Journal of the Georgian Geophysical Society,
Issue B. Physics of Atmosphere, Ocean and Space Plasma, v.16, 2013, pp. 137-156

Numerical modeling of water dynamics of Russian zone of the Black Sea within the framework of operational oceanography tasks

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Abstract

Modeling of the Black Sea waters dynamics (Russian zone) was conducted within the framework of the European ARENA and ECOOP projects and Russian project JISWO on the basis of Princeton Ocean Model (POM). Nowcasting and three 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. Examples of calculations are presented and their comparison with space remote sensing and in situ (hydrological measurements) data is fulfilled, results of model validation are discussed. Model data reproduce observed real dynamic structures. Increasing a spatial permit of processes allows reproduce in calculations the detail of hydrological structure, which do not principally find displaying in large-scale models (vortexes with horizontal spatial sizes ~10 km). The model and the observed vertical profiles are very similar. Synoptic eddies, reflected in the modeled salinity field show a high correspondence in the spatial size and horizontal location with satellite images. The comparison of modeled temperature field with satellite data also demonstrates their qualitative agreement. 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.

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 European ARENA (2003-2007 years) and ECOOP project (European COastal-shelf sea OPerational observing and forecasting system, 2007-2010 years) and National project JISWO (Joint Information System on World Ocean) and has continued to the present.

A well-known numerical Princeton Ocean Model (Blumberg and Mellor, 1987, 1991), adapted for the regional conditions, was used. As is known, the POM model is based on full system of the equations of hydrodynamics of the ocean with a free surface and Boussinesq, hydrostatics, liquids incompressibility approximations (vertical sigma-coordinate). The turbulence model with level 2.5 closure, based on the turbulence hypotheses of Rott-Kolmogorov generalized by Mellor and Yamada (1982) for the stratificated stream is used for vertical mixing parameterization. For horizontal diffusivity - the scheme of Smolarkevich is used.

The purpose of the paper is a description of automated system of nowcasting and forecasting of hydrophysical parameters which built during ECOOP and estimation of quality of modeled fields. 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.

2 Russian zone of Black Sea forecasting system

A first version of the Black Sea coastal forecasting system has been developed in the framework of Europian ARENA project (Kubryakov et al., 2006-2011; Kordzadze et al., 2008, 2011), Fig.1. The formal parameters of the numerical regional model in this case were the following: the grid for calculation which covered the Russian zone of the sea had dimension 305x105 points and lay in borders of 44.0^{o}-45.16^{o} northern latitude and 36.33^{o}-41.0^{o} east longitude. The horizontal grid step was equal ~1200 m. The 25 vertical layers 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. At the task of boundary conditions, nested grid technology (one-way nested grid model without a feedback) was used (Kubryakov, 2004), see below. Thus, necessary data on the open liquid borders of area were delivered by a basin-scale model of circulation of MHI (Demyshev and Korotaev, 1996), (Dorofeev and Korotaev, 2004).

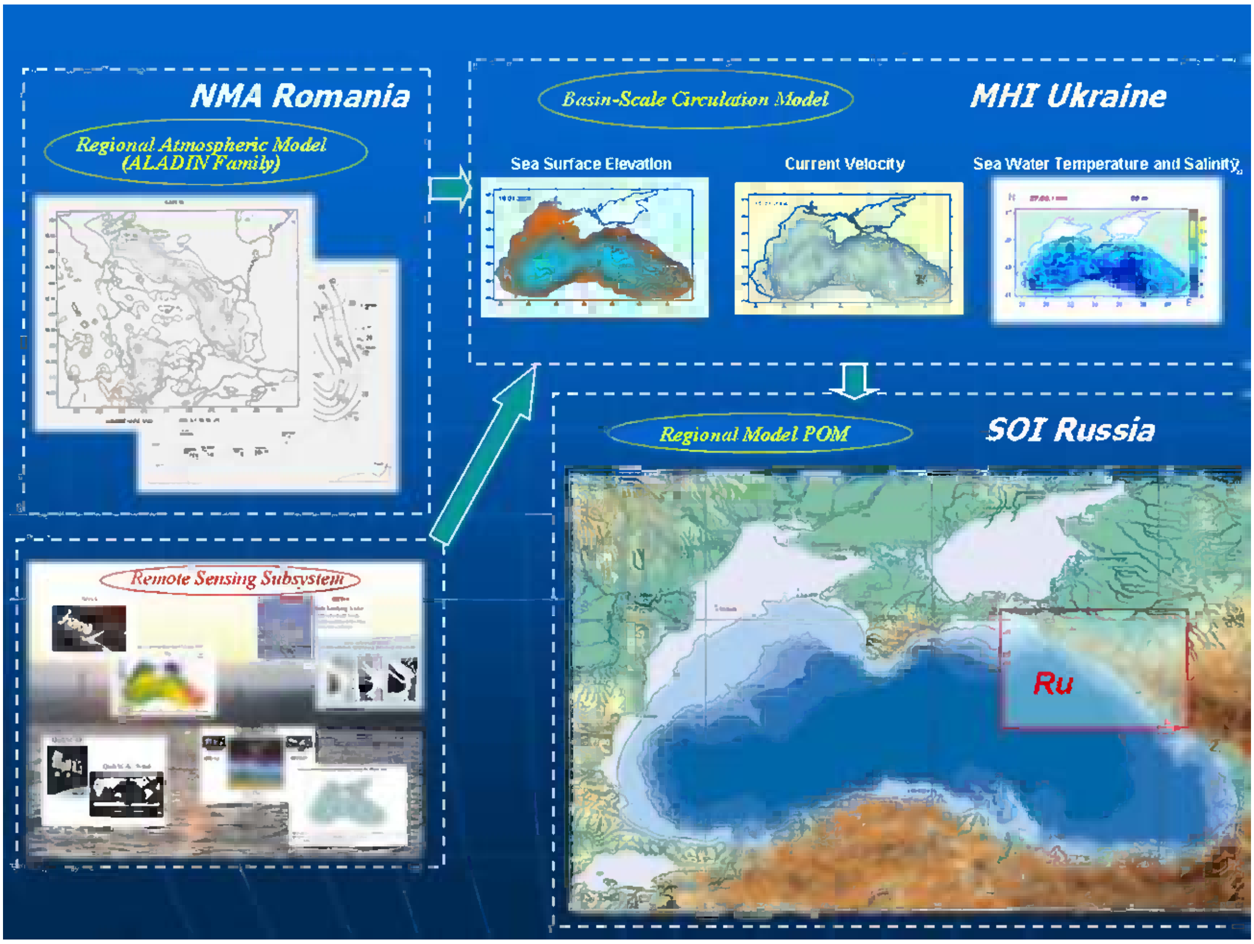


Fig. 1. System of nowcasting and forecasting of Black Sea water dynamics.

Calculations for the Russian zone of 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.2-5.

One of the first calculations was carried out for the period of 7 June until 14 June 2003. The result of calculations of a field of speed and corresponding in time satellite picture (NOAA) of sea surface temperature (SST) is shown in Fig.2. As seen in Fig.2, the model reproduces both anticyclonic vortexes located on the slope zone with a characteristic horizontal scale of ~80 km (Az_1), and vortexes diagnosed according to the contact and satellite measurements eddies with a scale of ~15 km (Az_2).

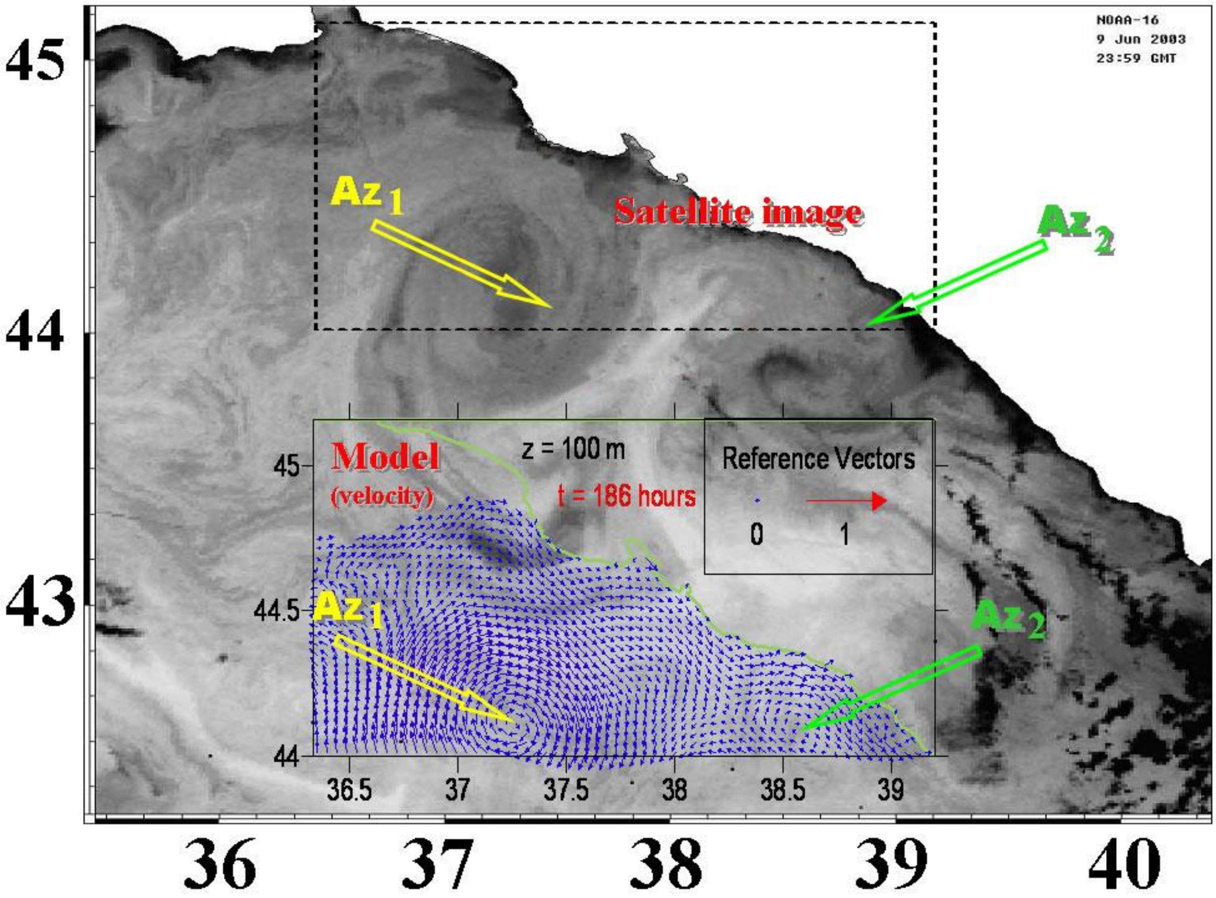


Fig. 2. Comparison of the modeled results (currents) with satellite image. The dotted line allocates area of modeling.

Comparison of modeled results with in situ data has been performed by using the contact measurements (CTD) obtained by R/V *Akvanavt* of “Shirshov’s” Institute of Oceanology (IO RAS) in July 2005. In Fig. 3, the regions of R/V *Section* and modeling are shown.

For example, the difference in the distributions of salinity sections constructed from the modeled and in situ data (Fig. 4) can be described as follows. The anticyclonic deflection of the isolines takes place both in CTD and modeled distribution of salinity. Along the section it has the same location. The halocline in the observed data is expressed more clearly than in the modeled. The isolines with equal values in the modeled data are about 20 meters deeper than in situ. In general we can note the qualitative agreement between the modeled and in situ data.

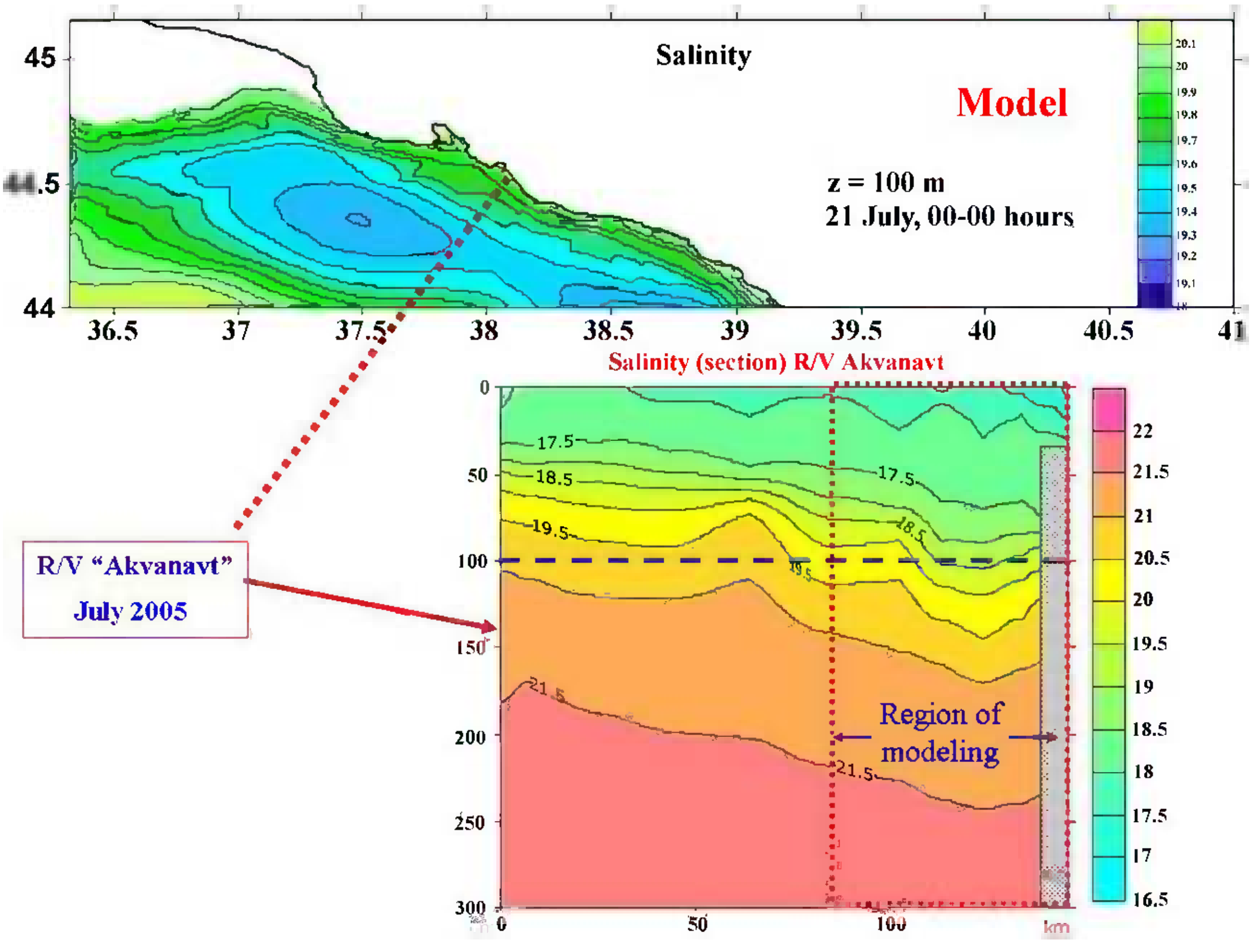


Fig. 3. Region of R/V *Akvanavt* section and modeling area.

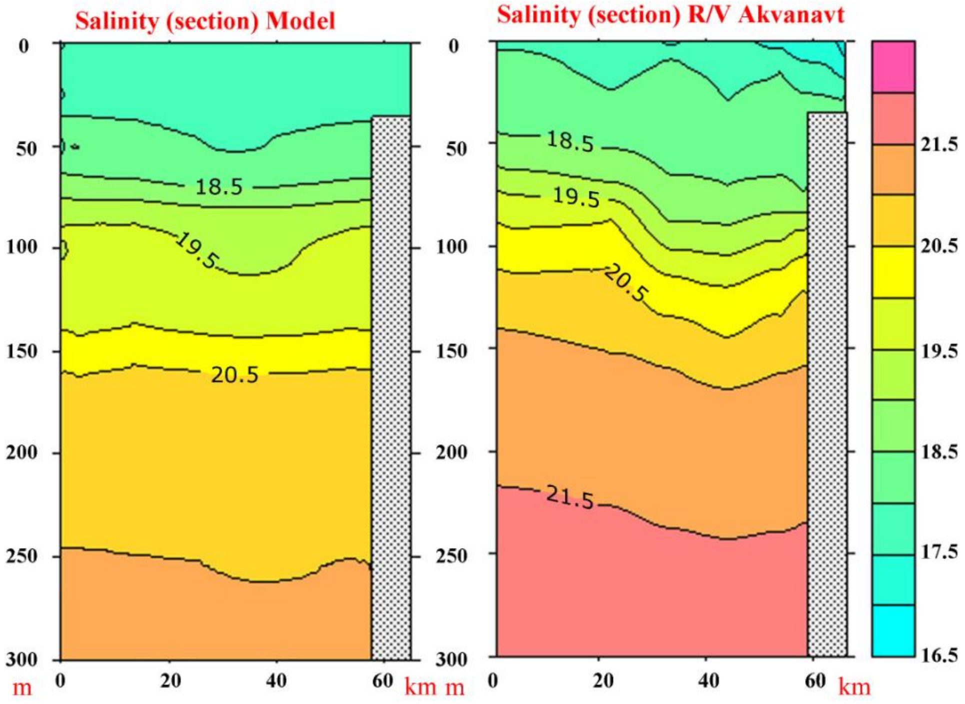


Fig. 4. Comparison of the modeled results (salinity) with in situ data (R/V *Akvanavt*), sections.

Comparison of modeled spatial distributions of salinity with satellite image received during the R/V *Aquanavt* cruise, shows a spatial displacement modeled salinity anomalies caused by anticyclonic eddies, with respect to remote data (Fig. 5). But qualitatively, the modeled vortexes correspond to the satellite image and their spatial sizes are the same (Az_3 , Az_4).

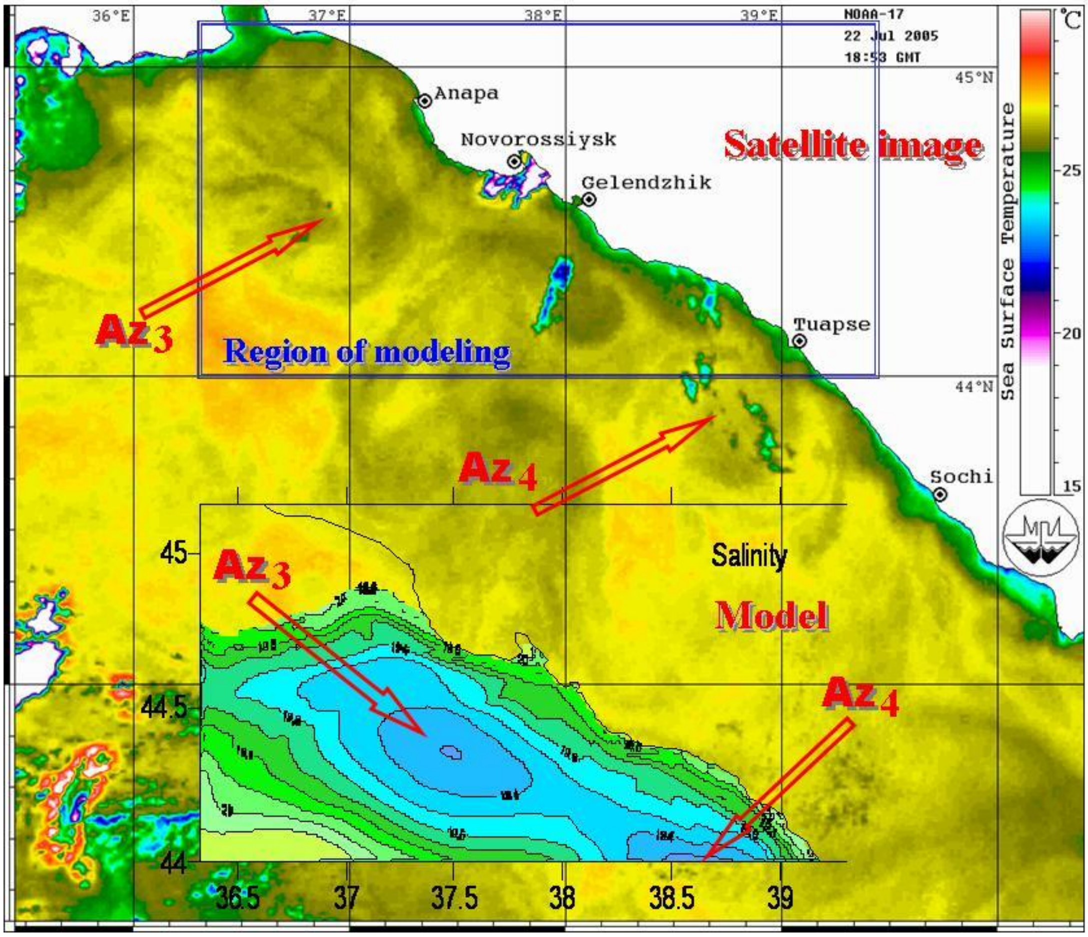


Fig. 5. Comparison of the modeled results (salinity) with satellite image (SST).

Resume of intercomparison between the Russian coastal zone nested model data and the data obtained during the ARENA project (R/V *Akvanavt* cruises and sattelite data) may be follows. Results of modeling are in general physically identical, increasing a spatial permit of processes allows reproduce in calculations the detail of hydrological structure, which do not find displaying in large-scale models. In particular, the eddies with horizontal spatial sizes ~10 km. Model calculations reproduce observed real dynamic structures. Their spatial position not wholly well complies with observed data. The main features of calculate parameters have a good correspondence with a measurements.

Thus, calculations of coastal circulation of waters of Black Sea by a nested grid method have shown the reasonable consent of the received results with available representations about dynamics of waters in considered area. The received conformity of results of modeling calculations to data in situ and remote supervision gives to hope for an opportunity of satisfactory realization of monitoring of hydrophysical fields in coastal area of Black Sea on the basis of use of the described technology for the developed series of regional models (Kubryakov et al., 2006).

Note, the debugging of technology before (and during) ECOOP project was done in close collaboration and cooperation with colleagues from other near Black Sea countries, and especially MHI. In particular, in terms of nesting and the parameterization of surface heat flux. These questions are highlighted in the work of our colleagues (Kubryakov et al., 2004-2011, Kordzadze et al., 2008, 2011) and will not be shown in this article.

During the ECOOP project the calculations were carried out daily for about 2 years, making it possible to obtain a large amount of simulation results. The formal parameters of the numerical regional model according to the terms of the Project in this case were the following: the grid for Russian zone of the sea had dimension 304x254 points and lay in borders of 43.0^o-45.26^o northern latitude and 37.25^o-41.0^o east longitude. Horizontal resolution of regional model is ~1 km at 18 vertical sigma-layers (Table 1). The number of vertical layers was limited by computational possibilities (the task was to provide daily the forecasting for 3 days ahead). The sigma-coordinates was follows: 0,-0.004,-0.009,-0.013,-0.022,-0.034,-0.046,-0.058,-0.079-0.11,-0.171,-0.268, -0.366,-0.463,-0.561,-0.78,-0.902,-1. We did not notice any problems with calculation of the pressure gradient forces using the terrain -following grids. The conditions at the lateral boundary: free slip for the flow and zero normal fluxes of salt, heat and momentum.

The cold intermediate layer (CIL) of the Black Sea in this case was resolved and well expressed not only by regional POM, but by the basin scale z-model (Dorofeev and Korotaev, 2004).

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 x 131 x 35**	**600 s**
Northeastern Russian Coastal Zone Regional Model	**POM-model**	**Terrain following σ-coordinates**	**~ 1000 m**	**304 x254 x 18**	**120 s (baroclinic mode) 3 s (barotropic mode)**

Table 1. Main features of global and regional models.

As in ARENA case, nested grid technology was used. Necessary data on the open liquid borders of area were calculated by a basin-scale model of circulation of MHI. 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 Romania 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).

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 basin-scale grid, and then by means of splines using vertical interpolation. Total fluxes through the section border in regional and basin-scale models strictly coincided. Both normal and tangential components of baroclinic velocity are specified by the coarse basin scale model interpolated fields, but after application of transport constraint to preserve coarse basin scale model transport. So

$$U_{POM}^{\tan g} = U_{COARSE}^{\tan g}$$

$$U_{CORR}^{normal} = U_{INTERP}^{normal} \cdot \left(\frac{Q_{COARSE}}{Q_{INTERP}} \right)$$

In boxes where water flowed into the high-resolution area, values of temperature and salinity were set. In points where water flowed out, the condition was used:

$$\frac{\partial T}{\partial n} = \frac{\partial S}{\partial n} = 0 \,.$$

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

$$U_{POM}^{normal} = U_{COARSE}^{normal} + \varepsilon \sqrt{\frac{g}{H}} (\eta_{POM} - \eta_{COARSE}) \,,$$

where $\varepsilon = 1$ for the eastern border and $\varepsilon = -1$ for the southern border; η – sea level. The subscript *"coarse"* specifies a large-scale model. *CORR* - corrected; *INTERP* - interpolated; *Q* - is the total mass flux through the lateral liquid wall.

The atmospheric forcing was the same as for MHI model, and the same with bathymetry, but interpolated to the regional grid. The atmospheric data was received from MHI ftr-server in common “CoarseFilds” files of boarder conditions. The impact of the river flow was considered to be not essential in Russian zone of Black Sea.

The process was fully automated in SOI and includes four stages (Fig. 6):

- 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. 7).

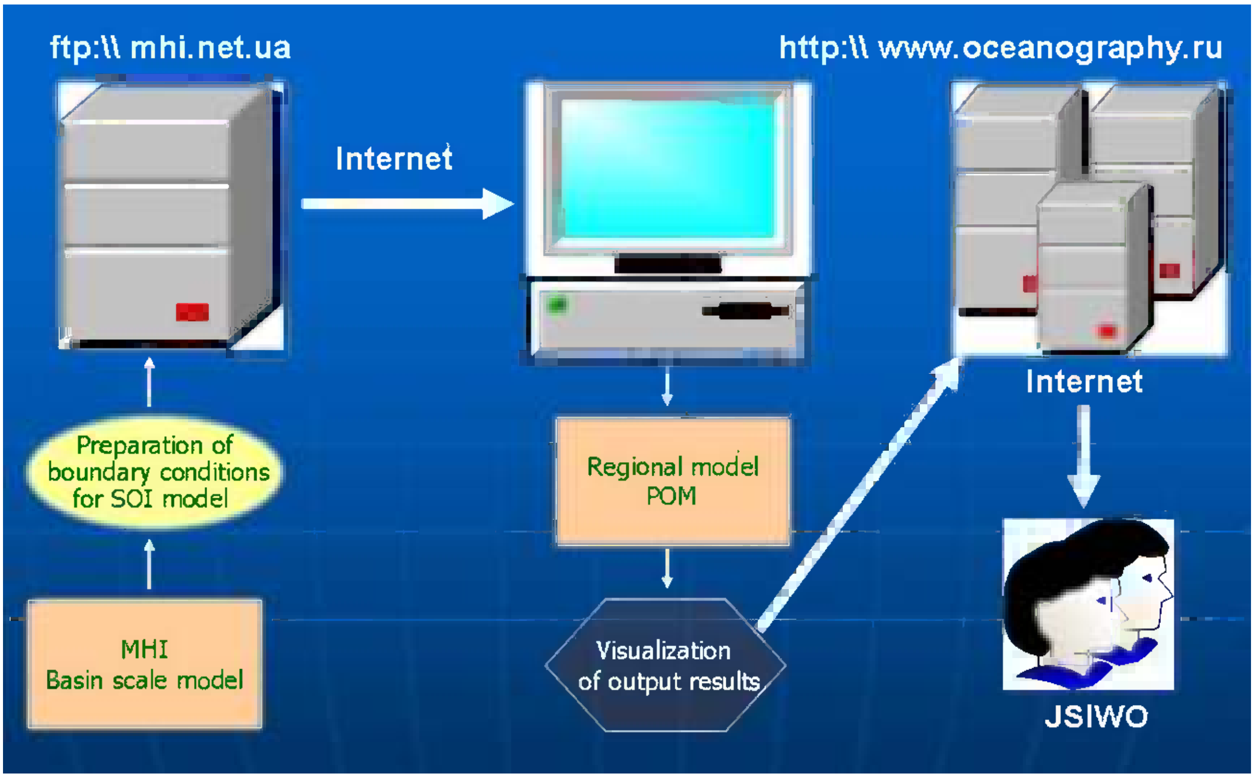


Fig. 6. Scheme of SOI automated system.

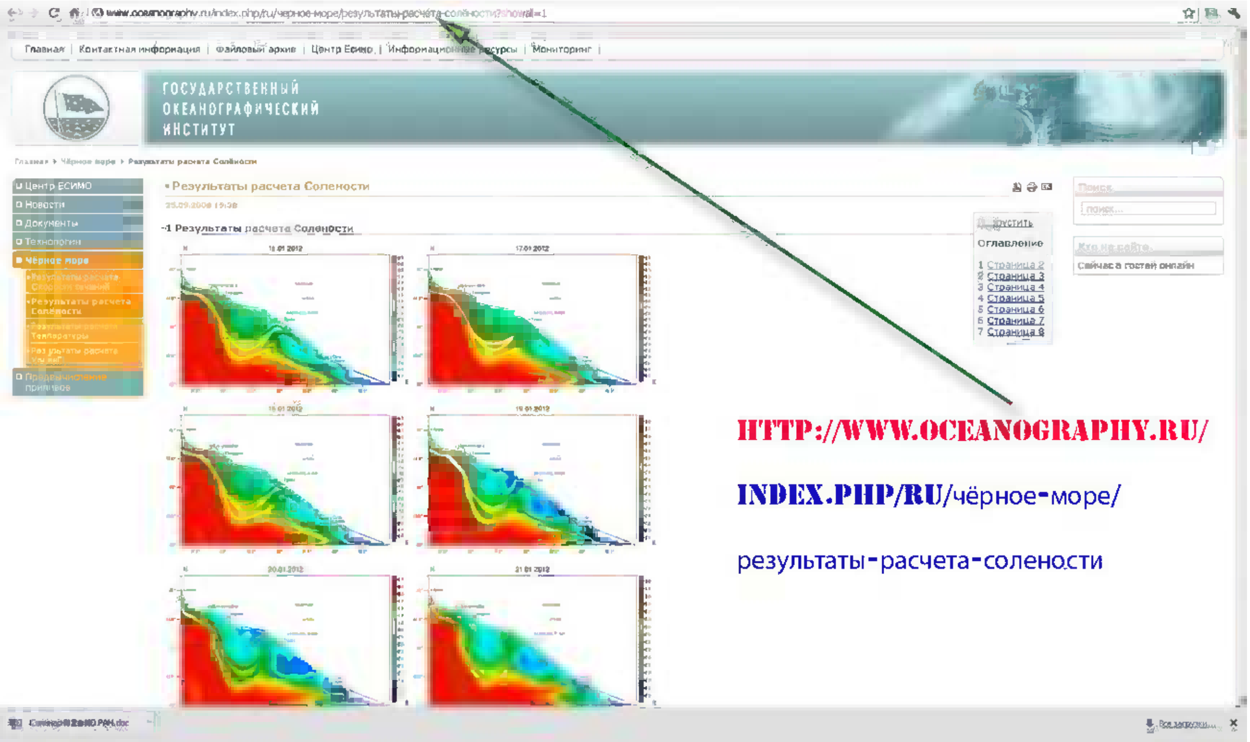


Fig. 7. Example of modeled results shown on the SOI website (in Russian).

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. 8, the regions of R/V *Survey* and modeling are shown.

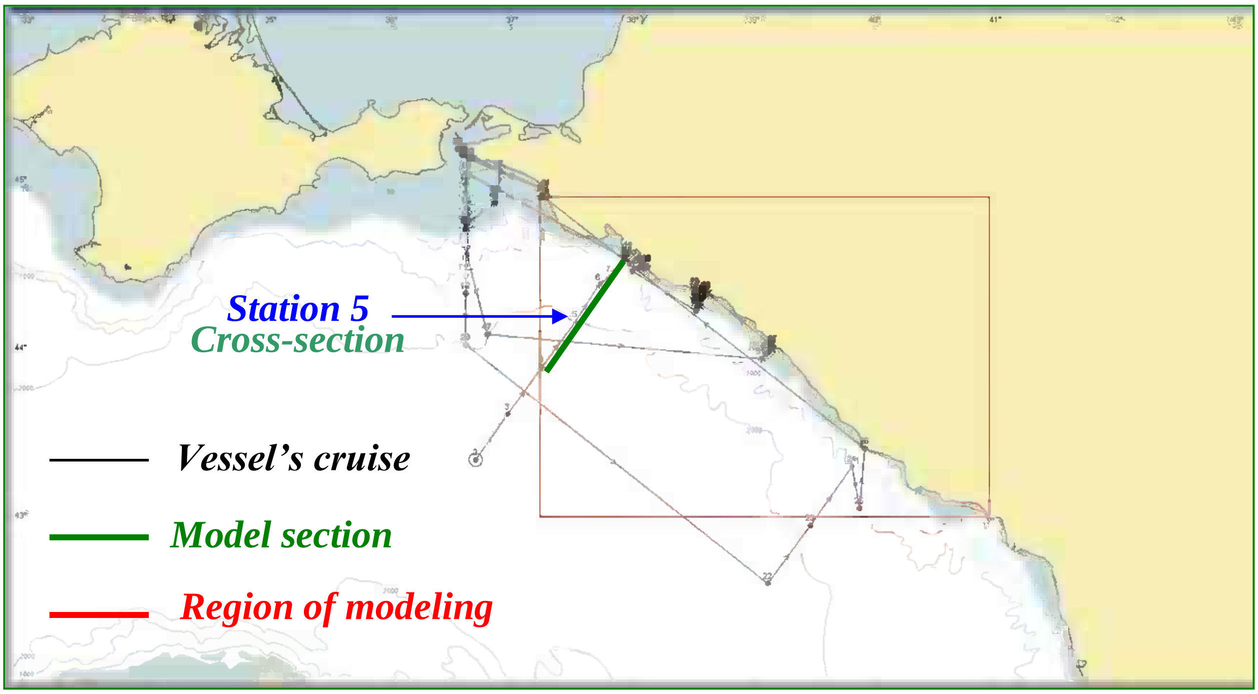


Fig. 8. Region of R/V *Professor Shtokman* survey and modeling area.

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 (Blatov and al., 1984). 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.

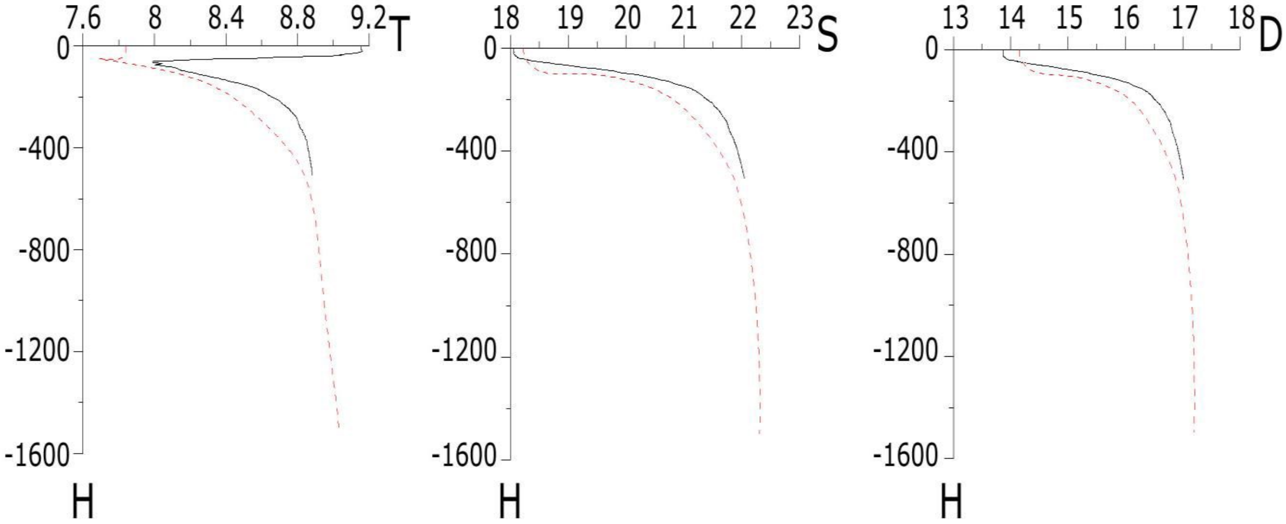
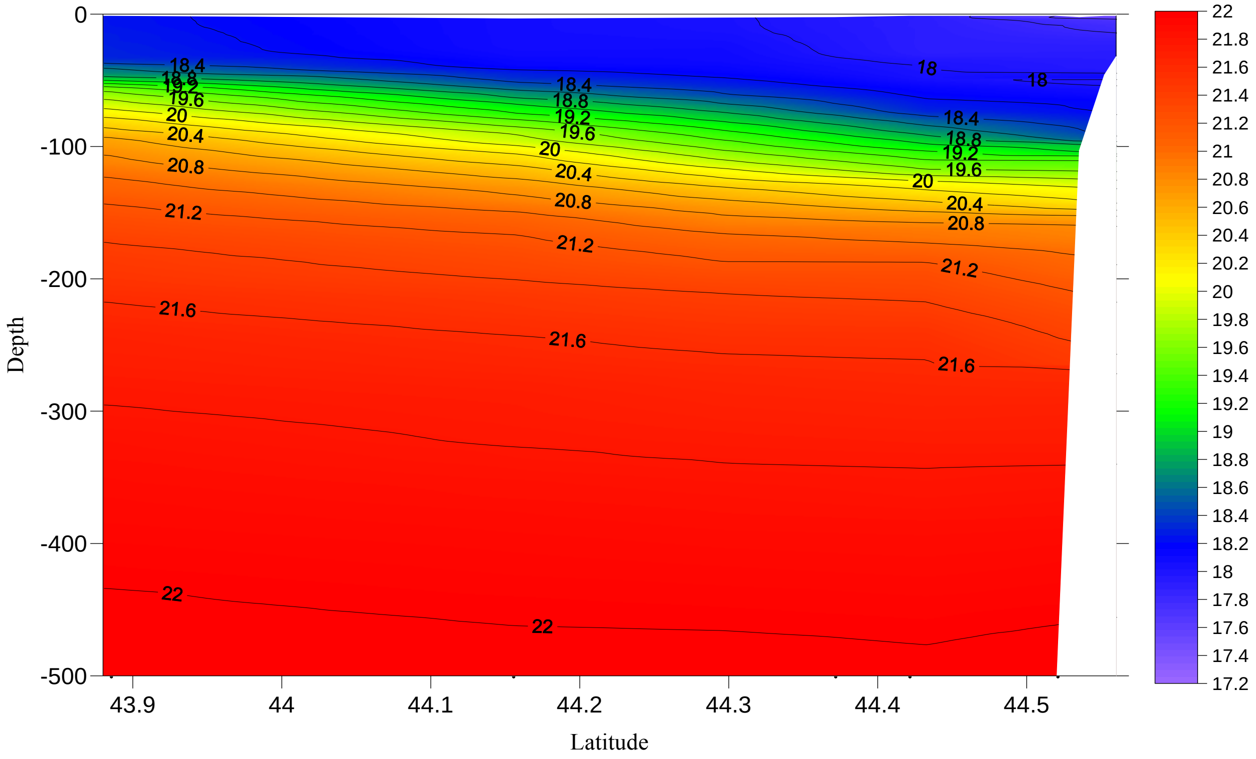


Fig. 9. Vertical profiles of temperature (*T*), salinity (*S*) and density (*D*) for Station No. 5 from CTD data (black) and modeling (red).

Vertical profiles built both from CTD and modeled data reflect the typical vertical structure of waters in the region in March (Fig. 9, 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$^{o}/_{oo}$, for the temperature there is the same order in degrees ^{o}C at depth. A maximum difference in temperatures is observed on a surface – approximately 1.5 ^{o}C. As the research of colleagues from MHI showed, this failing can be decreased by including the penetration of short-wave radiation (Kubryakov and al., 2011). But during the experiment we did not include this effect in SOI technology because do not receive the necessary information about the heat flows.

Distribution of thermohaline characteristics at a cross-section perpendicular to the coast (see Fig. 8) 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. 10). 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 10b is built from model data corresponding to the points and times of ship observations. Comparing Fig. 10a 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 cross-section is well defined deflection contour lines in the slope (right side of Fig. 10c) due to the presence of the anticyclonic vortex with the spatial size of ~ 10 km (see Fig. 11a). Analysis of a similar section for the temperature gives the same results. 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).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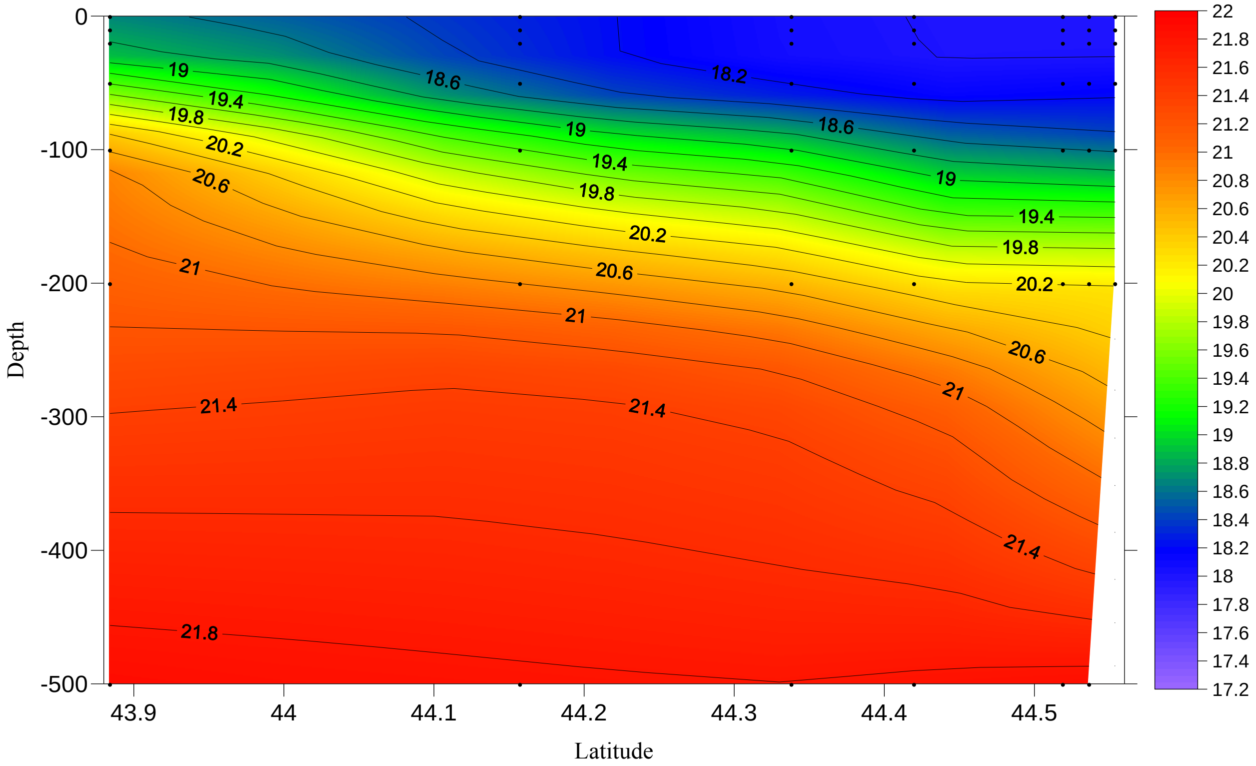
(a)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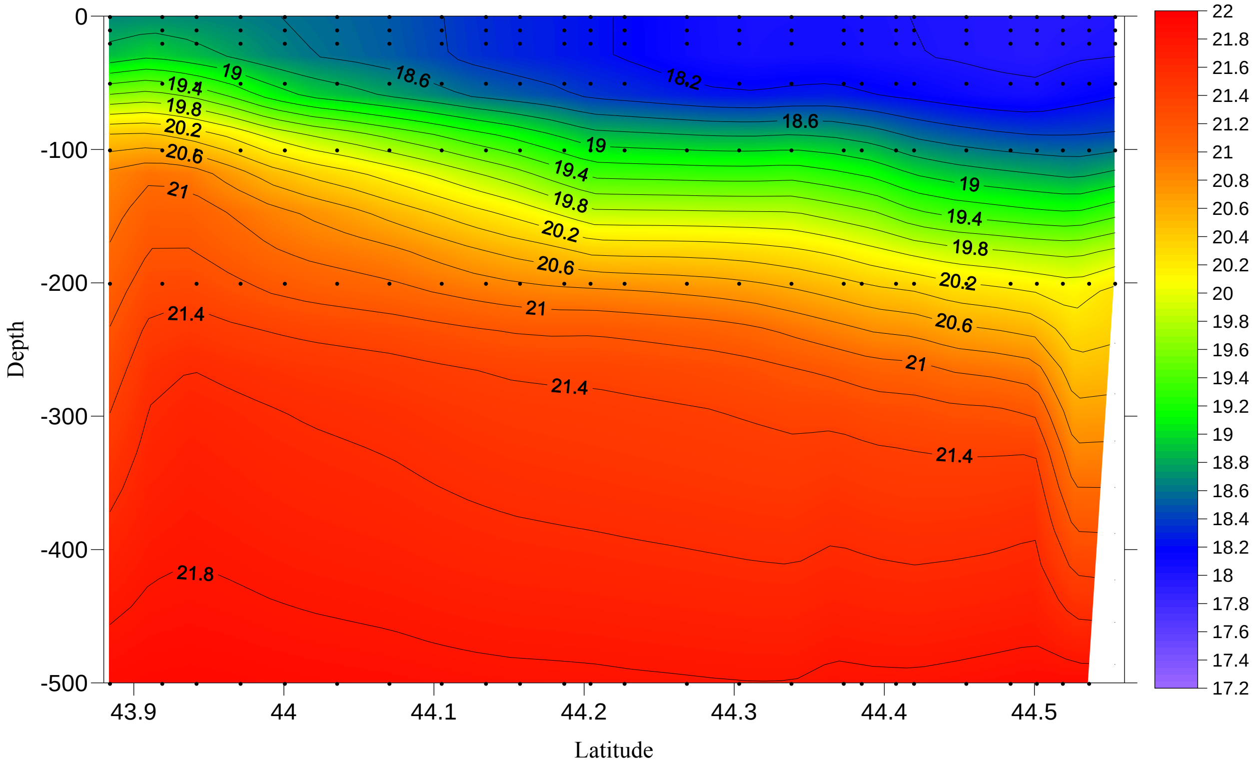


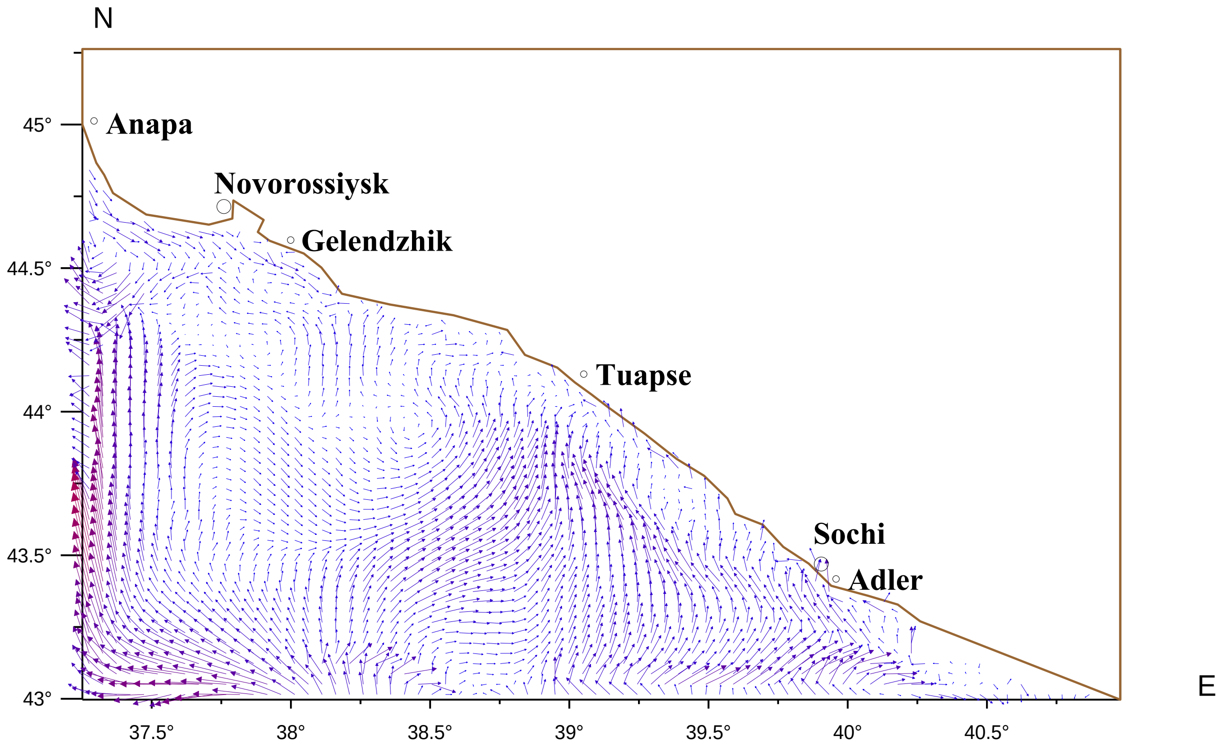
(c)

Fig. 10. Distribution of salinity on a cross-section (see the Fig. 5), obtained from CTD data **(a)** and model data **(b, c).**

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 hydrological survey R/V *Professor Shtokman* is shown in Fig. 11, and the model temperature and salinity fields corresponding to the beginning and end of section in the period 10/03/2009-13/03/2009 is shown in Fig. 12, 13. 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 (in situ) 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 Fig. 14, 15.

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. 14). As noted earlier, the salinity fields to better reflect the dynamics of the waters of the Black Sea in comparison with the fields of temperature. As well as images of chlorophyll are the best to fix the dynamic structures and their evolution than the SST (Sea Surface Temperature) images. Unfortunately, the analysis of of conformity the salinity fields and satellite images has only qualitative character. To obtain quantitative characteristics of the spatial accuracy of model estimates makes sense to use a fields of sea surface temperature. For example, the RMS of the difference between the model and the measured SST in area of modeling for 2 July, 2009, was equal to RMS=1.1°C (Fig. 15) and it is typical value. The comparison of modeled temperature field, shown in the Fig. 15, with satellite data also demonstrates their qualitative agreement. But using some standard methods to assess the quality of the model output in extended period of time was not performed, because modeled and observed sea surface temperatures have a big difference. The reasons have been described above (heat flux).

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).



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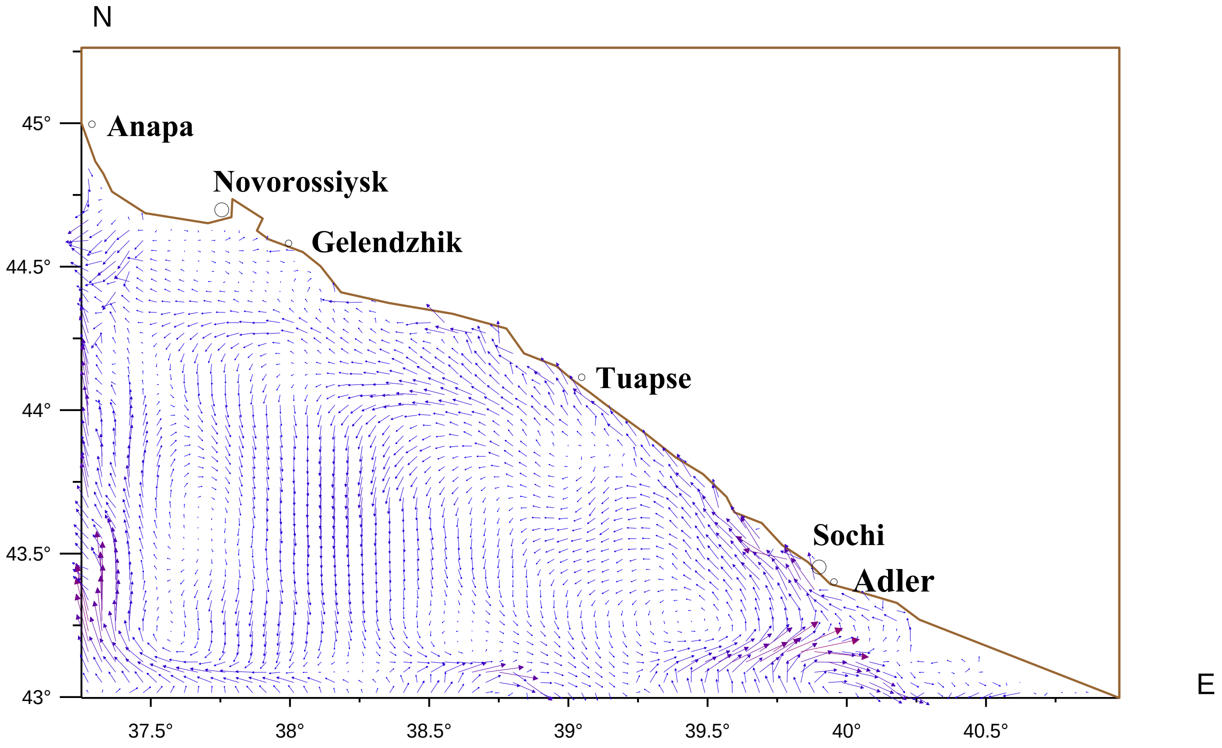
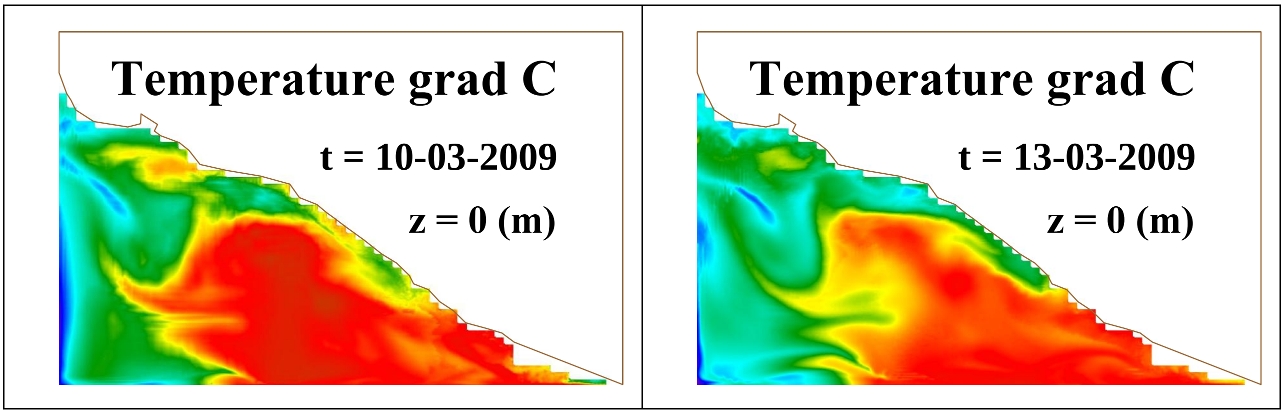


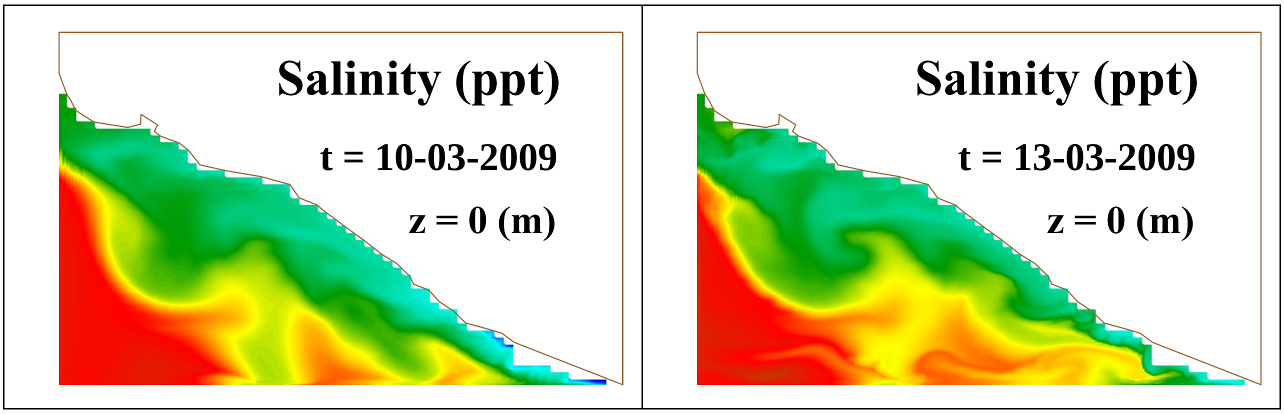
(b)

Fig. 11. Model fields of sea currents at a depth of 10 m 10/03/2009 **(a)** and 02/04/2009 **(b).**



(a) **(b)**

Fig. 12. Model fields of temperature at a depth of 0 m 10/03/2009 **(a)** and 13/03/2009 **(b).**



(a) **(b)**

Fig. 13. Model fields of salinity at a depth of 0 m 10/03/2009 **(a)** and 13/03/2009 **(b).**

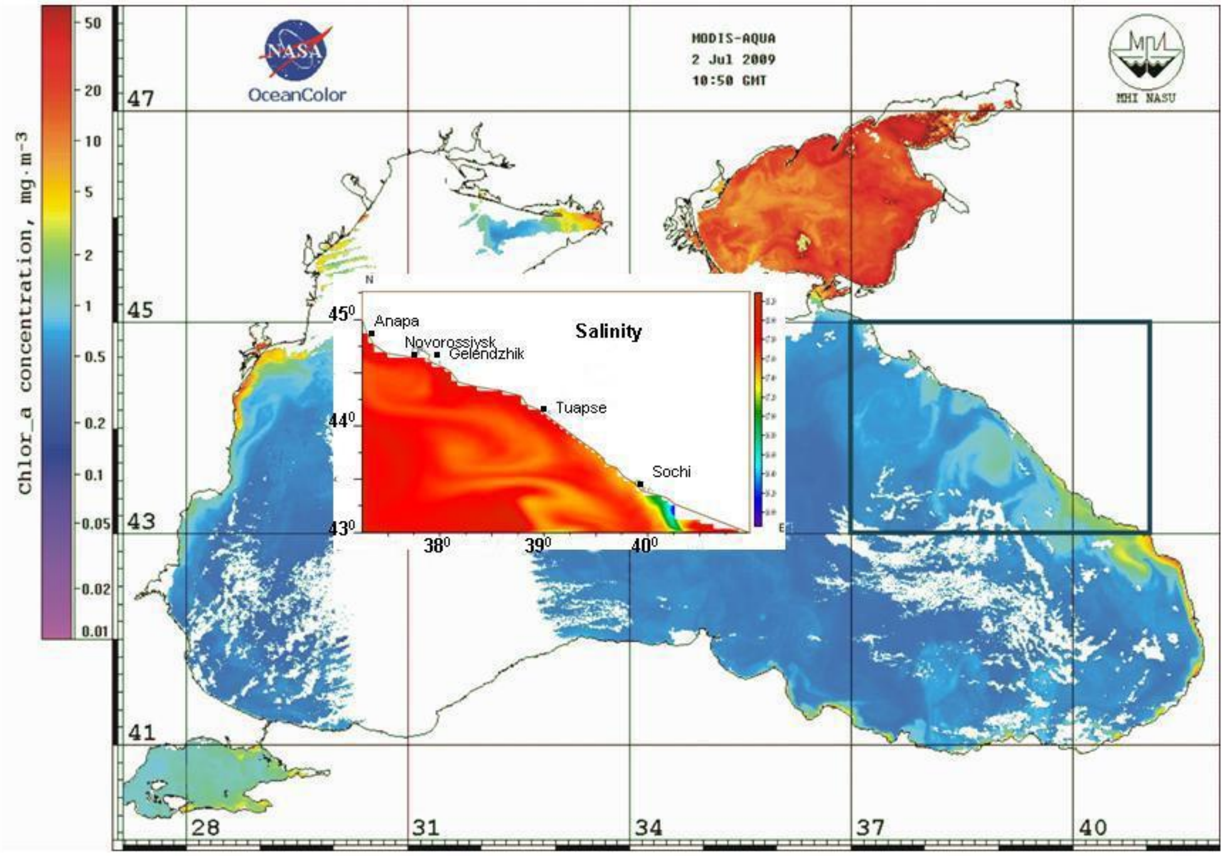


Fig. 14. Satellite image (Chlorophyll concentration) and modeled sea surface salinity at 2 July, 2009.

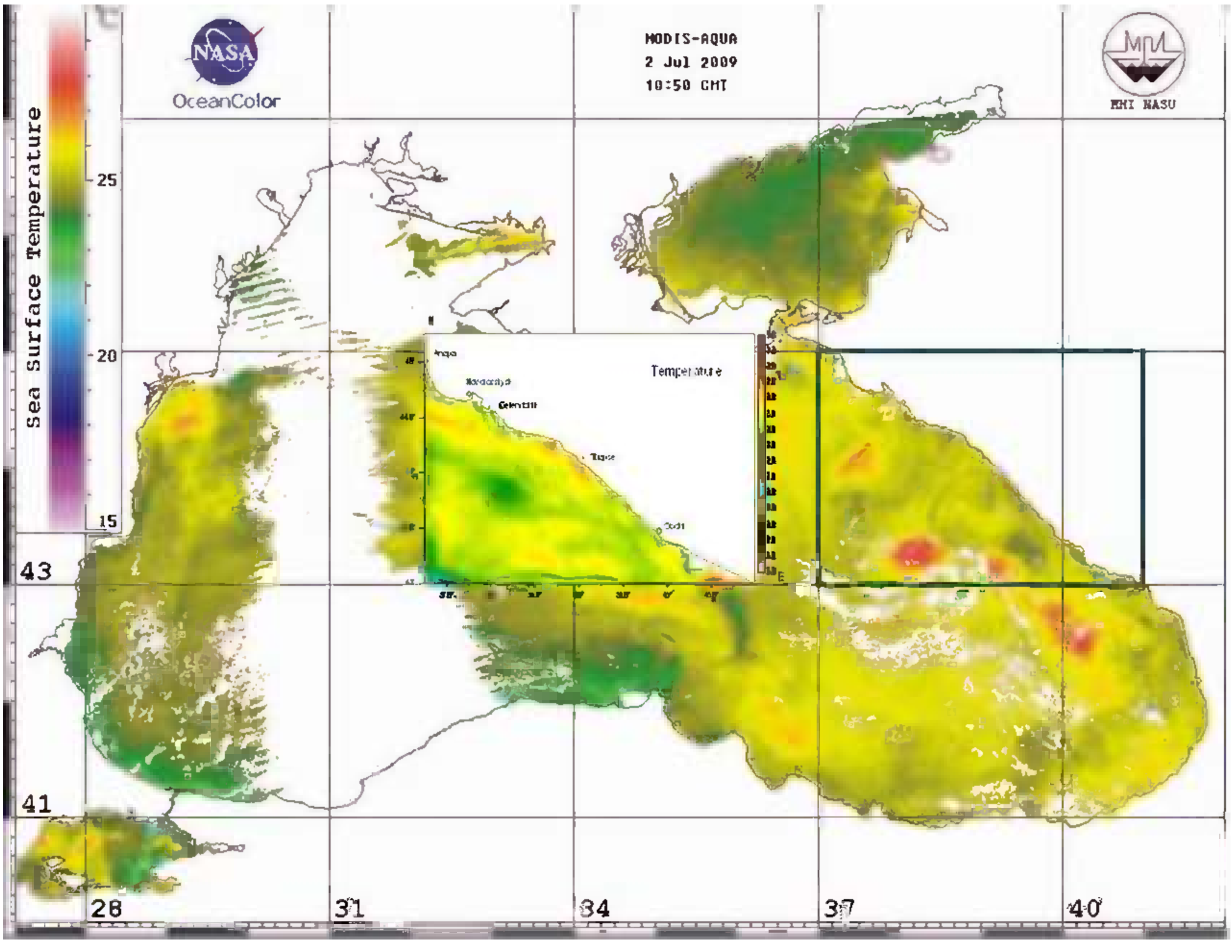
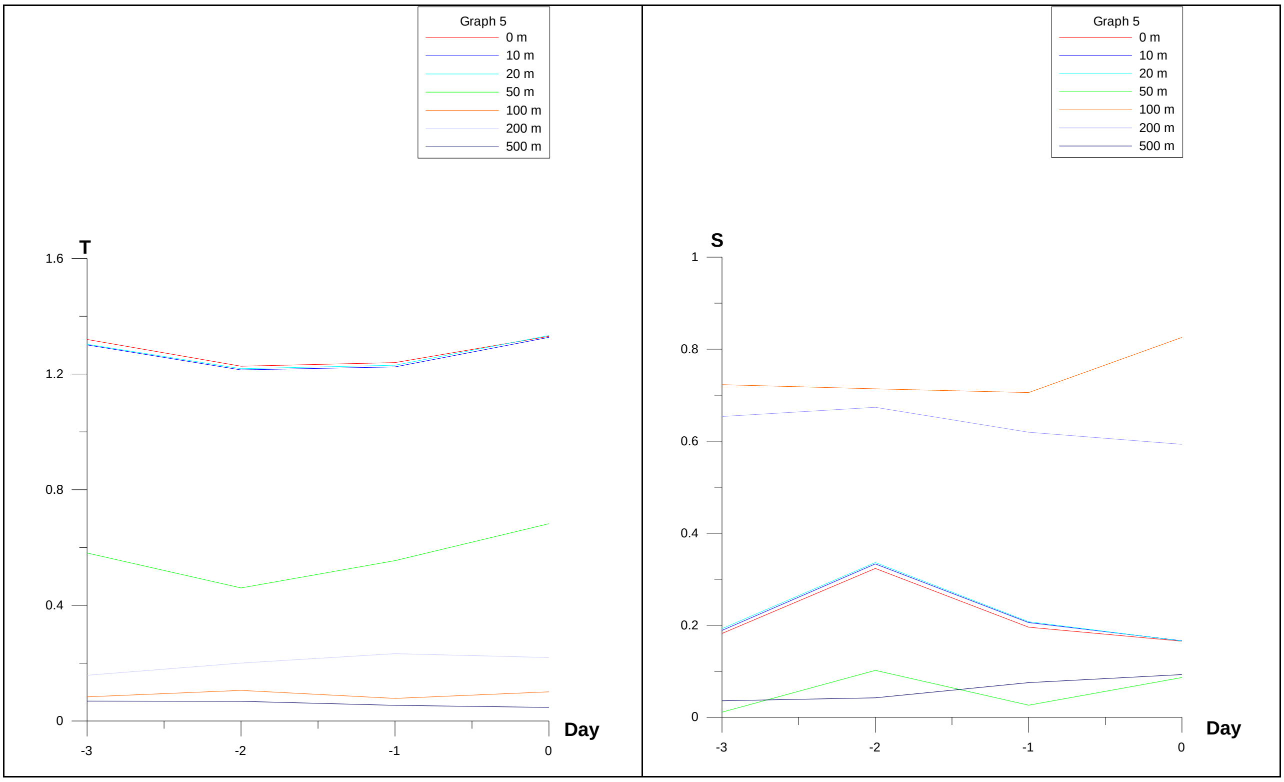


Fig. 15. Satellite image (SST) and modeled sea surface temperature at 2 July, 2009.

It is also interesting to analyze how the magnitude of the errors of forecasting (Fig. 16) 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 than nowcasting (0 days in the Fig. 16). It is worth mentioning the considerable errors of modeled temperature in the upper layer. For salinity, the maximum of errors is located in the range of depths about 100-200 м (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.



(a) **(b)**

Fig. 16. 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.

The reasons for such results could be following:

a) 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 that up to 2 days.

b) 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 the display in the variability of profiles of temperature and salinity.

Conclusions

During the Project, the automated system of modeling the dynamics of water of the Russian zone of Black Sea was created. It allows generation of physically adequate results of calculations of thermohaline structure of water and current fields. Such calculations are performed in nowcasting and forecasting (3 days) mode.

Results of modeling are in general physically identical. Increasing a spatial permit of processes allows reproduce in calculations the detail of hydrological structure, which do not principally find displaying in large-scale models (vortexes with horizontal spatial sizes ~10 km).

Model data reproduce observed real dynamic structures. The model and the observed vertical profiles are very similar. For the salinity difference in values of the order of ~0.1$^{o}/_{oo}$, for the temperature there is the same order in degrees ^{o}C at depth (but not at a surface). Synoptic eddies, reflected in the modeled salinity field show a high correspondence in the spatial size and horizontal location with satellite images. The comparison of modeled temperature field with satellite data also demonstrates their qualitative agreement. The typical RMS of the difference between the model and the measured SST was equal to RMS=1.1^{o}C.

Some shift of location of T, S anomalies in modeled calculations concerning supervision takes place. For elimination of this effect, data assimilation in a regional model can be used.

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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Численное моделирование динамики вод Российского сектора Черного моря в рамках задач оперативной океанографии

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Моделирование динамики вод Черного моря (российская зона) проводилось в рамках европейских проектов ARENA и ECOOP и российского проекта JISWO на основе Принстонской модели океана (POM). Диагноз и прогноз динамики Черного моря на 3 суток проводился в ежедневном режиме с горизонтальным разрешением 1 км для российской зоны бассейна. Приводятся примеры расчетов и их сравнение с данными дистанционных (спутниковых) и *in-situ* (гидрологические измерения) наблюдений, обсуждаются результаты валидации модели. Модельные данные воспроизводят наблюдаемые реальные динамические структуры. Увеличение пространственного разрешения позволяет воспроизводить детали гидрологической структуры (вихри с горизонтальными пространственными размерами ~10 км), которых в принципе невозможно описать в крупномасштабных моделях. Модельные и наблюдаемые вертикальные профили очень сходны. Пространственные размеры и горизонтальные положения синоптических вихрей, которые проявляются в модельном поле солености, находятся в хорошем соответствии со спутниковыми изображениями. Сравнение модельного температурного поля со спутниковыми данными также демонстрирует их количественное совпадение.

შავი ზღვის რუსეთის სექტორის წყლების დინამიკის რიცხვითი მოდელირება ოპერატიული ოკეანოგრაფიის ამოცანათა ჩარჩოებში

ალექსანდრე გრიგორიევი, ანდრეი ზაცეპინი

შავი ზღვის წყლების (რუსეთის ზონა) დინამიკის მოდელირება ხორციელდებოდა ევროპული პროექტების ARENA და ECOOP და რუსეთის პროექტის JISWO ჩარჩოებში პრინსტონის ოკეანის მოდელის (POM) საფუძველზე. შავი ზღვის დინამიკის დიაგნოზი და სამდღიანი პროგნოზი ტარდებოდა ყოველდღიურ რეჟიმში 1კმ ჰორიზონტალური გარჩევისუნარიანობით ზღვის აუზის რუსეთის ზონისათვის. მოყვანილია გამოთვლების მაგალითები და მათი შედარება დისტანციური (თანამგზავრული) ზონდირებისა და *in-situ* (ჰიდროლოგიური დაკვირვებები) მონაცემებთან, განიხილება მოდელის ვალიდაციის შედეგები. მოდელური შედეგები ასახავენ დაკვირვებულ რეალურ დინამიკურ სტრუქტურებს. სივრცითი გარჩევისუნარიანობის გადიდება საშუალებას იძლევა აღვწეროთ ჰიდროლოგიური სტრუქტურის დეტალები

(გრიგალები ჰორიზონტალური სივრცითი ზომებით ~10 კმ), რომელთა იდენტიფიკაცია დიდმასშტაბურ მოდელებში პრინციპულად შეუძლებელია. მოდელური და დაკვირვებული პროფილები ძალიან მსგავსია. სინოპტიკური გრიგალების სივრცითი ზომები და ჰორიზონტალური მდებარეობა, რომლებიც აისახება მარილიანობის მოდელურ ველში, კარგ შესაბამისობაშია თანამგზავრულ გამოსახულებებთან. მოდელური ტემპერატურული ველის შედარება თანამგზავრულ მონაცემებთან აჩვენებს კარგ რაოდენობრივ დამთხვევას.