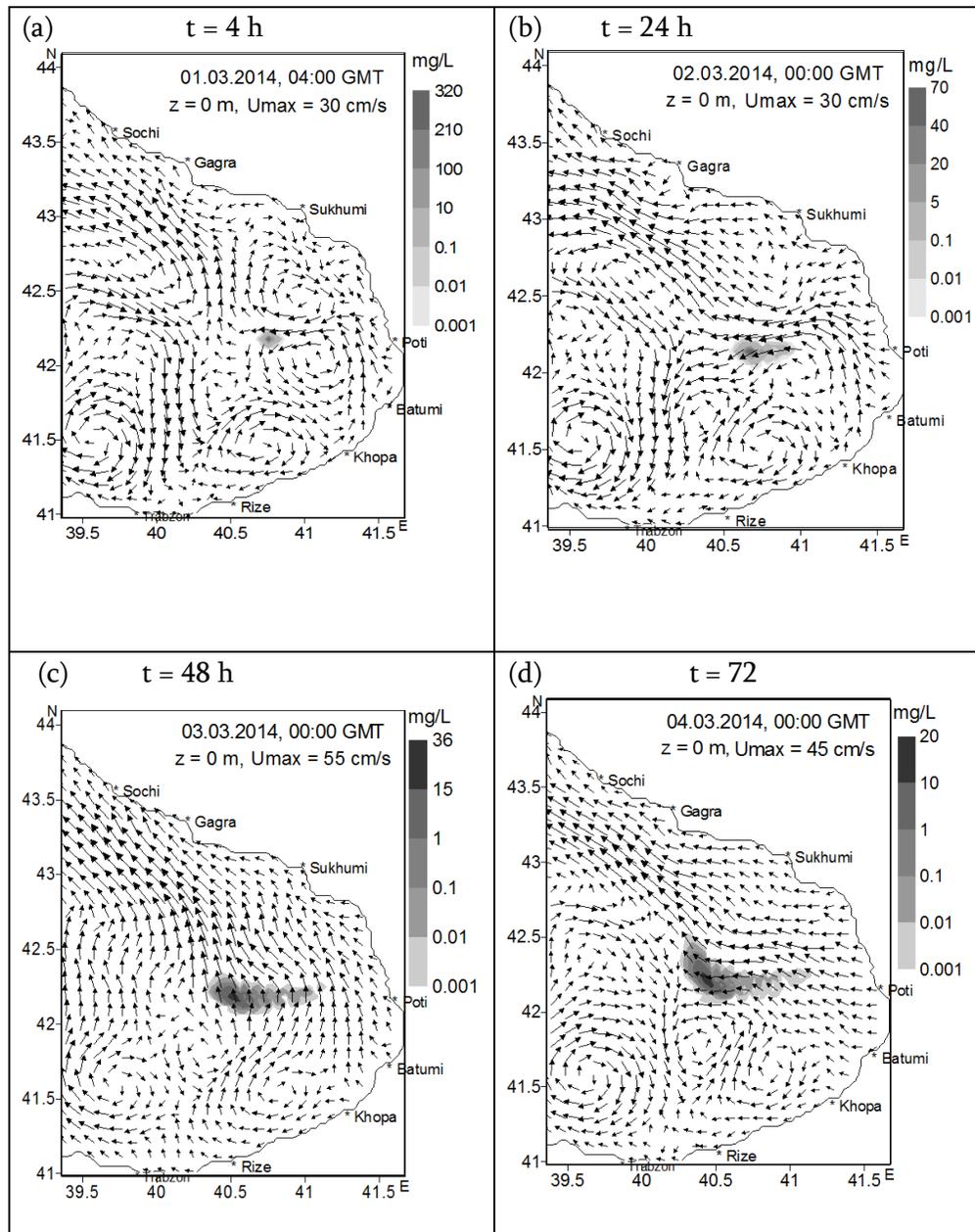
Acknowledgement

Fig.4. Simulated surface current field and oil spill transport corresponded to the following time moments after oil flood: (a) - 4h, (b) - 24 h, (c) - (48), (d) - (72). The forecasting interval: 00:00 GMT,1-4 March 2014. The source coordinates: 140Δx and 132Δy.

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AnavTobis laqis gadatanis procesebis modelireba da prognozi saqarTvelos Savi zRvis sanapiro zolSi regionuli prognozuli sitemis gamoyenebiT

avTandil korZaZe, demuri demetraSvili

reziume

statiaSi Savi zRvis saqarTvelos sanapiro zolSi navTobis laqis gadatanis modelirebisa da prognozis mizniT navTobis gavrcelebis 2-ganzomilebiani modeli calkeuli modulis saxiT CarTulia Savi zRvis mdgomareobis regionul prognozul sistemaSi. modeli dafuZnebulia arakonservatiuli minarevis adveqcia-gadatanis gantolebis amoxsnaze sivrciTi koordinatebis mimarT gaxleCis orcikliani meTodis gamoyenebiT. ricxviTma eqsperimentebma aCvena adveqciisa da turbulenturi difuziis arsebiTi roli navTobis daWuWyianebis sivrciT-droiTi gavrcelebis TaviseburebebSi.

Моделирование и прогноз процессов переноса нефтяного пятна в грузинской прибрежной зоне Черного моря с использованием региональной прогностической системы

Автандил Кордзадзе, Демури Деметрашвили

Резюме

В статье с целью моделирования и прогноза переноса нефтяного пятна в грузинской прибрежной зоне Черного моря двумерная модель распространения нефтяного загрязнения включена в региональную прогностическую систему состояния Черного моря в виде отдельного модуля. Модель основана на решении уравнения адвекции-диффузии для неконсервативной примеси с использованием двуциклического метода расщепления по пространственным координатам. Численные эксперименты показали существенную роль адвекции и диффузии в формировании пространственно-временного распределения нефтяных концентраций.