# HIGH-RESOLVING MODELING AND FORECAST OF REGIONAL DYNAMIC AND TRANSPORT PROCESSES IN THE EASTERNMOST BLACK SEA BASIN

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## ABSTRACT

The article deals with the simulation and short-range forecast of the current, temperature and salinity fields as well as contamination distribution processes in the easternmost part of the Black Sea covering the Georgian Black Sea coastal zone and surrounding water area. These studies are carried out on the basis of the coupled high-resolution Black Sea regional dynamics and transport models which are components of the regional forecasting system. By-turn, this system is one of the parts of the Black Sea basin-scale Nowcasting/Forecasting System. The regional model of the Black Sea dynamics developed at M. Nodia Institute of Geophysics of Ivane Javakhishvili Tbilisi State University is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol). Atmospheric forcing is provided by the atmospheric limited area model ALADIN adapted to the Black Sea region. Equations of the mathematical models involved in the forecasting system are solved by finite-difference methods using two-cycle splitting method with respect to physical processes, coordinate planes and lines. 3D dynamic fields – the current, temperature and salinity, also pollution concentration fields are calculated on a uniform grid with the horizontal grid step 1 km. Some results of 3-day forecast of dynamic fields are compared with the results obtained from MHI model using coarse grid and with observational data.

***Keywords:*** *Numerical modeling, boundary conditions, forecasting system, salinity field, satellite data.*

## INTRODUCTION

Numerous experimental and theoretical researches show that the coastal and shelf zones of the Black Sea are characterized with intensive vortex formations and high variability of dynamic processes [1], [2], [3], [4]. Such eddies make a significant contribution to transportation of different substances, heat and momentum in the coastal zones, which undergo the great anthropogenic loading. According to [3], the most intensive formation of the meso and submesoscale eddies are detected on the North-Western Shelf, near the Crimean Peninsula, the Caucasian and Anatolian coasts. The easternmost part of the Black Sea is one of the most dynamically active regions of the sea basin, where intensive generation of mesoscale and submesoscale eddies takes place [5], [6]. In [5] the results of observations of submesoscale eddies (with diameter of 2-8 km) on the narrow Black Sea shelf in the Gelendzhik (Russia) region for 2007-2008 are discussed. In [6] on the basis of an analysis of the results of modeling of the basic hydrophysical fields, the features of annual variability of regional circulation processes are investigated in the easternmost part of the Black Sea for 2010-2012. It is shown that the easternmost water area is dynamically very active zone with alternation of eddy-dominated circulation systems.

Besides the fact that coastal dynamic processes make an important contribution to the space-temporal distribution of various substances, studying these processes is of great importance due to the fact that the Black Sea and atmosphere are unified hydrothermodynamic system and circulation and thermal processes developing in the upper layer of the Black Sea play the significant role in the formation of the regional weather and climate.

In this study some results of modeling and forecast of hydrophysical fields with 1 km space resolution in the easternmost part of the Black Sea (the forecasting domain is limited by the liquid boundary from the West coinciding approximately with meridian $39.08^0$E) are presented. Some forecasted fields are compared with observational data and modeling results obtained from the basin-scale model (BSM) of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol) using coarse grid with 5 km space resolution. Forecasted dynamic fields are used to simulate spreading of polluting substances emitted from hypothetical sources.

## METHOD OF RESEARCH AND FORECASTING

At the present stage of development of Geosciences the method of mathematical modeling is one of the main tools for studying and understanding processes going in the natural environment. This method allows simulating and reproducing natural processes and phenomena on a computer, quantifying the role of various physical factors on the development of the studied processes and, finally, forecasting the evolution of these phenomena.

In the present paper the study of regional dynamic processes in the easternmost part of the Black Sea (including Georgian coastal zone and surrounding water area) is carried out on the basis of the regional model of the Black Sea dynamics developed at M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University (RM-IG). This is a z-level, hydrostatic model with upper rigid surface based on a primitive system of ocean hydrothermodynamics equations [6], [7]. The model takes into account: nonstationary atmospheric forcing provided from the atmospheric limited area model ALADIN adapted to the Black Sea region, quasi-realistic bottom relief, runoff of the main Georgian rivers, the absorption of solar radiation by the sea upper layer, space-temporal variability of turbulent viscosity and diffusion.

the total solar radiation flux $I$ is an exponentially decaying function with depth

$$I = \eta\,(1 - A)\,I_0\,e^{-\alpha z}\ ,$$

where $I_0$ is the total flux of solar radiation at the sea surface z = 0. Diurnal variation of radiation is calculated by the Albrecht formula [8]

$$I_0 = a \sinh_0 - b\sqrt{\sinh_0}\ ,$$

$$\sinh_0 = \sin\varphi \sin\psi + \cos\varphi \cos\psi \cos(\pi t/12).$$

Here α is the parameter of absorption of short-wave radiation by seawater; $h_0$ is the zenith angle of the Sun; *A* is the albedo of a sea surface, which depends on the zenith angle; φ is the geographical latitude, η is the factor which takes into account influence of a cloudness on a total radiation; ψ is the parameter of declination of the Sun; a and b are the empirical factors.

Like prior articles of authors [6], [7], factors of horizontal turbulent viscosity and diffusion for heat and salt were calculated by formula given in [9] and the factor of vertical turbulent diffusion – by formula presented in [10]. In case of arising unstable stratification ($\partial\rho/\partial z < 0$) during integration of model equations, the realization of this instability is taken into account by increase of heat and salt diffusion factors 20 times in appropriate columns from the surface to the bottom.

The RM-IG is nested in the BSM of MHI using one-way nesting technology, which provides forcing of basin-scale processes on the coastal processes via open boundary. Boundary conditions on the lateral liquid boundary for velocity components, temperature and salinity are provided from the BSM with an hour frequency during integration of model equations. More detailed description of the methodology of nested grid modeling used in the paper is given in [7].

The 3D transport model of polluting substances, which is coupled with the regional model of the Black Sea dynamics is based on solution of the advection-diffusion equation

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

where $\varphi$ is a volumetric concentration of a substance, $\mu_\varphi$ and $\nu_\varphi$ are horizontal and vertical diffusion factors, σ is the parameter describing changeability of concentration because of physical and biochemical factors, $w_G$ is the speed of gravitational sedimentation of particles, that could be determined by Stock's formula:

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

Here $r_p$ is particle's radius, $\rho_p$ is particles density, $\nu$ is the coefficient of kinematic viscosity of the sea water, g is gravitational acceleration, $\rho$ is marine water density, which is defined by the formula [11]

$$\rho = 1 + 10^{-3}[28{,}152 - 0{,}0735 \cdot T - 0{,}00469\ T^2 + (0{,}802 - 0{,}002 \cdot T)(S - 35)],$$

were $T$ and $S$ are the sea temperature and salinity. Nonstationary current, temperature and salinity fields are provided from the regional model of the sea dynamics on each time step of integration. To calculate turbulent diffusion coefficients the same formula are used as in RM-IG.

To solve the problems involved in the forecasting system a finite-difference methods are used based on the splitting method with respect to both physical processes, coordinate planes and lines [12].

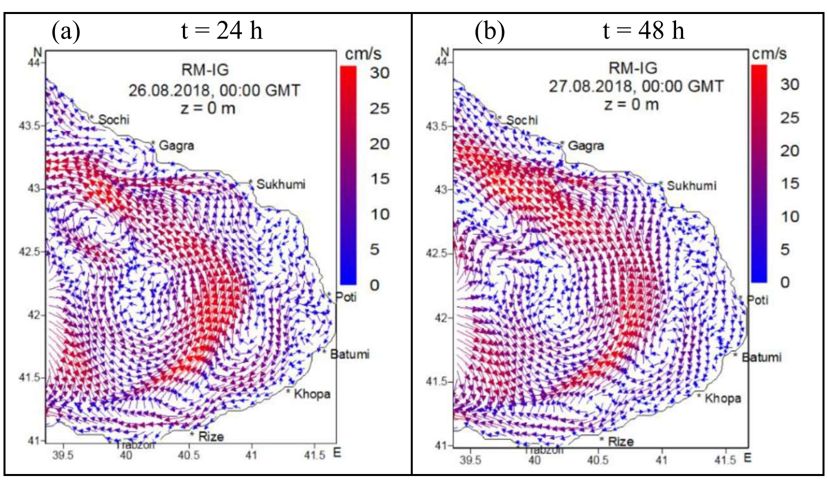
## RESULTS AND DISCUSSIONS

Numerical experiments carried out on the basis of RM-IG with use of real input data provided by MHI show that the hydrological mode of the easternmost water area of the Black Sea is characterized with alternation of eddy-dominated circulation systems, which make a significant contribution to the distribution of thermohaline fields and polluting substances. In most cases the Rim Current jet is located further away from the cost and is out of the considered easternmost water area.

Realization of the numerical models is carried out on a grid having 215 x 347 points on horizons with 1 km resolution. On a vertical the non-uniform grid with 30 calculated levels on depths: 2, 4, 6, 8, 12, 16, 26, 36, 56, 86, 136, 206, 306,…, 2006 m are considered. The time step is equal to 0.5 h.

Fig.1 illustrates the surface current field after 24 and 48 hours (time is counted from the initial moment of the forecast), when the forecasting time period was from 00:00 GMT, 25 August to 00:00 GMT, 28 August 2018. It should be noted that the sea surface current patterns showed in this Figure are not typical for summer circulation usually formed in the easternmost water area. Generally, for a warm season the circulation mode has anticyclonic character with dominating the quasi-permanent

*Fig.1. The surface current fields predicted by the RM-IG at 24h (a) and 48h (b). The forecasting period is 25-28 August 2018, 00:00 GMT.*



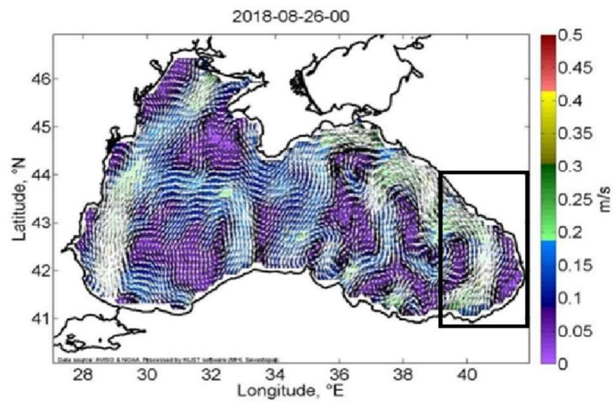



*Fig.2. Geostrophic current field on 26 August 2018, 00:00 GMT reconstructed using satellite altimeter data. By rectangle the forecasting area is marked.*

Batumy anticyclonic eddy, intensity of which is different in different years. Calculations presented in [6], [7] showed that the Batumi eddy was very stable formation in 2010 and 2011 and it covered entire Georgian Black Sea coastal zone and surrounding water area. From Fig.1 it is clear that in August 2019 during the forecasting period regional circulation mode was characterized by the narrow cyclonic jet which was passing near the Georgian shoreline. Comparison of model results (Fig.1) with the geostrophyc current (Fig.2) for 26 August 2018 reconstructed using satellite altimetry data (http://dvs.net.ru/mp/data/main.shtml) shows that the forecasted cyclonic current represents the eastern branch of the Black Sea Rim Current jet, which usually passes far from the Georgian Black Sea area, especially in summer season, but in August 2018 it passed near the Georgian shoreline. From Fig.1it is well visible submesoscale eddies of very small sizes near the coastline which are unstable formations and their lifetime is 1-2 day. Such eddies are not identify in Fig.2 because their very small sizes.

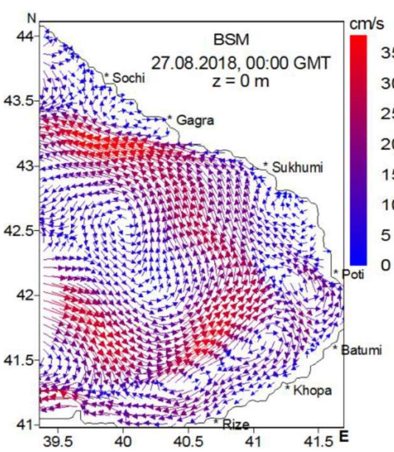



*Fig.3. The surface current field predicted by BSM of MHI at 00:00 GMT, 27 August 2018.*

In Fig.3 the current field on 27 August 2018 predicted by the BSM of MHI is shown. Comparison between Fig.1b and Fig.3 shows some differences of the predicted sea current obtained with use of both fine and coarse grids. The current calculated by the BSM has a relatively smoothed character with less expressed nearshore submesoscale eddies.

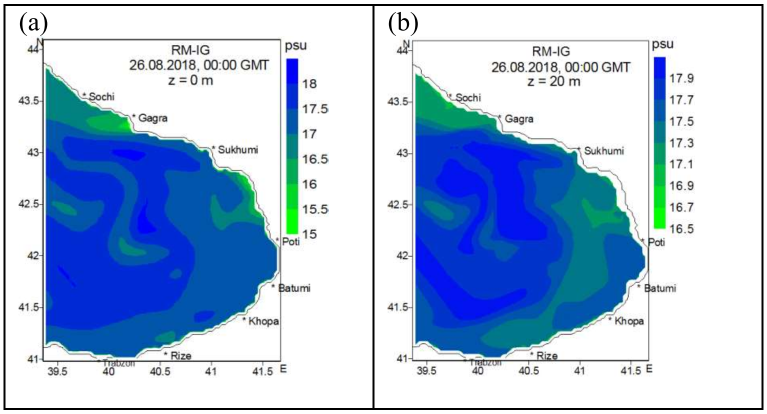



*Fig.4. predicted salinity fields by RM-IG at z = 0 (a) and z = 20 m (b) on 26 August 2018, 00:00 GMT.*

The sea current field has a significant effect on the formation of the salinity field. Comparison between Fig.1a and Fig.4, where predicted salinity fields by RM-IG on the depths of  z = 0 and z = 20 m on 26 August 2019 are illustrated, shows that zones of cyclonic rotation provide formation of water areas with relatively high salinity, whereas in areas of anticyclonic rotations waters with low salinity are observed. Unlike the anticyclonic gyres, cyclonic motions promote the raising of waters with high salinity from the lower layers.

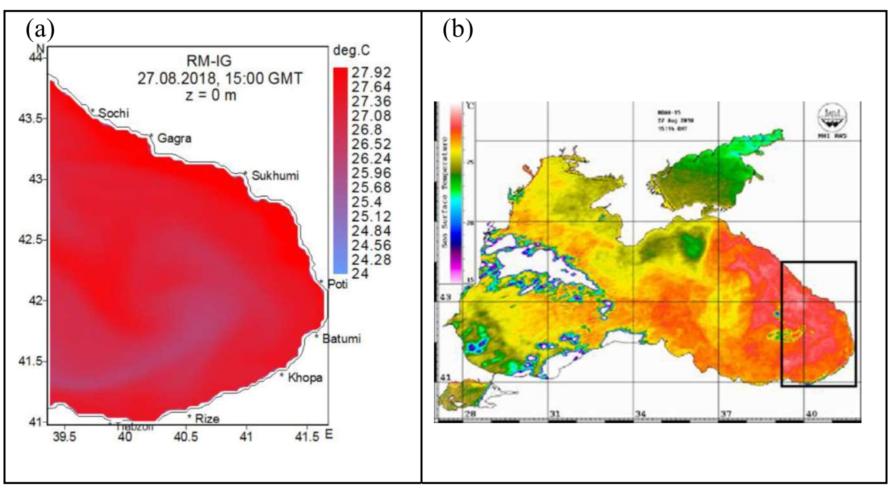



*Fig.5. Predicted (a) and satellite (b) SST (derived from NOAA) on 26 August 2018. By rectangle the forecasting area is marked.*

In Fig. 5 the sea surface temperature (SST) on 27 august 2018, 15:00 GMT (predicted by the RM-IG) and satellite SST derived from NOAA for the same moment are presented (http://dvs.net.ru/mp/data/201806bs_sst.shtml). From Fig.5 it is visible that, in general, the predicted and observed SST are in a good agreement with each other. According to both model and satellite results SST on 27 August was characterized by significant spatial uniformity and the water temperature in most of the considered water area was 270-280C.

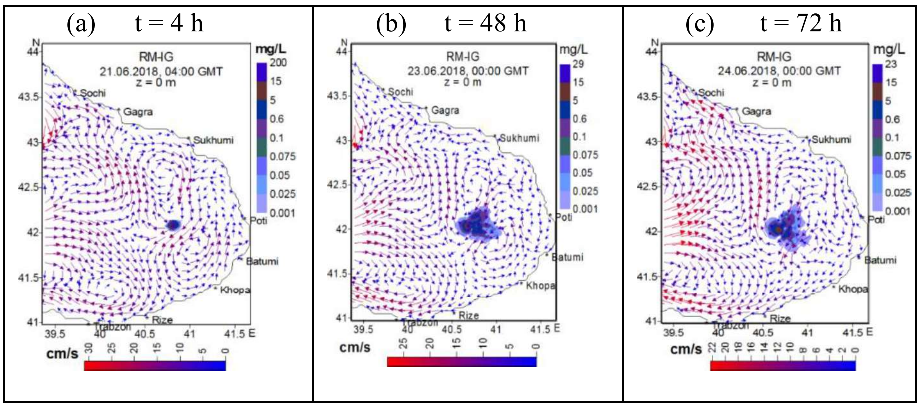



*Fig.6. Simulated surface current fields and oil spill transport corresponded to the following time moments after oil flood: (a) - 4 h, (b) – 48 h, (c) – 72 h. The forecasting period is 21-24 June 2018, 00:00 GMT.*

In the present paper we illustrate applying of 2D version of the transport model to simulate oil spill transport on the Black Sea surface in case of hypothetical accident. Nonstationary current field was derived from RM-IG. In case of short-range forecast evaporation is the most important factor. Taking this fact into consideration we accepted: $\sigma = 1.6.10^{-5}$ if $t \leq 24$ h and $\sigma = 8.2.10^{-7}$ if $t > 24$ h. The first value corresponds to double reduction of concentrations for 12 hours, the second one – to double reduction of concentrations during 10 days. Fig. 6 illustrates regional surface circulation and drifting of oil slick in case when 10 t hypothetically occurred during 4 hours on distance about 80 km from the Georgian shoreline. The forecasting period was: 00:00 GMT, 21-24 June 2018. From Fig.6 it is visible that the surface circulation structure strongly differs from the circulation mode taking place during 26-27 August 2018 (Fig.1). In the course of migration the oil slick gradually extends, is deformed and drifts under the influence of circulation. Other numerical experiments show a significant role of circulating processes in distribution of pollution areas. These calculations also showed sensitivity of oil spill transport to the turbulent diffusion coefficient.

## CONCLUSION

Numerical experiments presented in this paper have been carried out on the basis of the high-resolution regional model of the Black Sea dynamics and coupled with him the transport model. These models are the basis for the easternmost Black Sea regional forecasting system. All input data – the initial and prognostic hydrophysical fields on the open boundary obtained from BSM of MHI and 2D meteorological fields at the sea surface calculated from the atmospheric numerical model ALADIN needed for simulation and forecasting mesoscale circulation and thermohaline fields are provided by MHI in the near-operational mode.

Comparison of dynamic fields derived from both models with fine (RM-IG) and coarse grids (MHI model) confirmed our previous results that identification of small coastal eddies requires high-resolution modeling [7].

Nonstationary forecasted dynamic fields derived from RM-IG are used to simulate space-temporal distribution of polluting substances.

Using the regional forecasting system since 2010 we accumulated a significant volume of the results of modeling and 3-days forecasts of dynamic fields in the easternmost part of the Black Sea on the basis of which we created a unique database of 3D dynamic fields – the current, temperature and salinity with 1 km resolution in the Georgian coastal zone and surrounding water area. In perspective, an analysis of this material will promote better understanding the mechanisms of formation and evolution of hydro and thermodynamic processes in one of the dynamically active regions of the Black Sea and improve our knowledge about the regional dynamic processes, to estimate trend of the Black Sea temperature and salinity fields for the last decade, which is important indicator of regional climate changeability.

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