Mesoscale variability of the Black Sea circulation by the simulation results in 2011 and 2016

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Abstract. The paper analyzed the simulation results of the Black Sea circulation in 2011 and 2016. Numerical experiments were carried out with a horizontal resolution of 1.6 km and took into account the real atmospheric forcing SKIRON. The simulated temperature and salinity were compared with observations. It revealed the correspondence to real data except some deviations caused by the movement of intensive mesoscale eddies. Analysis of velocity fields showed that the reducing of the wind influence in 2016 led to the weakening of the Rim Current in contrast to 2011. The Sevastopol anticyclone in the spring-summer of 2011 was weaker than in 2016, but the Batumi anticyclone was stronger in 2011 due to intensification of coastal circulation near the Anatolian coast. The eddy energy associated with mesoscale variability had been growing in 2011 due to both barotropic and baroclinic instability processes. The eddy energy had been decreasing during 2016 and started increasing only at the end of 2016 due to development of baroclinic instability processes.

1. Introduction
Mesoscale variability in the oceans and seas plays an important role in the redistribution of hydrological, chemical and biological, energetic and other parameters. It is associated with the eddies of 10 – 100 km sizes and lifetime of about several months [1]. Eddies provide the exchange of mass and momentum between the abyssal and coastal zones [2]. Understanding of the generation and evolution mechanisms of these structures will provide an opportunity to correctly predict and diagnose environmental changes, especially in coastal areas. One of the methods for investigation of eddy variability is the analysis of energetics and fluxes characterizing the energy transformation from external sources and within the system due to barotropic and baroclinic instability. This approach has been developed since the second-half of the last century [3] and is used in present time [4].

The goal of our study was to investigate the mechanisms of the Black Sea sub-basin and mesoscale variability by using simulated hydrological fields. We have observations data for 2011 and 2016 obtained from the scientific cruises and the ARGO measurements. So we chose atmospheric forcing corresponding to these years as surface boundary conditions. Unlike in earlier our work [5] here the accuracy of the Black Sea bathymetry was improved and the eddy energetics was evaluated.

2. The numerical experiments setting
The numerical experiments were carried out by using an eddy-resolving z-model of the Marine Hydrophysical Institute of RAS (MHI-model) [6] with horizontal resolution of 1.6 km, that allowed us
to investigate the mesoscale eddies. The vertical turbulent coefficients were calculated by the Mellor-Yamada turbulence closure model [7]. The coefficients near the biharmonic operators in the terms describing the horizontal turbulent viscosity in the motion equations and the horizontal turbulent diffusion in the transport equations of temperature and salinity are $10^{16} \text{cm}^4\text{s}^{-1}$ and $5\times10^{14} \text{cm}^4\text{s}^{-1}$, respectively. As atmospheric forcing we set the wind stress fields, latent, sensible, long-wave heat fluxes, solar radiation, evaporation and precipitation obtained from the SKIRON atmospheric reanalysis with a spatial resolution of 0.1º [8]. The first experiment was run under forcing data for 2011, the second one – under forcing data for 2016. Bottom topography with resolution of 1/8 minutes was extracted from data available on the European Marine Observation and Data Network (EMODnet) portal http://portal.emodnet-bathymetry.eu/. Initial fields are taken by the Black Sea hydrophysical fields reanalysis data (http://marine.copernicus.eu/services-portfolio/access-to-products/). At the preliminary step we interpolated all input arrays into points of our model grid. Due to the fact that initial fields were derived by the Era-Interim atmospheric reanalysis we applied a procedure of quasi-geostrophic adjustment to adapt hydrological parameters beneath SKIRON data. The experiment 1 was run for the period from January till December, 2011. The experiment 2 was run from January till December, 2016. Three-dimensional fields of temperature, salinity, current velocity and sea level were obtained on each day of both time intervals.

3. Validation

The reconstructed hydrophysical fields were compared with the in-situ data. We considered the temperature and salinity obtained in #69 (August 2 – 11, 2011) and #87 (June 30 – July 18, 2016) cruises of the scientific vessel "Professor Vodyanicki". We also used ARGO floats data [9] which worked in the Black Sea in January 5 – December 31, 2011 (float #1901200) and January 2 – December 27, 2016 (float #6901832). As example, Figure 1 illustrates a deviation between measured and simulated temperature along the ARGO floats tracks in 2011 (Figure 1, a) and in 2016 (Figure 1, b) on horizons of 20, 50, 100 m.

![Figure 1. Deviation of simulated temperature from observations along the ARGO floats track on horizons of 20, 50, 100 m: a – float #1901200; b – float #6901832.](image)

The results analysis showed that the maximal temperature deviations were observed at the layer of 10 – 30 m in warm seasons for both experiments. The possible reason of such errors is associated with movement of intensive mesoscale eddies which can transport water with strong density anomalies. It is known that the weakening of the Rim Current in spring and summer leads to enhancement of
mesoscale variability causing significant inhomogeneity in the temperature fields [10]. The maximum differences with the measurement data in the salinity field were revealed at the layer of 50 – 100 m in all seasons for both experiments. Here deviations reached ±1‰. On the deep horizons (below 300 m) there was a good agreement with the observations: the mean difference between the measured and simulated temperature was 0.04°C, the salinity mean deviation was 0.05‰.

4. Results of the numerical experiment

Well known that the Black Sea dynamics is characterized by the basin-scale and mesoscale modes [11]. The Rim Current is a general basin-scale cyclonic gyre, which propagates over the continental slope. Mesoscale variability is associated with time-varying circulation and is described by the eddy kinetic energy (EKE) and eddy potential energy (EPE) [4]. The paper presents the comparative analysis of the Black Sea circulation for 2011 and 2016. The elements of the Black Sea circulation known from observations are reproduced in both experiments and the main features of their seasonal variability are qualitatively repeated.

4.1. Basin-scale circulation

The surface currents velocity averaged over June and December both in 2011 and 2016 are presented in Figure 2 as illustration. The abyssal sea part was covered by the Rim Current in winter and autumn of 2011. At that time, a midstream had smooth and pronounced structure, mean velocity reached 40 cm s\(^{-1}\) (Figure 2, b). Strong meandering of the Rim Current in the south and south-eastern part was observed in winter 2016 (Figure 2, d). The mean currents velocity was less by about 5 cm s\(^{-1}\) than in 2011. A continuity of the Rim Current is disturbed in the spring and summer of 2016 as result of the weakening of the midstream and the formation of intense cyclonic and anticyclonic eddies with a size of 50 – 70 km in the central part (Figure 2, c). In 2011 the Rim Current existed throughout the year and anticyclonic eddies were periodically generated on its periphery (Figure 2, a).

**Figure 2.** Surface currents velocity: a – averaged over June 2011; b – averaged over December 2011; c – averaged over June 2016; d – averaged over December 2016.

4.2. Mesoscale variability

Behavior of the Sevastopol and the Batumi anticyclones corresponded to observations and literature data. The next differences in the parameters of the Sevastopol and the Batumi anticyclones are obtained. The Sevastopol anticyclone in the spring-summer of 2011 was weaker than in 2016. In particular, its size varied from 60 to 90 km and the velocity was about 35 cm s\(^{-1}\) in 2011, meanwhile the maximum velocity reached 45 cm s\(^{-1}\) and the diameter was about 120 km in identical development
phases in 2016. The opposite situation was observed for the Batumi anticyclone due to the weakening of the Rim Current in the summer of 2016. The size and velocity of the eddy in 2011 (Figure 2, a) were two times more than the values of similar characteristics in 2016 (Figure 2, c).

Intensification of mesoscale variability is revealed in the spring-summer at the North-Western Shelf, the Crimean coast and the Anatolian coast for both experiments. The fragments of the surface currents maps are presented in Figure 3. It is found that in 2011 the stronger mesoscale variability was observed in the Southern part (Figure 3, a) and in 2016 conversely in the Northern sea part (Figure 3, b). Such features of coastal circulation near the Anatolian coast led to enhancement of the Batumi anticyclone in 2011.

5. Discussion
We considered the contributions of wind stress work and the energy fluxes due to exchange between the kinetic and potential energies to analyze the mechanisms determining variability of the circulation structure. One of the main factors causing variations of the kinetic energy of the Black sea circulation is the contribution of wind [12] especially in the winter. It was revealed that the month-mean wind velocity in the winter of 2011 was higher than in 2016. The predominating wind directions in the winter of 2011 were the Northern and North-Eastern, and directions in the winter of 2016 were the South and South-West. Thus the reducing of the wind stress work in winter of 2016 led to weakening of the Rim Current (Figure 2, d).

Mesoscale variability is defined by the change of EKE. Here and hereafter the C(Ke,Km) denotes the rate of conversion between the EKE and the mean current kinetic energy (MKE) associated with barotropic instability, the C(Pe,Ke) denotes the rate of conversion between the EKE and the EPE associated with baroclinic instability. It is known that EKE are formed by the time-varying wind stress ($\tau_e$), fluxes of C(Ke,Km) and C(Pe,Ke). We calculate these magnitudes with accordance to [4]. The temporal variations of EKE, C(Ke,Km) and C(Pe,Ke) volume integrals are illustrated in Figure 4 for 2011 and 2016. If C(Ke,Km) > 0 then EKE converts to MKE and conversely; it is analogical for C(Pe,Ke).
Figure 4. The temporal variations of volume integrals: a – EKE; b – C(Ke,Km); c – C(Pe,Ke).

We use fourth order polynomial trends in Figure 4, b, c because there is strong temporal variability of simulated energy fluxes. Analysis shows that the EKE increased during 2011 due to intensive MKE → EKE conversion in cold seasons. The EKE → MKE flux is observed in late spring and summer but its absolute value is less as compared with winter and autumn. The EKE in 2016 decreased from January till September because EKE converted to MKE. Growth of EKE was detected starting from October as a result of inflow from MKE to EKE. The EKE → EPE and EPE → EKE fluxes (Figure 4, c) almost completely compensated each other in first-half of 2011, the EKE → EPE from January till October of 2016. There was an antiphase in the exchange between EKE and EPE for second-half of both 2011 and 2016. Analysis of the time-varying wind stress (not presented here) showed that the wind...
fluctuations increased EKE in cold seasons of both 2011 and 2016, however their pronounced effect on EKE trend are not detected.

So the mesoscale variability had been growing in 2011 due to barotropic instability in the first-half of the year and both barotropic and baroclinic instabilities in the second-half of the year. The mesoscale variability has been weakening from January till September of 2016 due to conversion of EKE to both MKE and EPE. The eddy energy started increasing only in autumn of 2016 due to baroclinic instability.

6. Conclusion
In the result of the present research we reconstructed the basin-scale and mesoscale variability of the Black Sea circulation in 2011 and 2016. It is obtained that the reducing of the wind influence in 2016 led to the weakening of the Rim Current in contrast to 2011. The eddy energy associated with mesoscale variability had been growing in 2011 due to barotropic and baroclinic instability processes. The eddy energy had been decreasing in 2016 and started increasing only at the end of 2016 due to development of baroclinic instability processes. The mesoscale eddies generated near the Anatolian coast in the summer of 2016 had been low impacting the Batumi anticyclone due to the weakening of the Rim Current and decreasing eddy energy.

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