ISSN 1512-1461

UDC 551. 465. 5

MODELLING OF DYNAMICAL PROCESSES IN THE BLACK SEA

Avtandil Kordzadze[1], Demuri Demetrashvili[2]

[1]M. Nodia Institute of Geophysics, M. Alexidze str.,1, 0193 Tbilisi, Georgia *akordzadze@yahoo.com*

[2]M. Nodia Institute of Geophysics, M. Alexidze str.,1, 0193 Tbilisi, Georgia *demet_48@yahoo.com*

Abstract:

A 3D baroclinic prognostic numerical model of dynamics of the Black Sea and some results of simulation of hydrothermodynamic processes in the Black Sea are presented. The model is based on a full system of the ocean hydrothermodynamics equations in hydrostatic approximation, which is solved in z coordinates by using of a two-cycle splitting method. There are two versions of the model: the basin-scale model (BSM) and the regional model for the Georgian part of the Black Sea coastal zone. BSM is realized on a grid with resolution 5 km and the regional model – on the grid with resolution 1 km. Results of the numerical experiment performed by BSM showed that, under the influence of a strong nonstationarity of atmospheric processes, the water circulation in the upper layer of the Black Sea changes permanently qualitatively and quantitatively. For any character of atmospheric circulation, the Black Sea circulation below 15-20 m is nearly always cyclonic with internal cyclonic gyres. Simulation of coastal processes by the usage of the regional version of the model showed that the increase of resolution is very important for correct reproduction of coastal vortexes of small sizes.

Keywords: *Black Sea circulation, hydrothermodynamics equations, splitting method, numerical experiments.*

1. INTRODUCTION

The Black Sea, which is the inland water reservoir, since ancient times was the object of a significant interest among geographers and travelers, but the beginning of its scientific studying is the second half of the XIX century, when the Russian expeditions on studying of hydrophysical processes in the Black Sea have begun to be organized [1-3]. At present, interest of scientists in the processes occurring in the Black Sea is caused by some specific features of this sea and sharp deterioration of its ecological condition because of pollution by different chemical and toxic impurities [4-6].

One of the specific features of the Black Sea is that fact, that approximately below 150-200 m of depth the basin is polluted by hydrogen sulphide [7]. As a result, the flora and fauna of the Black Sea is basically only in the upper 150 meter layer. Discriminating feature of the Black Sea from other seas is also existence of a cold intermediate layer. Its core is at about 50-80 m and the 8^0 C isotherm marks its upper and lower boundaries [1, 2].

The ecological state of the Black Sea is very important for Georgia, because the Black Sea - the richest source of natural resources, has a great influence on social and economic condition of Georgia. Because the level of contamination of this unique basin with highly toxic substances is progressing bio-efficiency of the Black Sea has sharply decreased, degrades its recreational potential [4, 5].

Besides, the Black Sea is a rich source of mineral and biological resources and has the big transport and recreational value, it plays an important role in formation of weather and regional climate [8]. As well as ocean and atmosphere, the Black Sea and the atmosphere form uniform

ISSN 1512-1461

hydro-thermodynamic system, where exchangeable processes of energies and different substances on the interface sea-atmosphere take place continuously.

Without knowledge and understanding hydro and thermodynamic processes in the Black Sea it is impossible decision of mentioned problems. It is obvious that only experimental researches are insufficient for reception of a full picture of spatial–temporal distribution of hydrophysical parameters on the scale of whole basin.

The modern stage of studying the Black Sea processes is characterized by wide aplication of mathematical modeling methods with experimental methods [9-17]. The first prognostic numerical model of dynamics of the Black Sea based on a full system of the ocean hydrothermodynamics equations has been created at the Computing Center of Siberian Branch of the Academy of Sciences of USSR (Novosibirsk, Akademgorodok) by Marchuk, Kordzadze, *etc* [9-10]. This model has found the further development at the Department of Numerical Mathematics of the Academy of Sciences of USSR (Moscow; at present, Institute for Numerical Mathematics of Russian Academy of Sciences) [11-13]. The works on modelling of the Black Sea dynamics executed till 90th of the last century are described in details in monographies [13,18]. These works have shown ability of numerical models to really reproduce some general features of dynamical processes of the Black Sea: cyclonic character of the Black Sea general circulation, cyclonic vortexes in the open part of the basin, convex form of salinity field in the upper layer, *etc*., but because of the used rough grid these models were not able to give detail pictures of distribution of hydrophysical fields.

Further, the rapid progress of computer facilities and wide using of experimental methods (including methods of remote sensing) promoted a raising on a higher level of mathematical modelling of processes of the Black Sea. Now in the leading oceanographic centers of the countries of the Black Sea region (including M. Nodia Institute of Geophysics, Tbilisi) and the USA are developed prognostic models of the Black Sea dynamics which with sufficient adequacy and high resolution reproduce the basic features of the dynamic processes in the Black Sea [19-33]. These models differ from each other basically by methods of parameterization of different physical factors (turbulent diffusion, absorption of solar radiation, *etc*.), used coordinate system, methods of solution, parameters of a calculated grid. Works [28-33] may be considered as development of [9-13].

Now one of the priority of operative oceanography of the Black Sea is creation of the Nowcasting/Forecasting Operative System which will allow to receive the continuous information about current and future states of the Black Sea in real time [33-35]. In the last years the international projects **ARENA** and **ECOOP**, financed by the European Union, serve creation such operative prognostic systems for the Black Sea and other European seas. Within the framework of the **ARENA** project, a pilot experiment on the functioning of the Black Sea Nowcasting /Forecasting System was performed for the first time in July 2005. Leading oceanographyc scientific teams of all Black Sea riparian countries (Bulgaria, Georgia, Romania, Russia, Turkey, Ukraine) participated in the pilot experiment. The prognostic calculations of the main hydrophysical fields (currents, temperature, salinity) for 48 h with 1 km spacing in the Georgian part of the Black Sea coastal zone with the use of the regional model of M. Nodia Institute of Geophysics was a part of this experiment [33].

The purpose of the present paper is description of some results of modelling of hydrothermodynamic processes both in the entire Black Sea basin and in the Georgian part of the Black Sea coastal zone with use of basin scale and regional versions of the baroclinic prognostic model of the Black Sea dynamics, developed at M. Nodia Institute of Geophysics (Tbilisi/Georgia).

2. DESCRIPTION OF 3D PROGNOSTIC NUMERICAL MODEL

The model of sea dynamics is based on a full system of ocean hydro-thermodynamics equations, which is written in z coordinates for deviations of thermodynamic values from

ISSN 1512-1461

corresponding standard vertical distributions. There are two versions of the model: the basin scale model (BSM) and the regional model. These versions take into account: atmospheric wind and thermohaline forcing, sea bottom topography, absorption of short-wave radiation by the sea upper mixed layer, space-temporal variability of horizontal and vertical turbulent exchange. In BSM water exchange with the Mediterranean Sea and Danube River inflow are considered.

2.1. model equations, boundary conditions

The model equation system has the following form (the axes x, y and z are directed eastward, northward, and vertically downward from the sea surface, respectively):

$$\frac{\partial u}{\partial t} + div\vec{u}u - lv + \frac{1}{\rho_0}\frac{\partial p'}{\partial x} = \nabla\mu\nabla u + \frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z},$$

$$\frac{\partial \mathrm{v}}{\partial t} + div\vec{u}\mathrm{v} + lu + \frac{1}{\rho_0}\frac{\partial p'}{\partial y} = \nabla\mu\nabla \mathrm{v} + \frac{\partial}{\partial z}\nu\frac{\partial \mathrm{v}}{\partial z},$$

$$\frac{\partial p'}{\partial z} = g\rho', \qquad div\,\vec{u} = 0, \tag{1}$$

$$\frac{\partial T'}{\partial t} + div\,\vec{u}T' + \gamma_T.w = \nabla\mu_T\nabla T' + \frac{\partial}{\partial z}\nu_T\frac{\partial T'}{\partial z} + \frac{\partial \nu_{\mathrm{T}}\gamma_T}{\partial z} - \frac{1}{c\rho}\frac{\partial I}{\partial z} - \frac{\partial \overline{T}}{\partial t},$$

$$\frac{\partial S'}{\partial t} + div\,\vec{u}S' + \gamma_{\mathrm{S}}w = \nabla\mu_{\mathrm{S}}\nabla S' + \frac{\partial}{\partial z}\nu_{\mathrm{S}}\frac{\partial S'}{\partial z} + \frac{\partial \nu_{\mathrm{S}}\gamma_{\mathrm{S}}}{\partial z} - \frac{\partial \overline{S}}{\partial t},$$

$$\rho' = \alpha_{\mathrm{T}}\mathrm{T}' + \alpha_{\mathrm{S}}\mathrm{S}', \quad \gamma_T = \frac{\partial \overline{\mathrm{T}}}{\partial z}, \quad \gamma_{\mathrm{S}} = \frac{\partial \overline{\mathrm{S}}}{\partial z},$$

$$T = \overline{T}(z,t) + T', \; S = \overline{S}(z,t) + S', \; \rho = \overline{\rho}(z,t) + \rho', \; p = \overline{p}(z,t) + p',$$

$$\nabla\mu\nabla = \frac{\partial}{\partial x}\mu\frac{\partial}{\partial x} + \frac{\partial}{\partial y}\mu\frac{\partial}{\partial y}, \qquad I = \eta(1-A)\,I_0\,e^{-\alpha z},$$

$$I_0 = a\sinh_0 - b\sqrt{\sinh_0}, \qquad \sinh_0 = \sin\varphi\sin\psi + \cos\varphi\cos\psi\cos\frac{\pi}{12}t,$$

$$\eta = 1 - (\tilde{a} + \tilde{b}\tilde{n})\tilde{n}.$$

The coefficients
$\alpha_T = \partial f/\partial \overline{T} = -10^{-3}(0.0035 + 0.00938\overline{T} + 0.0025\overline{S}), \quad \alpha_S = \partial f/\partial s = 10^{-3}.(0.802 - 0.002\overline{T})$.
are determined from the empirical equation of state for marine water $\rho = f(T,S)$ specified by the Mamaev formula [36].

Here u, v, and w are the components of the current velocity vector $\vec{u}$ along axes x,y,z, respectively; T',S',P',ρ' are the deviations of temperature, salinity, pressure and density from their standard vertical distributions $\overline{T},\overline{S},\overline{P},\overline{\rho}$; $l = l_0 + \beta.y$ is the Coriolis parameter; $g, c\ \rho_0$ are the gravitational acceleration, the specific heat capacity and the average density of seawater; $\mu, \mu_{T,S}, \nu, \nu_{T,S}$ are the horizontal and vertical eddy viscosity, heat and salt diffusion coefficients,

ISSN 1512-1461

respectively; I_0 is the total radiation flux supplied to the sea surface and defined by the Albrecht formula [37] at z = 0; A is the albedo of the sea surface, h_0 is the zenithal angle of the Sun, φ is the geographical latitude, Ψ is the parameter of declination of the Sun, η is the factor which takes into account influence of a cloudiness on a total radiation and depends upon ball of cloudiness $\tilde{n}$ [38]; $a, b, \tilde{a}, \tilde{b}$ are the empirical factors; α is the parameter of absorption of short-wave radiation by seawater.

The equation system (1) is solved at the following boundary and initial conditions:

at the sea surface z = 0

$$\frac{\partial u}{\partial z} = -\frac{\tau_{zx}}{\rho_0 \nu}, \quad \frac{\partial v}{\partial z} = -\frac{\tau_{zy}}{\rho_0 \nu}, \quad w = 0,$$

$$T' = T^* - \overline{T}(0,t), \quad \text{or} \quad \nu \frac{\partial T}{\partial z} = Q^T - R_0; \quad \nu \frac{\partial S}{\partial z} = (PR - EV)S_0 \quad \text{or} \quad S' = S^* - \overline{S}(0,t)$$

on the lateral surfaces

$$u = 0, \ v = 0, \ \partial T'/\partial n = 0, \ \partial S'/\partial n = 0 \qquad \text{on} \quad \Gamma_0, \tag{2}$$

$$u = \tilde{u}, \ v = \tilde{v}, \ T' = \tilde{T}', \ S' = \tilde{S}' \qquad \text{on} \quad \Gamma_1,$$

at the sea bottom z = H(x, y)

$$u = 0, \ v = 0, w = 0, \ \partial T'/\partial z = -\gamma_T \ \partial S'/\partial z, = -\gamma_S \qquad \text{at} \quad z = H,$$

at the initial moment t = 0

$$u = u^0, \ v = v^0, \ T' = T'^0, \ S' = S'^0 \qquad \text{at} \quad t = 0, \tag{3}$$

where H describes the bottom relief of the sea basin; $\tau_{zx}, \tau_{zy}, T^*, S^*$ are the wind stress components along axes x and y, temperature and salinity at the sea surface z = 0, respectively; Γ_0 is the lateral surface adjacent to the land, and Γ_1 is the liquid boundary separating the sea basin from the remaining water area (in BSM it is the boundary between the Black Sea basin and the Bosporus or the Danube River); $Q^T(x, y, t)$, PR(x, y, t) and EV (x, y, t) are the total heat flux, precipitation and evaporation on the sea surface; n is the order normal to the surface Γ_0; $\tilde{u}$, $\tilde{v}$, $\tilde{T}'$, $\tilde{S}'$ are the current velocity components along x and y and the deviations of temperature and salinity at the liquid boundary, respectively.

The model enables to take into account atmospheric forcing by using Dirichlet conditions on a sea surface for temperature and salinity or Neumann conditions by given of heat fluxes, evaporation and atmospheric precipitation.

Factors of turbulence $\mu, \mu_{T,S}$, and $\nu_{T,S}$ were calculated by the formulas presented in [39, 40]

$$\mu = \Delta x . \Delta y \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2}, \ \mu_T = \mu / c_T, \ \mu_S = \mu / c_S,$$

ISSN 1512-1461

$$\nu_{T,S} = (0.05h)^2 \sqrt{\left(\frac{\partial \mathrm{u}}{\partial \mathrm{z}}\right)^2 + \left(\frac{\partial \mathrm{v}}{\partial \mathrm{z}}\right)^2 - \frac{\mathrm{g}}{\rho_0}\frac{\partial \rho}{\partial \mathrm{z}}},$$

where $\Delta \mathrm{x}$ and $\Delta \mathrm{y}$ are horizontal grid steps along x and y, respectively; c_T and c_S are some constants; h is the depth of the turbulent surface layer, which is defined by the first point z_m, in which following condition is satisfied:

$$(0.05z_m)^2 \sqrt{\left(\frac{\partial \mathrm{u}}{\partial \mathrm{z}}\right)^2 + \left(\frac{\partial \mathrm{v}}{\partial \mathrm{z}}\right)^2 - \frac{\mathrm{g}}{\rho_0}\frac{\partial \rho}{\partial \mathrm{z}}} \le \nu_{T,S}^0 \ .$$

In case of unstable stratification($\frac{\partial \rho}{\partial \mathrm{z}} \prec 0$), which may be appear during integration of the equations, the realization of this instability in model was taken into account by increase of factor of turbulent diffusion, $\nu_{T,S}$, 20 times in appropriate columns from the surface to the bottom.

2.2. Numerical scheme

The existence and uniqueness theorems of the problems of ocean dynamics (including the problem (1)–(3)) are established in [41-46]. To solve the problem (1)-(3), the two-cycle splitting method with respect to both physical processes and coordinate planes and lines is used [13, 47]. This method enables to reduce solution of 3D nonstationary problems to solution of more simple 2D and 1D problems. For approximation on a time of these problems the Krank-Nickolson scheme is used. Received difference schemes provide the second order accuracy by time and by space coordinates in case of uniform grid.

3. SIMULATION OF BASIN SCALE CIRCULATION

The suggested model was realized for the Black Sea basin with the purpose of research of influence of various physical factors on structure of the basin-scale circulation of the Black Sea. Besides the calculated circulating parameters have been used in different problems on distribution of impurity in the Black Sea [48-50].

3.1. Input data and values of parameters

The calculated grid with nodes 225x111 and with horizontal step 5 km was used. 32 calculated levels were located at depths of 1, 3, 5, 7, 11, 15, 25, 35, 55, 85, 135, 205, 305, 405,…, 2205 m.

The parameter of absorption of solar radiation was accepted equal to α = 0.0023 m^{-1} which corresponds to usual ocean water, in which about 10 % of the incident radiation reaches a depth of 10 m [51]. The time step was 1 h. The empirical factors had the following values [37, 38]: *a=1.54 kW/m²*, *b=0.22 kW/m²*, $\tilde{a} = \tilde{b} = 0.38$. The specific heat capacity c = 4.09 $\mathrm{Jg^{-1}K^{-1}}$, which corresponds to seawater with a salinity of about 18 ‰. The other parameters had the following values:

$\mathrm{g} = 980\ \mathrm{cm^2/s}$, ρ_0 =1g/cm³, l_0 = 0,95.10⁻⁴s⁻¹, $\beta = 10^{-13}\mathrm{cm^{-1}s^{-1}}$, $\Delta t = 1h$, $\mathrm{c_T} = c_\mathrm{S} = 10$,

$$\nu_{T,S}^0 = 1\,\mathrm{cm^2\,s^{-1}} \quad , \qquad \nu = \begin{cases} 50\,cm^2/s, & z \le 55m \\ 10\,cm^2/s, & z \succ 10\,m \end{cases}$$

ISSN 1512-1461

3.2. Results of simulation

The role of different physical factors on formation of a hydrophysical mode of the Black Sea has been studied. Numerical experiments have shown, that the effect of rotation of the Earth is very significant in layers up to depth about 700 m, and in deeper layers of the Black Sea character of circulation practically does not change by neglect of Coriolis force. It is easy to explain this fact with reduction of Coriolis effect because of easing of intensity of circulation with depth and with significant growth of contribution of other factors: the sea bottom relief and configuration of coasts.

The contribution of absorption by sea water of total solar radiation to the formation of a thermal mode of the upper layer of the Black Sea was estimated [52]. Calculations have shown, that absorption of radiation by sea water causes small daily fluctuations of temperature of the uppermost layer of the sea with thickness about 10-15 m with amplitude 0.2-0.3^{0}C. Estimations have shown that despite such small changes of temperature, because of large volumetric heat capacity of marine water the upper layer of the Black Sea can accumulate a significant amount of heat and this factor will play not a minor role during interaction between the Black Sea and atmosphere. The analysis of annual course of growth of sensible heat of the upper 55 m layer caused by absorption of radiation has shown that the energetic influence of radiation is most of all in August and during this period the upper layer of the Black Sea can accumulate such thermal energy which would be sufficient for heating by 10^{0}C air with thickness about 600 m, lying over the Black Sea surface.

One of the principal numerical experiments carried out on the basis of this model was simulation of inner-annual variability of the Black Sea hydrological regime in conditions of alternation of different atmospheric wind types. This experiment aimed to study how the circulation system of the Black Sea responds to the variability of atmospheric processes. These types of winds have been taken from [53] in which on the basis of processing observed data for 1946-1962 is established 41 types of atmospheric circulation above the Black Sea.

Annual cycles of temperature and salinity at the sea surface and their vertical profiles, as well as the annual cycles of temperature, salinity, and water discharges at the open boundaries near the Danube River and the Bosporus reproduced on known monthly mean values with the use of a linear interpolation.

The beginning of integration corresponded to the 1st January and as initial conditions annual mean climatic model fields of current, salinity and temperature, calculated by the same model, were used. Nonstationarity of atmospheric circulation was reduced to alternation of 24 wind types, that are characterized by the greatest repeatability over the Black Sea basin [54]. When one wind type changed to another, a state close to calm, with a wind speed of 1 m/s and wind direction corresponding to the arithmetic mean between the two consecutive wind directions, took place between these wind types. The total duration of nearly calm situations was minimal in February (30%) and maximal in August (70%).

Analysis of the results of the numerical experiment has shown that, due to the nonstationarity of atmospheric processes, the circulation of the sea-surface layer substantially changed qualitatively and quantitatively and was continuously transformed during the year. The sea circulation became less intense in summer, as the atmospheric circulation weakened, and more intense in autumn and winter, when winds became stronger. For example, during some summer periods, under nearly calm conditions, the surface-current velocity dropped to 10–12 cm/s, whereas in autumn and winter, during a storm wind, it attained or slightly exceeded 100 cm/s. Such high velocities are actually observed in the Black Sea [18, 55]. During the transformation of atmospheric circulation processes, circulation possessing all main features characteristic of the averaged circulation of the upper layer of the Black Sea, such as the Black Sea Rim Current (BSRC), internal cyclonic gyres, and anticyclonic vortices in coastal areas, often formed in the sea-surface layer [2, 18, 19, 55], but for some types of atmospheric circulation these features of the sea surface

ISSN 1512-1461

circulation were less pronounced. Numerical simulation has shown that intensive atmospheric circulation promotes disintegration of vortical formations in the upper layer and on the contrary - in case of weak winds vortex motion is well developed. For any character of atmospheric circulation, with increasing depth, the sea circulation acquired again a clear vortical character with internal cyclonic rotations and coastal anticyclonic vortices.

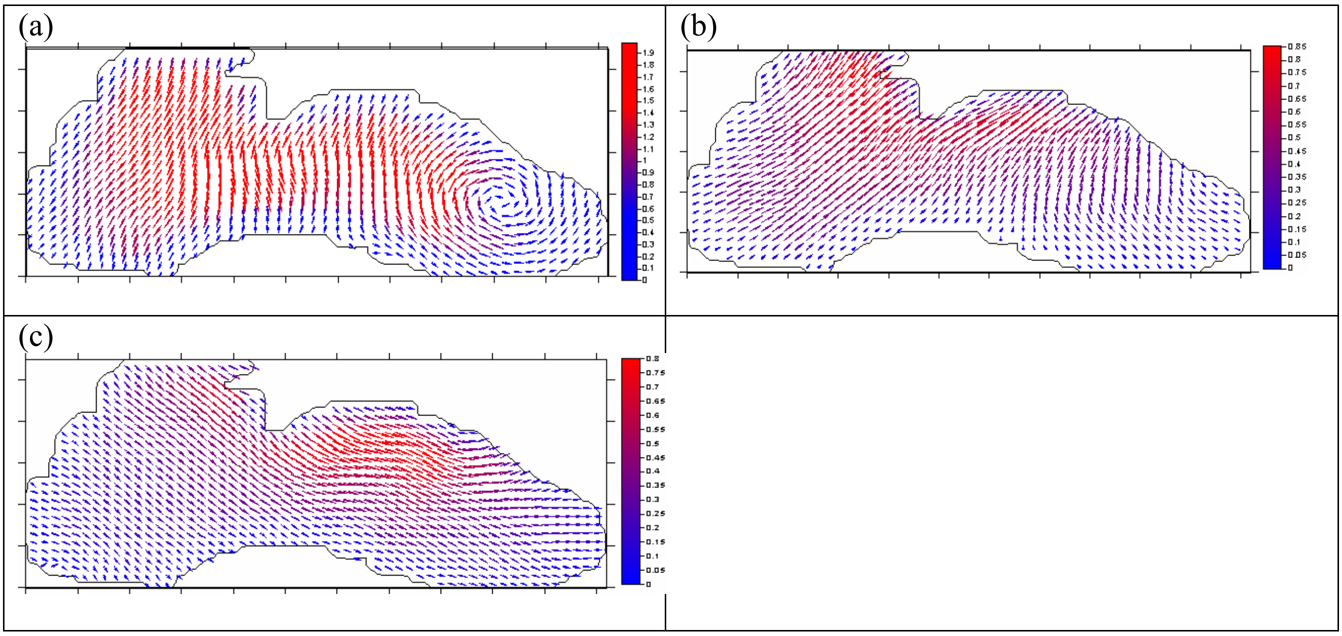
In order to illustrate the transformation of sea-surface circulation during the winter period, we chose the time interval 622–744 h (January; hereinafter, the time was counted from January 1), when the circulation was reorganized as shown in Table 1.

Figure 1 shows the fields of wind stress at the sea surface corresponding to the northerly (10–15 m/s), southwesterly (5-10 m/s) and northwesterly (5–10 m/s) wind types indicated in Table 1. Figure 2 illustrates the transformation of the Black Sea circulation at the horizon z = 1m under the influence of the reorganization of atmospheric circulation indicated in this table.

Table 1. Alternation of wind types in the interval 622-744 h (January)

№	Wind direction	Wind speed, m/s	Time intervals, hours
1	Northeasterly	1	622-636
2	Northerly	10-15	636-660
3	Northwesterly	1	660-674
4	Southwesterly	5-10	674-692
5	Westerly	1	692-706
6	Northwesterly	5-10	706-744

It should be noted that over such a relatively short time, the transformation of sea circulation is virtually caused by the nonstationarity of atmospheric wind action. From this Figure it is visible, that vortex circulations in the uppermost layer is more well expressed in case of weak wind speeds. Strong winds above the Black Sea have smoothing action and cause disintegration of vortical formations near the sea surface (Figs. 2b, 2f).



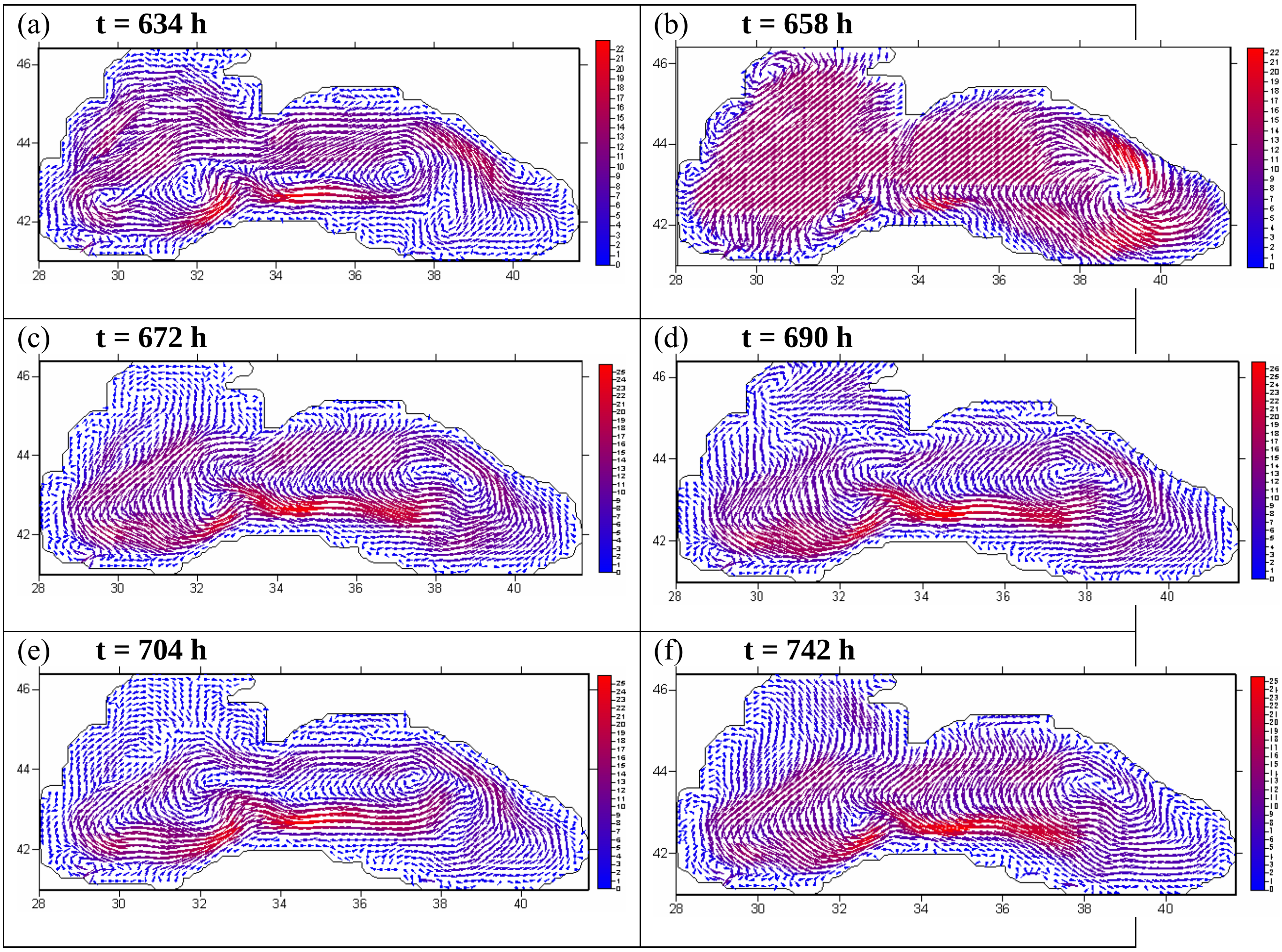
ISSN 1512-1461

Fig. 1. Vector fields of the wind stress corresponding to (a) northerly (10-15m/s), (b) southwesterly (5-10m/s) and (c) northwesterly (5-10 m/s) winds.

Additionally, it can be concluded from comparison of Figs. 1a and 2b that during strong winds near the sea surface sea currents in the major part of the basin are deflected to the right from the direction of wind stress, that corresponds to the well-known result of the Ekman theory of drift currents [56]. Analysis of other numerous current patterns obtained in the course of our numerical experiment has shown that the more intense the atmospheric circulation, the more clearly these effects of action are defined.

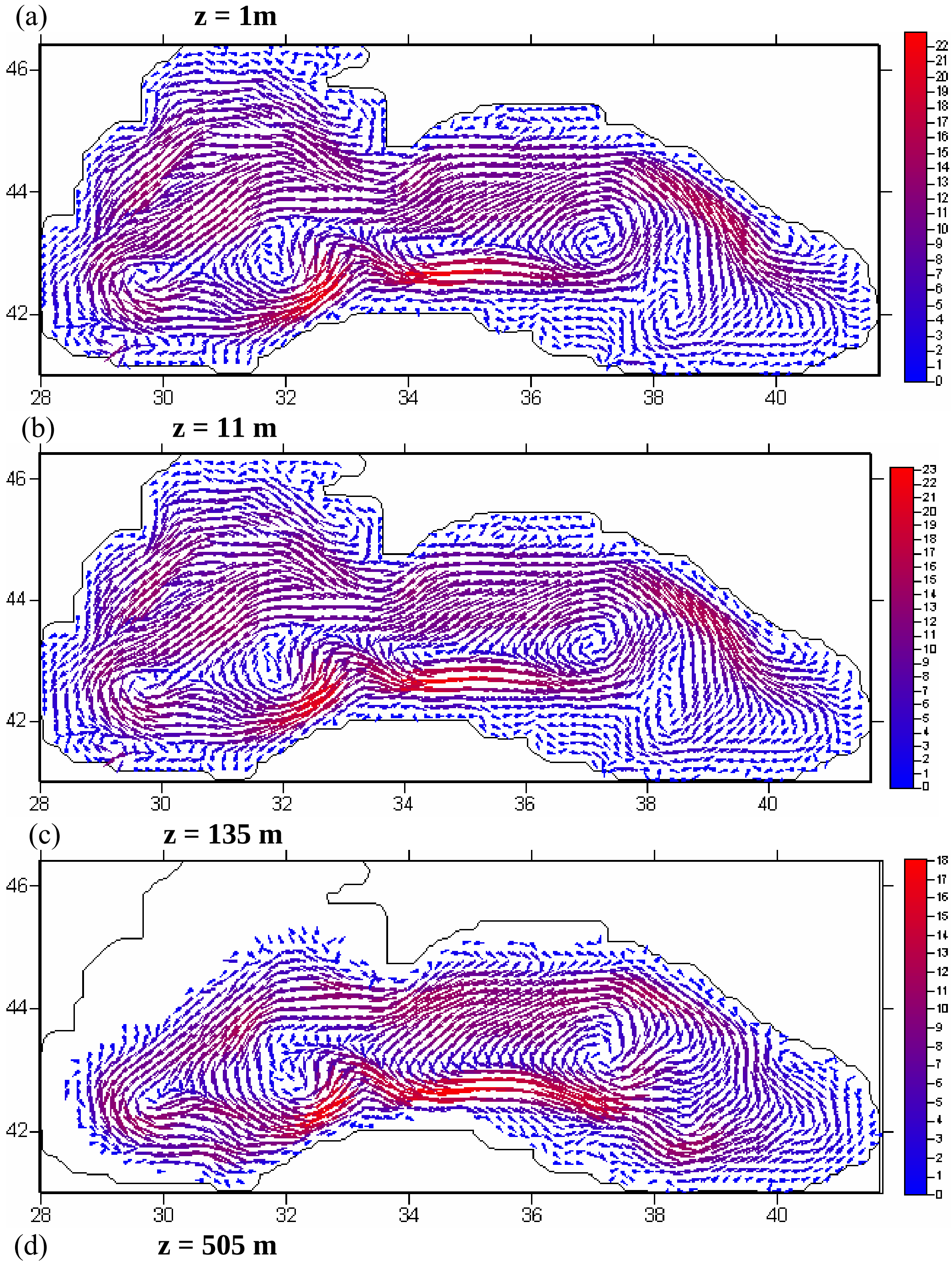
Figures 3 and 4 illustrate the vertical structure of sea circulation in two cases, when the state of the atmosphere was close to calm (Fig. 3) and at strong winds (Fig. 4). During the moderate and strong winds, which favors the breakup of vortical formations near the sea surface (Fig. 4a), as the depth increases, the sea circulation experiences more substantial qualitative and quantitative changes than during weak winds. As a result from a depth of about 15-20m, the circulation acquires a vortical character with the BSRC and cyclonic gyres in the open part of the basin. At the state of the atmosphere close to calm, the sea circulation with well expressed vortexes it is almost homogeneous on a vertical (Fig.3).

Figure 5 illustrate changeability of the surface temperature field for the time period 634-742 h. The temperature field changed insignificantly in such short–term period. The same may be said about salinity field. The annual variability of these fields in the model was caused mainly by the annual variations in the fields of salinity and temperature at the sea surface that were used as the boundary conditions.



ISSN 1512-1461

Fig.2. Calculated current fields at a depth of 1 m corresponding to the following wind types (January): (a) northeasterly (1 m/s), t = 634 h; (b) northerly (10-15 m/s), t = 658 h; (c) northwesterly (1 m/s), t = 672 h; (d) southwesterly (5-10 m/s), t = 690 h; (e) westerly (1m/s), t = 704 h; (f) northwesterly (5-10m/s), t = 472 h.



ISSN 1512-1461

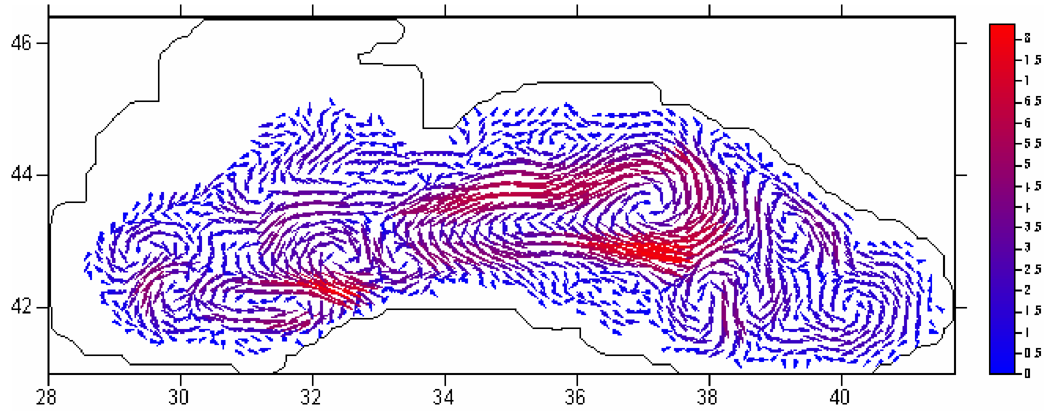
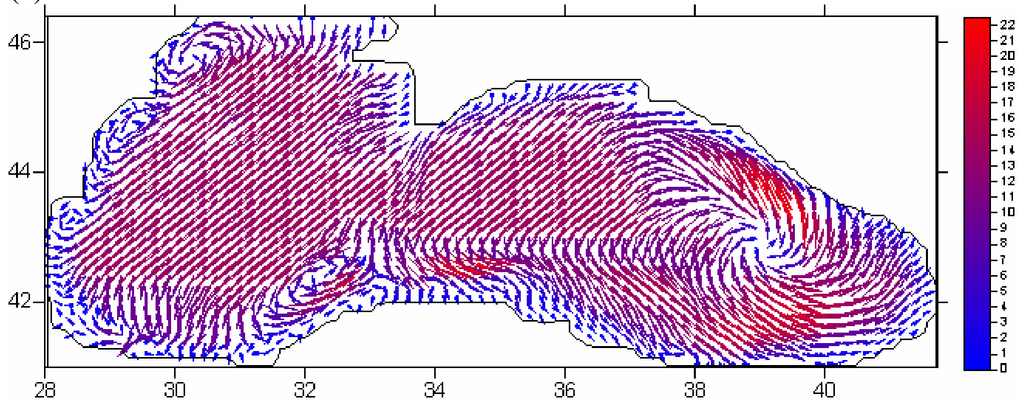
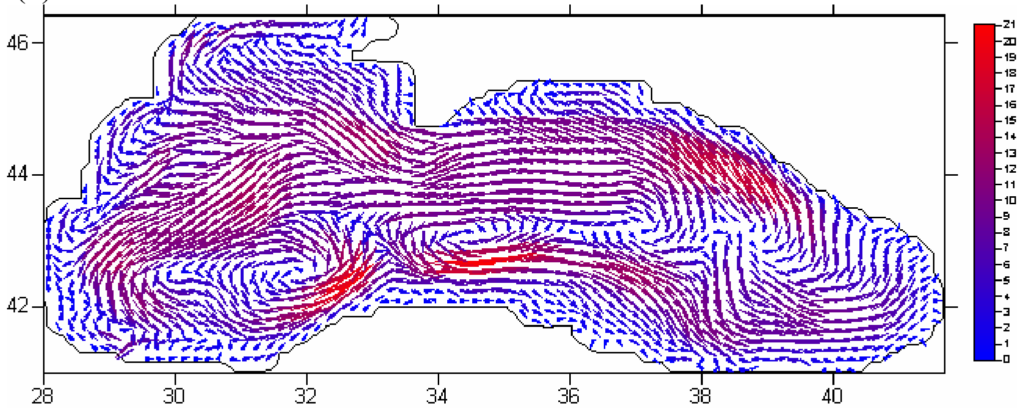


Fig. 3. Computed current patterns on different depths at t = 634 h, when the state of the atmosphere was close to calm (1m/s).

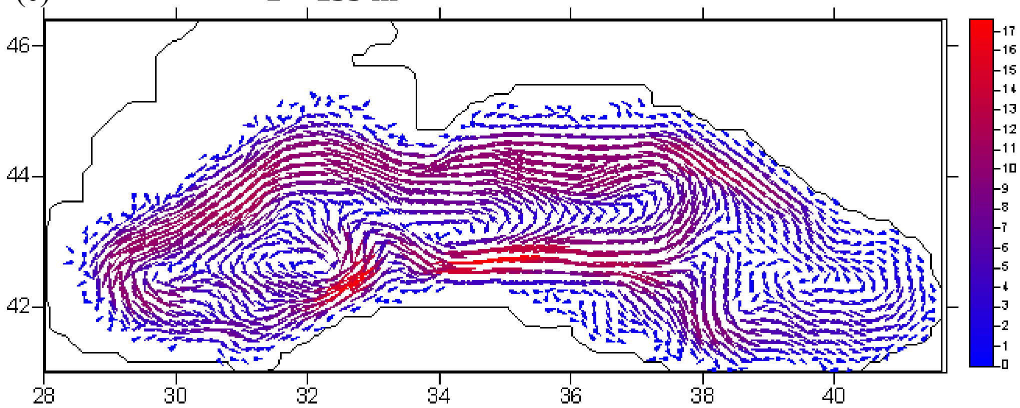
(a) **z = 1m**



(b) **z = 11m**



(c) **z = 135 m**



(d) **z = 505 m**

ISSN 1512-1461

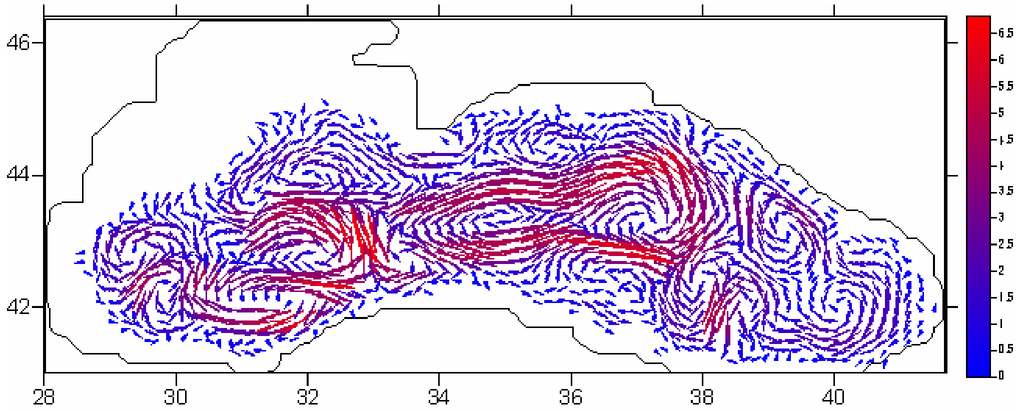


Fig. 4. Computed current patterns on different depths at t = 658 h, when above the sea surface acted northerly wind (10-15m/s).

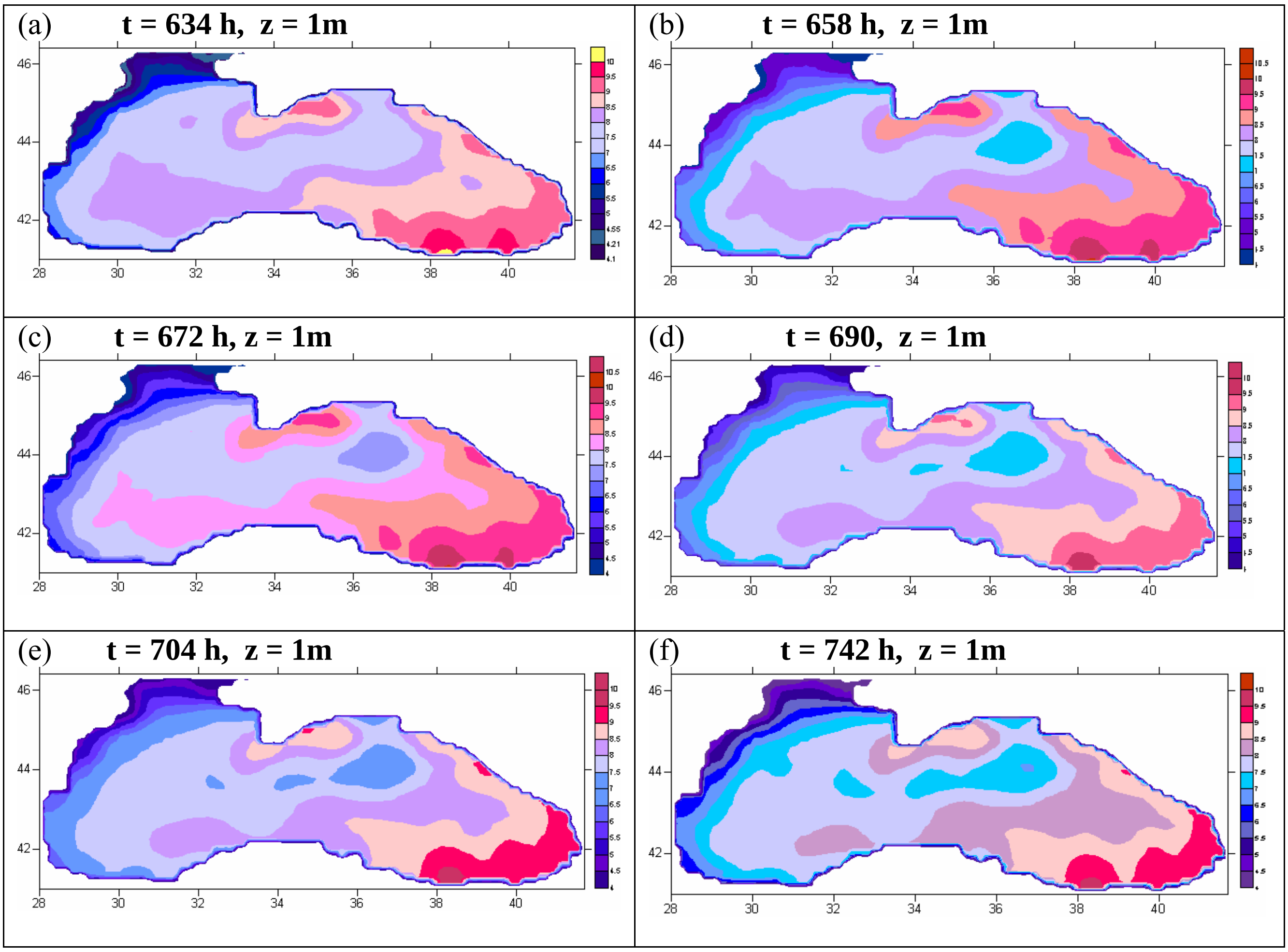


Fig. 5. Computed temperature fields at a depth of 1 m corresponding to the following wind types (January): (a) northeasterly (1 m/s), t = 634 h; (b) northerly (10-15 m/s), t = 658 h; (c) northwesterly (1 m/s), t = 672 h; (d) southwesterly (5-10 m/s), t = 690 h; (e) westerly (1m/s), t = 704 h; (f) northwesterly (5-10m/s), t = 472 h.

In order to illustrate the transformation of sea-surface circulation during the warm period we chose the time interval 2774 – 2862 h (the end of April), when the circulation was reorganized as shown in the table 2. In Fig. 6 are shown wind stress fields at the Black Sea surface corresponding to the cyclonic (5-10 m/s) and northwesterly (10-15 m/s) winds.

ISSN 1512-1461

Table 2. Alternation of wind types in the interval 2774-2862 h (April)

№	Wind direction	Wind speed, m/s	Time intervals, hours
1	Cyclonic	5-10	2774-2798
2	Northwest.	1	2798-2822
3	Northwest.	10-15	2822-2838
4	Southwest.	1	2838-2862

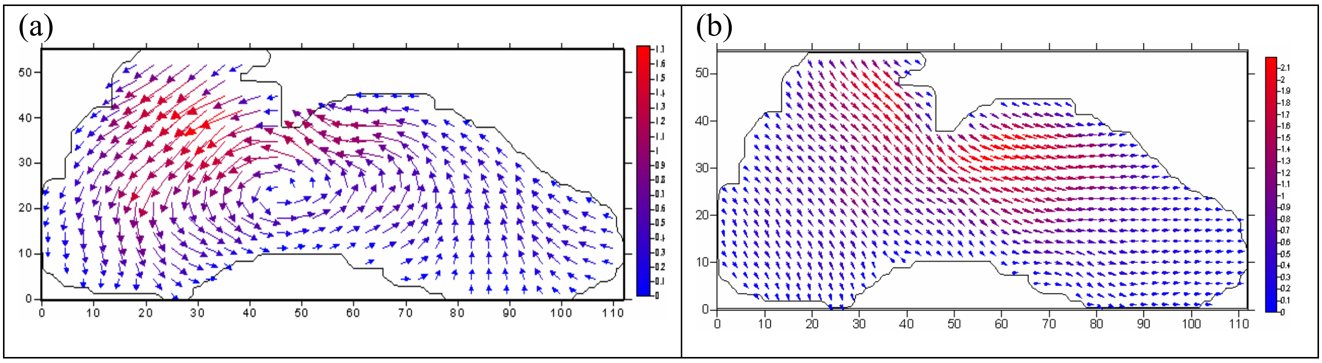
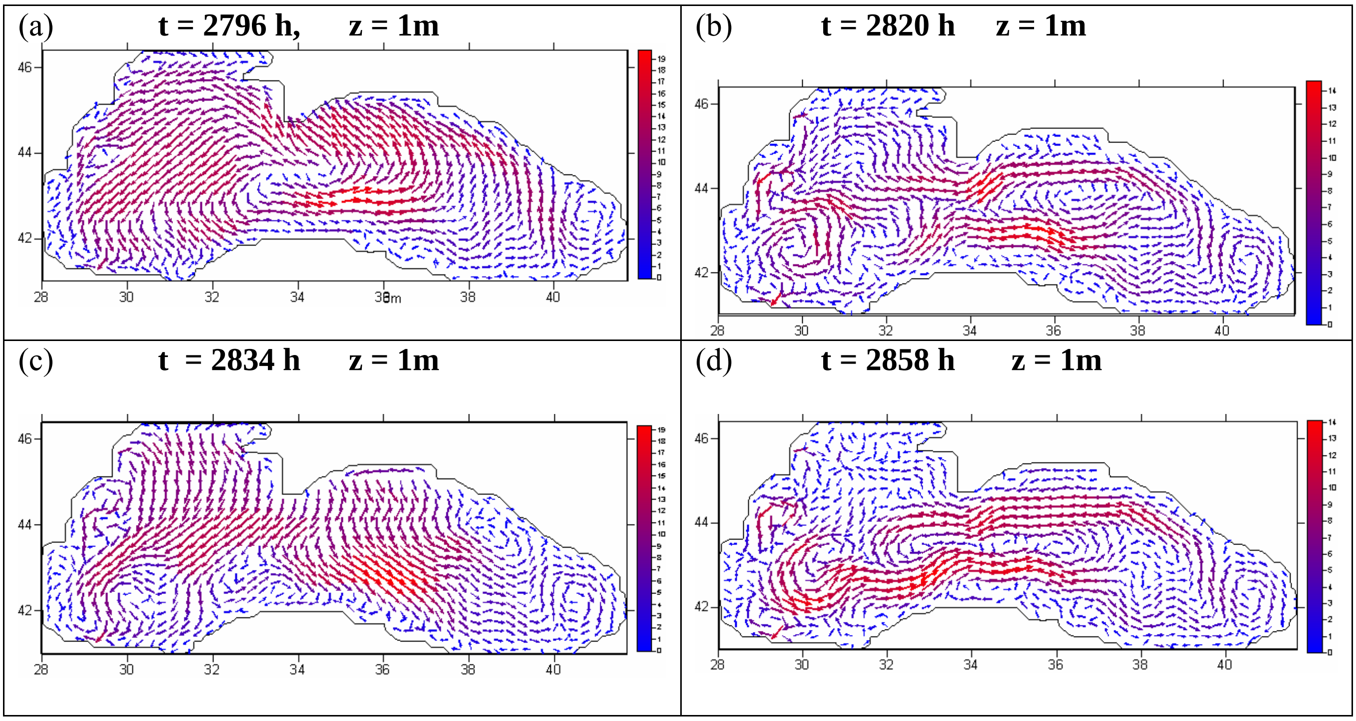


Fig. 6. Vector fields of the wind stress corresponding to (a) cyclonic (5-10 m/s) and (b) northwesterly (10-15 m/s) winds.



ISSN 1512-1461

Fig. 7. Calculated current fields at a depth of 1 m corresponding to the following wind types (August): (a) cyclonic (5-10 m/s), t = 2796 h; (b) northwesterly (1 m/s), t = 2820 h; (c) northwesterly (10-15 m/s), t = 2834 h; (d) southwesterly (1 m/s), t = 2858 h.

Figure 7 illustrates transformation of the sea circulation at depth of 1 m under the forcing of atmospheric circulation indicated in table 2. From this Figure it is also visible, that vortex circulations are more well expressed in case of weak wind speeds (Figs 7b and 7d). Among coastal anti-cyclonic eddies the anticyclonic vortex in the southeast part of the basin is more intensive (the so-called Batumi anticyclone). Numerical experiment has shown that Batumi eddy is rather steady formation during warm season. It is interesting to note, that the similar conclusion is obtained in [23].

4. SIMULATION AND FORECAST OF REGIONAL CIRCULATION

Simulation and forecast of regional circulation processes in the Georgian near-shore zone of the Black Sea was carried out on the basis of the regional model (developed on the basis [28-32]), which was nested in the grid of BSM of Marine Hydrophysical Institute (MHI, Sevastopol/Ukraine) within the International project **ARENA**. The regional area was limited by Georgian coastline and liquid boundary along 41^0E covering Sokhumi, Poti and Batumi ports.

Methodology of nested grid modelling and input data

At realization of the suggested regional model for the local area the sea surface was covered with a grid using horizontal constant step equal 1 km and grid nodes 69 and 203 along axes x and y, respectively. On a vertical the non-uniform grid with 27 calculated levels on depths: 1, 3, 5, 7, 11, 15, 25, 35, 55, 85, 135, 205, 305, …, 1505 m were considered. Time step $\Delta t = 1$ h.

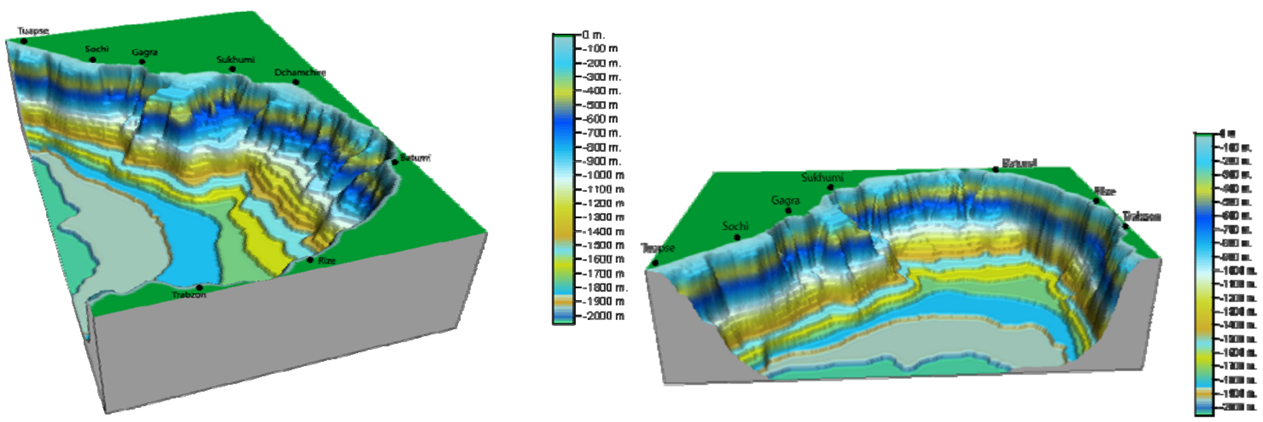


Fig. 8. The spatial images of the bottom relief of the east part of the Black Sea.

In Figure 8 the spatial image of the east part of the Black Sea (the western boundary is along meridian passed approximately through Tuapse city) with different orientation is shown.

All input data needed for forecast of hydrophysical fields were obtained from MHI on a grid of BSM with 5 km spacing. These input data represented the initial fields corresponded to the Georgian water area and two-hour-step data of forecast obtained by BSM and atmosphere forcing data during 48 hours. Particularly, these data were following: (1) Wind stress components on the Black Sea surface, (2) surface heat fluxes, (3) evaporation, (4) precipitation, (5) 3D hydrophysical fields (temperature, salinity, current velocities) as at initial moment t = 0, also their prognostic values (obtained from BSM) for our local area.

ISSN 1512-1461

During realization of the nested grid model the received 3D initial fields and atmosphere forcing data were interpolated from the grid of BSM (with 5 km resolution) to the grid of nested grid model (with 1 km resolution). Besides, after each 2 hours during integration from 3D prognostic hydrophysical fields have been obtained lateral boundary conditions for velocity components, temperature and salinity on the liquid boundary.

The regional model outputs were 1-day and 2-days forecasts of current, temperature and salinity fields with 1 km spacing on all calculated levels in the Georgian near-shore zone.

4.4 Results of forecast

An International scientific and technical pilot experiment on functioning of the Black Sea Nowcasting/Forecasting System in the near-real time regime has been carried out during July 2005. Before carrying out of the pilot experiment there was a preparatory stage whose main goal was joining our regional model with the BSM of MHI. With this purpose test numerical experiment on forecast of Black Sea regional circulation was carried out for time period ***7 June, ooh, 2003 – 15 June, 00h, 2003.*** All needed input data received from MHI were the same as described in previous section, but there were climatic atmospheric input data instead of prognostic one. Integration of the model equation system started on 00h, 7 June 2003 with duration 8 days.

Figures 9-12 show calculated current fields computed from the regional high resolution model (left side) and from BSM of MHI (right side) at different time moments on depths 5 and 55 m.

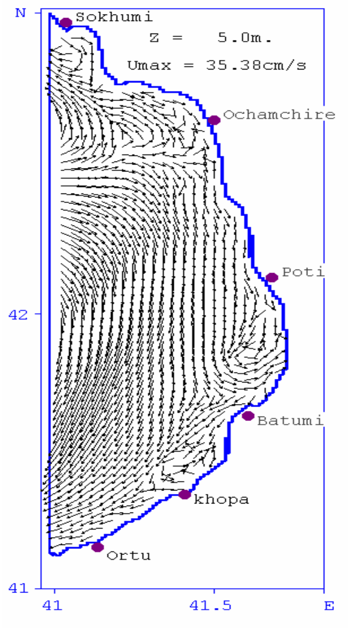
Comparison of current patterns received from these models shows that results of regional simulation closely follow the simulation of the BSM. The main difference is in the narrow shelf region - the high-resolution nested-grid model describes formation of small coastal eddies while they are not observed in BSM results.

After that, the International pilot experiment on operational functioning of the Black Sea Nowcasting/Forecasting System has been carried out. The experiment started at 12-00 o'clock on July 22, 2005. Every day during 5 days we calculated forecasts of hydrophysical fields (currents, temperature, salinity) for 48 hours and placed results of calculations on ftp-site for the time moments of 24 and 48 hours after the beginning of calculations.

To illustrate the results of forecast there are presented prognostic fields (Figs. 13 and 14) in case of forecast times: 12-00 h, 22 July – 12-00 h, 24 July.

8 June 2003, 18 h

ISSN 1512-1461



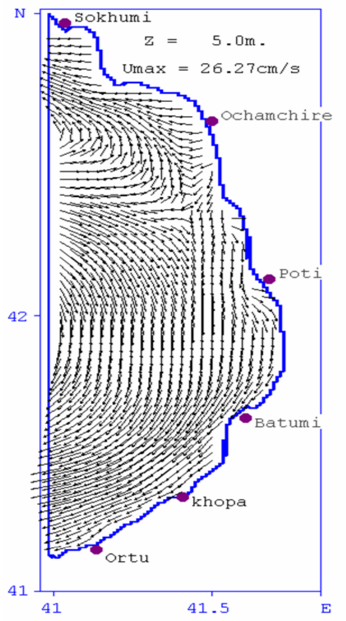


Fig. 9. Computed current fields obtained (a) from regional model and (b) from BSM of MHI. on depth of 5m at time moment 18h 8 June 2003.

8 June 2003, 18 h

ISSN 1512-1461

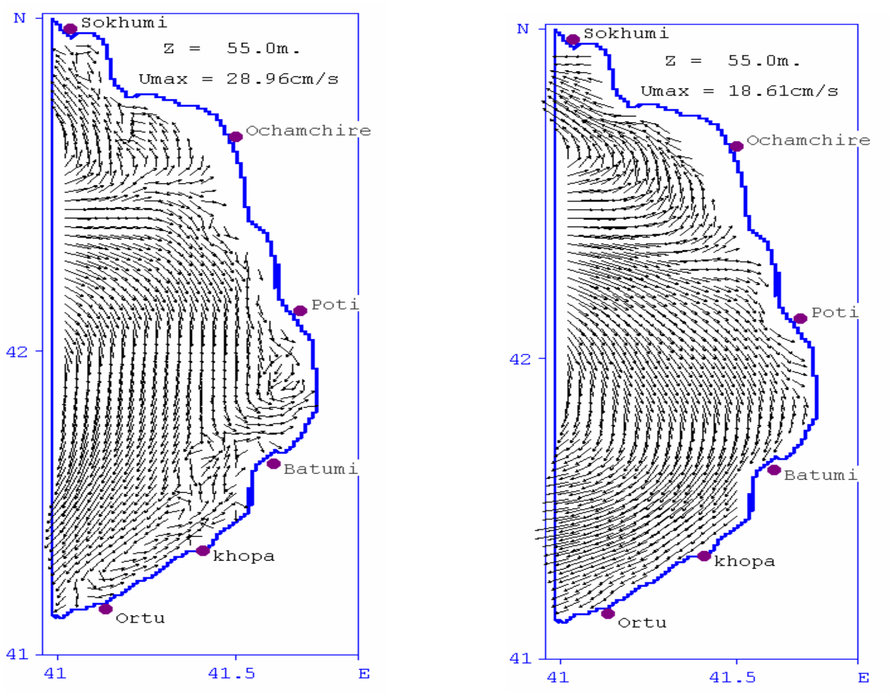


Fig. 10. The same as in Fig.9, but on depth of 55m.

10 June 2003, 18 h

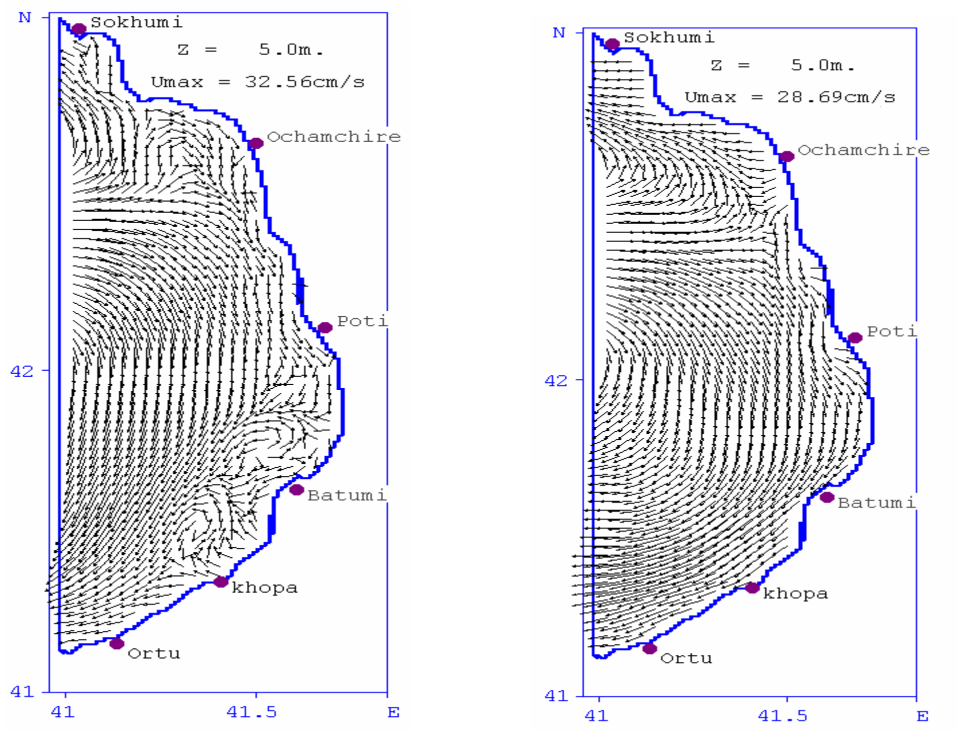


Fig.11. The same as in Fig.9, but at time moment 18 h, 10 june 2003

10 June 2003, 18 h

ISSN 1512-1461

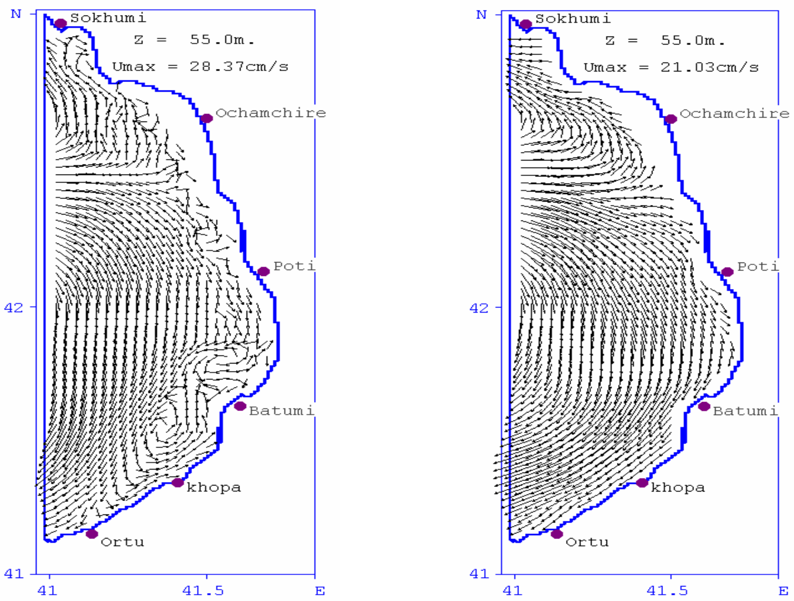


Fig.12. The same as in Fig.11, but on depth of 55 m

The analysis of results of marine forecasts, which was carried out in MHI, has shown that results of the forecast are in the good agreement with observational data. It is necessary to notice that the conducted International scientific and technical experiment on functioning of the Black Sea Nowcasting/Forecasting System has caused wide interest and both its scientific and practical value has been highly appreciated by experts-oceanologists of the Black Sea riparian countries [57].

Forecast time: 12-00 h 22 July - 12-00 h, 24 July

23 July 12-00 o'clock

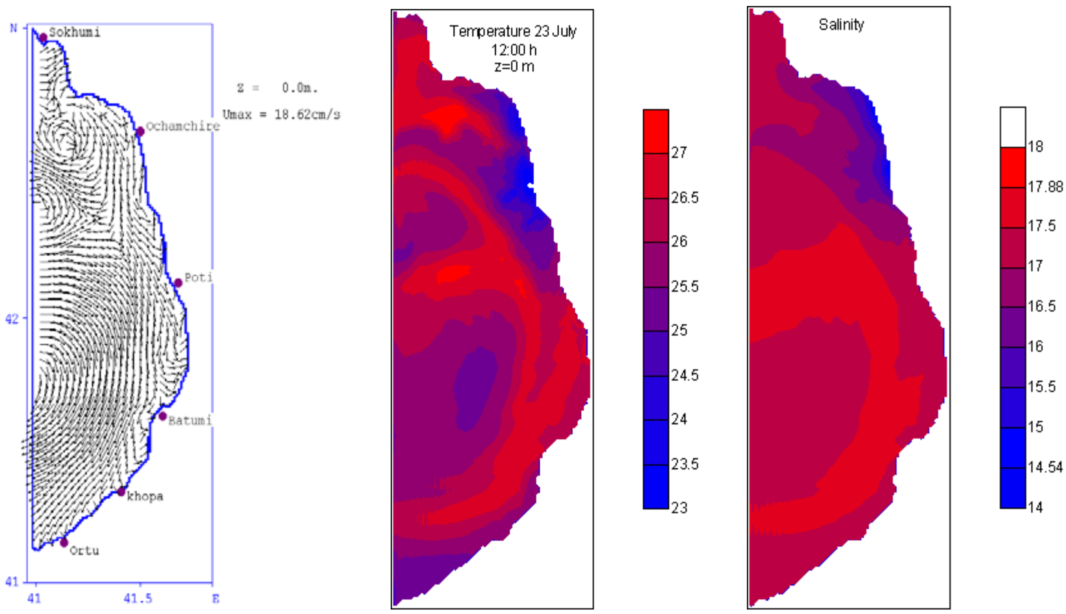


Fig.13. Calculated prognostic fields of current, temperature and salinity on the sea surface at 12- 00 o'clock, 23 July 2005.

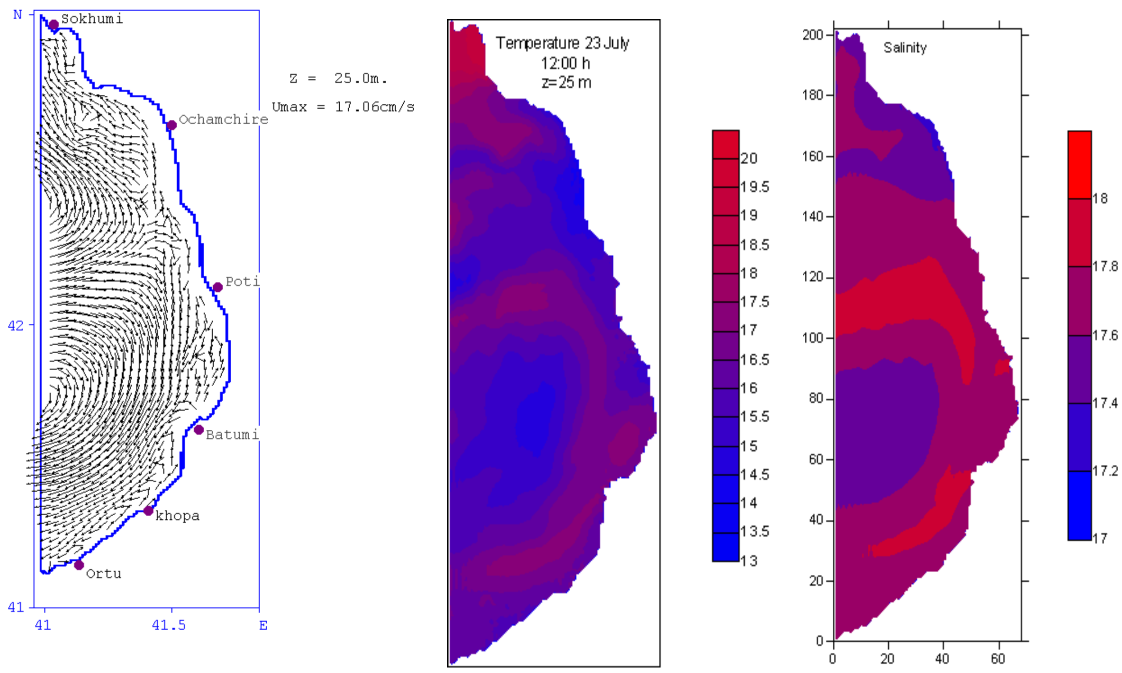


Fig.14. The same as in Fig.13, but on depth of 25 m

5. CONCLUSION

Two versions of the 3D baroclinic prognostic model of dynamical processes in the Black Sea are developed at M. Nodia Institute of Geophysics: the model of basin-scale circulation (BSM) and the model of regional circulation. These models were applied to simulate and forecast dynamical processes in the Black Sea. The numerical experiments performed by the use of the BSM, have allowed to receive a number of the conclusions concerning the influence of separate physical factors on character of the general circulation in the Black Sea. Significant conclusions are that strong winds developed above the territory of the Black Sea promote disintegration of vortexes in the upper layer of the Black Sea and on the contrary - at weak atmospheric winds vortical motion is well expressed. At the moderate and strong winds with increase of depth, the Black Sea circulation undergoes more essential qualitative and quantitative changes than at weak winds as a result of which, starting from depth approximately 15-20 meters, circulation accepts vortical character with formation of BSRC and cyclonic eddies in the open part of the basin.

Calculations on simulation and forecast of hydrophysical fields in the Georgian water area of the Black Sea with 1 km spacing with the use of the regional model are performed**.** As boundary conditions on the liquid boundary separating this water area from the open part of the Black Sea, results of calculation on BSM of MHI were used.

The pilot experiment on operational functioning of the Black Sea Nowcasting/Forecasting System has been carried out for the first time in the framework of the International project **ARENA**. This experiment showed that developed system can function in the near-real time regime successfully. Comparison of results of forecasts computed from BSM of MHI and our high resolution nested grid model showed that the increase of spatial resolution of the regional model is very important in order to adequately reproduce coastal eddies of small sizes near the Georgian seashore.

ISSN 1512-1461

REFERENCES

1. Filippov D. M. Circulation and Structure of Waters of the Black Sea. Moscow, Nauka, 1968, 132 p (in Russian).
2. Hydrometeorology and Hydrochemistry of seas of USSR. The Black Sea. Sankt-Peterburg, 1991. t.4 (in Russian).
3. Knipovich N. M. Hydrological Researches in the Black Sea. Proceed. of Azov - Black Sea scientific industrial expedition, 1932, issue 10, 272 p (in Russian).
4. Practical Ecology of Marine Regions. The Black Sea. Kiev, Naukova Dumka, 1990, 251 p (in Russian).
5. Mazmanidi N.,Komaxidze A. Basis of an ecology-tocsin diagnostic of influence of pollution on the sea's organisms. Regional Conference of the UNESCO-MAB - „ A Man and Nature". Abstracts, Tbilisi, 1995, pp. 122-123.
6. Mirtskhulava Ts. Saving of the Black Sea we must search in a timely prognosis of its state. Regional Conference of the UNESCO-MAB - „ A man and nature". Abstracts, Tbilisi, 1995, pp. 134-135.
7. Riabinin A. I., Kravec V. N. The modern state of a hydrosulphuric zone of the Black Sea. Moscow, Gidrometeoizdat, 1989, 230 p (in Russian).
8. Soliankin E. V. The macroclimatic role of the Black Sea. Oceanology. 1964, v.4, Issue 2, pp. 45-52 (In Russian).
9. Marchuk G. I., Kordzadze A. A., Skiba J. N. calculation of the basic hydrological fields of the Black Sea on the basis of a splitting method. Izv. Acad. Sci. USSR, Atmospheric and oceanic Physics. 1975, vol..11, N 4, p. 379 - 393.
10. Marchuk G. I., Kordzadze A. A., Zalesny V. B. A problem of mathematical modeling of sea and oceanic currents. In: The Differential and Integrated Equations. Boundary Problems. Tbilisi, 1979. p. 99 – 151 (in Russian).
11. Marchuk G. I., Kordzadze A. A. The perturbation theory and statement of inverse problems of ocean dynamics. In: Proceedings of Tbilisi State University. Mathematics, Mechanics Astronomy, 1986, vol. 259 , p. 49-65 (in Russian).
12. Kordzadze A. A. Numerical modeling of circulation of waters of the Black Sea basin. In: Modeling of Hydrophysical Processes in Closed Water Basins and Seas. Moscow, Nauka, 1988. pp.125-140 (in Russian).
13. Kordzadze A. A. Mathematical modeling of sea current dynamics (theory, algorithms, numerical experiments), Moscow, Depart. Comp. Math. Acad. Sci. USSR, 1989, p.218 (in Russian).
14. Girgvliani A. G. On numerical modeling of shallow water problems. Preprint № 454, Comp. Cent. Siberian Branch Acad. Sci. USSR, Novosibirsk, 1983, 18 p (in Russian).
15. Demin Iu. L., Trukhchev D. I. Numerical modeling of currents near the western coast of the Black Sea. Meteorologia i Gidrologia, 1984, № 2, pp.54-61 (in Russian).
16. Zalesny V. B., Kordzadze A. A., Girgvliani A. G. Numerical modeling of seasonal course of the Black Sea hydrodynamics. In: Numerical solution of problems of ocean dynamics. Comp. Cent. Siberian Branch Acad. Sci. USSR, Novosibirsk, 1982, pp.75-85 (in Russian).
17. Klimok V. I., Makeshov K. K., Pertseva M. V. On numerical modeling of currents on the north-western shelf of the Black Sea. Morskoy Gidrophysicheskiy Journal, 1989, N 3, pp.20-27 (in Russian).
18. Stanev E., Trukhchev D., Rusenov B. The Black Sea Water Circulation and Numerical Modelling of Currents. Sofia, Kliment Ohridski University Press, 1988, 221 p (in Russian).
19. Oguz T., Latun V. S., Latif M. A. et al . - Circulation in the surface and intermediate layers in the Black Sea. Deep Sea Res. 1993, v. 1, N 40, pp. 597-612.
20. Demyshev S. G., Korotaev G. K. Numerical modeling of the seasonal course of the synoptic variability of the Black Sea. Izv. RAN, Atmospheric and Oceanic Physics, 1996, t.32, № 1, pp. 108-116 (in Russian).

ISSN 1512-1461

21. Oguz T., P. Malanotte-Rizzoli, D. Aubrey. - Wind and thermohaline circulation of the Black Sea Driven by yearly mean climatological forcing, J. Geophys. Res., 100 (C4), 1995, pp.6845-6863.
22. Staneva, J. V., D. E. Dietrich, E. V. Stanev, M. J. Bowman. - Rim current and coastal eddy mechanisms in an eddy-resolving Black Sea general circulation model, J. Marine Systems, Elsevier, 2001, v. 31, pp. 137-157.
23. Korotaev, G., T. Oguz, A. Nikiforov, and C. Koblinsky. Seasonal, interannual, and mesoscale variability of the Black Sea upper layer circulation derived from altimeter data, J. Geophys. Res., 108(C4), 3122, 2003, doi:10.1029/2002JC001508.
24. Korotenko K. A., Dietrich D. E., Bowman M. J. Modeling Circulation and oil spill transport in the Black Sea. Okeanologia, 2003, t. 43, №3, pp. 367-378 (in Russian).
25. Kara, A. B., A. J. Wallcraft and H. E, Hurlburt. - A New Solar Radiation Penetration Scheme for use in Ocean Mixed Layer Studies: An Application to the Black Sea Using a Fine –Resolution Hybrid Coordinate Ocean Model (HYCOM), J. Physical Oceanography, *vol 35,* 2005, pp.13-32.
26. Kara, A. B., A. J. Wallcraft and H. E. Hurlburt. - Sea Surface Temperature Sensitivity to Water Turbidity from Simulations of the Turbid Black Sea Using HYCOM, Journal of Physical Oceanography, vo*l* 35, 2005, pp.33-54.
27. Kara, A. B., H. E. Hurlburt, A. J. Wallcraft and M. A. Bourassa, - Black Sea Mixed Layer Sensitivity to Various Wind and Thermal Forcing Products on Climatological Time Scales, J. Climate, vol. 18, 2005, pp. 5266-5293.
28. Demetrashvili D. I.- Modeling of hydrophysical fields in the Black Sea, J. Georgian Geophys.Soc., v.8b, 2003, pp.19-27.
29. Kordzadze A. A., Demetrashvili D. I. - Results of numerical experiment on modeling of inner-annual hydrological regime of the Black Sea, J. Georgian Geophys. Soc., v.8b, 2003, pp.3-18.
30. Kordzadze A. A., Demetrashvili D. I. - Numerical modeling of inner-annual variability of the hydrological regime of the Black Sea with taking into account of alternation of different types of the wind above its surface. Proceed. of Intern. Conference: "A year after Johanesburg-Ocean Governance and Sustainable Development: Ocean and Coasts – a Glimpse into the Future". Kiev, Ukraine, October 27-30, 2003, pp.495-505.
31. Kordzadze A. A., Demetrashvili D. I., Surmava A. A. About circulation in the Black Sea at very strong and weak winds. Meteorologia i Gidrologia, № 9, 2007, pp. 58-64 (in Russian).
32. Kordzadze A. A., Demetrashvili D. I., Surmava A. A. Numerical modeling of hydrophysical fields of the Black Sea under the conditions of alternation of atmospheric circulation processes. Izvestiya AN. Fizika Atmosphery i Okeana, т.44, № 2, 2008, pp. 227- 238.
33. Kordzadze A., Demetrashvili D. - Simulation and forecast of hydrophysical fields in the part of the Georgian Black Sea coastal zone. J. Georgian Geophys. Soc.,v.12b, 2008, pp.3-16.
34. Korotaev G., Cordoneanu E., Dorofeyev V., Fomin V., Grigoriev A., Kordzadze A., Kubryakov A., Oguz T., Ratner Yu., and Slabakov H. Near-operational Black Sea nowcasting/forecasting System. In: European Operational Oceanography: Present and Future. 4th EuroGOOS Conference, 6-9 June 2005, Brest, France. 2006, pp.269-275.
35. Korotaev G. K., Eremeev V. N. Introduction to the Operative Oceanography of the Black Sea. Sevastopol/Ukraine, NPC "EKOCI-Gidrophizika", 2006, 382p (in Russian).
36. Mamaev O. I., The simplified dependence between density, temperature and salinity of sea water. *Izv. Acad. Nauk SSSR, Ser. Geofiz., 1964, N 2, pp.309-311.*
37. Budyko M. I. Heat balance of the Earth's surface. Leningrad, Gidrometeoizdat, 1956, 254 p (in

ISSN 1512-1461

Russian).
38. Berlyand G. G. Method of climatological calculation of the net radiation. Meteorologia I Gidrologia. 1960, N 6, pp.9-12 (in Russian).
39. Zilitinkevich S. S., Monin A. S. The turbulence in dynamical models of the atmosphere, Leningrad, Nauka, 1971, 44 p (in Russian).
40. Marchuk G. I., Kochergin V. P., Sarkisyan A. S., et al. Mathematical models of ocean circulation, Novosibirsk, Nauka, 1980, 288 p (in Russian).
41. Bubnov M. A., Kazhikhov A. B. Theorems of existence and uniqueness in some problems of the linear theory of oceanic circulation. In.: Dynamics of the Continuous Environment. 1970, issue 6., pp.223-237(in Russian).
42. Kordzadze A. About uniqueness of the solution of one problem of ocean dynamics. Dokladi AN SSSR, 1974, t.219, N 4, pp.856-859 (in Russian).
43. Kordzadze A. About resolvability of one stationary problem of the baroclinic ocean dynamics. Dokladi AN SSSR, 1977, t.232, N 2, pp.308-311 (in Russian).
44. Kordzadze A. About resolvability of problems of ocean dynamics with taken into account wind driven currents. Dokladi AN SSSR, 1977, t.237, N 1, pp.52-55 (in Russian).
45. Kordzadze A. A. Mathematical Problems of Solving Problems of Ocean Dynamics. VTs SO AN SSSR, Novosibirsk, 1982, 148 p (in Russian) (in Russian).
46. Sukhonosov V. I. On the Correctness as a whole of a three-dimensional problem of ocean dynamics. In: Mechanics of Inhomogeneous Continuous Media. VTs CO AN SSSR, Novosibirsk, 1981, N 52, pp.37-53 (in Russian).
47. Marchyk G. I. The numerical solution of the problems of the atmosphere and ocean dynamics. Leningrad, Gidrometeoizdat, 1974, 303 p.(in Russian).
48. Demetrashvili D., Kordzadze A. Numerical modeling of distribution of pollution substances in the Black Sea. Reports of enlarged sessions of the seminar of I. Vekua Institute of Applied Mathematics. 2002, vol. 17, N 3, pp. 44-57.
49. Demetrashvili D., Kordzadze A. Determination of the pollution source location in the Black Sea on the basis of conjugate equations theory. Reports of enlarged sessions of the seminar of I. Vekua Institute of Applied Mathematics. 2002, vol. 17, N 3, pp. 58-70.
50. Kordzadze A., Demetrashvili D., About the forecast of distribution of anthropogenous impurity and about an establishment of coordinates of a source of pollution in the Black Sea. Proceed. of the 2st Intern. Silk Road Symposium "BSEC Studies", Tbilisi, 6-7 May, 2005, pp.103-109.
51. Harvey D. The atmosphere and the ocean. Moscow, Progress, 1986, 183 p (in Russian).
52. Kordzadze A., Demetrashvili D. Numerical experiments on model of the Black Sea dynamics taking into account absorption of solar radiation. In: Comput. Mathemat. and Mathematical Modeling. Proceed. Intern. Workshop Devoted to 75-years of Academ. G. I. Marchuk and 20-years of Institute for Numerical Mathematics. Moscow, 19 - 22 June, 2000 , pp. 125 – 134 (in Russian).
53. Atlas of excitement and a wind of the Black Sea, Leningrad, Gidrometeoizdat, 1969, 112 p (in Russian).
54. Kordzadze A., Tavartkiladze K., Kvaratskhelia D. A structure of the wind continuous field on the Black Sea surface. J. Georgian Geophys. Soc. 2000., v. 5b, p.28-38.
55. Boguslavsky S. G. Efimov V. V., Cherkesov L. V., et al., Complex Oceanographic Studies of the Black Sea. Naukova Dumka, Kiev, 1980 (in Russian).
56. Lacombe H. Cours d'Oceanographie Physique. Gauthier-Villars, Paris, 1965; Mir, Moscow, 1981.
57. Operative oceanography: Black Sea under the control of scientists. The newspaper "Slava Sevastopolia" Ukraine, #153 (22088), 19 August, 2005 (in Russian).

Article received: 2010-05-24