The structure of the Black Sea mesoscale eddies from the numerical modeling with various spatial resolution

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Abstract. The paper is based on the numerical modeling results and investigates the dynamics of the Batumi vertical structure of anti-cyclonic eddy. In the autumn-winter period, the Batumi Eddy intensifies; in the spring-summer period, the eddy weakens. In the calculation with a higher resolution, the eddy dynamics is more pronounced in comparison with the calculation with a low spatial resolution. The vertical structure of the Batumi Eddy was determined for temperature fields, current velocity and salinity.

1. Introduction
The large scale structure of the Black Sea circulation became well-known due to hydrographic surveys of the XX century and was confirmed fairly well with the use of satellite altimetry. One can usually identify well pronounced phenomena like the Rim Current, which changes significantly during the year, and transforms sometimes to two isolated gyres (eastern and western). However, the altimetry observations allowed obtaining more complex structure of currents as a result of the interaction of the large scale dynamics with the coastline and bottom topography, forming mesoscale eddies in the coastal area of the basin. The larger mesoscale eddies (usually anticyclonic) were also observed from hydrography, but were considered to be nearly steady. Altimetric measurement together with the high resolution satellite imagery allowed us to reveal their continuous evolution, and motions in the area of their location are even more complicated.

An assumption of near stationarity of the larger coastal eddies (with the scales from 10 km to 100 km) arises from the similarity of mechanisms causing cyclogenesis in the area of the specific eddy. Hence, formed dynamical structures can have spatial characteristics that are rather close to each other and in case of absence of the satellite observations (e.g., due to cloudiness, equipment failure, e.t.c.), these structures complicate for the observer the problem of phenomena separation to two different structures or vice versa, to identify the same one. Usually such mesoscale structures are attached to geographical locations. Several areas can be defined in the Black Sea basin where the generation of eddy is the most intense. They are: Sochi-Sukhumi region, Turkish coast and northwestern Black Sea near the coast of the Crimean peninsula.

One of the most pronounced Black Sea eddies is located in the south-eastern part of the basin [2], near Batumi. The circulation in the area is rather seasonal, resulting in the eddy intensification in summer, and weakening and almost complete destruction in the fall.

A number of studies have been devoted to the analysis of circulation in this region. In paper [3], the dynamics of the Batumi Eddy was studied on the basis of reconstructed fields of geostrophic velocities and analysis of optical and infrared satellite images. Also in this work, automatic eddy identification was obtained using Lagrangian methods [4]. In [5], the simulated climate temperature, salinity, and
currents obtained with the spatial resolution of 5 km were analyzed. The Eddy was represented in the temperature field by three separate eddy formations. Note that a number of simulations of the Black Sea dynamics with high spatial resolution were carried out. For example in [6] the DieCAST numerical model with the resolution of 1/30º (≈ 2.6 km) is used, where coastal eddies are realistically reproduced off the Caucasus coast, and their evolution is in good agreement with satellite observations. In [7] two regional configurations for NEMO [8] modelling framework with 5 km and 2.5 km spatial resolution were proposed, comparing simulations with available satellite data using correlation and spectral analysis.

For some coastal regions of the Black Sea, an operational forecast was carried out using the nested mesh method. So in [9], this method was used to create a regional circulation model for the western part of the basin off the coast of Romania, the northeastern part, and for the Calamite Gulf. The spatial resolution of the global model was 4.9 km, and resolution of the regional models were 1.2 km and 0.6 km. A similar method was used in [10], where a forecast was made for the Georgian coastal zone. The Batumi Eddy also enters into this region. As a global model, the fields of the basin-scale model of Marine Hydrophysical Institute were used. The resolution of the regional model was 1 km.

In this paper, the dynamics and vertical structure based of the Batumi anticyclonic Eddy is analyzed using the results of numerical simulation for the period of 2008-2009 carried out using NEMO at spatial resolution of 1/24º (≈ 4.6 km) and 1/96º (≈ 1.2 km). The results obtained were compared with each other.

2. Materials and methods

Two regional configurations of NEMO modeling framework covering the basins of the Euxinus cascade (Azov, Black and Marmora seas) were proposed earlier [11, 12].

The bottom topography of both configurations was prepared using EMODnet bathymetry data. The configuration uses vertical z-coordinate with a partial step. Vertical turbulent mixing is parameterized by the k-ε closure hypothesis [13, 14]. For the equation of momentum on solid lateral boundaries the slip condition is set. Lateral turbulent exchange is described by a biharmonic operator.

Table 1 shows the main characteristics of the analyzed calculations.

| Simulation | Spatial resolution | Time step | Viscosity coefficient | Diffusion coefficient of temperature and salinity |
|------------|--------------------|-----------|----------------------|--------------------------------------------------|
| exp1       | 1/24º (≈ 4.6 km)   | 5 min     | −5×10^9 m^4/s        | −4×10^8 m^4/s                                   |
| exp2       | 1/96º (≈ 1.2 km)   | 1 min     | −4×10^7 m^4/s        | −8×10^6 m^4/s                                   |

3. Results

In the present work, the simulation results in the area limited by coordinates 41 – 43ºN and 38 – 41.53ºE were investigated.

3.1. Dynamic properties

Simulated currents from exp1 and exp2 model runs (Fig. 1) show the typical evolution of the eddy lifecycle, from formation to advection and weakening (vanishing). In both simulations in winter, there is a strong stream of Rim Current and intensification of the Batumi Eddy. Starting from spring a sequence of small eddies is observed in exp2, moving north along the the Black Sea southeast coast. Starting from spring a sequence of eddies is observed in exp2, moving north along the Black Sea southeast coast. In exp1, these structures are not pronounced well. The meandering of the Rim Current jet is obtained. In summer, in exp1, intensity of the currents reduced and an eddy is observed off the coast of Georgia.
Figure 1. Velocity fields (m/s) on the sea surface in the area of the Batumi anticyclonic Eddy according to the results of numerical modeling a) 2008-01-06, b) 2008-03-11, c) 2008-07-13, c) 2008-11-06.
In exp2 at the end of summer, the Batumi Eddy becomes more intensive. Eddies from the left move towards the eddy and they are absorbed by it. The process is slightly different in exp1 simulation, the Batumi Eddy is formed later and it is less intense, although its geographical position coincides with the position in exp2. As a result, in calculations with a higher spatial resolution as compared with the calculation of exp1, the eddy dynamics is more pronounced.

3.2. Vertical structure

During the analysis of the sea water temperature and the horizontal current velocity, the vertical structure across 41.5°N was analyzed. (Fig. 2). The eddy temperature is about 2°C higher as comparing to the temperature outside the eddy. This situation is observed in the autumn-winter period, when eddies are intense. The vertical distribution of the thermohaline and dynamical characteristics of the eddy has a concave shape, where the highest temperature is observed in the central part of the anticyclonic eddy. The depth of this concave contour of temperature can reach almost 150 m. Isotherms deeper than such a structure descend, repeating the shape of the eddy. With increasing depth, such contours smooth out. In some cases, a cold intermediate layer breaks through the eddy.

Analyzing vertical structure of the circulation, one can note that in the central part of the eddy, the current velocity is similar to the currents outside the eddy. At the periphery of the eddy, the velocities are high and the contours have a concave shape. The depth of such contours, as in the case of temperature, can reach 150 m. With the weakening of the eddy dynamics, the size of such concave isolines decreases and, correspondingly, the depth of the isotachs decreases. Note that in this case, the distance between the concave contours of current velocity is also reduced.

The vertical structure of salinity in the 0-50 m layer echoes the structure of the velocity field. Salinity contours are two concave isohaline with low salinity. With increasing depth, salinity increases, but the shape of the salinity isolines does not correspond to the isohaline in the upper layer.

a)
Figure 2. The vertical structure across 41.5°N; a) of sea water temperature (°C); b) horizontal velocity (m/s); c) salinity (‰) for 2008-01-06

Conclusions
Using the results of numerical modeling, we analyzed the dynamics of the Batumi anticyclonic Eddy, its vertical structure. The selected area is limited by coordinates 41 - 43°N and 38 – 41.53°E. Simulations were carried out for the period of 2008-2009. In the calculation with ultra high resolution (1/96°), the eddy dynamics is more pronounced than in the simulation with a resolution of 1/24°.

The vertical temperature structure of the Batumi anticyclonic eddy has a concave shape, where the highest temperature value is observed in the central part of the eddy. In the central part of the eddy, the current velocity is similar to the velocity outside the Batumi eddy. At the periphery of the eddy, the velocities are high and the contours have a concave shape. The depth of such contours, as in the case of temperature, can reach 150 m. The vertical salinity structure only in the upper layer corresponds to the current structure. With increasing depth, the shape of the isohaline is smoothed out.

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