

# Numerical study of the circulation and its contribution to the oil slick transport in the southeastern part of the Black Sea

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## Research Article

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# Abstract

The relevance of studying and forecasting regional circulation and the spread of impurities in the shelf/coastal zones of the seas is determined by intensive human economic activity, which causes a large anthropogenic load on coastal marine ecosystems. The aim of this paper is to study the mesoscale circulation under real atmospheric forcing and its contribution to the oil slick transport in the southeastern part of the Black Sea using a regional model of the Black Sea dynamics (RM-IG) and a 2-D oil slick transport model, which is coupled to the RM-IG. The RM-IG with 1 km horizontal resolution is based on a z-level primitive equations system of ocean hydrothermodynamics. During the EC project ARENA (2003–2005) the RM-IG was nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (Sevastopol, Ukraine) with 5 km horizontal resolution. The transport model is based on 2-D advection-diffusion equation for non-conservative substances. Atmospheric forcing is taken into account by prognostic meteorological fields derived from the atmospheric model SKIRON. Numerical experiments have shown that during all seasons there is a generation, deformation, and disappearance of anticyclonic and cyclonic meso- and submesoscale vortex formations, which have a significant impact on the pollutants dispersion process. Intensive vortex formations are observed during light winds. Strong winds have a smoothing effect and prevent the formation of vortex structures. In a number of cases, the unstable eddy formations with a diameter of 5–20 km are generated in a narrow strip along the Georgian coast presenting a width of about 20–30 km.

## Introduction

The study and forecast of mesoscale circulation and pollutants distribution processes near the coastal water areas of seas and oceans is one of the most important issues of modern oceanology, since the coastal and shelf zones experience the greatest anthropogenic load. Regional circulation processes are one of the important factors, which make a significant contribution to the main features of the distribution of oil products and other substances entering the marine environment by anthropogenic or natural ways. The sea circulation also largely determines formation and changeability of temperature and salinity fields, to which marine organisms are very sensitive (Cuthbert et al. 2021). Besides, formation of the thermal regime in the sea upper layer is very important factor in the problem of interaction between the sea and the atmosphere.

Studies show that dynamic processes in coastal/shelf areas of the Black Sea are characterized with high variability (Zatsepin et al. 2011; Dymova 2017). In coastal waters, mesoscale and submesoscale eddy structures of small spatial dimensions are formed which can significantly affect the distribution of various impurities. In addition, the configuration of the coastline, the inflow of rivers, the sea bottom relief are important factors making a significant contribution to the coastal circulation processes. All of the above mentioned factors require high resolution of numerical models to adequately reproduce hydrodynamic processes in coastal areas.

At present, numerical modeling is one of the most effective tools for studying and predicting dynamic processes in the seas and oceans. Numerical models based on solving the equations of geophysical fluid dynamics began to be used to study the variability of the state of the waters of the World Ocean in the early 1960s (Bryan 1969; Sarkisyan and Sundermann 2009). Pioneering work on modeling dynamic processes in the Black Sea based on a primitive system of ocean hydrothermodynamics equations was performed by Marchuk et al. (1975), where two-cycle splitting method was applied to solve the primitive equation system, written in  $z$  coordinates. The calculations confirmed the general cyclonic nature of the Black Sea circulation and showed the important role of the sea bottom relief in the formation of the circulation, especially in the northwestern part of the Black Sea. An overview of the state of mathematical modeling of the dynamics of the Black Sea for the 80s of the last century is presented in the monographs by Stanev (1987) and Kordzadze (1989). The level of computational techniques of this period did not provide the necessary spatial resolution for the implementation of non-stationary spatial problems to adequately describe the spatio-temporal variability of hydrophysical fields.

Over the last 2–3 decades studies of the Black Sea dynamics using numerical models have been widely developed. Advances in computational technology have contributed to the development of high-resolution models capable of adequately reflecting the marine dynamic processes. The number of publications on this issue is increasing. Modern mathematical models mainly differ from each other in the used coordinate system, methods of parameterization of physical factors, the solution algorithm, solution domain and grid parameters (e. g., Oguz et al. 1995; Oguz and Malanote-Rizzoli 1996; Girgylani 1998, 1999; Kara et al. 2005a, 2005b; Stanev 2005; Zatsepin et al. 2011; Demyshev and Dymova 2011; Demyshev and Evstigneeva 2012; Grigoriev and Zatsepin 2013; Zalesny et al. 2013; Dymova 2017). Almost all modern numerical models of the Black Sea dynamics are based on a primitive equation system of ocean hydrothermodynamics. Most of these models use the hydrostatic approximation to model basin-scale dynamics and regional circulation in coastal-shelf zones. We will briefly describe some of these publications.

Modeling of the wind and thermohaline circulation of the Black Sea driven by yearly mean climatological forcing is carried out by Oguz et al. (1995). For this purpose, the Princeton ocean model (POM) was used (Blumberg and Mellor 1987), that is a free-surface primitive equation model using bottom-following  $\sigma$  coordinate in the vertical and a coast-following orthogonal curvilinear coordinate system in the horizontal. POM was implemented for the Black Sea basin with 5 km resolution along most of the southern coast, where the topography undergoes most drastic variations, but in the interior of the basin, where topography is almost flat, the grid spacing increased to 15 km. On the basis of the model, interesting studies were conducted in order to evaluate the contribution of individual factors to the sea circulation. POM is also used for some individual regions of the Black Sea (Grigoriev and Zatsepin 2013). Eddy resolving Hybrid Coordinate Ocean Model (HYCOM) was applied to the Black Sea to investigate the sensitivity of the Black Sea surface temperature to water turbidity by Kara et al. (2005a). A low-dissipative DieCAST Ocean model was adapted for the Black Sea to apply for modeling the Black Sea dynamics with 9.4 km spatial resolution By Staneva et al. (2001). The results of numerical experiments showed that the

model describes well the main features of the Black Sea circulation – the Rim Current, cyclonic eddies, anticyclonic coastal eddies, etc.

High-resolution modeling was applied to simulate and study vortex structure in different regions of the Black Sea. The analysis of modeling results of the Black Sea hydrophysical fields with 1,64 km resolution for the period January-September 2006 are presented with the real atmospheric forcing by Demyshev and Dymova (2011). The coefficients of the vertical turbulent exchange and vertical diffusion were calculated on the well-known Mellor – Yamada theory 2.5. Note that there is a good agreement between the calculated and observed data at points close to the shore. An increase in horizontal resolution made it possible to reproduce the dynamics of sea waters at synoptic and mesoscales with high accuracy. By Demyshev and Evstigneeva (2012) results of two Numerical experiments on studying circulation in January-February and July – August are analyzed on the basis of the Black Sea dynamics model. Due to the fine grid step of 1.6 km and the refined bottom topography, the currents on the northwestern shelf of the Black Sea are described, the elements of eddy motion are obtained that are not reproduced by the model with a coarser grid (grid step 5 km). The simulation of the Black sea circulation with a horizontal resolution of 1,6 km was carried out by the eddy-resolving model by Dymova (2017). The most intensive generation of eddies was observed near the Crimean peninsula, the North-Western shelf, the north-eastern and south-eastern parts of the Black Sea.

Advances in numerical modeling of circulation processes promoted to develop modeling methods of the distribution of oil and other pollutants in the sea environment. A sufficient amount of work is devoted to this problem for the Black Sea and -other seas (e. g., Daniel 1997; Korotenko et al 2002, 2010; Yong-Sik Cho and et al 2012; Dianskii et al 2013; korotenko 2018; ). These models use circulation parameters derived from numerical models of the sea dynamics. The analysis of these works show that mainly two approaches are used: a Lagrangian particle-tracking method, which allows tracking the motion of individual particles and Eulerian models based on the solution of advection-diffusion equation. We will briefly mention some of these studies. A 3-D hybrid flow/transport model is developed to predict the dispersal of oil pollution in the south part of the Caspian Sea by Korotenko et al. (2002). The transport module of the model uses Lagrangian tracking to predict the motion of individual particles (droplets), the sum of which constitutes a hypothetical oil spill. Current and turbulent diffusivities used in the model are generated by POM, which is adapted to the Caspian Sea. The high-resolution coupled DieCAST/transport model was used to predict the transport and dispersal of contaminant resulting from representative hypothetical oil spills in the Black Sea by Korotenko et al. (2010) and by Korotenko (2018). Like in the above mentioned paper, it was used Lagrangian tracking algorithm to predict the motion of a large number of seeded particles, whose sum (~ 1 million) form the oil plume. It was shown that mesoscale structures play a significant role in the coastal and open water dynamics of the Black Sea and have a great impact on the ecology and pollution transport within the Sea. Meteo-France has developed an oil spill transport model (Daniel 1997). A hydrodynamic ocean model is linked to an oil spill model including current shear, vertical movements and fate of the oil.

The aim of this paper is to study the mesoscale circulation under real atmospheric forcing and its contribution to the oil slick transport in the southeastern part of the Black Sea. For this purpose, a modeling system is presented that provides modeling and a 3-day forecast of regional circulation and oil slick transport with 1 km spatial resolution. Some of the results are discussed.

## Materials And Methods

This work is based on a modeling system consisting of a regional model of the Black Sea dynamics developed by the Institute of Geophysics (RM-IG) of I. Javakhishvili Tbilisi State University, coupled with a 2-D advection-diffusion numerical model of pollutants in the sea environment. The 2-D model is used to simulate the oil slick transport in the sea surface. It should be noted that this model has also been used to simulate the distribution of floating solid objects (marine litter) in Georgian coastal waters (Demetrashvili et al. 2022a).

## Regional Model of the Black Sea Dynamics

The high-resolution RM-IG is received by adaptation of the basin-scale model of the Black Sea (Demetrashvili et al. 2008; Kordzadze and Demetrashvili 2008; Kvaratskhelia et al 2021) to the physical and geographical conditions of the southeastern part, which covers Georgian sector of the Black Sea and surrounding water area bounded between  $40.8^{\circ}\text{N}$  –  $44.09^{\circ}\text{N}$  and  $39.07^{\circ}\text{E}$  –  $41.8^{\circ}\text{E}$ . In its turn, the basin-scale model is advanced version of the model by Marchuk et al. (1975). The RM-IG is a z-level hydrostatic model with 1 km horizontal spatial resolution based on the solution of a primitive system of ocean hydro and thermodynamics equations, which is nested in the basin-scale model (BSM) of the Black Sea dynamics with 5 km spatial resolution of the Marine Hydrophysical Institute (MHI, Sevastopol, Ukraine) within the EC project ARENA (2003–2005) (Kordzadze and Demetrashvili 2011, 2017; Demetrashvili and Kukhalashvili 2019; Demetrashvili et al. 2022b). The RM-IG provides a 3-day forecast of 3-D main hydrophysical fields – the current, temperature, salinity, density in the southeastern water area of the Black Sea. All input data providing initial and boundary conditions were available in the Internet via ftp service. These data on the open boundary are values of velocity components, temperature and salinity predicted by the BSM of MHI. On the sea surface 2D meteorological fields (wind stress, heat fluxes, precipitation, evaporation) derived from the atmospheric model SKIRON are used.

The RM-IG takes into account: (1) atmospheric wind and thermohaline forcing, (2) atmospheric precipitation, (3) evaporation from the sea surface, (4) absorption of short-wave radiation by the upper layer of the sea, (5) the sea bottom relief and configuration of the water area, (6) spatial-temporal variation of horizontal and vertical turbulent viscosity and diffusion coefficients, (7) inflow of the main rivers of Georgia, (8) Influence of dynamic processes developed in the open sea on regional processes.

To solve the equation system of the RM-IG, splitting method is used (Marchuk 1974). The numerical scheme consists of splitting of main operator into physical processes and then into geometrical coordinates and planes. The baroclinic and barotropic parts are also separated. The solution algorithm

makes it possible to reduce the solution of complex nonstationary problems to the solution of simpler 2-D and 1-D problems.

The simulated and predicted sea surface temperature (SST) and currents were compared with available observational data – satellite SST derived from NOAA satellites and Geostrophic currents reconstructed on the basis of satellite altimeter data. Comparison showed sufficient reliability of the model results (Kordzadze and Demetrashvili 2011, 2017; Demetrashvili and Kukhalashvili 2019) .

## Oil Slick Transport Model

The spread and transformation of an oil spill in the marine environment is a complex process that depends on many factors. The mechanism of oil distribution and change in the concentration in the marine environment is described sufficient in detail by Korotenko et al. (2002), Vragov (2002). After spilling oil on the sea surface, an oil slick is formed under the influence of gravity, viscosity and surface tension forces, the thickness of which reaches several tens of micrometers. The oil slick begins to drift on the sea surface and at the same time its transformation takes place.

Oil concentrations change under the influence of such physical and biochemical factors as turbulent diffusion, oil evaporation, dispersion, emulsification, biodegradation, sedimentation, etc. Evaporation rate is the main characteristic parameter for any type of oil (especially in the first hours after an oil spill). Evaporation depends on both the fractional composition of oil and the area of oil spilled on the surface, as well as external conditions - sea temperature and wind speed.

Oil is a mixture of hydrocarbon compounds, and after it is spilled, volatile components with low boiling points quickly evaporate. That is why the intensity of evaporation depends significantly on the composition of the oil. As a result of evaporation, on average, from 1/3 to 2/3 of the oil mass is lost within a time interval from several hours to 24 hours after an oil spill (Vragov 2022).

To describe the spread of oil pollution in the marine environment, we consider a non-stationary advection-diffusion equation for a non-conservative substance in two-dimensional area  $\Omega$  bounded by a lateral line  $S$

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

with the following boundary and initial conditions

$$\frac{\partial \varphi}{\partial n} = \beta \varphi \quad \text{on } S \quad (2)$$

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

Here  $\varphi$  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);  $\mu_\varphi$  is the turbulent diffusion coefficient;  $n$  is the vector of the outer normal to  $S$ ;  $\sigma$  is parameter of non-conservatively, taking into account the change in impurity concentration due to some nonhydrodynamic factors (evaporation, sedimentation, etc.) and, in the general case, being a function of coordinates and time. In some particular case, it can be represented  $\sigma = \ln 2 / T_0$ ;  $T_0$  represents a time interval, during which the intensity of the pollution concentration will decrease by half compared to the initial concentration.  $\beta \geq 0$  is some function characterizing the interaction of impurity with the coastline.  $f$  describes the source of the pollutant, which is a function of time and coordinates. In the case of a point source,  $f$  may be represented by delta function

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

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

If the location of the source is far from the lateral boundaries, then instead of (2) boundary condition we can consider zero concentration on lateral boundary.

The turbulent diffusion coefficient was calculated by the formula (Zilitinkevich and Monin 1971)

$$\mu_\varphi = \gamma \Delta x \Delta y \sqrt{2 \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + 2 \left( \frac{\partial v}{\partial y} \right)^2}$$

where  $\Delta x$  and  $\Delta y$  are horizontal grid steps along  $x$  and  $y$  axes, respectively,  $\gamma$  is some constant. Note that the same formula is applied in the RM-IG.

The current velocity components  $u$  and  $v$  are derived from the RM-IG at each time level during integration of Eq. (1).

Thus, the model takes into consideration: (1). nonstationary current field, (2). special and temporal variability of the turbulent diffusion, (3). non-hydrodynamic factors (evaporation, biochemical transformation, etc.) parametrically, (3). non-stationary pollution source, (4). configuration of solution area.

To solve the problem (1)–(3) the two-cycle splitting method with respect to spatial coordinates is used (Marchuk 1982). For the finite-difference approximation of this problem we consider a grid domain  $\Omega^h$ , which consists of main and auxiliary nodes. Let us signify the values of function  $\varphi$  in the grid nodes  $(x_k, y_l)$  by  $\varphi_{k,l}$ , i.e.  $\varphi(x_k, y_l) = \varphi_{k,l}$ . Precisely similarly we have defined other functions, included in the problem. Let  $\Delta$  is the finite – difference operator on spatial variables, which we introduce in the form

$$\Lambda = \Lambda_1 + \Lambda_2.$$

$\Lambda_1$  and  $\Lambda_2$  are finite-difference operators on variables  $x$  and  $y$ , having the following form:

$$\Lambda_1 \varphi = \frac{u_{k+1/2,j} \varphi_{k+1,j} - u_{k-1/2,j} \varphi_{k-1,j}}{2 \Delta x} - \frac{1}{(\Delta x)^2} [\mu_{k+1/2,j} (\varphi_{k+1,j} - \varphi_{k,j}) - \mu_{k-1/2,j} (\varphi_{k,j} - \varphi_{k-1,j})],$$

$$\Lambda_2 \varphi = \frac{v_{k,j+1/2} \varphi_{k,j+1} - v_{k,j-1/2} \varphi_{k,j-1}}{2 \Delta y} - \frac{1}{(\Delta y)^2} [\mu_{k,j+1/2} (\varphi_{k,j+1} - \varphi_{k,j}) - \mu_{k,j-1/2} (\varphi_{k,j} - \varphi_{k,j-1})],$$

The problem (1)-(3) may be written in the following form:

$$\frac{d\varphi}{dt} + \Lambda \varphi = F, \quad (4)$$

where  $\varphi$  and  $F$  are the vector-functions with components  $\{\varphi_{k,l}\}$  and  $\{F_{k,l}\}$ , respectively. Generally,  $F$  represents a combination of function  $f$  and function produced due to taking into account inhomogeneous boundary conditions. The Crank-Nicholson scheme is used to approximate Eq. (4) on each broadened time interval  $t_{j-1} \leq t \leq t_{j+1}$  using a two-cycle splitting method with respect to coordinates  $x$  and  $y$ . As a result, a set of more simple one-dimensional finite-difference equations is received, which can be effectively solved by factorization method. These equations have the following form:

$$\left(E + \frac{\tau}{2} \Lambda_1\right) \varphi^{j-1/2} = \left(E - \frac{\tau}{2} \Lambda_1\right) \varphi^{j-1}, \quad (5)$$

$$\left(E + \frac{\tau}{2} \Lambda_2\right) (\varphi^j - \tau F) = \left(E - \frac{\tau}{2} \Lambda_2\right) \varphi^{j-1/2},$$

$$\left(E + \frac{\tau}{2} \Lambda_2\right) \varphi^{j+1/2} = \left(E - \frac{\tau}{2} \Lambda_2\right) (\varphi^j - \tau F),$$

$$\left(E + \frac{\tau}{2} \Lambda_1\right) \varphi^{j+1} = \left(E - \frac{\tau}{2} \Lambda_1\right) \varphi^{j+1/2},$$

where  $\tau$  is the time step;  $E$  is the unit matrix.

The serial solving of equations (5) enables to obtain a solution of the problems with the second order accuracy in time and space.

## Results And Discussion

Both the RM-IG and oil slick transport models are implemented on a grid having 215 x 347 points on horizon with 1 km resolution. Time step of both models – 0.5 hrs. In the RM-IG 30 calculated levels on a



vertical with non-uniform vertical steps are taken (minimum step – 2 m at the surface, maximum – 100 m in the deep layers below 200 m).

Modeling and forecasting of regional dynamic processes based on the use of RM-IG showed that the circulation mode in the southeastern part of the Black Sea is characterized by great diversity and significant seasonal and interannual variability. Various structural elements of circulation are continuously generated here - mesoscale cyclonic and anticyclonic eddy formations, including the well-known Batumi anticyclonic eddy, the “cyclone-anticyclone” dipole structure, submesoscale eddies, which have a significant impact on the pollutants dispersion process. Non-stationary atmospheric forcing is one of the main external factors that ensure the variability of the hydrological mode. In winter, the regional circulation as a whole has a cyclonic character, but in some cases anticyclonic mesoscale eddies form against this background. In summer and early autumn, anticyclonic movement prevails, although the formation of cyclonic structures can also be observed. In many cases, the formation of an intense anticyclonic eddy, known as the Batumi eddy, is observed, mainly in the warm season.

Figure 1 illustrates prognostic sea surface circulation fields corresponding to June 2010, 2012 and 2018, which show that in the same season the surface circulation structure can differ significantly from each other. Figure 1a shows, that on June 12, 2010 the main element of the regional circulation was the Batumi eddy, which has an elliptical shape with a diameter of about 150 km. It should be noted that the Batumi eddy was a very intense and stable structure throughout the summer 2010 and reached its maximal intensity in August. In nearshore waters near Gagra and Sukhumi two submesoscale anticyclonic eddies are also observed, which are very unstable formations. Figure 1b shows the circulation on June 17, 2012, which differs significantly from the June 2010 circulation (Fig. 1a). The circulation on that day was characterized by a pair of anticyclonic eddies with a diameter of about 100 km. In addition, small unstable cyclonic structures are formed along the Caucasian coast in a narrow strip about 20–25 km wide. Generation of submesoscale cyclonic and anticyclonic unstable eddies is typical for the nearshore area. Calculations showed that the summer circulation of 2018 was characterized by the formation of eddy cyclonic and anticyclonic structures of different sizes, and the Batumi eddy practically did not dominate. The circulation pattern on June 10, 2018 shown in Fig. 1c is typical for the 2018 summer circulation.

An analysis of the results of numerical experiments shows that the atmospheric wind speed is an important factor in the formation of the horizontal and vertical structure of the sea circulation in the upper layer. In all seasons, weak winds acting over the water area contribute to the formation of intense eddy formations, but high wind speeds have a smoothing effect on sea currents, providing almost vortex-free circulation in the upper layer with a thickness of about 5–10 m. It should be noted that a similar result was obtained for basin-scale circulation (Dymova 2017). The vertical structure of the circulation differs significantly in winds with low and high speeds. In a weak wind, the vertical eddy structure of the circulation is homogeneous and practically does not change with a depth of several tens of meters. Under conditions of high wind speed, the structure of the sea circulation undergoes strong qualitative and quantitative changes with depths. With increasing depth, the influence of wind stress as an external

factor weakens and the circulation mode in the lower layers is formed mainly under the influence of internal factors (baroclinicity, configuration of the basin, etc.).

To illustrate the vertical transformation of sea circulation, in Fig. 2 simulated circulation patterns at the depths of 0, 20 and 50 m on September 29, 2019 are shown (Fig. 2a, b, c), when the maximum wind speed was 2.5 m/s and on October 19, 2013 (Fig. 2d,e,f), when the maximum wind speed was 14 m /s. This Figure clearly shows the large difference in the vertical structure of the circulation in these two cases. Weak winds contributed to the formation of intense vortex motion with cyclonic and anticyclonic mesoscale eddies of different sizes. From Figure is well visible that the circulation structure is uniform in the vertical, the maximum speed of the sea current is reduced by only 3 m/s in a layer 50 meters thick (Fig. 2a, b, c). Under strong atmospheric wind forcing vortex-free circulation is observed with maximum speed 60 cm/s on the sea surface, which is directed from west to east in the most part of the considered area (Fig. 2d), corresponded to the wind direction. There is a sharp change in the circulation mode vertically, on a depth of 20 m and below the anticyclonic eddy with diameter about 150 m is observed (Fig. 2e, f). The maximum current velocity decreased from 60 cm/s at the surface to 30 cm/s at a depth of 20 m.

In Numerical experiments on modeling oil slick transport, values of model parameters were as follows:  $\gamma = 0.1$ ,  $\beta = 0$ . Taking into account the fact that evaporation is essential on the first day from the moment of oil spill, the parameter  $\sigma$  describing changes of concentration due to nonhydrodynamical factors was taken as follows:  $\sigma = 1,6 \cdot 10^{-5} \text{ s}^{-1}$ , when  $t < 12 \text{ h}$ , which corresponds to the lost of 50% of the spilled oil mass during 1/2 day.  $\sigma = 2,3 \cdot 10^{-6} \text{ s}^{-1}$ , when  $t \geq 12 \text{ h}$ . At graphical interpretation of model results, in grid points, where calculated concentration was less than 0.001 mg/L, the concentration was considered zero.

Numerical experiments were conducted under different real circulation modes and at different locations of the hypothetical oil spill point. The results of the calculations show that the circulation mode, characterized by various eddy structures, is one of the most important factors that essentially determines the transport of the oil slick. The turbulent diffusion factor is also important. During the spreading process of the oil slick, it changes shape, expands diffusely, and occupies more area. At the same time, the concentrations gradually decrease due to diffusion expansion and nonhydrodynamic factors.

A series of numerical experiments were conducted, when a hypothetical oil spill was carried out in different points of the sea water area under the same circulation mode. The calculation showed that the features of the spread of accidentally spilled oil on the sea surface depend significantly on the location of the oil spill point, especially when the circulation field is characterized by significant horizontal inhomogeneities accompanied by various vortex structures.

To illustrate above fact, Figs. 3, 4, 5 present the results of three numerical experiments that differ only in the location of the oil spill. In all three numerical experiments, the forecast fields of surface circulation and oil pollution correspond to August 5, 7, and 8, 2022. During this period, the main element of circulation was the Batumi anticyclonic eddy with a diameter of about 80 km. As can be seen from the

Figures, the Batumi eddy was practically unchanged during the forecasting period. In all numerical experiment 10 tons of oil were hypothetically spilled for 4 hours at different points of the Batumi eddy: at the right peripheral part of the eddy with coordinates  $136\Delta x$ ,  $142\Delta y$  (Fig. 3), at the left peripheral part with coordinates  $96\Delta x$ ,  $142\Delta y$  (Fig. 4) and at the center with coordinates  $120\Delta x$ ,  $142\Delta y$  (Fig. 5) It is clear from the Figs. 3, 4, 5 that the oil spreading process is significantly different from each other. When the oil spill occurs at the center of the eddy, the drift of the oil slick is negligible and the zone of high concentrations remains practically at the center of the vortex, only its diffusive expansion is observed (Fig. 5a,b,c). In other cases, under the influence of circulation and diffusion processes, the oil slick moves, changes shape and expands (Fig. 3 and Fig. 4). Other conducted numerical experiments have shown that the location of the oil spill is very important factor, which significantly determines the further spread of the oil spill.

## Conclusion

The RM-IG and the oil spill transport model have been implemented for the southeastern part of the Black Sea with 1 km horizontal resolution under real atmospheric forcing. Numerical calculations have shown that this water area is characterized by a variety of circulation modes, where, in addition to the Batumi eddy, various cyclonic and anticyclonic mesoscale eddy structures are formed. In some cases, along the eastern coastline in the water area with a width of approximately 20–30 km unsteady submesoscale eddies are formed, whose identification requires high resolution of numerical models. Weak winds over the sea contribute to the formation of eddy structures, while strong winds have a smoothing effect on the sea surface circulation and prevent the formation of vortex structures. A significant difference in the vertical structure of sea circulation is shown for weak and strong winds. Mesoscale eddy formations have a great impact on the spread of oil pollution. Water circulation and the initial position of oil spill largely predetermine the main peculiarities of oil slick transport. For example, simulations have shown that if a hypothetical accidental oil spill occurs in the central part of the vortex, then pollution is localized in the central area of the vortex and oil slick practically does not migrate, only diffusive expansion is observed.

## Declarations

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**Author contribution** Demuri Demetrashvili: Planning and conducting computational experiments, analysis of results, writing of an article. Vepkhia Kukhalshvili: Participation in computational experiments, visualization and graphical interpretation of model outputs, analysis of results. Diana Kvaratskhelia: Participation in computational experiments, analysis of results.

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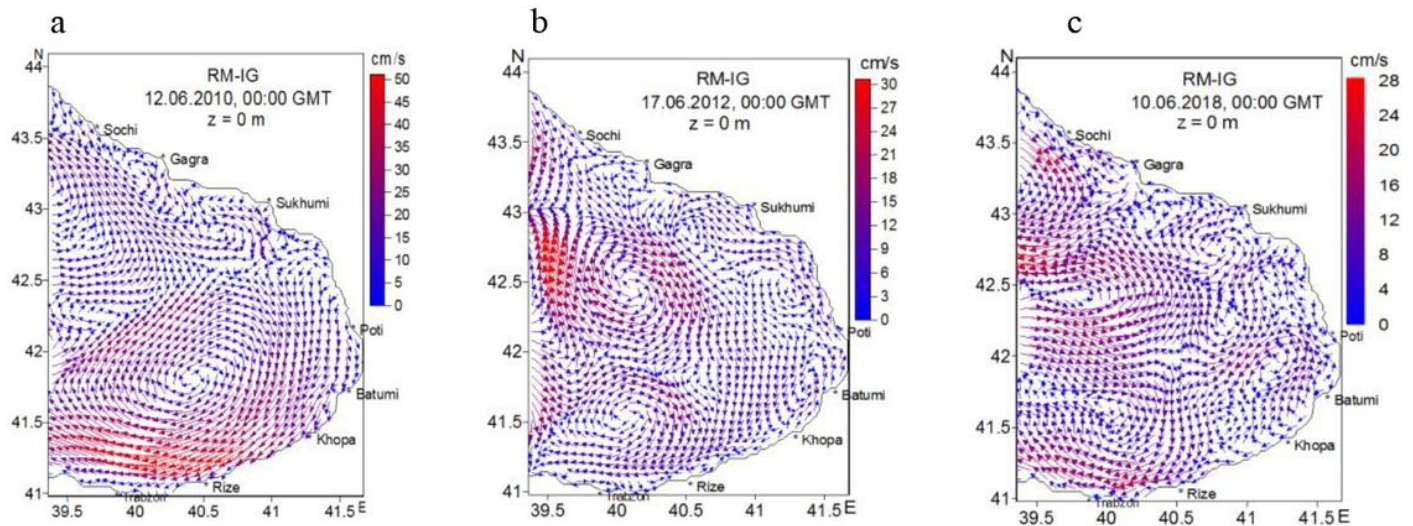
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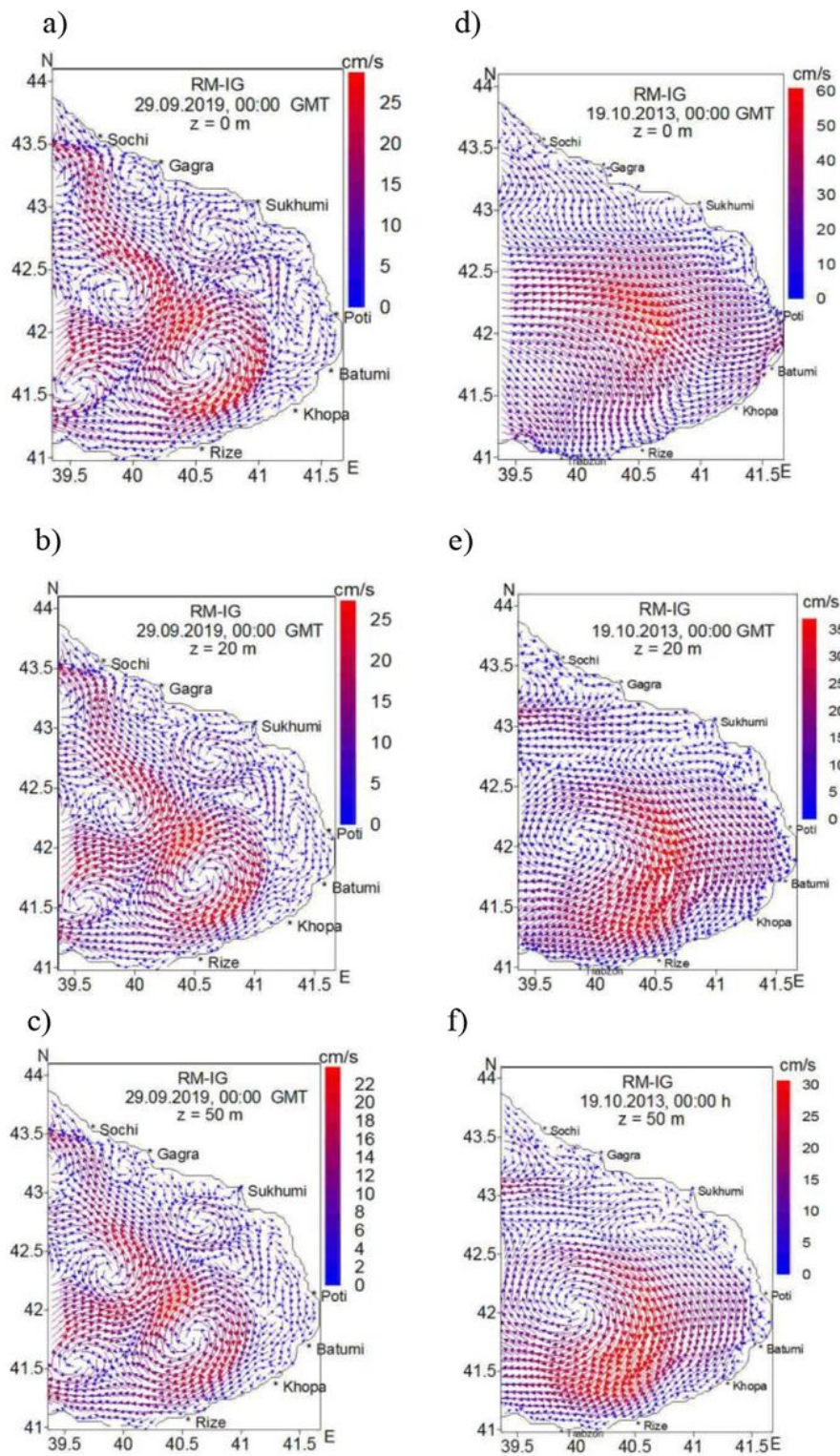
## Figures



**Figure 1**

Predicted surface current fields at 00:00 GMT for the following days and years: a - 12 June 2010 (start of forecast 09.06.2010, 00:00 GMT); b – 17 June 2012 (start of forecast 14.06.2012, 00:00 GMT); c - 10 June 2018, (start of forecast 7.06.2018, 00:00 GMT)

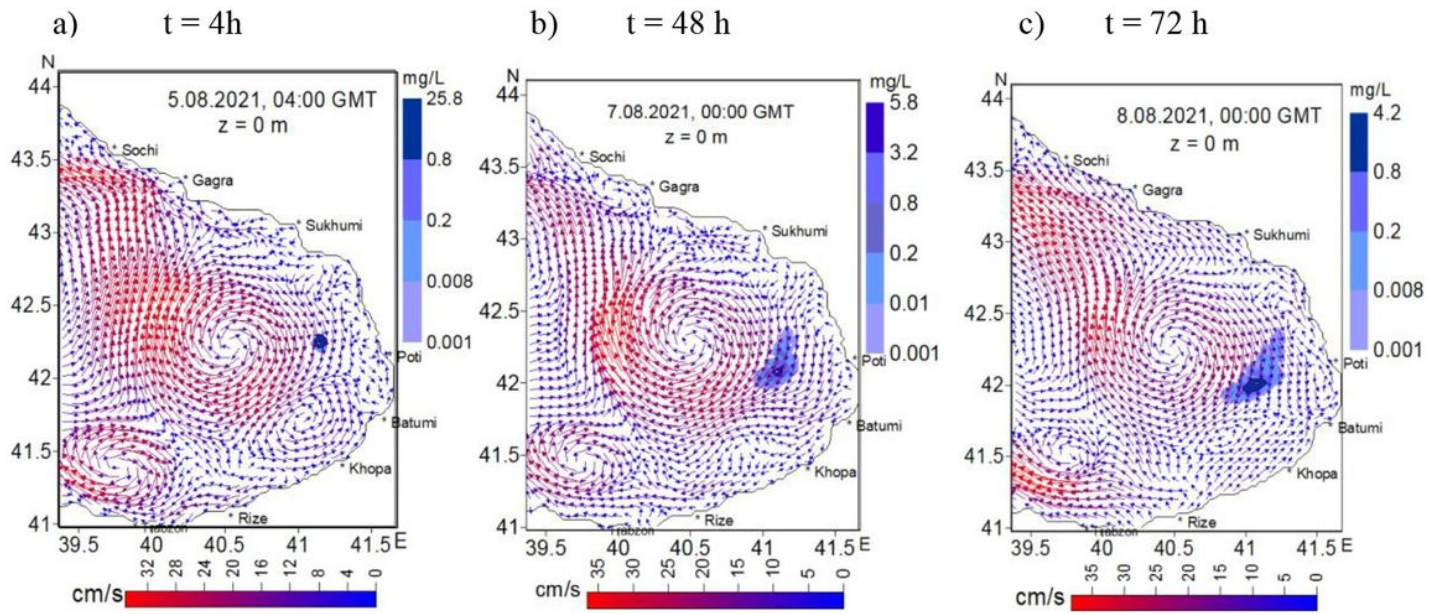




**Figure 2**

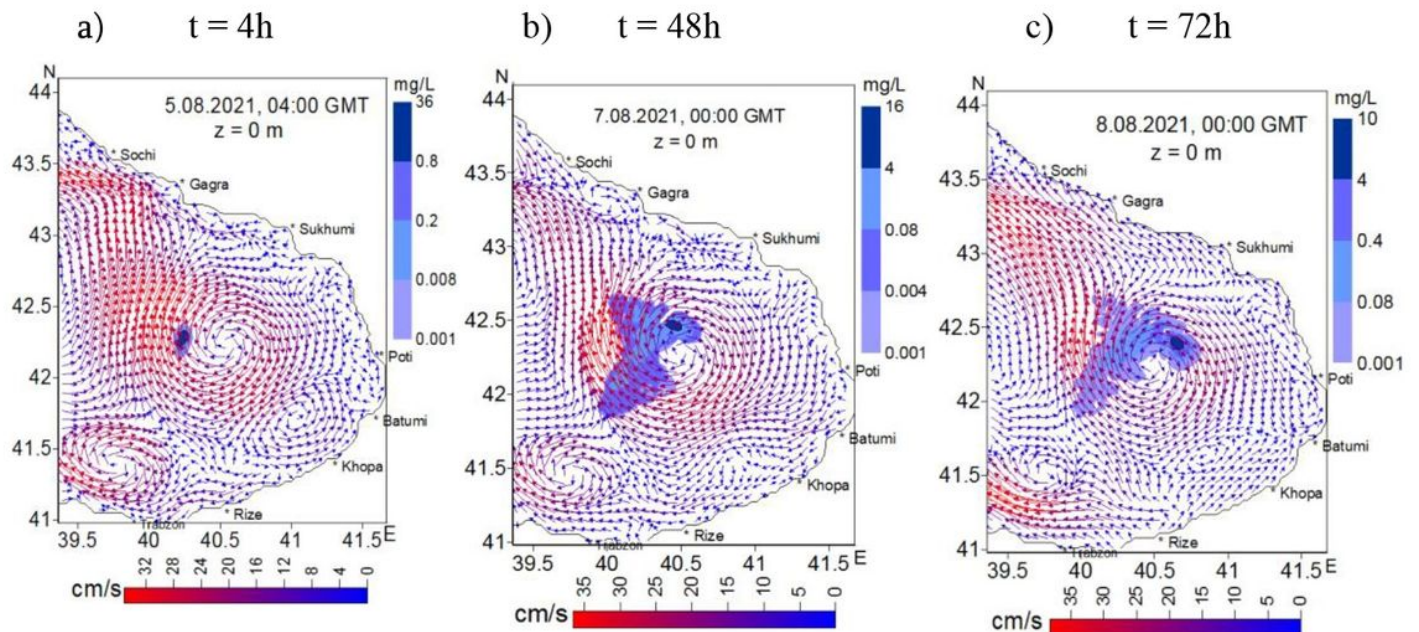
Calculated flow field on September 29, 2019 at the 0 (a), 20 (b), 50 m(c) horizons (during weak wind) and on October 19, 2013 at the 0 (d), 20 (e), 50 m (f) horizons (during strong wind)





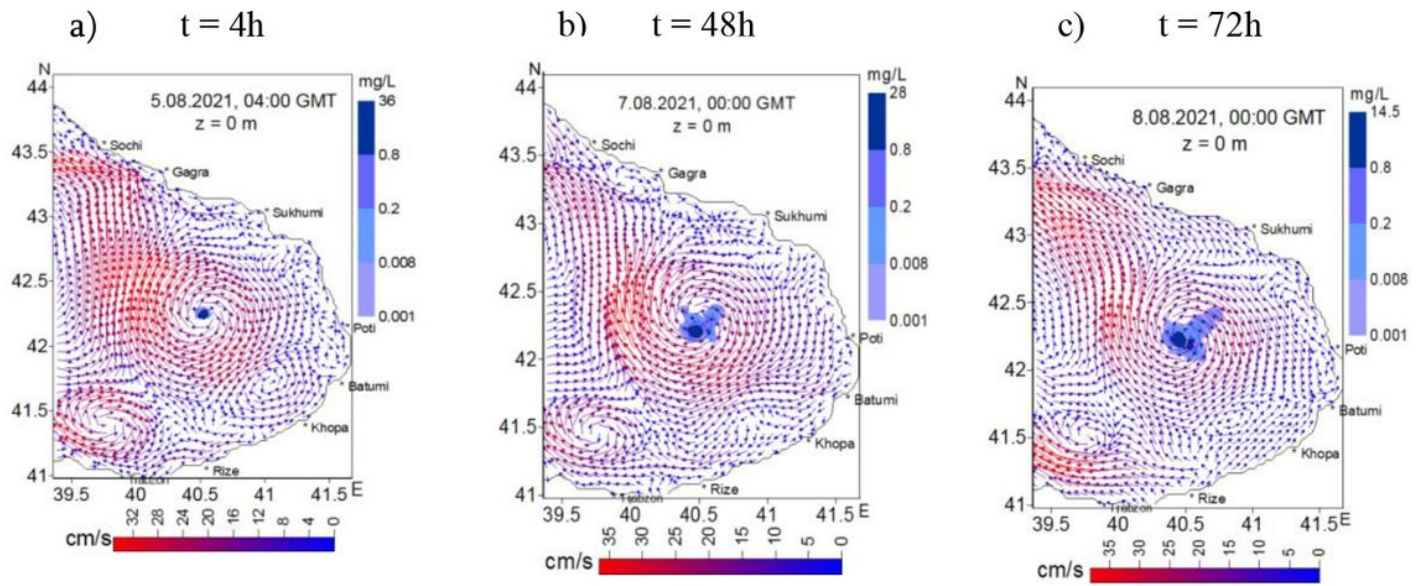
**Figure 3**

Predicted surface flow field and oil slick transport to the following time moments after the hypothetical spill: a – 4 h, b – 48 h, c – 72 h. The forecasting period is: 00:00 GMT, 5-8 August 2021. The oil spill occurred at the point with coordinates  $136\Delta x, 142\Delta y$



**Figure 4**

The same as in Fig. 3, but the oil spill occurred at the point with coordinates  $96\Delta x, 142\Delta y$



**Figure 5**

The same as in Fig. 3, but the oil spill occurred at the point with coordinates  $120\Delta x, 142\Delta y$