Study of the Black Sea dynamics on the basis of reanalysis results

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Abstract. The Black Sea dynamics during 25 years is analysed using numerical simulation and assimilation of remote sensing data. Numerical circulation model has horizontal space resolution of 4.8 km and 40 vertical levels. It includes a turbulent model of the Mellor-Yamada type. Results of simulation were validated by comparing with temperature and salinity profiles from hydrological surveys. Analysis of the results shows that the temperature of the sea upper layer grows. Salinity of upper 30m layer also increases, but in the layer 30-100m it decreases. The results of simulation reproduce authentically circulation in the upper layer of the Black Sea. According to simulation, mean currents, directed opposite to the surface one, are observed at a depth of more than 400 m.

1. Introduction
The Black Sea is a nearly enclosed basin with a simple coastal line and maximum depth of about 2 km. It is connected to the Marmara Sea by the shallow Bosphorus Strait. Due to its small size the Black Sea is more sensitive compared with oceans to changes in atmospheric processes. Climate variations can reconstruct seawater stratification in the upper layer and, as a consequence, change parameters of the marine ecosystem. That is why study of the long-term variations of oceans and seas is an important oceanography problem. Last time such a tool as reanalysis of local (seas) and global (World Ocean) systems is used for these purposes. Reanalysis is a synthesis of data provided by a hydrodynamic model and observations. It allows you to combine the possibilities that the model gives with the information obtained by measuring certain parameters of the marine environment. This paper presents the results of the analysis of the Black Sea dynamics during more then 20-year period (1993 – 2016). In this period only few hydrological surveys, mainly local, were made in the Black Sea. This lack of measurements is compensated by routine satellite remote sensing data performed at that time. These are measurements of the sea level anomalies (SLA) and sea surface temperature (SST).

2. Data and methods
The main reanalysis components are a numerical model of the Black Sea circulation, measurement data, and algorithm for data assimilation by the model.

2.1. Circulation model
The model of the Black Sea circulation is a z-coordinate model based on the traditional primitive equations [1]. In this study the simulation was performed with horizontally uniform grid and 40
vertical levels, which are compressed towards the free surface and the bottom (in the upper 60 m layer, the vertical resolution is 4 m). Horizontal space resolution is 4.8 km. This spatial resolution permits to resolve inter-annual, seasonal and mesoscale variability of the Black Sea (Rossby radius for the first baroclinic mode is about 25 km). For a more accurate description of thermodynamic processes in the active layer of the sea, especially vertical exchange processes, a turbulent model has been added coupled with the circulation model. This is the quasi-equilibrium turbulent energy (QETE) model [2], which is a part of the Mellor–Yamada family of models [3], consisting of two equations for the evolution of turbulent energy and the scale of turbulence. The coefficients of vertical turbulent viscosity and diffusion where computed using turbulent energy and length scale, which were defined by solving evolution equations. At the lateral boundaries, in river mouths and straits, nonzero values of the normal velocity component are set, which is determined by the climatic values of the water flow: the velocity of the Lower Bosporus Current was set at a constant value, which ensures the total water balance for the period under consideration (river and strait expenditures, evaporation, and precipitation). The heat fluxes at the lateral boundaries were set to zero. Salt fluxes were also set to zero on the lateral boundaries except the mouths of rivers, where its values was 3%, and in the lower Bosporus current, where salinity corresponds to Mediterranean water (36%).

2.2. Atmospheric forcing
Atmospheric forcing is one of the key factors determining the circulation. In this study, atmospheric fields derived from ERA-Interim (ECMWF) data are used as boundary conditions for the circulation model equations on the free sea surface: surface wind (each 6 h), heat flux, freshwater flux, and solar radiation (each 12 h). For temperature, we used the fields of sensible and latent heat fluxes on the sea surface and long- and short-wavelength radiation. The fields of evaporation and precipitation were used for the boundary conditions for salinity, and the wind speed fields at an altitude of 10 m (which were recalculated according to the standard formula into the wind friction stress) were used under the boundary conditions for the velocity equations.

2.3. Data assimilation
The Black Sea circulation model assimilates data of the sea-surface temperature (SST), sea level anomalies, and annual-mean temperature and salinity profiles. The SST values for the 1993–2009 were taken from GHRSSST and NODC archives. For the last reanalysis period (2010–2016), the SST data were taken from OSI TAC archive. To assimilate data on the sea surface level, all available satellite altimetry data for the reanalysis period from NASA, AVISO, and SL TAC archives were used. The annual-mean profiles of temperature and salinity were prepared on the basis of all hydrographic survey and floating buoy data available for the period under study. Briefly, the procedure of assimilation of satellite altimetry data is the following. The temperature and salinity profiles are corrected at each point proportionally to the difference between measured and modeled free surface elevations. The depth-dependent weight coefficients are calculated by cross-covariance error functions of level, salinity, and/or temperature. The SST assimilation technique is based on the optimal interpolation and the nudging procedure.

3. Results and discussions
Using the circulation model and data assimilation technique, described above, we simulated the dynamics of the Black Sea during about 25 years. To evaluate the simulation quality we validated the results by comparing them with temperature and salinity resulted from hydrological surveys fulfilled in the Black Sea during this period.

3.1. Validation
The salinity and temperature profiles obtained from hydrological surveys and drifting ARGO buoys for the period from 1992 to 2013 were prepared by V.N. Belokopytov. The simulated temperature and salinity fields were interpolated in space and time at the point and time for which the profiles were
measured. Then, the model data were interpolated to the horizons of the measurement data and compared with them. Figure 1 presents temperature profiles for four seasons obtained from measurements and simulation results. Figure 2 shows profiles of mean and standard deviations of the observational data from the simulation results. The greatest deviations in winter temperature are observed at a depth of about 50 m, approximately corresponding to lower boundary of the upper mixed layer in the winter season. The model gives an overestimation of about 0.25°C. In the spring and summer seasons, maximum deviations are observed at a depth of about 20 m corresponding to the center of the seasonal thermocline. Because of the high gradient, even a small error in determining the position of the thermocline leads to large temperature deviations at a fixed horizon. In autumn, the average temperature deviation is maximum in the region of 40 m. The model values of the temperature are higher than those from the measurements. The maximum root mean-square deviation is observed at the horizon of 25 m, which corresponds to seasonal thermocline as well as in cases of spring and summer.

![Figure 1. Mean temperature profiles from in-situ measurements (solid lines) and appropriate profiles from simulation (dotted lines).](image1)

![Figure 2. Mean (solid lines) and standard deviations (dotted lines) of the observational temperature from the simulation results.](image2)

The corresponding profiles for salinity are shown in figures 3 and 4. According to the simulation results, the salinity in the upper layer of the sea (about 50 m) is, on average, very close to measurement data (in autumn simulated salinity is smaller by 0.1‰). At lower horizons the salinity values obtained from the model are lower than the measured data. The highest mean-square deviations of the simulated salinity from the measured values are observed near and within the halocline (between 50 and 120 m) in all seasons. This is because (as in the case of temperature) the halocline is the area of most significant natural variability of the salinity field, since the maximum vertical gradients are observed here.

![Figure 3. Mean salinity profiles from in-situ measurements (solid lines) and appropriate profiles from simulation (dotted lines).](image3)

![Figure 4. Mean (solid lines) and standard deviations (dotted lines) of the observational salinity from the simulation results](image4)

3.2. Thermohaline structure
Time evolution of the temperature in the upper 200 m water column can be illustrated with time diagram (figure 5), where basin-averaged temperature is represented as a function of depth and time.
This figure demonstrates the main processes forming thermal structure of Black Sea waters. The main signal is the season changes during the annual cycle. The seasonal thermocline is formed at the 15-40 m depth during spring-summer heating. The prominent feature of the Black Sea is the cold intermediate layer. Its upper and lower boundaries are identified by 8°C isotherm. In the figure this water mass is marked by a solid line. In addition to strong seasonal variability, inter-annual changes in water temperature are also well pronounced. It can be clearly seen in variations of the CIL thickness and lower boundary of the thermocline.

![Figure 5. Time evolution of the basin averaged temperature in the upper 200m water column.](image)

Long-term evolution of the mean temperature in the three layers 0-30, 30-100 and 100-200 m is represented in figure 6. Behavior of the temperature in the two upper layers has a pronounced seasonal variability. But in all these layers warming of the sea water can be clearly seen by positive linear trends. This warming is also confirmed by degradation of the cold intermediate layer, which is obvious from figure 5.

![Figure 6. Mean temperature in the layer 0-30 m (solid line, left axis); in the layer 30-100 (dotted line) and 100-200 m (bold solid line, right axis). Straight lines show linear trends.](image)

Salinity is the next important hydrological parameter, characterizing thermohaline structure of the Black Sea waters. Evolution of salinity in the upper 100 m water column is presented in figure 7. Analysis of the salinity distribution in the layer 0-100 m shows that a seasonal signal is traced clearly in the upper 40 meters. Minimum salinity of surface waters is observed in June as a result of spring river flooding. Salinity of the surface waters grows after July till February when its maximum is observed.

![Figure 7. Time evolution of the basin averaged salinity in the upper 100 m water column.](image)
To illustrate tendency of the salinity changes in the upper layer of the Black Sea, figure 8 shows variations of the mean monthly values in the 0–30 and 30–100 m sea layers. Along with seasonal variability (especially in the layer 0-30 m) inter-annual changeability is also well pronounced. In general, salinity in the upper 30 m layer tends to a decrease, it is seen from negative linear trend. It means that surface waters in the Black Sea become fresher during the period under review. And vice versa, in the 30–100 m layer a positive linear trend is clearly visible. A similar increase in sea salt content was found in [4], where changes in the thermohaline structure of the Black Sea were analyzed over a period of about 100 years on the basis of hydrological measurements. The greatest increase of salinity is observed in the layer of the main halocline that corresponds to the layer we consider. The author explains this salination process by the continuing increase in the volume of Sea of Marmara waters.

![Figure 8. Mean salinity in the layer 0-30m (solid line, left axis) and 30-100m (dotted line, right axis). Straight lines show linear trends.](image)

Space distribution of the sea surface salinity can be illustrated by figure 9. These are February and June monthly averaged maps of 2010. In these months maximum and minimum values of salinity are observed in the Black Sea surface layer during the annual cycle. The saltiest water is in the center of the basin and the freshest one is near north western shelf caused by rivers runoff and particularly the Danube River. In June shelf waters are noticeably fresher than in February. Apart from this, anticyclone eddies in the form of fresh water spots can be seen along the coast.

![Figure 9. Examples of surface salinity distribution in winter and summer.](image)

3.3. Circulation
The most pronounced feature of circulation in the upper layer of the Black Sea is Rim Current (RC). It encircles the Black Sea along the perimeter and forms a large-scale cyclonic gyre. The winter circulation of the Black Sea is dominated by a two cyclonic gyre system in the western and eastern basins, encircled by a weakly meandering, organized and strong Rim Current jet. In summer time the upper layer circulation attains its most disorganized form, identified by a series of cyclonic eddies within the interior cell and accompanying by larger coastal anticyclonic eddies around the periphery. Examples of the winter and summer circulation in the Black Sea 30 m upper layer derived from the simulation are presented in figure 10.
Below the surface layer, the intensity of currents in the Black Sea reduces noticeably. According to the simulation, presented in this study, the current velocities in deep layers do not exceed several centimeters per second. An interesting feature of the circulation of deep waters, derived from the results of modelling, is the presence of currents directed oppositely, in comparison with surface currents. Moreover, this is observed in the circulation averaged over the entire considered period. Figure 10 demonstrates a map of average currents at a depth of 700 m. The current jet along the northern coast is directed to the east, and along the southern coast is directed to the west. Cross section along 36°E of the mean zonal velocity is shown in figure 11. Under intense surface currents we can observe areas with countercurrents.

![Figure 10](image1.png)

**Figure 10.** Examples of winter (left panel) and summer (right panel) surface circulation.

![Figure 11](image2.png)

**Figure 11.** Averaged over the considered period currents at the depth of 700 m.

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