Analysis of circulation near the coast of Western Crimea and the region of Sevastopol with assimilation of temperature and salinity observations

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Abstract. Hydrophysical fields which are continuous in time and space are reconstructed in the coastal zone of the Black Sea (near the coast of Western Crimea and the region of Sevastopol) by a three-dimensional nonlinear hydrodynamic model with assimilation of observational data of the 2007 hydrological survey. A sequential optimal interpolation of temperature and salinity observations is used as the assimilation procedure. We use real atmospheric forcing and a high resolution (a horizontal grid of ~1.6 × 1.6 km and 31 vertical layers from 1 m to 1300 m). Mesoscale features of the currents are obtained, and coastal upwelling in the Kalamitsky Bay is reconstructed and registered in satellite observations.

1. Introduction
The reconstruction of the spatio-temporal structure of the coastal circulation of the Black Sea, close to the observed one, allows one to determine the regions of generation of mesoscale and submesoscale eddies, frontal zones and jets. It is important in solving problems connected with the construction of coastal and port facilities, navigation, mining, forecasting the impact of accidental emissions of pollutants on the marine environment. Overwater and underwater shipping, intensive exploitation of the port in Sevastopol, which is the naval base of Russia, require analysis and forecast of hydrophysical fields throughout the entire sea. It is practically impossible to solve these problems without reconstruction of the circulation on the basis of the synthesis of a numerical model of high spatial resolution and observational data from hydrological surveys.

Some calculations of hydrophysical fields on the basis of the assimilation of observational data in numerical models were carried out earlier. A problem of variational assimilation of satellite observational data on the temperature and the ocean surface level and temperature and salinity data on the basis of a three-dimensional model of hydrothermodynamics of INM RAS was formulated in [1], and the expediency of using the model with the assimilation unit of operational observational data was demonstrated on the example of a numerical experiment for the Indian Ocean. The main steps in improving the methods for calculating the dynamics of the ocean with observations of the temperature and salinity of sea water were listed in [2], and the problem of integrated use of measurements of currents, while assimilating them in a hydrodynamic model using the Kalman filter, was considered for the western Atlantic equatorial region. The Argo-based Model for Investigation of the Global Ocean (AMIGO) was described in [3]. It consists of a block of variational interpolation onto a regular grid of profiling data for drift Argo meters and a block of model hydrodynamic adaptation of variationally interpolated fields, which allowed one to obtain a complete set of oceanographic
characteristics from irregularly located measurement data. A technique for modeling the dynamics of the Black Sea for calculating the distribution of pollutants in the coastal zone of the Adler – Sochi region was proposed in [4] on the basis of the hydrodynamic model of INM RAS implemented in two versions (with a uniform spatial resolution of ~4 km and a non-uniform one, with a step reduction of up to 50 m). It was shown that the model version with higher spatial resolution reproduced the eddy circulation more adequately. The results of modeling the submesoscale variability and eddy formation of the northeastern shelf of the Black Sea based on a numerical model with high spatial resolution were presented in [5], and a comparison of these results with direct measurements for September 2008, January 2011 and March 2013 was performed. Several hydrological surveys were analyzed in [6, 7] in the region of the western coast of Crimea and on the north-western shelf of the Black Sea, using a hydrodynamic model and an assimilation procedure on the basis of e sequential correction of the model values by the method of optimal interpolation of residuals.

The Marine Hydrophysical Institute (MHI) regularly performs expeditionary studies in the coastal zone of the Black Sea, whose tasks are to obtain experimental data on the vertical and lateral distributions of hydrological characteristics. This study is devoted to an analysis of the results of numerical modeling of the coastal circulation of the Black Sea on the basis of the assimilation of experimental data on temperature and salinity measurements in a hydrodynamic model. A z-coordinate three-dimensional nonlinear model of the Black Sea [8], which was developed at MHI and adapted to the conditions of the coastal zone in [6], was chosen as a research tool. Sequential optimal interpolation of the observational data on temperature and salinity was used as an assimilation procedure.

A hydrological survey of the scientific research vessel “Experiment” in September 2007, in which experimental data on temperature and salinity in the coastal region of the Black Sea were obtained (Figure 1), was chosen for analysis.

The purpose of this work is to reconstruct and analyze three-dimensional fields of currents, temperature and salinity, continuous in time and space, with a horizontal resolution of ~1.6 km on the basis of the assimilation in the hydrodynamic model of observational data obtained from 16 to 22 September, 2007 in the western region of Crimea and near Sevastopol, to analyze the mesoscale features of the coastal circulation, and to show the effectiveness of applying the assimilation procedure in a numerical model while reconstructing hydrophysical fields (on the basis of comparison of the results of two numerical experiments without and with observational data).

2. Parameters of the model and description of the numerical experiment

The system of model equations of the dynamics of the Black Sea on the basis of the complete equations of thermohydrodynamics of the ocean in the Boussinesq approximation, hydrostatics and incompressibility of the sea water in the Gromeka-Lamb form, the boundary conditions on the surface, on the bottom, and on the solid lateral walls were described in detail in [8]. We considered a region of the Black Sea located between the meridians of 28.5 and 33.5° E with an open southern boundary, corresponding to the parallel of 44.4°N (we used a detailed presentation of the bottom topography with a resolution of ~1.6 km). The numerical experiment was carried out with a resolution of ~1.6 km. The time step was equal to 30 s. The horizontal coefficients of turbulent viscosity and diffusion were equal.
\[ \nu_H = 5 \cdot 10^7 \text{cm}^2/\text{s}, \kappa_H = 5 \cdot 10^5 \text{cm}^2/\text{s}. \] 

The total period of integration of the model equations was 10 days (from 14 to 24 September 2007). Along the vertical, the horizontal components of the current velocity, temperature, and salinity were computed at 31 depths: 1; 3; 5; 7; 10; 13; 16; 20; 25; 30; 36; 42; 48; 55; 65; 80; 95; 120; 150; 200; 300... 1300 m. The vertical component of velocity was calculated for intermediate horizons. The vertical coefficients of turbulent exchange of momentum and diffusion were calculated according to the Philander–Pacanowski approximation [9]. The fields of currents, temperature, and salinity obtained by the model for the entire sea on a 5 × 5 km horizontal grid were used to specify initial and boundary conditions on the open boundary of the domain. The following conditions were selected on the open southern boundary. The components of the current velocity, temperature, and salinity (the Dirichlet conditions) were specified in the boundary regions where the water flowed into the domain \((v > 0)\); conditions \(\partial u/\partial n = 0\), \(\partial v/\partial n = 0\), and radiation conditions for \(T\) and \(S\) were specified in the boundary regions where the water flowed out of the domain \((v < 0)\).

We took into account the discharges of rivers: Danube, Dnieper, Dniester, and South Bug. The fields of tangential wind stress, heat fluxes, shortwave radiation fluxes, precipitation and evaporation obtained from data of the regional atmospheric model ALADIN [10] with a spatial resolution of 1/4° × 1/4° provided by the Department of Marine Forecasts [11] of MHI and bilinearly interpolated to the selected grid were specified for each day on the sea surface. It was found by analysis of the wind fields that a south-western wind prevailed with a maximum velocity of 11 m/s from 14 to 18 September, and north and north-eastern winds with a maximum velocity of 16 m/s were acting from 19 to 24 September.

A simplified procedure of four-dimensional analysis [12, 13], based on the method of sequential optimal interpolation, when the covariance functions of the temperature and salinity fields were calculated under the assumption of homogeneity and isotropy, was used to realize the procedure of observational data assimilation.

The maximum depth to which soundings were carried out in the hydrological survey of the scientific research vessel “Experiment” varied from 5 to 300 m, and the number of stations was 44. The coordinates of all the stations where the temperature and salinity were measured were correlated with the calculated model grid, and the data were prepared for assimilation in the hydrodynamic model. A correlation radius of ~20 km was determined from the analysis of the statistical structure of the fields (calculation of the spatial correlation functions of the fields of temperature and salinity). We approximated the covariance functions of the thermohaline fields by a function of the exponential type

\[ \exp\left[ -\lambda \left( (x-x)^2 + (y-y)^2 \right) \right], \]

where \(\lambda\) is a dimensional parameter (equal to \(0.016 \cdot (\Delta x)^{-2}\)), corresponding to a correlation function value of 0.1. The hydrological survey data were grouped for six days, and assimilation was carried out once a day: September 16 – 3, September 17 – 7, September 18 – 8, September 19 – 7, September 20 – 4, and September 22 – 15 stations. Thus, thermohaline fields were calculated using the model equations until the moments of receiving of the data observations. Correction of the temperature and salinity fields was performed at the moments of assimilation taking into account the correlation radius.

The region located between the meridians 32.2 and 33.8°E and the parallels 44.4 and 45.5°N was analyzed in detail.

3. Fields of currents

The level fields for September 15, 20 and 23, 2007 are presented in Figures 2a, b, c (the contours were drawn every 0.2 cm), on which circulation elements, such as eddies and jets, were clearly observed. An eddy with a radius of about 15 km (most noticeable in Figure 2b, c) and an eddy between 32.2 and 32.4°E associated with the meandering of the Rim Current (RC) (most noticeable in Figure 2b) were generated during the calculation period. These eddies were repeatedly recorded on satellite images of surface temperature from the NOAA satellite. Thickening of the isolines near Sevastopol and along the western coast of Crimea associated with the formation of a jet was noted in the fields of level on September 23 (Figure 2c), in addition to the eddy in the Kalamitsky Bay. We observed variability of
the level fields with time (Figures 2b and c) associated with the influence of the observational data of September 22 located between 33 and 33.5° E (Figure 1).

The fields of currents are presented in Figures 2d, e, f, g, h, i, j, k, l at different horizons for September 15, 20 and 23, 2007 (every third arrow was shown). Due to the shallow water of the region, the wind regime had a great influence on the formation of circulation.
Under the influence of the south-west wind acting from 14 to 18 of September the main direction of the surface currents was eastern. We present the current fields for September 15 (Figures 2d, g, j) as an illustration. An anticyclonic eddy with a radius of about 15 km was obtained in the Kalamitksy Bay in the upper 36-meter layer, which was most noticeable in the 5–20 m layer (Figure 2g) and whose orbital velocity decreased with depth from 24 to 12 cm/s (Figure 2j).

Intensification of the currents was noticed near Cape Tarkhankut to values of 44 cm/s on the upper horizon (Figure 2d), and a cyclonic eddy with a radius of about 10 km near Evpatoria was generated in a layer of 10–20 m (Figure 2g). A possible mechanism for the formation of eddies was the flow of a current over inhomogeneities of the bottom topography and coastal orography.

We noted that no eddy was observed in the Kalamitksy Bay in the upper layer at sufficiently high wind velocities (about 10 m/s); the current velocity reached 54 cm/s. The features of a circulation associated with meandering of the RC (which is located to the south of the calculation area) passing along the depth slope began to form from September 17 below the 10-m horizon.

Under the influence of the north and north-east winds acting from 19 to 24 of September the main direction of the surface currents was western, an element of meander of the RC (an anticyclonic eddy with a radius of about 15 km) between 32.2 and 32.6° E was observed in the entire water layer. We noted that it was also obtained in the results of the model with a step of 5 km. We present the current fields for September 20 (Figures 2e, h, k) as an illustration.

An intense jet formed in the upper 36-meter layer (with a maximum velocity of 32 cm/s on the upper horizon) on September 22 and 23 near Sevastopol and along the western coast of Crimea directed to the north and north-west, an anticyclonic eddy was observed in the Kalamitksy Bay. These features of the coastal circulation in the current fields for September 23 are presented in Figures 2f, i, l.

4. Fields of temperature and salinity
The initial field of surface temperature was characterized by values from 19 to 22°C; the maximum values were obtained in the Kalamitksy Bay, and the minimum ones along the coast to the east of Cape Tarkhankut. An area with increased temperature of about 21°C relatively adjacent waters was observed near Evpatoria. The initial field of surface salinity was characterized by values from 17.7 to 18.3‰; the maximum values were obtained in the western part of the region, and the minimum ones along the coast to the east of Cape Tarkhankut. There was a jump layer at a depth of ~20–25 m in the vertical profiles. Figure 3 shows the surface temperature fields for September 15, 17, 19, 21, 22, 23 and the surface salinity fields for September 15, 19 and 23.

During the calculation period there was some cooling of the surface waters, which was most noticeable along the coast to the east of Cape Tarkhankut (the temperature decreased from 18°C on September 15 (Figure 3a), to 16°C on September 17 (Figure 3b), to 15°C on September 19 (Figure 3c), and to 14°C on September 21 (Figure 3d)). The water temperature decreased to 21°C on September 19 (the fifth day of calculations, Figure 3c) in the Kalamitksy Bay, and near Evpatoria to 17.5°C. The salinity fields (Figures 3g and h) changed insignificantly during the calculating period until September 21.

According to the measurements and images from the NOAA satellite (NOAA-17 and NOAA-18 with a resolution of 1 km, data server http://dvs.net.ru/mp/data/200709bs_sst_ru.shtml), a rise of the cold salt waters was observed in the southern part of the Kalamitksy Bay on September 22 and 23, due to the action of the north and north-eastern winds. Water with a temperature below 14°C and salinity more than 18% was observed on the surface. That was confirmed by the results of numerical calculation (Figures 3e, f, i). We noted a distribution of cold water in the model fields (Figures 3d, e, f, i) of temperature from September 21. The maximum values of the vertical velocity (0.01 cm/s) were obtained along the coastline.
5. Analysis of the influence of observational data assimilation on the accuracy of the reconstruction of fields of currents, temperature and salinity

The influence of the assimilation procedure in the numerical model on the formation of fields of currents, temperature, and salinity was analyzed on the basis of comparison of the results of two numerical experiments on the calculation of hydrophysical fields without assimilation and with assimilation of temperature and salinity data measurements.

Taking into account the observational data led to some qualitative and quantitative differences in the structure of the fields of currents (intensification of currents, change in the direction of currents, eddy formations were more noticeable). We present Figures 4a, b, c, and d as an illustration, which shows the current fields at a depth of 5 m for the two experiments. We noted an intensification of the currents in the central part and a change in the direction of the currents at the southwestern boundary of the region for September 17 (Figure 4b) compared with the results presented in Figure 4a. An intense jet along the western coast of Crimea was more noticeable on September 22 (Figure 4d) in comparison with the results presented in Figure 4c, the maximum velocity increased from 27 to 34 cm/s, and an anticyclonic eddy was obtained between 32.2 and 32.4°E (Figure 4d).

Taking into account the observational data led to a more accurate reproduction of the upwelling structure in the fields of temperature and salinity, which was also observed in the calculation without data assimilation. Figures 4e, f, g, and h shows the temperature and salinity fields at a depth of 5 m for
the two experiments. A rise of the water with a minimum temperature of 8°C and a maximum salinity of 18.4‰ was observed in the upper layer taking into account the observational data (Figures 4f and h).

Figure 4. A: Current field (cm/s) at a depth of 5 m on September 17 calculated not taking into account the observational data; b: velocity field (cm/s) at a depth of 5 m on September 17 calculated taking into account the observational data; c: velocity field (cm/s) at a depth of 5 m on September 22 calculated not taking into account the observational data; d: velocity field (cm/s) at a depth of 5 m on September 22 calculated taking into account the observational data; e: temperature field (°C) at a depth of 5 m on September 23 calculated not taking into account the observational data; f: temperature field (°C) at a depth of 5 m on September 23 calculated taking into account the observational data; g: salinity field (‰) at a depth of 5 m on September 23 calculated not taking into account the
observational data; h: salinity field (%) at a depth of 5 m on September 23 calculated taking into account the observational data.

6. Conclusions
In this paper, fields of sea level, currents, temperature, and salinity were reconstructed in the coastal area of the Black Sea (near the coast of Western Crimea and the region of Sevastopol) with a high spatial resolution (a horizontal grid of ~1.6×1.6 km and 31 vertical layers) by a hydrodynamic model and observational data of a hydrological survey performed by a scientific research vessel, “Experiment”, in 2007. The areas of generation of mesoscale and submesoscale eddies and jets were determined. An anticyclonic eddy with a radius of about 15 km in the Kalamitsky Bay in the upper water layer and a cyclonic eddy with a radius of about 10 km near Evpatoria in a layer of 10–20 m were formed in a current flow over the coastal orography and inhomogeneities of the bottom relief. The anticyclonic eddy with a radius of about 15 km between 32.2 and 32.6°E in the entire water layer was associated with meandering of the RC. An intensification of the currents near Cape Tarkhankut was revealed. An intensive current near Sevastopol and along the western coast of Crimea, directed to the north and north-west, was observed.

The spatio-temporal structure of temperature and salinity fields was reconstructed along the western coast of Crimea and near the region of Sevastopol. Cooling and desalination of the surface waters, which was most noticeable along the coast to the east of Cape Tarkhankut, was detected. Coastal upwelling in the Kalamitsky Bay was reconstructed on September 21–23, 2007 and registered in data observations, as a result of a rise in the underlying cold waters.

Based on a comparison of the results of two numerical experiments with and without observational data, it has been shown that using the observational data made it possible to more accurately reconstruct the mesoscale features of the coastal circulation near the western and north-western coast of Crimea.

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