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Numerical modeling of dynamics of Russian south waters within the framework of operational oceanography tasks

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Abstract

Modeling of the Black Sea and Caspian Sea waters dynamics was conducted within the framework of the European ECOOP project and Russian project JISWO on the basis of the Princeton Ocean Model (POM). Nowcasting and tree days forecasting of the Black Sea dynamics was carried out in a daily mode with horizontal resolution of ∼1 km along the Russian coast of the basin. The nowcasting of the Caspian Sea dynamics was carried out every ten days with horizontal resolution of ∼5 km on the basis of climatic information about water temperature and salinity and decade-averaged wind NCEP-NCAR. Examples of calculations are presented here and their comparison with space remote sensing and in situ (hydrological measurements) data is fulfilled, and the results of model validation are discussed.

1 Introduction

Numerical modeling of the Black and Caspian seas' dynamics was fulfilled in the State Oceanographic Institute of Russian Federation (SOI) within the framework of the European ECOOP project (European COastal-shelf sea OPerational observing and forecasting system, 2007–2010 years) and the national project JISWO (Joint Information System on World Ocean). In both cases, a well-known numerical Princeton Ocean Model (POM,/1,5,6/), adapted for the regional conditions, was used.

The purpose of the paper is a description of the automated system of nowcasting and forecasting of hydrophysical parameters built during ECOOP and the estimation of quality of modeled fields. First of all, the system output in the Russian part of the Black Sea is described. These results were obtained in close co-operation with other participants of the project, particularly with the Marine Hydrophysical Institute of National Academy of Sciences of Ukraine, Sevastopol (MHI). The comparison of observations and modeled fields is also presented below. The results of the modeling of the Caspian Sea are presented in this paper. This work represents the Russian Federation in a

project and has been carried out for several years now. The continuation of the work is planned.

2 Black Sea

At the task of boundary conditions, nested grid technology (one-way nested grid model/4/ without a feedback) was used. Thus, necessary data on the open liquid borders of area were delivered by a basin-scale model of circulation of MHI/2/.

Values of parameters in nodes of regional models were calculated first with the use of horizontal linear interpolation of the values in the adjacent nodes of a global grid, and then by means of splines using vertical interpolation. Total fluxes through the section border in regional and global models strictly coincided, and components of baroclinic speeds of currents in regional models were equal to corresponding components of global baroclinic speeds. In boxes where water flowed into the settlement area, values of temperature and salinity were set. In points where water flowed out, the condition was used:

$$\frac{\partial T}{\partial n} = \frac{\partial S}{\partial n} = 0 \tag{1}$$

For the barotropic mode of normal component of barotropic speed on eastern and western borders, the following conditions were used:

$$\bar{U}^{\text{normal}}_{\text{POM}} = \bar{U}^{\text{normal}}_{\text{COARSE}} + \varepsilon\sqrt{\frac{g}{H}}(\eta_{\text{POM}} - \eta_{\text{COARSE}}), \tag{2}$$

where $\varepsilon = 1$ for the eastern border and $\varepsilon = -1$ for the southern border. The subscript "coarse" specifies a large-scale model. For a tangent component of barotropic speed, the following conditions were used:

$$\bar{U}^{\text{tang}}_{\text{POM}} = \bar{U}^{\text{tang}}_{\text{COARSE}} \tag{3}$$

Horizontal resolution of regional model is ~1 km at 18 vertical sigma-layers/1/), for MHI model ~5 km (Table 1). The MHI model uses satellite data assimilation of altimetry and sea surface temperatures and also meteorological data (wind stress, flows of heat and mass) received from the National Meteorological Administration of Rumania within the framework of the European cooperation (Fig. 1). The SOI receives the necessary border conditions for the regional Russian model in a daily mode from the MHI server and makes nowcasting and forecasting (for 3 days) calculations of thermohaline structures and water dynamics of the region. The initial data for the forecast is generated daily as a result of the MHI Black Sea Forecasting Operational System work (BSFOS).

Before the year 2009, calculations for the Black Sea were carried out in the test mode for debugging of technology. The results of the design were compared with the information of in-situ (CTD) and remote (SST) observations. An example of these results is shown in Fig. 2.

As seen in Fig. 2, the model reproduces both anticyclonic vortexes located on the shelf-slope zone with a characteristic horizontal scale of ~100 km (Az_1), and vortexes diagnosed according to the contact and satellite measurements eddies with a scale of ~10 km (Az_2).

The process was fully automated in SOI and includes four stages (Fig. 3):

- receipt of initial information from the MHI ftp-server by internet;
- realization of model calculations;
- visualization of the results of calculations (temperature, salinity, current velocity, sea level);
- transmission of results to the SOI server and website and for use in the national JSIWO program (Fig. 4).

It is interesting to compare the results with the measured data, in situ and remote, to assess the quality of modeling of dynamics and the thermohaline structure of waters in that Black Sea region. Comparison of modeled results with in situ and remote data has

been performed. Contact measurements (CTD) obtained by R/V *Professor Shtokman* of "Shirshov's" Institute of Oceanology (IO RAS) for the period of 9 March until 2 April 2009 were used. In Fig. 5, the regions of R/V *Survey* and modeling are shown.

It should be noted at the beginning that some characteristics of water in the region in March should be reflected in the measurement data and modeling/7/. The vertical structure is an upper quasi-homogeneous layer (UQHL, several tens meters), thermo-halo- pycnocline below to depths of 500 m and the underlying quasi-homogeneous layer. The main feature of the vertical structure of the waters of the Black Sea is the so-called cold intermediate layer (CIL) with the axis at depths of 50–100 m depending on the point of observation. Rim Current has extending along the continental slope, roughly along the isobath 1200 m, and produces a general cyclonic circulation in the sea. In the area of the continental slope, the eddies with spatial scales of ∼100 km are also observed, and directly in the shelf-slope zone – anticyclonic eddies with horizontal dimensions are about 10 km (see Fig. 2). These dynamic characteristics are reflected in the distributions of isolines in the cross-sections. Note also that the salinity is a major contributor to the spatial distribution of the density of Black Sea water, determining its dynamics. Therefore, profiles, sections and maps are constructed from the values of salinity, the most informative in analyzing the features of water dynamics in the region.

Vertical profiles built both from CTD and modeled data reflect the typical vertical structure of waters in the region in March (Fig. 6, for hydrological Station 5), in particular, the presence of the upper quasi-homogeneous layer (UQHL) with a capacity of ∼40 m, the cold intermediate layer (CIL) with the axis at a depth of 60 m, the main pycnocline to depths of 500 m and the underlying quasi-homogeneous layer. The vertical profiles of salinity and density are of the same type because the water density in Black Sea is mostly defined by salinity. Qualitatively, the model and the observed profiles are very similar. For the salinity difference in values of the order of ∼0.1 ‰, for the temperature there is the same order in degrees ˚C at depth. A maximum difference in temperatures is observed on a surface – approximately 1.5 ˚C.

Distribution of thermohaline characteristics at a cross-section perpendicular to the coast (see Fig. 5) is typical for the Black Sea, and shows a decline in the depth of isolines from coast to the center of the sea, caused by a general cyclonic circulation (Fig. 7). The section shown in Fig. 7a is built from asynchronous CTD-data made by R/V *Professor Shtokman* in the period 10/03/2009–13/03/2009. Figure 7b is built from model data corresponding to the points and times of ship observations. Comparing Fig. 7a and b, we can conclude that the salinity distribution in sections are similar and have similar quantitative values. As the differences can be noted, large vertical salinity gradients in halocline on the cross-section, which was built from CTD-data. But reducing the spatial discreteness of the model data in the cross-section is well defined deflection contour lines in the shelf-slope (right side of Fig. 7c) due to the presence of the anticyclonic vortex with the spatial size of ∼10 km (see Fig. 8a). A similar distribution of isolines on the edge of the continental slope of Black Sea is fixed often from CTD data of many hydrological surveys with a small horizontal step (∼1 km).

Synoptic variability in space and time is clearly expressed in the model calculations of water dynamics in the region. As an example, the model velocity fields corresponding to the beginning and end of the hydrological survey R/V *Professor Shtokman* is shown in Fig. 8. With regard to estimates of the degree of differences of model and measured values, then, due to high degree of asynchrony of the hydrological survey, comparison between measured and modeled data does not make any sense. Therefore, the estimations of quality of modeling are possible using remote sensing. Examples of comparisons of modeled data with satellite observations are shown in Figs. 8, 9. Thus, synoptic eddies, reflected in the salinity field (model) and the concentration of chlorophyll A (satellite image) show a high correspondence in the spatial size and horizontal location (Fig. 9). The RMS of the difference between the model and the measured (Sea Surface Temperature, SST) temperature in area of modeling for 2 July, 2009, was equal to RMS = 1.1 ˚C (Fig. 10).

As seen in the figures presented, some shift of location of T, S anomalies in modeled calculations concerning supervision takes place. For elimination of this effect, data assimilation in a local model can be used (now it can only be assimilated in a basin-scale model).

It is also interesting to analyze how the magnitude of the errors of forecasting (Fig. 11) is dependent on the time of forecasting. This is done using the information about temperature and salinity at the moments of contact measurements (for Station 5). For temperature, the minimum number of errors takes place in the case of 1–2 days forecasting (except the depths below CIL, where variability is considerably low than within UQHL). In the upper layers, the forecasting is closer to measurements then nowcasting (0 days in the Fig. 11). It is worth mentioning the considerable errors of modeled temperature in the upper layer. (As the research of colleagues from MHI showed, this failing can be decreased by the division of the heat flow on the surface of the sea into long-wave and short-wave parts.) For salinity, the maximum of errors is located in the range of depths about 100–200 m (main halo- pycnocline). In the upper layers, the presence of local maximum of errors when forecasting for 2 days is distinct. But in general, a forecasting for 1 day (and at some depths for 3 days) does not yield or excels nowcasting in quality.

The reasons for such results could be following:

- Nowcasting during the Project was carried out by the model for the time span of 1 day. Possibly, this time is not enough and it is necessary to increase it up to 2 days.
- In addition, dynamic features of interaction between the currents and bottom relief and adaptation with the wind stress likely show up during the forecast, which finds display in the variability of profiles of temperature and salinity.

3 Caspian Sea

The formal parameters of the numerical model were the following: the grid for calculation which covered the total water area of the sea had the dimensions 243 × 193 × 18 points and lay in borders of 36.6°–47.0° northern latitude and 47.0°–54.0° east longitude. The grid step was equal to 4.9 km in latitude and 3.7 km in longitude. The levels were thickening exponentially from the middle layers to the surface and to the bottom of the sea for the best resolution of the surface and bottom border layers. Initial temperature and salinity fields were climatic /3/, and have been time interpolated for every decade of the months. The data of NCEP/NCAR reanalysis was used for a daily pressure field over the Caspian Sea (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml), which was interpolated by means of splines on the chosen spatial grid. The wind stress fields were calculated according to the data about atmospheric pressure. Along with temperature and salinity fields, the wind stress fields are used as input data and are sufficient for every decade nowcasting calculations of the current fields in the Caspian Sea.

As well as for the Black Sea, the process includes several stages which have been completely automated. The stages are:

1. information read-out of atmospheric pressure over the Caspian Sea;
2. the calculation of the average decade fields of atmospheric pressure;
3. the calculation of the average decade wind stress according to the data about atmospheric pressure;
4. the placement of the files of initial (temperature, salinity) and boundary (wind stress) conditions in folders corresponding to each decade of the month;
5. realization of model calculations;
6. visualization of the results;

7. results transfer to the SOI server.

The results of calculations – the current velocity fields, – are transferred to the SOI server in a numerical and graphic form every decade for their use in JISWO project (Fig. 12).

Besides regular (every decade) calculations of the current fields in the Caspian Sea, that are intended to be used in problems of operation oceanography, it is of interest to estimate the volatility of energy characteristics and their spectra according to the modeling calculations for the long-term period. Such estimations are of interest, both to the detection of within year regularity of processes in the sea and to the verification of the physical adequacy of modeling. These estimations have been made according to the data about every decade calculations that have been executed within 2008–2009. Some of the results are given in Figs. 13 and 14.

The autumn-winter maxima are expressed in the time dependence of kinetic energy (Fig. 13). Apparently, they are caused by the generated top uniform layer that is the consequence of the autumn-winter convection and also of the winter intensification of wind circulation that is typical for the seas of middle latitudes. On the surface the process of a seasonal intensification of circulation is shifted to the autumn. This indicates that the factors defining the intensification first of all influence the surface layer, and with the lapse of time, extend the influence onto deeper layers. The spectral analysis of series of volatility of circulation shows that local maxima correspond to frequencies of ~10 days, ~1 and ~3 months (Fig. 14), thus corresponding to synoptic processes (10 days), mesoscale (1 month), connected with the restructuring of thermohaline structure of water, and seasonal (3 months). The spectral characteristics of the variability of kinetic energy, calculated according to the results of numerical modeling, are physically adequate and internally consistent. This confirms the correctness of the calculations and of the results received.

4 Conclusions

During the Project, an automated system of modeling the dynamics of water of the Black Sea and the Caspian Sea was created. It allows generation of physically adequate results of calculations of thermohaline structure of water and current fields. For the Black Sea such calculations are performed in nowcasting and forecasting (3 days) mode, while for the Caspian Sea the calculations are performed in the decade mode of nowcasting of current fields.

In addition to a satisfactory qualitative and quantitative agreement between the model data, CTD and remote measurements of the dynamics and water structure in the Russian Black Sea area, another result is important. On the basis of this experiment,the conclusion that the proposed modeling technology can adequately monitor the variability of the waters of the region with the spatial and temporal resolution, unattainable using only field data, can prove important for operational oceanography.

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Table 1. Main features of global and regional models

Main features of models	Type	Vertical coordinates	Grid size	Number of grid points	Time step
Basin scale model (MHI)	MHI-model with remote sensing data assimilation	Fixed levels in the vertical z-direction	~4900 m	237 × 131 × 35	600 s
Northeastern Russian Coastal Zone Regional Model	POM-model σ-coordinates	Terrain following	~1000 m	304 × 254 × 18	120 s (baroclinic mode) 3 s (barotropic mode)

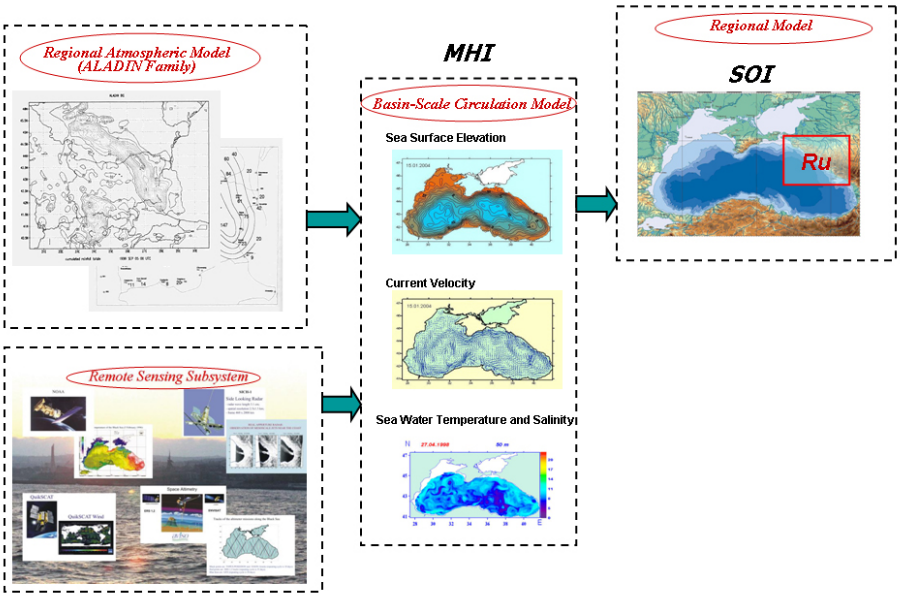

Fig. 1. System of nowcasting and forecasting of Black Sea water dynamics.

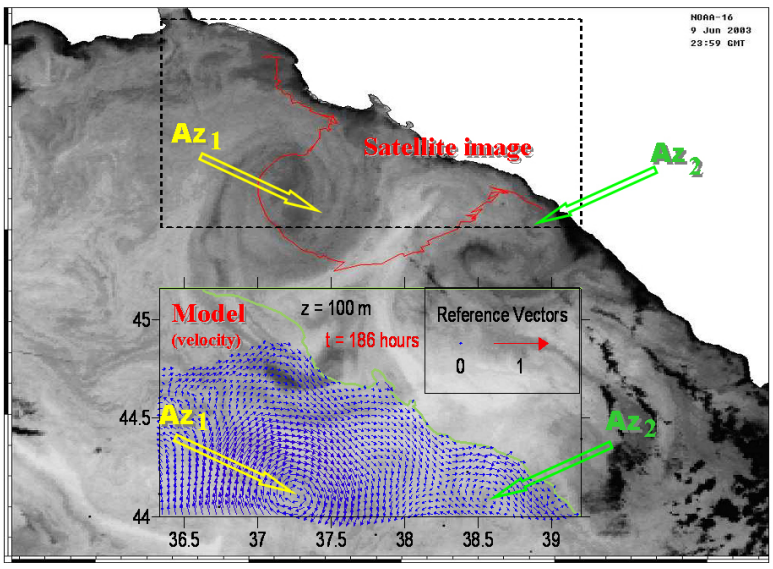

Fig. 2. Comparison of the modeled results (currents) with satellite image.

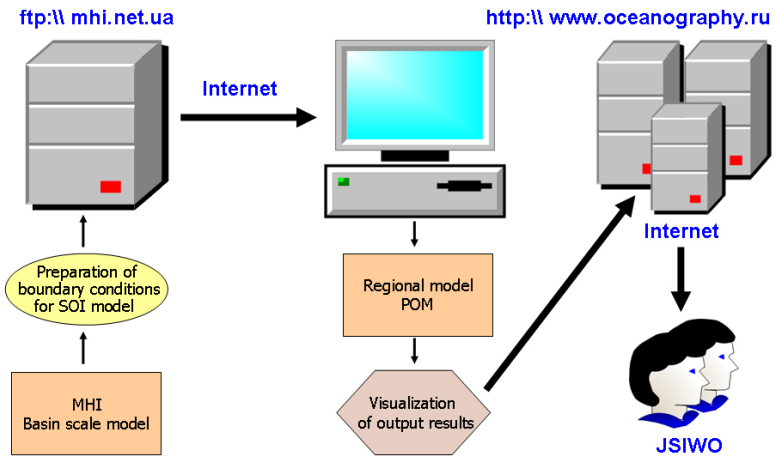

Fig. 3. Scheme of SOI automated system.

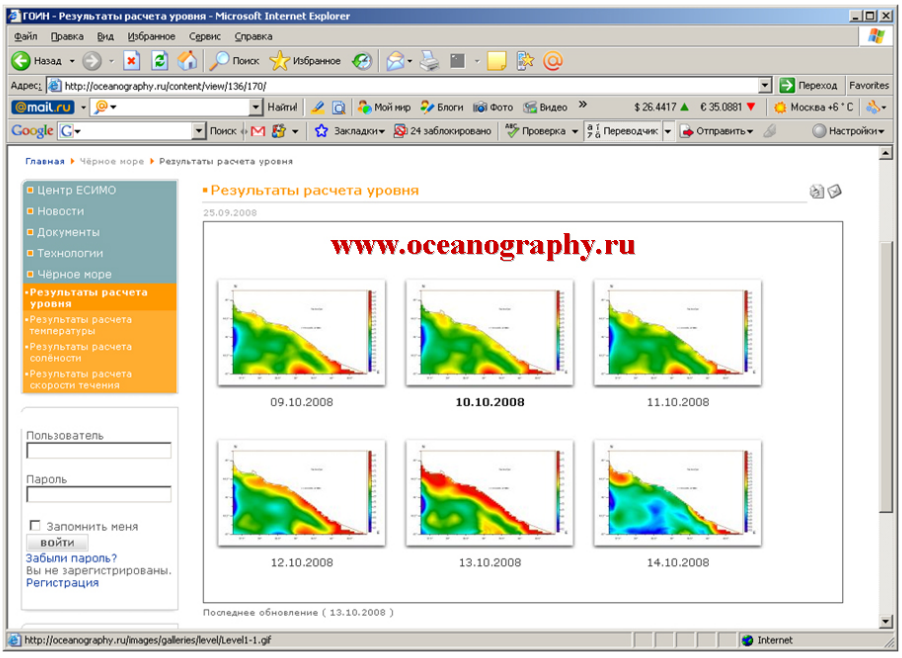

Fig. 4. Example of modeled results shown on the SOI website.

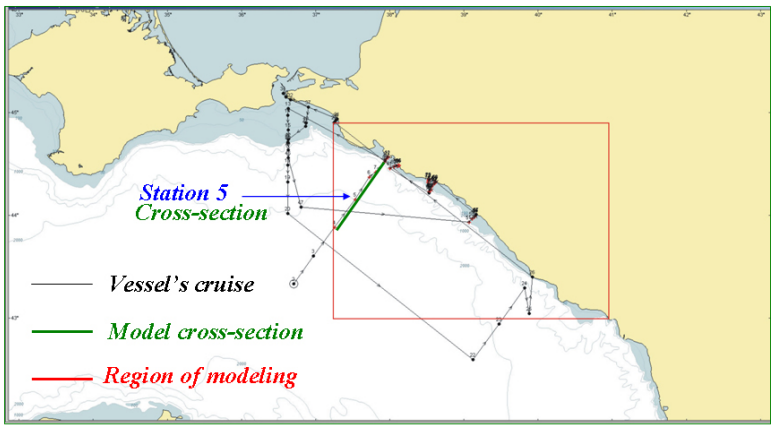

Fig. 5. Region of R/V *Professor Shtokman* survey and modeling area.

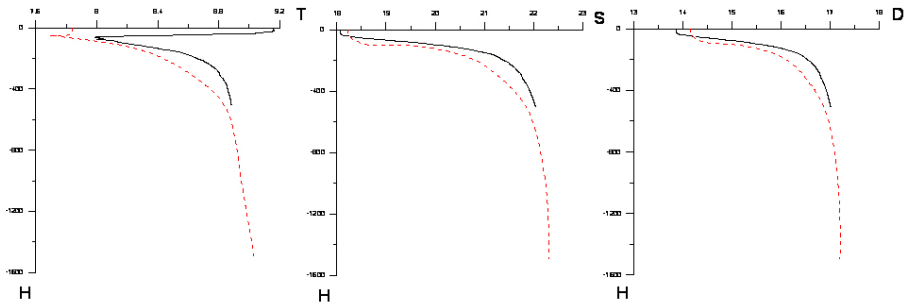

Fig. 6. Vertical profiles of temperature (T), salinity (S) and density (D) for Station No. 5 from CTD data (black) and modeling (red).

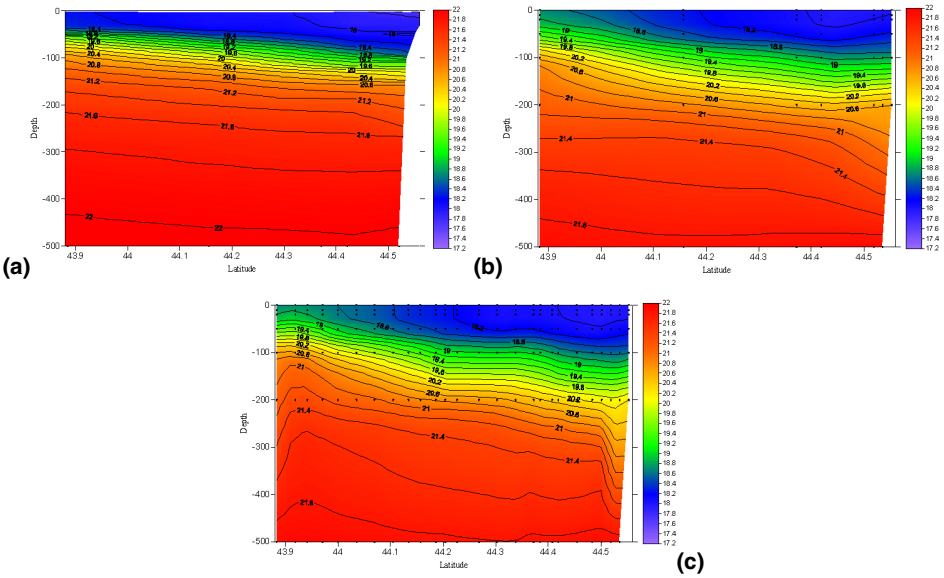

Fig. 7. Distribution of salinity on a cross-section (see the Fig. 5), obtained from CTD data **(a)** and model data **(b, c)**.

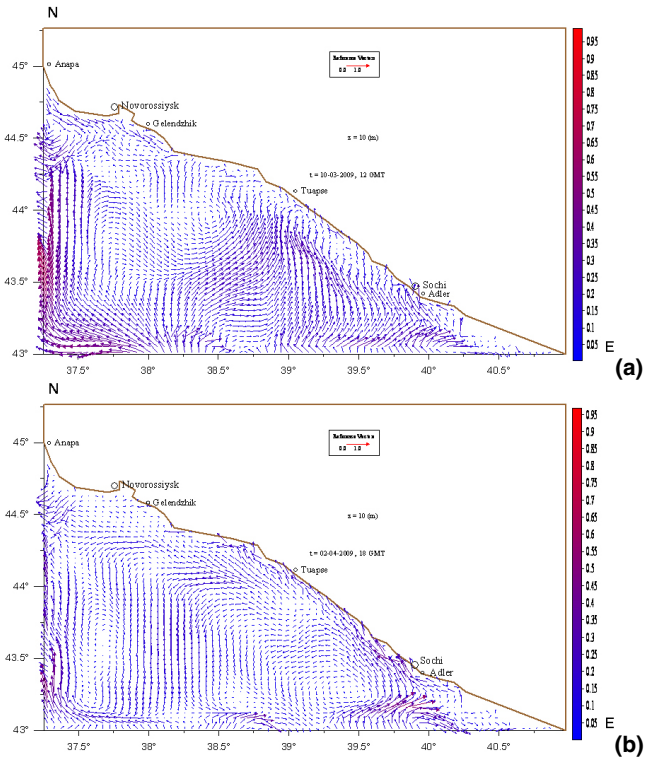

Fig. 8. Model fields of sea currents at a depth of 10 m 10/03/2009 **(a)** and 02/04/2009 **(b).**

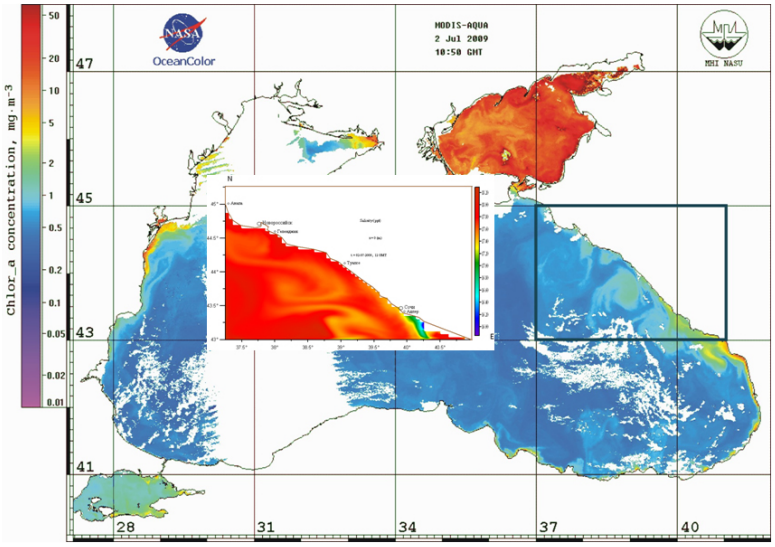

Fig. 9. Satellite image (Chlorophyll concentration) and modeled sea surface salinity at 2 July, 2009.

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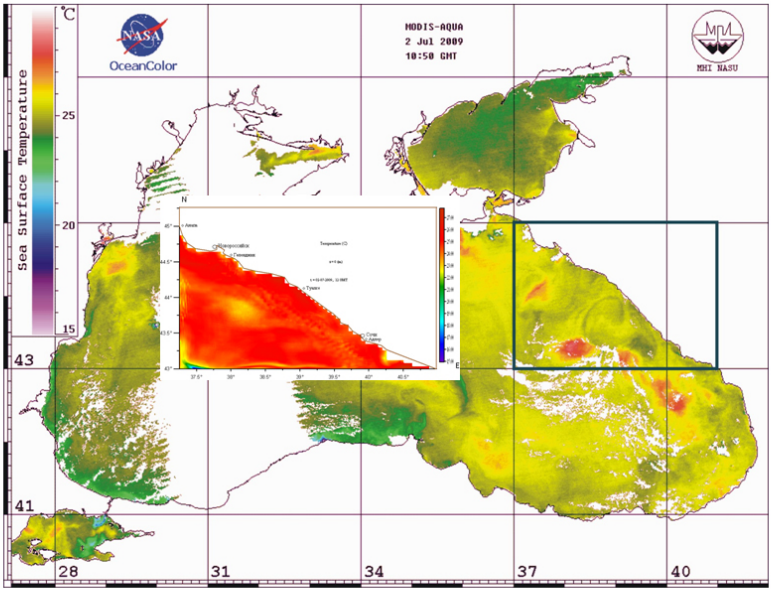

Fig. 10. Satellite image (SST) and modeled sea surface temperature at 2 July, 2009.

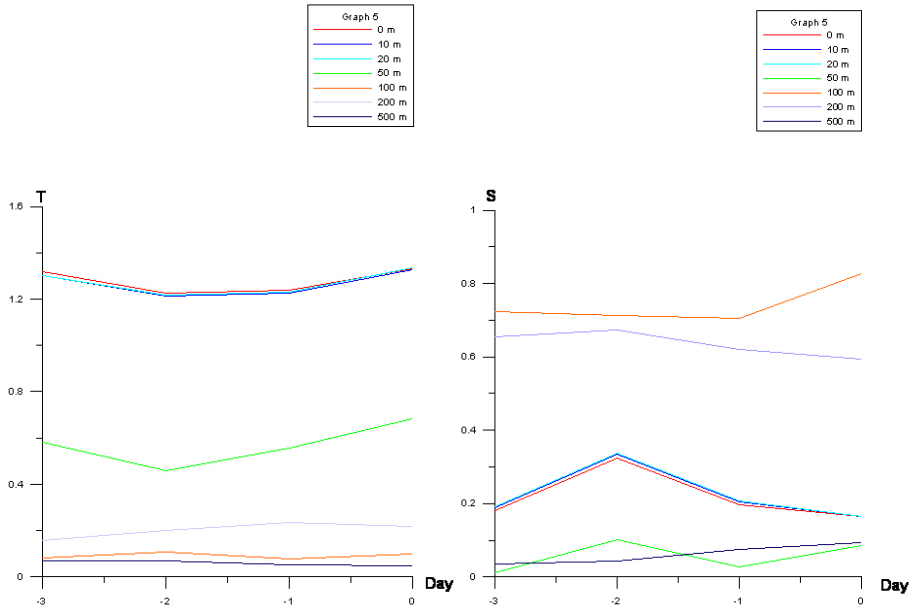

Fig. 11. Differences (absolute value) between measured and modeled temperature **(a)** and salinity **(b)** as a function of time of forecasting (1–3 days, 0 is nowcasting). Station 5.

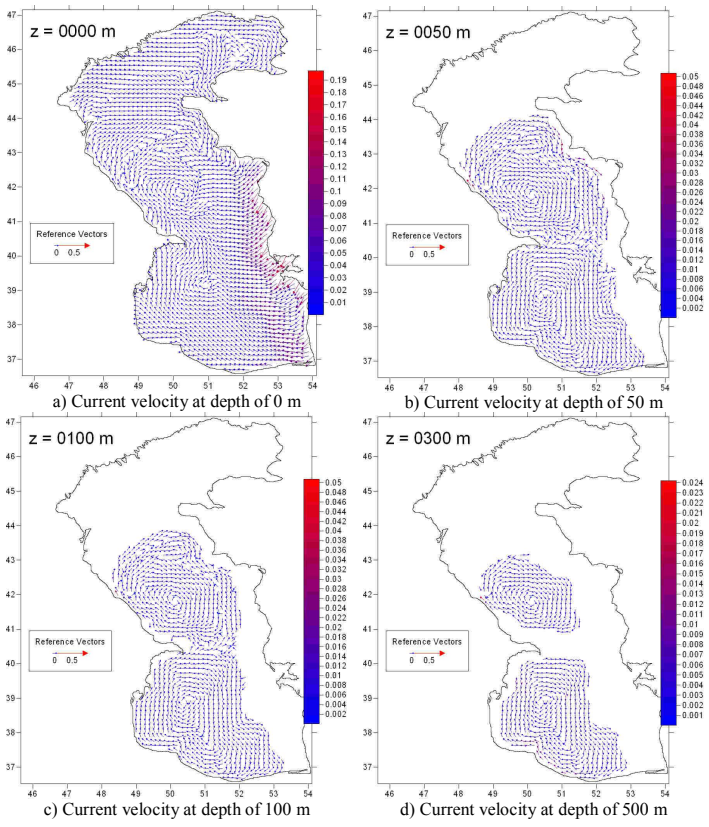

Fig. 12. Examples of the calculated fields of current velocity at horizons 0 **(a)**, 50 **(b)**, 100 **(c)** and 300 **(d)** meters.

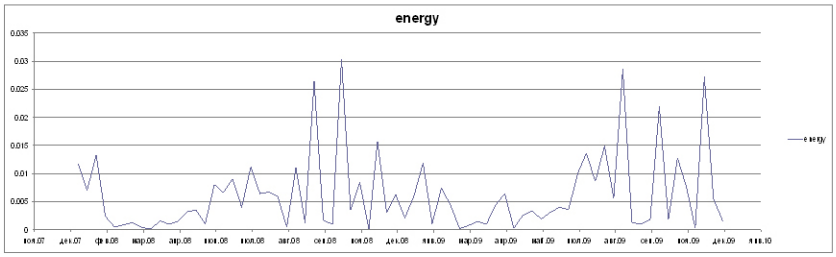

Fig. 13. Average kinetic energy of currents for depth 0 m.

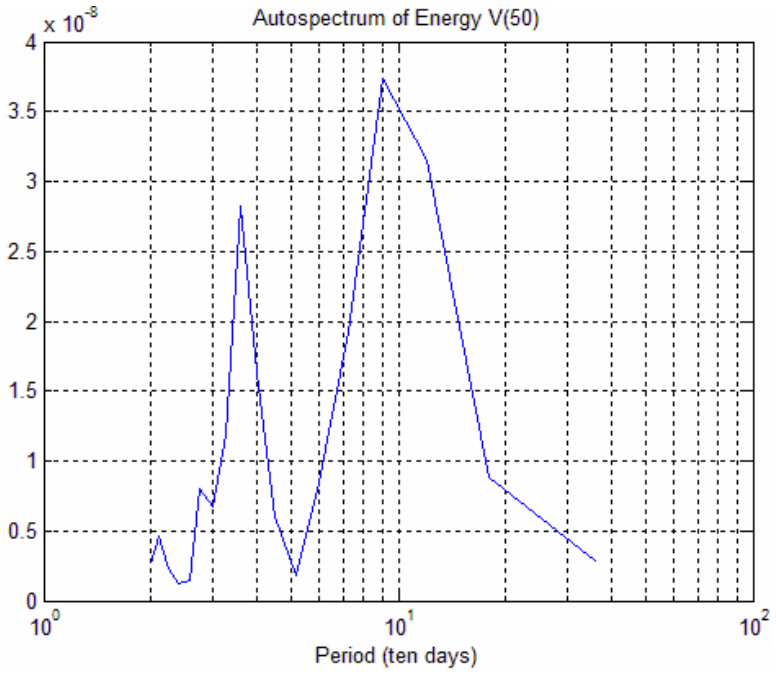

Fig. 14. Autospectrum of kinetic energy of currents for depth 50 m.