Analysis of hydrophysical fields in the northern part of the Black Sea on the basis of assimilation in the hydrodynamic model of temperature and salinity observations in the summer season of 2016

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Abstract. A numerical experiment was conducted to reconstruct the fields of the currents, the level, temperature and salinity of the Black Sea for the summer season of 2016 on the basis of the hydrodynamic model that included nonlinear equations of motion, advection equations of heat and salt. We used a high spatial resolution (horizontal grid ~1.6 ×1.6 km and 27 vertical layers) and real atmospheric forcing. The assimilation procedure of observational data was based on a modified Kalman filter taking into account the heterogeneity and non-isotropy of estimates of the temperature and salinity fields. Areas of generation of meso- and submesoscale features of hydrophysical fields were determined in the northern part of the Black Sea (eddies of different signs of rotation with a radius of about 30 km in the western part of the region, a cyclonic eddy with a radius of about 40 km in the eastern deep-water part of the region, anticyclonic eddy with a radius of about 25 km near the city of Yalta, intense jets along the Crimean coast and eddies of small scales of a different sign of rotation along the coast of Crimea and on the north-western shelf) and possible reasons of their formation were discussed.

1. Introduction
Analysis of hydrophysical fields, reconstructed on the basis of numerical models of high spatial resolution and observational data of hydrological surveys, is important in solving problems, connected with surface and submarine navigation, construction and exploitation of port facilities, social and economic activities. The existing methods of assimilating of observational data in the model of dynamics can be divided into two large groups. One group of methods is based on variational principles (a search for a minimum of a functional that describes the "proximity" of a model solution and measurement data in some given metric). For example, in [1] the problem of variational assimilation of the sea surface temperature data for the model of the Black Sea dynamics was formulated and numerically studied in order to reconstruct heat fluxes on the surface. In [2] the formulation of the problem, the solution algorithm and the results of four-dimensional variational assimilation of temperature and salinity in the hydrodynamic model of the World Ocean were discussed. Another approach, called "Kalman filtering", is based on the statistical theory of estimation and filtering processes on the background of "noise" with known statistical properties. For example, in [3] a problem of the complex use of data measurements of temperature, salinity and current velocity during their assimilation was solved on the basis of the Kalman filter in the hydrodynamic model in the near equatorial region of the western Atlantic. In [4] several hydrological surveys were processed in the region of the western coast of Crimea and on the
northwestern shelf of the Black Sea using the hydrodynamic model and the assimilation procedure, based on the sequential correction of model values by the method of optimal interpolation of residuals.

Since 2016 the Marine Hydrophysical Institute (MHI) has resumed regular expeditionary research in the Black Sea, whose mission is to obtain experimental data on the vertical and spatial distribution of hydrological characteristics. The aim of this study was to reproduce and analyze the circulation in the northern part of the Black Sea for the summer season of 2016 with the help of the z-coordinate three-dimensional non-linear model [5], developed at MHI, and the procedure of assimilation of observational data (hydrological survey of the 87th cruise of the scientific research vessel "Professor Vodyanitsky") on the basis of the Kalman filter taking into account the heterogeneity and non-isotropy of estimates of the temperature and salinity fields. Identifying possible reasons of the formation of meso- and submesoscale features of circulation is also of interest.

2. The procedure of the assimilation of observational data, taking into account the heterogeneity and non-isotropy of estimates of temperature and salinity fields on the basis of a modified Kalman filter

A procedure of data assimilation taking into account the heterogeneity and non-isotropy of estimates of temperature and salinity fields was developed in [6], following which we describe the assimilation scheme used in this work.

Suppose that by the time point \( t_n \) of the receipt of data measurements, the thermohaline fields had been calculated using the model equations [5], then they were corrected by the formulas [6, 7]:

\[
T(\bar{x}, t_n) = T(\bar{x}, t_n) + \sum_{m=1}^{M} \Delta_m^T(\bar{x}, t_n)[T(\bar{x}, t_n) - T(\bar{x}, t_n)],
\]

(1)

\[
S(\bar{x}, t_n) = S(\bar{x}, t_n) + \sum_{m=1}^{M} \Delta_m^S(\bar{x}, t_n)[S(\bar{x}, t_n) - S(\bar{x}, t_n)],
\]

(2)

The first terms in square brackets in (1) and (2) were the T, S measurement data, received at the time point \( t_n \), and the second terms were the calculated temperature and salinity fields according to the numerical model at the same time point. The minus sign of \( t_n \) meant that the corresponding fields were obtained without taking into account the measurement data received at a given time, and the plus was for the calculation of the required characteristics taking into account the field observations available at the time \( t_n \). M was the number of measurements, determined by the correlation radius. The weights were determined from the ratios [6, 7]:

\[
\Delta_m^T(\bar{x}, t_n) = \sum_{l=1}^{M} P_{TT}(\bar{x}, \bar{x}_m, t_n)[P_{TT}(\bar{x}_m, \bar{x}_l, t_n) + R_T(\bar{x}_m, \bar{x}_l, t_n)]^{-1},
\]

(3)

\[
\Delta_m^S(\bar{x}, t_n) = \sum_{l=1}^{M} P_{SS}(\bar{x}, \bar{x}_m, t_n)[P_{SS}(\bar{x}_m, \bar{x}_l, t_n) + R_S(\bar{x}_m, \bar{x}_l, t_n)]^{-1},
\]

(4)

where \( R_T, R_S \) are the covariance functions of the errors of measuring temperature and salinity respectively, and \( P_{TT}, P_{SS} \) are the covariance functions of errors of estimating the temperature and salinity fields, approximated by the following expressions:

\[
P_{TT}(\bar{x}, \bar{x}', t) = \sigma_T(\bar{x}, t) \sigma_T(\bar{x}', t) P_T(x - x', y - y'),
\]

(5)

\[
P_{SS}(\bar{x}, \bar{x}', t) = \sigma_S(\bar{x}, t) \sigma_S(\bar{x}', t) P_S(x - x', y - y'),
\]

(6)

where \( \sigma_T, \sigma_S \) are the root-mean-square error field estimates for the T and S fields; and \( P_T, P_S \) are the covariance functions of temperature and salinity fields.

The equations for calculating the dispersion of error estimates of the temperature and salinity fields were as follows:

\[
\partial \sigma^2_T / \partial t + \partial (\sigma^2_T u) / \partial x + \partial (\sigma^2_T v) / \partial y + \partial (\sigma^2_T w) / \partial z = k_{ij} \Delta \sigma^2_T + \partial (k_{ij} \partial \sigma^2_T / \partial z) / \partial z,
\]

(7)
\[
\frac{\partial \sigma_z^2}{\partial t} + \frac{\partial (\sigma_z^2 u)}{\partial x} + \frac{\partial (\sigma_z^2 v)}{\partial y} + \frac{\partial (\sigma_z^2 w)}{\partial z} = k_H \Delta \sigma_z^2 + \frac{\partial (k^\nu \partial \sigma_z^2 / \partial z)}{\partial z},
\]

where \( k_H, k^\nu \) are the coefficients of turbulent diffusion.

\[\sigma_T, \sigma_S \]

were corrected at the moments of receipt of observational data by the ratios:

\[
\sigma_T^2(\hat{x}, \hat{t}_n^+) = \frac{\sigma_T^2(\hat{x}, \hat{t}_n^-)}{\sum_{m=1}^{M} \Delta^T_m(\hat{x}, \hat{t}_n^-) p_T^T(x_m - x, y_m - y)},
\]

\[
\sigma_S^2(\hat{x}, \hat{t}_n^+) = \frac{\sigma_S^2(\hat{x}, \hat{t}_n^-)}{\sum_{m=1}^{M} \Delta^S_m(\hat{x}, \hat{t}_n^-) p_S(x_m - x, y_m - y)}.
\]

Thus, the fields of \( T, S, \sigma_T, \sigma_S \) were predicted using the model equations until the moments of receipt of observational data. The \( T, S \) fields were corrected at the moments of assimilation according to relations (1) – (10).

### 3. Statement of the problem and description of numerical experiments

The system of equations for the Black Sea model of dynamics based on the complete thermohydrodynamic equations of the ocean in the Boussinesq approximation, hydrostatics and incompressibility of sea water in the form of Gromeki-Lamb, the boundary conditions on the surface, on the bottom and on solid side walls were described in detail in [5]. The differential equations of the model were supplemented with equations (7), (8), for which the boundary conditions had the same form as for the equations of advection of heat and salt. At the initial time, the covariance functions were assumed to be equal to the covariance functions of the field itself (that is, the dispersion of error estimates of the temperature and salinity fields was equal to unity). Adveктив terms of the equations of transfer-diffusion of the dispersion of error prediction were approximated using TVD-schemes. We used a horizontal grid of 1.64×1.64 km (698×390 points) and 27 vertical horizons. A time step was equal to 96 s. The coefficients of turbulent momentum exchange and vertical diffusion were calculated in accordance with the Mellor-Yamada parameterization 2.5, the river runoff and water exchange through the straits were taken into account. A choice of the horizontal coefficients of turbulent viscosity and diffusion (\( \nu_H=10^{16} \text{ sm}^4/\text{s}, k_H=10^{16} \text{ sm}^4/\text{s} \)) and the coefficient of horizontal turbulent diffusion of the error dispersion in (7), (8) \( k_H = 10^5 \text{ sm}^2/\text{s} \) was based on a series of specialized numerical experiments. A total period of integration of model equations was 21 days (from 28th of June to 18th of July, 2016). To set the initial conditions of the problem, we used the fields of currents, temperature, and salinity, obtained in previous calculations with a spatial resolution of 1.64 km. The fields of tangential frictional stresses of wind, heat fluxes, shortwave radiation, precipitation and evaporation, obtained from the reanalysis data of the model of the Greek atmospheric forecast center SKIRON (1/10°) were specified for each day on the surface of the sea.

A hydrological survey of the 87th cruise of the scientific research vessel “Professor Vodyanitsky” was chosen for the analysis. Experimental data on the vertical and spatial distribution of temperature and salinity were obtained in the northern part of the Black Sea from 30th of June to 18th of July, 2016. Hydrological characteristics from surface to bottom were measured at each station using the CTD SBE 911 plus complex. The maximum depth to which probing was carried out varied from 30 to 1700 m. Covariance functions of the fields \( T, S \) were approximated by a function of exponential type \[ \exp(-\lambda (|x-x'|^2 + |y-y'|^2)) \] [6]. A dimensional parameter \( \lambda = 0.023 \Delta x^2 \) corresponded to the value of the correlation function 0.1.

An estimate of the correlation radius (16 km) was made on the basis of the analysis of the statistical structure of the fields of the measured temperature and salinity. Data (125 stations) were grouped for 17 days and assimilation was carried out once a day. The numerical calculation was carried out for the whole Black Sea; the area between the 31 and 37º E meridians and 43 and 45.5º N parallels, in which hydrological data were obtained, was analyzed in detail.
4. Fields of currents and level

The following circulation elements were noted in the initial field of currents: an anticyclonic eddy on the south-eastern coast of Crimea, two cyclonic and three anticyclonic eddies in the western part of the region (to a depth of 100 m, with a radius of about 30 km), cyclonic eddies along the western coast of Crimea (to a depth of 30 m, with a radius of about 15 km). The maximum value of velocity of 50 cm/s (in the upper layer) was obtained in the central part, along the western coast of the Crimea, a current with a maximum value of velocity of 30 cm/s, directed to the north, was observed. Two dynamic zones were formed in the eastern part of the field: the coastal zone with anticyclonic vorticity of currents and the area of cyclonic vorticity in the deep-water part of the sea. An intense jet of the Rim Current (RC) was observed along the Crimean coast, directed to the west and north-west, with a maximum speed of 55 cm/s was obtained on the upper horizon (on 1\textsuperscript{st}, 13\textsuperscript{th} and 17\textsuperscript{th} of July) during the calculating period. Large eddies of various signs of rotation with a radius of about 30 km in the western part of the region and a cyclonic eddy with a radius of about 40 km in the eastern deep-water part of the region were observed throughout the calculation. Anticyclonic eddy near Yalta was formed quasi-periodically (lifetime of 5–6 days) and moved in the direction of movement of RC. A possible mechanism of their formation was shear instability (the current on the shelf was directed to the northeast and in the deep-water part of the sea – to the southwest). We gave Fig. 1a as an illustration. Anticyclonic and cyclonic eddies with a radius of about 20 km were observed in the eastern part of the region from 11\textsuperscript{th} to 18\textsuperscript{th} of July (to a depth of 30 m). We gave Fig. 1b as an illustration.

Anticyclonic eddies along the Crimean coast were also clearly observed. Small-scale eddies of different rotation signs were generated in the upper layer on the northwestern shelf and near the coast of the Crimea during the calculating period. The velocities did not exceed 20 cm/s, the lifetime was 2–3 days (for example, the chains of eddies were shown in Fig. 1a and 1b). A possible mechanism of formation was the flow of a current over inhomogeneities of the coastal orography and bottom relief. All that features of circulation were also noticeable in the fields of the level (Fig. 1c, d). The described model fields of currents did not contradict the measurements of the zonal and meridional component of the velocity of currents in the upper layer up to 300 m using an acoustic meter Acoustic Doppler Current
Profiler [8]. Analysis of the instrumental data has shown that the circulation of water was mainly represented by streams of the western directions of RC, the core of which was located above the descent of the depths. RC was a meandering flow, anticyclonic and cyclonic eddies were formed. Anticyclonic eddies were manifested in the distribution of thermohaline characteristics near the city of Sevastopol and on the south-eastern coast of the Crimea.

5. Fields of temperature and salinity
The temperature field in the upper layer was characterized by values of 24.8–25.8 ºС, and the salinity field had 17.8–18.2 PSU at the initial moment of time (28th of June). Water with a temperature of more than 25 ºС and a salinity of 17.8–17.9 PSU was located along the Crimean coast, water with a temperature of less than 25 ºС and a salinity of more than 18 PSU was in the deep-water part.

![Figure 2. Fields at the horizon of 10 m a: of temperature on 5th of July, b: of temperature on 18th of July, c: of salinity on 5th of July, d: of salinity on 18th of July.](image)

During the calculation period, maximum temperatures up to 28.5°C were achieved near the coast of the Crimea, and maximum salinity values of 18.3 PSU were noted in the deep-water part. The lowest values of salinity (about 17 PSU) were observed in the western region of the survey (for example, Fig. 3d) due to intense desalination on the northwestern shelf of the Black Sea. Zones of low temperature and high temperature in adjacent waters were formed, which could be associated with features in the fields of currents. The correspondence of zones with warmer desalinated water to anticyclonic formations and zones with colder salty water to cyclonic eddies was noted. We present the temperature and salinity fields for July 5 (Fig. 3a and 3c) and July 18 (Fig. 3b and 3d) of 2016 as an illustration. The water temperature was more than 26°C, and salinity was less than 18 PSU in the area of Yalta, where the anticyclonic eddy was formed. A correspondence of cyclonic eddy formations to features in the temperature field was also noted in the western part: regions with a water temperature of 22–23°C and a salinity of more than 18 PSU were formed. The maximum depth of the jump layer was about 30 m in the coastal region and about 10 m in the deep-water part according to the results of the calculation. The temperature difference was about 10–12°C. The maximum temperature in the core of the cold intermediate layer (about 90 m) was about 8.4°C on the north-western shelf and was about 8.2°C in the deep-water part (at a depth of about 50 m). A slight increase in temperature and salinity was observed below that layer.
Conclusions
Hydrophysical fields of the Black Sea, continuous in time and space, were reconstructed in the summer season of 2016 on the base of a three-dimensional non-linear hydrodynamic model and observational data of temperature and salinity. The procedure of the assimilation of observational data was based on a modified Kalman filter, taking into account the heterogeneity and non-isotropy of the estimates of the temperature and salinity fields. From the analysis of the fields of currents it was shown that the features of water dynamics were determined by the intensive flow of the RC to the west and southwest, by an uneven wind, by the influence of the coastline of the Southern coast of Crimea and relief inhomogeneities on the RC. Eddies of different signs of rotation with a radius of about 30 km in the western part of the region and a cyclonic eddy with a radius of about 40 km in the eastern deep-water part of the region were constantly observed during the calculation. An anticyclonic eddy with a radius of about 25 km near the city of Yalta was formed quasi-periodically and moved in the direction of the RC. Intensive jets were also observed along the Crimean coast and small-scale eddies of various signs of rotation in the upper layer along the coast of Crimea and on the northwestern shelf. The thickness of the upper quasi-homogeneous layer varied from 5 to 25 m, below there was a jump layer, the temperature difference in which was 10–12°C. The formation of zones of low temperature and high temperature relative to the adjacent waters may be associated with features in the current fields. The correspondence of zones with warmer freshened water to the anticyclonic formations, zones with colder salt water to the cyclonic eddies was noted.

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