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Easternmost Black Sea Regional Forecasting System

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Abstract

The study presents general description of the regional forecasting system for the easternmost part of the Black Sea with demonstrating results of modeling and short-range forecast of circulation and spread of oil and other pollutants. The regional forecasting system, which is one of the parts of the Black Sea Nowcasting /Forecasting System, is limited to the Caucasus and Turkish coastal lines and the western liquid boundary coinciding with the meridian 39.08^0 E. This system consists of hydrodynamic and ecological blocks. The hydrodynamic block is based on the application of the Institute of Geophysics of I. Javakhishvili Tbilisi State University high-resolution regional model of the Black Sea dynamics, which is based on a primitive equation system of ocean hydro and thermodynamics in hydrostatic approximation. This model is nested in the basin-scale model (BSM) of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol). The Input data - the initial and prognostic hydrophysical fields on the open boundary, also 2D prognostic meteorological fields at the sea surface are provided from MHI in the near-real time mode via Internet. Prognostic hydrophysical fields are the results of forecasting by the BSM of MHI, but 2D meteorological boundary fields represent the results of forecasting by regional atmospheric model ALADIN. The ecological block is based on 2D and 3D diffusion models describing the spread of anthropogenic pollutants in the sea environment with the use nonstationary flow field calculated from the hydrodynamic block. Splitting methods are used to solve the problems in both blocks.

Introduction

In conditions of growing human activity for the last decades and taking into account the intensification of anthropogenic loading on a natural environment, development of a monitoring and forecasting system providing to receive operative information on parameters describing current and future conditions of the environment is one of the most actual and important problems of modern geophysics. As one of the parts of the natural environment, the Black Sea coastal and shelf zone undergoes significant degradation (Fabry et al., 1993; Gruzinov et al., 2012; Dianskii et al., 2013). This fact also concerns the Georgian coastal area. The significant increase in tourists in recent years, the construction and planning of appropriate infrastructures, hydraulic structures and ports (e. g., Anaklya port) dramatically increases the possibility of contamination of Georgian coastal waters by oil and other toxic ingredients. In such conditions development of the coastal forecasting system is considerably urgent, which should become the basic component of the coastal zone monitoring and management system.

The main achievement of the Black Sea operative oceanography for the last decade is the development of the marine Nowcasting/Forecasting System, which is based on the basin-scale model (BSM) of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol) and high-resolution regional models providing the forecast of dynamical fields in separate coastal areas (Korotaev et al., 2011; Kubryakov et al., 2012; Grigoriev and Zatsepin, 2013). Creation of such system was promoted by the leading oceanographic Centers of the Black Sea riparian countries (Bulgaria, Georgia, Romania, Russia, Turkey, Ukraine) within the EU framework projects ARENA, ASCABOS and ECOOP. One of the parts of this system is the regional forecasting system for the easternmost part of the Black Sea. Description of this regional forecasting system and some results of verification, simulation and prediction of dynamic fields are given by Kordzadze and Demetrashvili (2010, 2011, 2012, 2013). Further progress in development of the regional forecasting system was made in the framework of the Georgian National Scientific Foundation by inclusion of impurity dispersion models into the system.

In the present study, the advanced version of the Black Sea regional forecasting system extended by inclusion of 2D and 3D impurity dispersion models is shortly described. In addition, some results of modelling and short-range forecast of circulation and spreading of polluting substances are also presented.

Advanced Version of the Regional Forecasting System

In Fig. 1 the forecasting area, structure and scheme of functioning of the regional forecasting system are shown. The forecasting area is limited to the Caucasus and Turkish coastal lines and the western liquid boundary coinciding with the meridian 39.08^0 E. The advanced version of the regional forecasting system consists of hydrodynamic and ecological blocks.

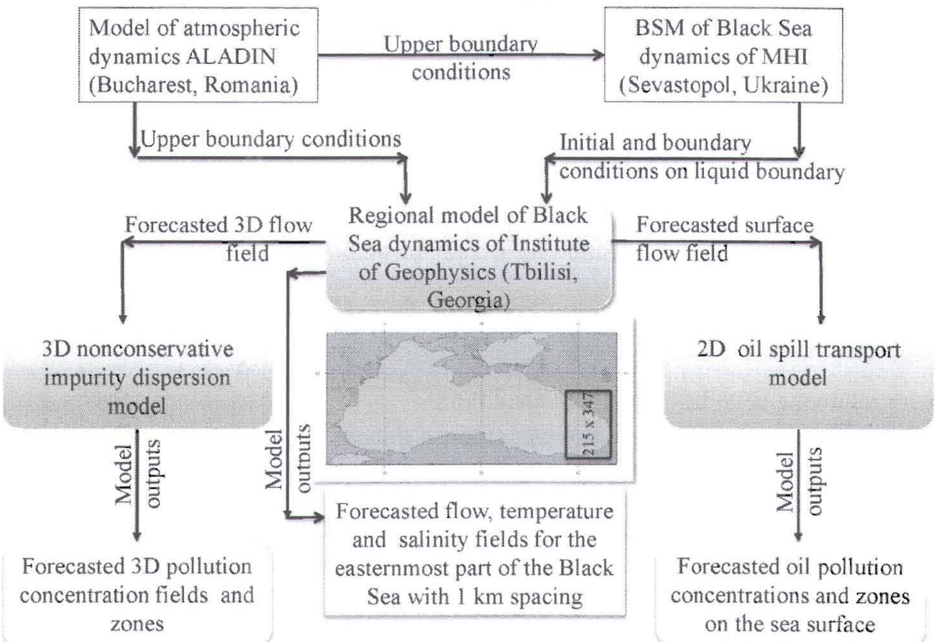

Fig. 1: The forecasting area, structure and scheme of functioning of the advanced version of the regional forecasting System.

The hydrodynamic block is based on application of the Institute of Geophysics of I. Javakhishvili Tbilisi State University high-resolution regional model of the Black Sea dynamics (RM-IG), which is z-level model and is based on a primitive equation system of ocean hydro and thermodynamics in hydrostatic approximation. This model is nested (one-way nesting) in the BSM of MHI. The input data - the initial and prognostic hydrophysical fields on the open boundary, also 2D prognostic meteorological fields at the sea surface –wind stress, heat fluxes, evaporation and precipitation rates needed for the regional forecast of dynamic fields are provided from MHI in the near-real time mode via Internet. Atmospheric forcing of the RM-IG is the same as for the BSM. Prognostic hydrophysical fields are results of forecast by the BSM of MHI (Dorofeev and Korotaev, 2004) and 2D meteorological boundary fields represent the results of the forecast by regional atmospheric model ALADIN (Brozkova et al, 2006), provided by the National Meteorological Administration of Romania. All these fields are given on the coarse grid of BSM with 5 km spacing and with one-hour time step frequency for the integrated period. During implementation of RM-IG these fields are interpolated to the grid with 1 km spacing at every time step.

The RM-IG takes into account the sea bottom relief and the configuration of the basin; atmospheric forcing; discharge of the rivers: Bzipi, Kodori, Erisckali, Enguri, Khobi, Rioni and Chorokhi; 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. In case of unstable stratification, which might appear during integration of the model equation system, the realization of this instability in the model is taken into account by the increase of factor of turbulent diffusion 20 times in appropriate columns from the surface to the bottom.

The ecological block is based on 2D and 3D diffusion models describing spreading of oil and other nonconservative substances in the water area and using nonstationary flow field calculated from the hydrodynamic block. The 3D diffusion model is based on nonstationary advection-diffusion equation for nonconservative substance considered in a bounded region of cylindrical form with a lateral surface S and depth $H(x, y)$:

$$\partial\varphi/\partial t+\partial u\varphi/\partial x+\partial v\varphi/\partial y+\partial(w+w_G)\varphi/\partial z+\sigma\varphi=\partial(\mu_\varphi\,\partial\varphi/\partial x)/\partial x+\partial(\mu_\varphi\,\partial\varphi/\partial y)/\partial y+ +\partial(\nu_\varphi\,\partial\varphi/\partial z)/\partial z+f \tag{1}$$

with following boundary and initial conditions

$$\partial\varphi/\partial z=0 \quad \text{on} \quad z=0,$$

$$\partial\varphi/\partial z=\alpha\varphi \quad \text{on} \quad z=H(x,y),$$

$$\alpha\,(\mu_\varphi\,\partial\varphi/\partial n-\beta\varphi)+bQ=0 \quad \text{on} \quad S,$$

$$\varphi=\varphi^0 \quad \text{at} \quad t=0,$$

where φ is the volume concentration of a substance; u, v, and w are the sea current velocity components along x, y and z, respectively (the axes x, y, and z are directed eastward, northward, and vertically downward from the sea surface, respectively); w_G is the own gravitational speed of particles; μ_φ and ν_φ are the factors of horizontal and vertical turbulent diffusion, respectively; n is the vector of the outer normal to S; $\sigma=ln2/T_0$ is the parameter describing changeability of concentration because of the physical and biochemical factors; T_0 represents the time interval, during which the initial pollution concentrations decrease twice; a and b are the factors accepting values either unit or zero. α and β are the parameters describing interaction of admixture with the sea bottom and lateral surface, respectively. In general, f describes the spatial-temporal distribution of the source power, which in case of the point source may be represent by the delta function

$$f=Q\,\delta(x-x_0)\delta(y-y_0)\delta(z-z_0) \tag{2}$$

where x_0, y_0 and z_0 are coordinates of the source location. Q is power of oil emission from the point source.

The variable horizontal diffusion coefficient was calculated on each time step by the formula offered in Zilitinkevich and Monin (1971)

$$\mu_\varphi=\gamma\Delta x\Delta x\,(2(\partial u/\partial x)^2+(\partial u/\partial y+\partial v/\partial x)^2+2(\partial v/\partial y)^2)^{1/2} \tag{3}$$

where Δx and Δy are horizontal grid steps along x and y axes, respectively; γ is some constant. The same formula was applied in the RM-IG. It is supposed that the velocity components u, v and w satisfy the continuity equation for incompressible liquid. 2D version of this model was applied for simulation and forecast of oil spill transport.

To solve the problems in both blocks splitting methods are used, which enable solving of complex nonstationary problems to reduce to solutions of relatively simple two-dimensional and one-dimensional problems (Marchuk, 1974; 1982) .

Thus, the regional forecasting system provides 3 days' forecast of 3D dynamic fields – flow, temperature and salinity with 1 km spacing, and in case of accidental situations – the forecast of spreading of the oil and other pollutants in the Georgian Black Sea coastal zone and adjoining water area.

Implementation of the Regional Forecasting System

The 2D and 3D dispersion models are included in the software of the forecasting system as separate modules and enable calculating pollution zones and concentrations in special cases. 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 emission, duration of emission and the parameter σ depending on the type of polluting substance. The nonstationary sea flow field on each time step is provided from the RM-IG.

All numerical models included in the regional forecasting system use a grid having 215 x 347 points with horizontal resolution 1 km. On the vertical, the nonuniform grid with 30 calculated levels on depths 2, 4, 6, 8, 12, 16, 26, 36, 56, 86, 136, 206, 306 to 2006 m are considered. The time step is equal to 0.5 h.

Despite the fact that a large number of articles (e. g., Stanev et al, 1988; 2002; Oguz et al, 1995; Ozsoy and Unluata, 1997; Staneva et al, 2001; Demyshev, 2011; Zalesny et al, 2013) is devoted to the study of the Black Sea dynamics, some specific features of circulation mode in the coastal and shelf zones remain relatively poorly studied. Regular calculations of the regional forecasts started since 2010 show that the easternmost part of the Black Sea, including the Georgian water area, is dynamically very active zone, where continuous generation, deformation, and disappearance of the mesoscale and submesoscale cyclonic and anticyclonic eddies occur throughout the year (Kordzadze and Demetrashvili, 2013). Among these eddies the Batumi anticyclonic eddy is often most stable formation in warm season, but it may also appear in cold season. In that case, when the Batumi eddy is intensive and occupies a significant part of the easternmost water area, it forms a certain mode of salinity: the salinity of waters considerably decreases in the central part of the vortex and penetration of more salty waters from the open part of the Black Sea into the Georgian water area is distinctly observed. In most cases, in the narrow zone along the Caucasian coast with a width of about 20–30 km, an area of intense vortex formation is observed, where the generation of small unstable eddies with sizes from about 5 to 25 km occurs. It is necessary to note that such coastal small eddies are identified also in other coastal areas of the Black Sea (Demyshev, 2011; Zatsepin et al., 2011).

Generally, transformation of oil pollution in the marine environment is influenced by hydrodynamic and nonhydrodynamic factors. After the oil slick is formed under the influence of gravity, viscosity and surface tension forces, it starts to migrate and changes its sizes and configuration under the effect of hydrodynamic factors –advection and turbulent diffusion. Simultaneously oil slick on the sea surface undergoes some physical and biochemical transformation.

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 (Korotenko et al, 2003). It is estimated that during the period of time from several till 24 hours, probably, from 1/3 to 2/3 oil mass is lost (Vragov, 2002). Therefore, for 3 days' forecast of oil spill transport evaporation is the most important factor. Taking into consideration this fact, we accepted $\sigma = 1{,}6.10^{-5}$ if $t \leq 24$ h and $\sigma = 8{,}2.10^{-7}$ if $t > 24$. The first value corresponds to double reduction of concentrations during 12 hours, and the second one - to double reduction of concentrations during 10 days.

Fig. 2 illustrates forecasted regional circulation in the easternmost part of the Black Sea and drifting of oil slick in case, when 50 t of oil was abnormally spilled during 2 hours on distance about 65 km from Poti shoreline in the coordinates 140Δx and 132Δy (the forecasting period is 00:00 GMT,1-4 March 2014). Taking into account that the maximum allowable concentration of oil pollution is usually taken to be 0.05 mg/L in all the numerical experiments we have taken to be zero concentration of less than 0.001 mg/L.

From Fig. 2 it is well visible that in the eastern part of the considered area the triplet structure consisting of two anticyclonic vortexes and one middle cyclonic vortex is formed on 1-2 March 2014 (Fig. 2a and 2b). During the forecasting interval the current is substantially transformed - the triplet structure gradually breaks up and the current directed to the north-west is formed, but there are also some vortexes with relatively small sizes (Fig. 2c and 2d). Such circulating reorganization is essentially reflected on moving of the oil spill. In the course of migration the oil slick extends gradually and deforms. Simultaneously there is a reduction of oil pollution concentrations, that is caused by diffusion expansion and other nonhydrodynamic factors, which are taken into account in the model indirectly.

Fig. 3 shows the results of forecast of the surface circulation and oil slick transport during the forecasting interval: 00:00 GMT, 6-9 December 2014. Hypothetical emergency oil spill occurred on the following scenario: 30 t of oil was spilled during 2 hours at a distance of approximately 20 km from Poti shoreline. Comparing Figs. 2 and 3, are well visible that the sea surface circulation during 6-9 December 2014 sharply differs from the previous case. During this period over the east part of the Black Sea very strong winds operated, which have the smoothing effect on the sea surface current and promote disappearance of vortex formations. Under the influence of strong wind stress the sea current with very high speed is generated in the north-eastern part of the considered region. From Fig. 3b it is visible that the current speed exceeds 100 cm/s on 7 December. In conditions of such circulating mode, the process of spatial-temporal distribution of oil pollution has absolutely other character than in the previous considered case. The strong sea current carries away an oil slick far from the flood point in the north-west direction and oil slick covers relatively more territory. During 3 days the oil slick is transferred on distance about 120-140 km at the same time extending and being deformed.

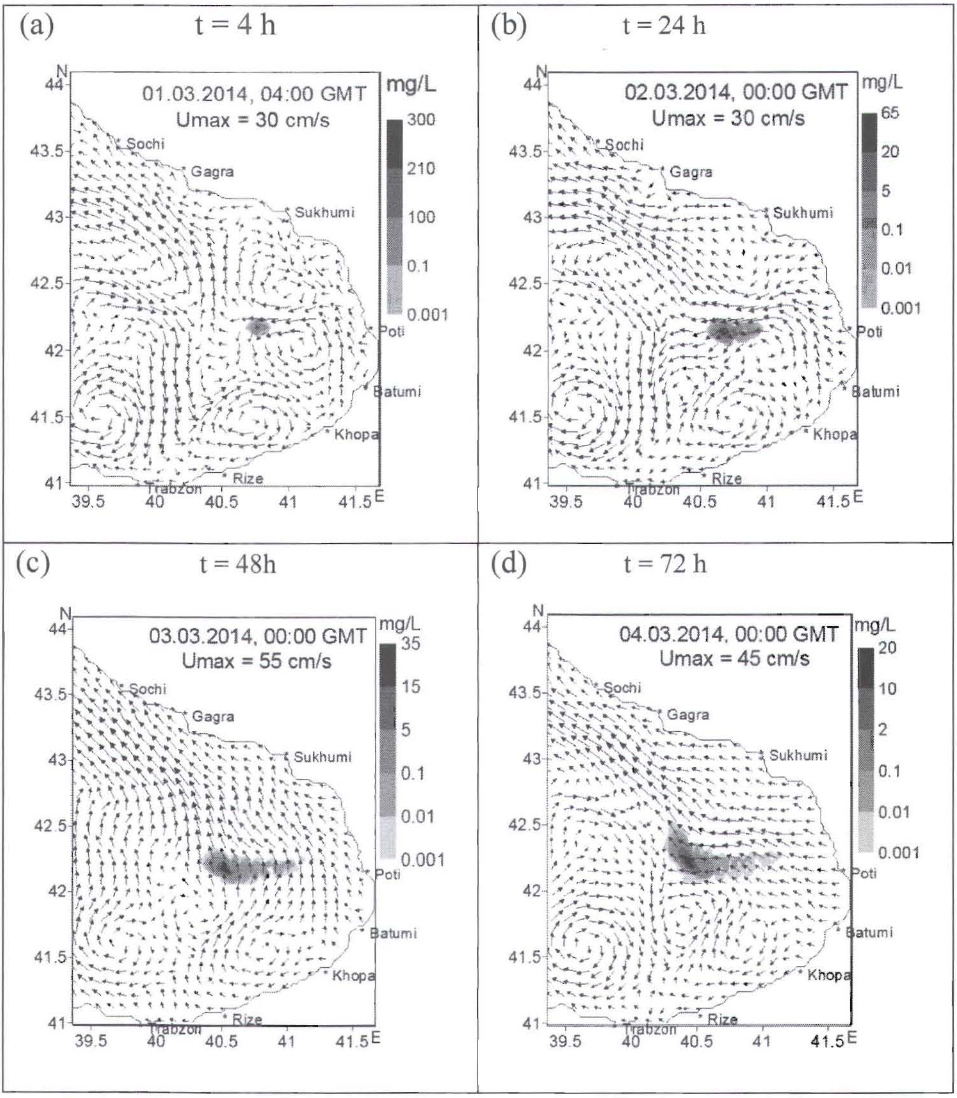

Fig. 2: Simulated surface current field and oil spill transport corresponded to the following time moments after hypothetical oil flood: (a) - 4h, (b) - 24 h, (c) - (48), (d) -(72). The forecasting interval is 00:00 GMT,1-4 March 2014. The source coordinates: 140Δx and 132Δy.

Fig. 4 illustrates the results of simulation of the nonconservative conditional impurity which has been discharged into the sea from the rivers Rioni and Chorokhi in the following amount per 1 s: from river Chorokhi - 100000 reference units, from Rioni - 10000 reference units, respectively. The time of disintegration T_0 was taken equal to 10 days. The factor of vertical turbulent diffusion was 15 cm^2/s and the gravitational speed $w_G = 0$. The forecasting period was the same as in the previous case. From Fig. 4 it is visible, that the character of circulation considerably predetermines the basic features of impurity distribution processes. The analysis of the 3D pollution concentration fields showed that the impurity is distributed not only in a horizontal direction, but also a vertically due to vertical diffusion and vertical flows. pollution concentrations reached up to depth approximately 50-60 m during 3 days.

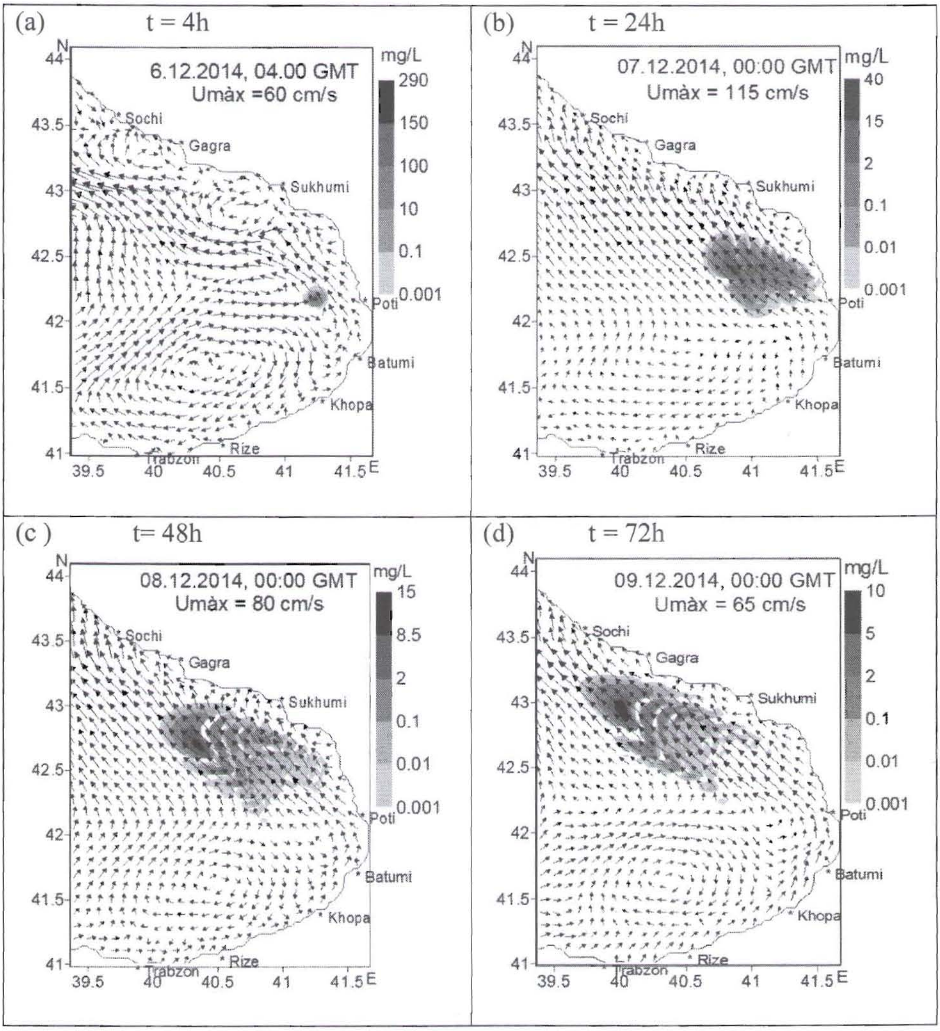

Fig. 3: The same as in Fig. 2, but forecasting interval is 00:00 GMT, 6-9 December 2014. The source coordinates: $180\,\Delta x$, $132\,\Delta y$.

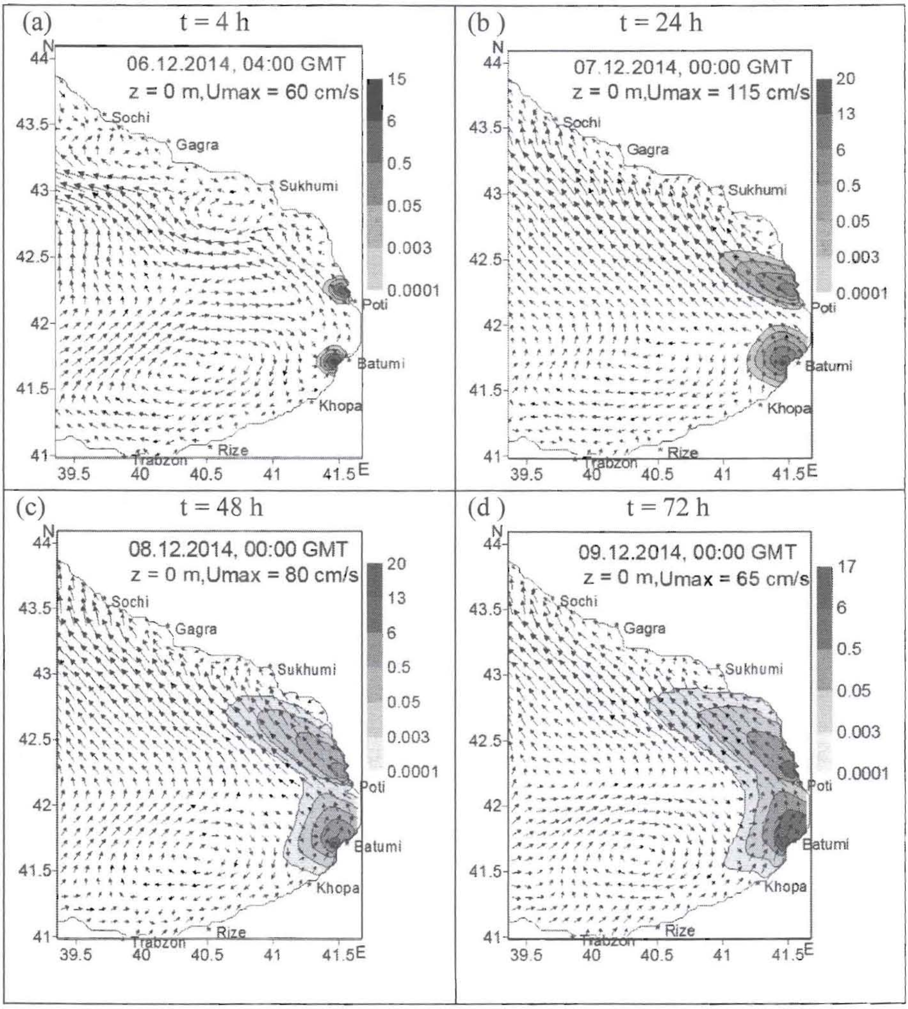

Fig. 4: Simulated surface current field and distribution of impurity at t = 4, 24, 48 and 72 h after start of getting impurity to the sea from the rivers Chorokhi and Rioni. The forecasting period is 00:00 GMT, 6-9 December, 2014.

Conclusion

The paper presents a new version of the easternmost Black Sea regional forecasting system, which is one of the parts of the Black Sea Nowcasting/Forecasting system. The main components of the regional forecasting system are the regional model of the Black Sea dynamics and 2D and 3D advection-diffusion models of spreading of nonconservative polluting substances. The advection-diffusion models uses forecasted current field by the regional model of dynamics, which is nested in the BSM of MHI.

All required input data are provided from MHI in the near-real time mode via Internet. The regional forecasting system allows to calculate in the near-real time 3 days' forecast of main dynamic fields – the current, temperature and salinity with 1 km spacing for the easternmost part of the Black Sea, also spreading of pollution zones and concentrations of oil and other pollutants in the accidental situations.

The analysis of the forecasted fields shows that: to use the model with high resolution is very important factor for identification of nearshore eddies of small sizes; the easternmost water area of the Black Sea is dynamically very active zone, where there is a continuous formation of different mesoscale and submesoscale eddies. The numerical experiments carried out in different locations of hypothetical sources and real circulating modes show a significant role of circulating processes in formation of the spatial-temporary distribution of pollution.

Further improvement of the regional forecasting system is connected with development of very high-resolution forecasting subsystem for Batumi water area (with 100-200 m horizontal resolution) with inclusion in the system the forecasting models of surface waves and biochemical processes.

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