MODELING OF VARIABILITY OF THE REGIONAL DYNAMIC PROCESSES DEVELOPED DURING 2017-2019 IN THE EASTERNMOST PART OF THE BLACK SEA

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ABSTRACT

The study of water circulation and thermohaline processes in the coastal zones of the seas and oceans, subjected to the most intense anthropogenic press, is an important problem of modern Oceanology. According to experimental and theoretical researches the coastal water areas of the Black Sea are dynamically active regions, where intensive generation of mesoscale and submesoscale eddies takes place. Such eddies make a significant contribution to the horizontal and vertical transport of different polluting substances, heat, momentum, *etc*. Therefore, the modeling and study of main peculiarities of variability of regional dynamic processes is of great scientific and practical interest.

The goal of this study is to investigate numerically the structure and spatial – temporal distribution of the sea flow and thermohaline fields taking place during the period 2017-2019 in the easternmost part of the Black Sea, which is limited from the open part of the sea basin with liquid boundary coinciding 39.08^0E. With this purpose a high-resolution numerical regional model of the Black Sea dynamics of M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University (RM-IG) is used. The RM-IG is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (Sevastopol) and is based on a primitive system of ocean hydrothermodynamics equations. The RM-IG uses a calculated grid having 215x347 points on horizons with 1 km spatial resolution.

Results of researches presented in the paper show significant variability of the regional dynamic processes in the easternmost water area during 2017-2019, where continuously generation, deformation and disappearance of the cyclonic and anticyclonic vortex formations of difference sizes takes place.

Keywords: *Dynamic processes, current field, nesting modeling, anticyclonic eddy, satellite data*

INTRODUCTION

The study of the structure and evolution of mesoscale and submesoscale eddies, which are permanently generated in the coastal waters of the Black Sea [1], [2], [3], [4], [5], [6], [7] is one of the main issues of the Black Sea Oceanography. Coastal circulation determines many coastal processes, such as spreading of different substances of anthropogenic and natural origin, spatial-temporal distribution of temperature and salinity fields, to which many marine living organisms are very sensitive, *etc.*

Understanding the Black Sea circulation has significantly increased since 1990s as a result of in-situ and satellite observations and high-resolution numerical modeling [8], [9], [10]. Based on these studies, a more perfect scheme of the Black Sea basin-scale circulation is created, the main elements of which are the Rim Current, large-scale interior cyclonic gyres in the eastern and western parts of the sea basin, and a series of quasi-stable coastal anticyclonic eddies between the Rim Current and the shoreline. the schematic picture of the averaged Black Sea basin-scale surface circulation, presented in [8], [10] does not reflect coastal processes accompanied by mesoscale and submesoscale eddies. In this picture the easternmost part of the Black Sea is only represented by the Batumi anticyclonic eddy which covers almost the entire easternmost water area. The studies conducted in [6], [7] show that in addition to the Batumi eddy, the easternmost part of the Black Sea is characterized with formation and evolution of numerous vortex structures with various sizes.

The purpose of this paper is to investigate numerically the structure and spatial –temporal distribution of sea currents and thermohaline fields taking place during the period 2017-2019 in the easternmost part of the Black Sea, which is limited from the open part of the sea basin with liquid boundary coinciding 39.08^{0}E. With this purpose a high-resolution numerical regional model of the Black Sea dynamics of M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University (RM-IG) is used. The RM-IG is obtained by adaptation of the basin-scale model of the Black Sea dynamics [11] to the easternmost part of the sea basin and is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (Sevastopol). The RM-IG is the core of the regional forecasting system for the easternmost part of the Black Sea. The regional forecasting system is one of the components of the Black Sea basin-scale nowcasting/forecasting system [12].

MODEL DESCRIPTION

The RM-IG is based on a primitive equation system of ocean hydrothermodynamics and takes into account nonstationary atmospheric forcing, sea bottom relief and configuration of the sea basin, absorption of solar radiation by the sea upper layer, spatial-temporal variability of horizontal and vertical turbulent exchange, runoff of main rivers of Georgia, impact of basin-scale processes on regional processes.

The system of model equations written in the Cartesian coordinate system has the following form (the axis x is directed eastward, y – northward, z – from a sea surface vertically downwards)

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+\mathrm{v}\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p'}{\partial x}+\mathrm{l}\,\mathrm{v}+\mathrm{D}_{\mathrm{u}}^{\mathrm{xy}}+\mathrm{D}_{\mathrm{u}}^{\mathrm{z}}, \tag{1}$$

(2) $$\frac{\partial \mathrm{v}}{\partial t}+u\frac{\partial \mathrm{v}}{\partial x}+\mathrm{v}\frac{\partial \mathrm{v}}{\partial y}+w\frac{\partial \mathrm{v}}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p'}{\partial \mathrm{y}}-l\mathrm{u}+\mathrm{D}_{\mathrm{v}}^{\mathrm{xy}}+\mathrm{D}_{\mathrm{v}}^{\mathrm{z}},$$

(3) $$\frac{\partial T'}{\partial t}+u\frac{\partial T'}{\partial x}+\mathrm{v}\frac{\partial T'}{\partial y}+w\frac{\partial T'}{\partial z}+\gamma_T w=-\frac{1}{c\rho_0}\frac{\partial I}{\partial z}+\frac{\partial \nu_T\gamma_T}{\partial z}+\mathrm{D}_{\mathrm{T}}^{\mathrm{xy}}+\mathrm{D}_{\mathrm{T}}^{\mathrm{z}},$$

(4) $$\frac{\partial S'}{\partial t}+u\frac{\partial S'}{\partial x}+\mathrm{v}\frac{\partial S'}{\partial y}+w\frac{\partial S'}{\partial z}+\gamma_S w=\frac{\partial \nu_S\gamma_S}{\partial z}+\mathrm{D}_{\mathrm{S}}^{\mathrm{xy}}+\mathrm{D}_{\mathrm{S}}^{\mathrm{z}},$$

(5) $$\frac{\partial u}{\partial \mathrm{x}}+\frac{\partial \mathrm{v}}{\partial y}+\frac{\partial w}{\partial z}=0, \qquad \gamma_{\mathrm{T}}=\frac{\partial \overline{T}}{\partial z},\ \ \gamma_S=\frac{\partial \overline{S}}{\partial z}.$$

(6) $$\frac{\partial p'}{\partial z}=g\rho', \qquad \rho'=\alpha_{\mathrm{T}}\mathrm{T}'+\alpha_{\mathrm{S}}\mathrm{S}', \qquad I=\eta(1-A)I_0e^{-\alpha z},$$

$$p=\overline{p}(z,t)+p',\ \ \rho=\overline{\rho}(z,t)+\rho',\ T=\overline{T}(z,t)+T',\ \ S=\overline{S}(z,t)+S',$$

Here u, v, and w are the components of a current velocity along axes x, y, z, respectively; p', ρ', T', S' - deviations of pressure, density, temperature and salinity from their standard vertical distribution $\overline{p},\ \overline{\rho},\ \overline{T}, \overline{S}$; $l = l_0 + \beta . y$– the Coriolis parameter; g, c, ρ_0 – the gravitational acceleration, the specific heat capacity of sea water and average density of seawater, respectively; I_0 – the total radiation flux at z = 0 determined by the Albrecht formula; A – albedo of a sea surface; η – the factor which takes into account influence of a cloudiness on a total radiation and depends upon a ball of cloudiness; α – the parameter of absorption of short-wave radiation by seawater. The last two terms on the right-hand side of equations (1) - (4) are the terms of horizontal and vertical viscosity and diffusion of heat and salts, respectively, which have the form

$$\mathrm{D}_{\varphi}^{\mathrm{xy}}=\frac{\partial}{\partial x}\mu_{\varphi}\frac{\partial \varphi}{\partial \mathrm{x}}+\frac{\partial}{\partial y}\mu_{\varphi}\frac{\partial \varphi}{\partial \mathrm{y}},\ \ \mathrm{D}_{\varphi}^{\mathrm{z}}=\frac{\partial}{\partial z}\nu_{\varphi}\frac{\partial \varphi}{\partial z},\quad \varphi=\{\mathrm{u}, \mathrm{v}, \mathrm{T}', \mathrm{S}'\},$$

where $\mu_{u,v}$ and $\nu_{u,v}$ are the horizontal and vertical turbulent viscosity coefficients, $\mu_{T,S}$ and $\nu_{T,S}$ - coefficients of horizontal and vertical turbulent diffusion for heat and salts.

The coefficients of turbulent horizontal and vertical viscosity and diffusion are calculated by the same formulas that were used in [6], [7]. The sea surface is considered as a rigid surface, where Neumann conditions are used by given wind stress components, heat fluxes and precipitation minus evaporation, which are provided from atmospheric model SKIRON. On the sea bottom the velocity components, heat and salt fluxes are equal to zero. On the solid lateral surfaces components of the current velocity, gradients of temperature and salinity normal to the lateral surface are equal to zero. At the western liquid boundary and river mouths Dirichlet's boundary conditions for velocity components, temperature and salinity are used.

To solve the model equation system (1) - (6), the two-cycle splitting method is used with respect to both physical processes, coordinate lines, and vertical planes [13].

All input data required for the initial and boundary conditions are provided from Marine Hydrophysical Institute via Internet in the near-operational mode.

RESULTS AND DISCUSIONS

The RM-IG is realized with use of calculated grid having 215x347 points on horizons. On a vertical the non-uniform grid with 30 calculated levels are considered. The time step is equal to 0.5 h.

The model was validated in 2005, when the pilot experiment on the functioning of the Black Sea operative Nowcasting/Forecasting system was carried out for the first time for the Black Sea. Further, the simulated and forecasted results were compared with available observational data - satellite SST (sea surface temperature) derived from NOAA satellites (http://dvs.net.ru/mp/data/201806bs_sst.shtml) and the Geostrophyc currents reconstructed on the basis of satellite altimeter data. These comparisons have shown the ability of the RM–IG to reliably predict hydrophysical fields in the easternmost coastal zone of the Black Sea.

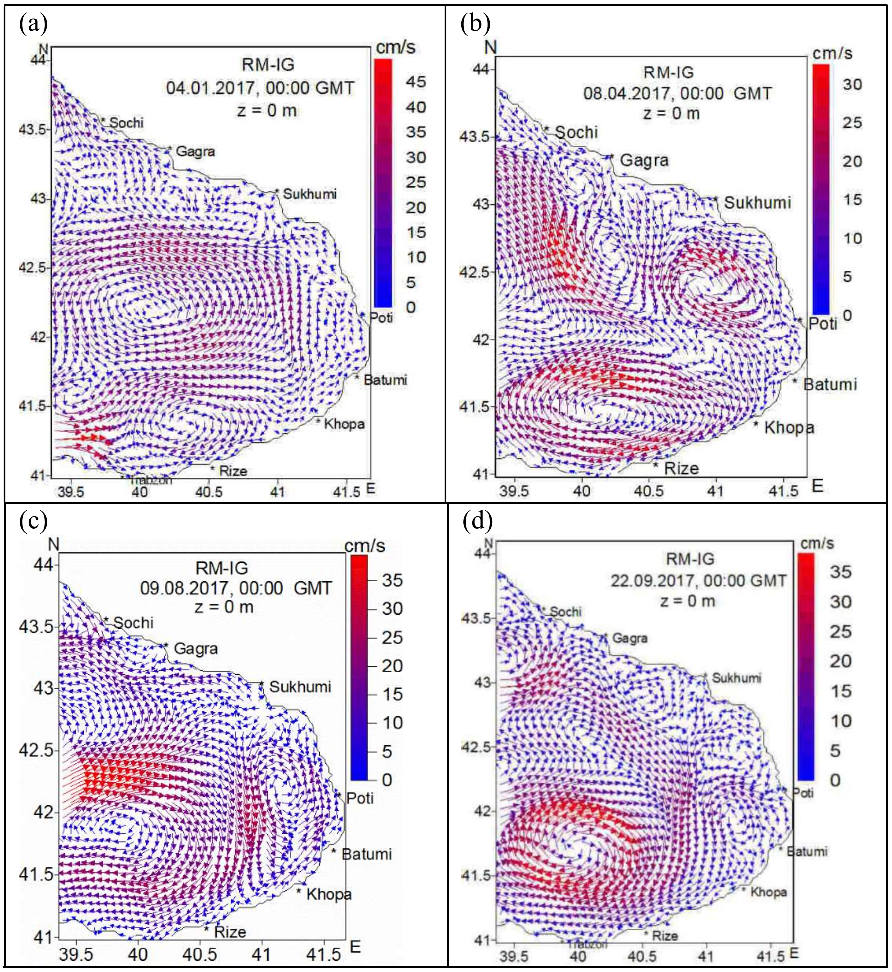

Fig.1. Simulated surface current fields in 2017, 00:00 GMT. (a) – 4 January, (b) - 8 April, (c) – 9 August, (d) – 22 September.

Numerical experiments performed on the basis of the RM-IG showed that surface regional circulation patterns for 2017-2019 are characterized with diversity of circulation modes in the easternmost water area. There are observed significant seasonal and interannual variability of dynamic fields. In the same seasons the main peculiarities of the circulation regimes can significantly differ from each other for different years. Nonstationary atmospheric forcing is the most important factor providing variety of hydrophysical fields. In Figs. 1-3 some simulated regional circulation patterns for 2017-2019 are presented illustrating the variety of the regional circulation in the Black Sea easternmost water area.

The winters of 2017 and 2019 were characterized, generally, with cyclonic rotations of coastal waters (Figs.1a and 3a), on the background of which formation of some cyclonic and anticyclonic eddies is observed. For example, from Fig.1a is visible that on 4 January 2017 anticyclonic eddy is observed in water area between Trabzon and Rize with diameter about 25 km. some submesoscale eddies with diameter about 5-10 km are forming in the narrow zone along Georgian shoreline, which are very unstable formations and break up in a few days. Some small eddy formations along the Caucasus shoreline are observed very often in all seasons [2], [3], [6].

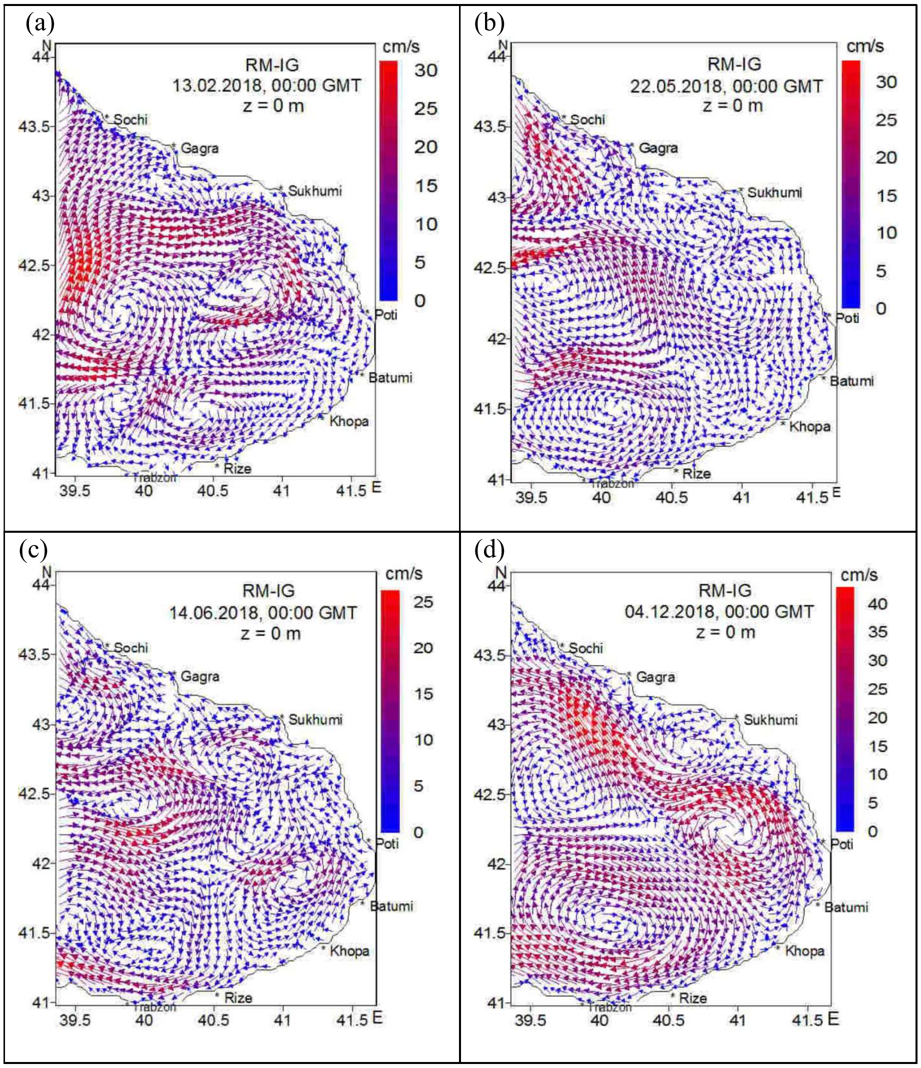

Fig.2. Simulated surface current fields in 2018, 00:00 GMT. (a) – 13 February, (b) - 22 May, (c) – 14June, (d) – 4 December.

The 2018 winter circulation did not have a general cyclonic character and anticyclonic eddies often prevailed. Fig.2a illustrates regional circulation on 13 February 2018, where several anticyclonic eddies are dominated (Fig.2a).

The main element of summer regional circulations in 2017 and 2019 were anticyclonic eddy (so called Batumy eddy) (Figs. 1c and 3c), which is well-known in this region of the Black Sea in warm period [2], [8]. The main feature of the summer circulation in 2018 was that the Batumi eddy was practically absent during the summer season and regional circulation had vortex structure with formation of separate eddies with small sizes (Fig3c).The other feature was that in August 2018 the eastern brunch of the Rim Current was passing near the Georgian shoreline. It should be noted that usually the Rim Current passes far from the Georgian Black Sea area, especially in summer season [2].

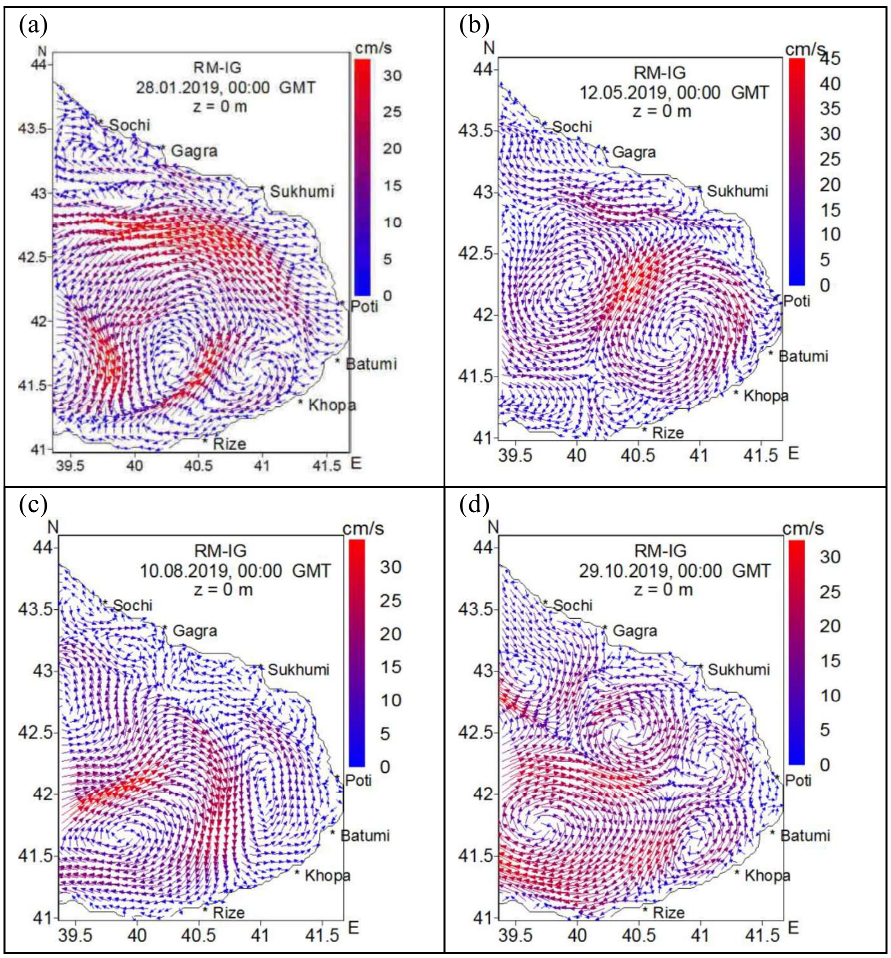

Fig.3. Simulated surface current fields in 2019, 00:00 GMT. (a) – 28 January, (b) 12 May, (c) – 10 August, (d) – 29 October.

Temperature and salinity fields, which are important factors for marine organisms, underwent significant variability. In the formation of the temperature field, the sea-atmosphere heat interaction is very important. The seasonal nature of these interaction results in a quantitative and qualitative change in the temperature field.

The sea circulation structure significantly determines the peculiarities of the salinity field distribution. The upward and downward currents formed in the central part of the cyclonic and anticyclonic eddies provide high salinity waters in the cyclone centers and relatively low salinity waters in the anticyclone centers. To illustrate, Fig. 4 shows the calculated temperature and salinity fields corresponding to 12 May 2019.

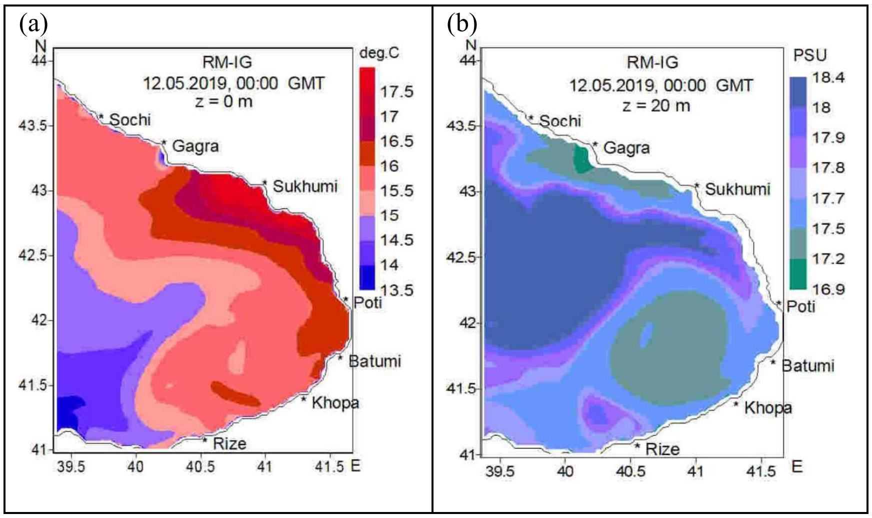

Fig.4. Simulated SST (a) and salinity field (b) on z = 20 m (b) at 12 May 2019, 00:00 GMT.

CONCLUSION

Numerical experiments on modelling and predicting dynamic fields in the easternmost part of the Black Sea were carried out on the basis of RM-IG, which reproduces 3D hydrophysical fields with a spatial resolution of 1 km. The RM-IG, which is a core of the easternmost Black Sea regional marine forecasting system, is based on the solution of a primitive system of the ocean hydrothermodynamics equations written in the Cartesian coordinate system for deviations of thermodynamic variables from mean climatic values.

The present study shows that circulation processes in the Georgian Black Sea coastal zone and surrounding water area in 2017-2019 were characterized with intense mesoscale and submesoscale vortex formations. In some time periods in this zone a dipole structure “cyclone-anticyclone“ is formed (Fig.3b), as well as more complex structures of vortex formations, which significantly affect the distribution of thermohaline fields. The cold season of 2017 and 2019 was characterized by the predominance of cyclonic circulation, the warm season - by anticyclonic circulation. In winter 2018 anticyclonic eddies often prevailed.

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