Dynamics of the Azov-Black Sea basin by means of parallel ocean circulation modeling

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Abstract. The paper presents the methodology of free-run simulations for investigation of joint circulation of the Black and Azov Seas with high and ultra-high spatial resolution (4.5 and 1.1 km) and general characteristics of hydrophysical fields based on the results of simulations. Regional configurations used for numerical experiments are almost identical and differ only in spatial resolution with the corresponding tuning of the parameters of lateral turbulent mixing. We analyze the spatial variability of the results as well as water exchange between two basins through the Strait of Kerch. Enhancement of the resolution changes the structure of the basin circulation significantly and has to be validated using high resolution satellite data.

1. Introduction

The high fish productivity of the Azov Sea is a result of a large ratio of the volume of river inflow to the volume of the sea, which also determines the low salinity of the waters with high concentration of biogenic substances. However, recently there have been noticeable changes in the hydrological regime of the basin due to a significant reduction in the river runoff (the Don, Kuban, Mius, etc.). As a result, the level difference between the Azov and Black Seas decreases, which may lead to an increase in salt flux into the Sea of Azov. Don River runoff reduced to historic values, and intensive cyclonic activity and anomalous advection of the Black Sea waters led to the fact that during 2014–2016 an anomalously high salinity was observed in the Taganrog Bay (up to 12 ppt). Thus, the overall balance of saline and fresh waters in the basin is changing and an assessment of its anomalous change in conditions of sustained anthropogenic impact, reduction of river flow and growth of water exchange with the Black Sea in long-term time scales is a rather topical problem.

One of its solutions is research based on the hydrophysical reanalysis obtained by numerical simulation of circulation for the basins of the Black and Azov seas with the observational data assimilation. However, leading marine forecasting centers of the region could not provide such information in full, limiting only to the Black Sea basin. Available freely distributed results of reanalysis of the Global Ocean do not have sufficient spatial resolution to demonstrate local circulation features in the Sea of Azov and are often poorly validated for the basin. Therefore, the available knowledge is limited to only a few short-term simulations of the dynamics by means of a number of domestic and foreign models adapted for this region [1-5].

In [1] the dynamics of the Black and Azov Seas were calculated using the model of the Institute of Numerical Mathematics, RAS (INMOM) for the period of 2006–2008. The spatial resolution of the
model is rather adequate (4 km). The study demonstrates generally good agreement between the results of numerical simulation and measurements. In [3] the approach of cascading basins (Azov-Black-Marble-Mediterranean Sea) was implemented using a finite-element numerical model on an unstructured grid, providing a significant refinement especially in straits.

Earlier [4] we developed a regional configuration for the NEMO (Nucleus for European Modeling of the Ocean) modeling framework [5] for cascading basins (Azov – Black – Marmara Sea), which allowed reproducing the positive salinity tendency in the Sea of Azov within long-term simulations. The results have shown rather good consistency with observational data despite a long integration period (≈ 10 years) and a low resolution (4.6 km). Further studies have shown the need for increased spatial resolution.

In this study, we compare the simulations results with similar results obtained on the basis of a parallel version of the NEMO model with an ultra-high spatial resolution of 1.1 km, recently developed at Marine Hydrophysical Institute of RAS. The paper consists of three sections. The second one provides a brief description of the numerical circulation model and regional configurations developed for it, as well as the boundary and initial conditions. Some results of the comparison are presented in the third section. The fourth section briefly discusses the results obtained due to spatial resolution refinement.

2. Materials and methods

2.1. Numerical model and boundary conditions

The study uses the simulation results obtained from two regional configurations with high (HR) and ultrahigh (UHR) spatial resolutions for NEMO ocean numerical modeling framework [5]. This ocean component of the system is based on primitive equations discretized using Arakawa’s C grid.

The configurations for numerical runs are almost identical and differ only in horizontal spatial resolution with the corresponding adjustment of the parameters of the lateral turbulent mixing. The numerical domain is a geographical grid covering the basins of the Marmara, Black and Azov seas with steps in the meridional and zonal directions: a) 1/24 ° and 1/17 ° for high resolution (HR) and b) 1/96 ° and 1/69 ° for ultra-high resolution (UHR), which correspond to approximately 4.6 and 1.2 km. In vertical direction z-coordinate is used with partial step. The domain bottom topography is constructed using EMODNet bathymetry data [6]. Vertical mixing is parameterized using the k-ε closure hypothesis. Free slip condition is set on lateral boundaries for the equations of motion. Non-linear bottom friction is used. Lateral turbulent exchange is described by a bilaplacian operator.

The model was forced by the surface conditions obtained from ERA5 atmospheric reanalysis product [7]. The presented simulations were carried out ignoring the sea ice thermodynamics. Instead we correct the surface boundary conditions as follows: when the sea water temperature reaches the freezing point (about –0.6 °C for salinity of Azov Sea waters), we impose zero heat flux as surface boundary condition assuming the formation of the sea ice will prevent transport of the heat from the sea to air and vice versa. River runoffs in basin of the Black Sea were taken into account using climate data and for the rivers of the Azov Sea we use volume discharge data from [8], based on measurements.

2.2. Initialization and simulation setup

The initial temperature and salinity in the Sea of Azov are constructed by means of optimal interpolation of in-situ data provided by CMEMS (http://marine.copernicus.eu) and SeaDataNet (European Ocean and Maritime Data Management) oceanographic base data from the combined Black Sea data array (https://www.seadatanet.org/). Monthly climate fields we formed assuming that all stations in a given month belong to its middle (the time correlation function was not taken into account).

In the Black Sea basin, for initialization we use temperature and salinity for August 15, 2007 from physics reanalysis provided by BS MFC (http://mis.bsmfc.net, last accessed March 29, 2018), and for the Sea of Marmara we use global CMEMS analysis (http://marine.copernicus.eu) for the same date.

The initial resolution of the prepared initial fields was 1/24° (HR). Further, the obtained data were interpolated to the grid of the UHR configuration and preliminary adaptive calculations of the cascade circulation were performed from August 15 to December 31, 2007. The results of previous studies
showed that the adjustment of hydrophysical fields to high resolution during simulations demands a period of about 4 months [11].

Thus, initial fields for two prognostic experiments were obtained (fig. 1). Analysis shows rather adequate picture of the general circulation of the Black Sea. In the initial fields obtained (fig. 1, a, c), elements of mesoscale circulation can be distinguished: meandering of the Rim Current on the northwestern shelf, mesoscale eddies near the Anatolian coast. Along with mesoscale, a large number of submesoscale dynamic structures are pronounced. This is especially noticed when comparing the results from HR with UHR (fig. 1, b, d). Also, smaller-scale eddies are observed in the deep part of the Black Sea basin (for example, in the region of 42.5 ° N, 37 ° E). The cascade of anticyclones at the Anatolian coast is better manifested (fig. 1, a, b). A significant number of submesoscale structures occur in the frontal zone on the northwestern shelf and on the edge of the Batumi anticyclone in the region of 41.5 ° N, 40 ° E (fig. 1, a).

Starting from 1 of January 2008 two model runs (experiments) were carried out for 2 years till 31 of December 2009. Obtained daily averaged ocean state parameters were used for further intercomparison.

3. Results

In the initial fields we can already observe significant differences in the simulation results with the resolutions of UHR and HR. Let’s consider in details the seasonal and inter-annual variability of currents in one of the cyclogenesis areas of the Black Sea basin – steep bottom topography on the north-western Black Sea shelf, beyond the tip of the Crimea peninsula (fig. 2). It can be seen, according to the results of the UHR model run, that mesoscale eddies are formed here throughout the whole simulation period (fig. 2, a – d). The jet of Rim Current can be traced poorly, mainly in the winter period. Most of the time the structure of the currents is represented by a system of fairly intense meso- and submesoscale eddies. As a result of the meandering of the jet, anticyclones (fig. 2, a – b) or a cyclone-anticyclone pair (fig. 2, d) are continuously generated. The most intensive so-called Sevastopol anticyclonic eddy with a diameter of ≈ 100 km is pronounced most of the time. Structures with size of ≈ 20 km are also expressed. Note that the size of the Sevastopol mesoscale eddy in the winter period is somewhat smaller, which indicates a falling of jet flow intensity and the redistribution of energy into eddies.

In the HR model run, in this part of the basin one can observe a rather intense jet of Rim Current (fig. 2, e – h). The formation of the Sevastopol anticyclone in the summer period also occurs, however, it is extremely weaker than in the UHR experiment. At the same time, the Rim Current jet weakens noticeably, since the intensity of wind circulation in this period decreases.
Figure 1. The initial conditions for January 1, 2008: a, c) sea surface temperature and current velocities at a depth of 28.75 m in the UHR model run; b, d) the same for HR model run.

Similar features of the circulation can be noted for the entire basin. Significant qualitative and quantitative differences in the structure of currents are probably the result of changing the balance of kinetic energy of motions. The spatial variability of the thermohaline fields in the Black Sea also varies considerably while the fields look quantitatively close, which is partially demonstrated by fig.1 (a, c). However, this may be the result of a small period of numerical integration.

In certain parts of the cascading basins the difference between the simulation results with different resolutions is likely to increase. Consider here the salinity field of the Azov Sea waters. It can be noticed that qualitatively structures of the fields are close. One can see the freshening of waters in the Taganrog Bay and an increase in salinity towards the center of the basin (fig.3).

Figure 2. Current velocities (m/s) at a depth of 28.75 m: a to d – in the UHR model run; e to h – in the HR model run.

However, sea waters in the UHR experiment are somewhat saltier (reaching 13 ppt) (fig.3, a). A possible explanation for this is a more accurate and intensive water exchange through the Strait of Kerch,
for which a resolution of 4.6 km gives underestimated values. These waters have already partially penetrated the Taganrog Bay. We can also notice that the opposite flow of the Azov waters in the Black Sea basin is also manifested better in the UHR model run (fig.3, a), where the freshened jet after the Kerch Strait moves to the right and reaches the Feodosia Gulf.

**Figure 3.** Surface salinity on May 7, 2008: a – in the UHR model run; b – in the HR model run.

4. Discussion

On the basis of NEMO numerical model, we simulate the joint circulation in the Black and Azov Seas basins. A new resolution allowed to reconstruct qualitatively new features of spatial variability. This however requires more detailed analysis and validation using high resolution satellite observations.

The positive salinity tendency in the basin of the Sea of Azov, which is well pronounced according to observations, was reproduced for both spatial resolutions. However, a more accurate simulation of the water exchange is likely to allow reproducing the observed anomalous local inflow of salt waters into the Taganrog Bay, taking into account the decrease in the flow of rivers Don and Kuban.

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