Oscillations of the Marine Hydrodynamic Parameters in Subinertial Range: Statistical Analysis and Numerical Modeling for the Crimean Shelf

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Subinertial waves at the Black Sea shelf have been thoroughly studied in the last decades from the theoretical, observational and experimental points of view. Results of numerical prognostic experiments on modeling of the Black Sea circulation based on thermo-hydrodynamic eddy-resolving MHI model are studied. Spectral peaks in the oscillations of the current velocity component vector, temperature, salinity and vertical velocity are identified for the selected stations by means of the Fourier spectral analysis. The obtained energy-transporting oscillations are interpreted using expert estimates and comparison with the previous research. Time range of numerical calculation is conditioned by availability of data on the mass and energy external flows (reanalysis of the atmosphere state). Hydrodynamic parameters for April, 2006 and May – September, 2013 are considered. It is noted that seasonal variability of stratification and the model high sensitivity to the wind effects condition spectral characteristics of the wave processes on sub-inertial scales and intensity of mixing of the upper mixed layer. Two main energy-carrying intervals where the oscillations are confidently reconstructed by the modelare pointed out: large-scale relatively slow movements with the periods from 4 to 7 days and short-period waves with the periods from 10 to 40 hours. Due to relatively smooth bathymetry, origins of the short-period oscillations are hard to trace.

Keywords: oscillation, internal waves, shelf, the Black Sea, numerical modeling, spectra.

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Introduction. The Black Sea Crimean shelf stands out as the area affected by the most intensive economic and recreational impact. As it was pointed out in [1], to study the human impact on the shelf it is necessary to know the nature of water circulation and thermohaline structure dependence on the various meteorological factors. The sea dynamics on the climate scale was analyzed by means of experimental methods and numerical simulation. New generation of sensors and platforms such as drifters, gliders, optical and infrared satellites and high-frequency radars, provides access to information about the current state of the ocean with a higher degree of accuracy and efficiency. Active and widespread use of high-performance calculations in the simulation generates huge amount of reanalysis data and marine environment forecast with high spatial and temporal resolution. Only joined efforts of scientists and government agencies from different countries made possible the appearance of integrated monitoring system of the ocean in the global and regional scale, which allows filling a database with information on phenomena and structures occurring on subinertial frequencies and synoptic scales.

The purpose of this stage of the research was obtaining information on the parameters of wave dynamics, water circulation oscillation structure and vertical thermohaline structure of the sea on the Crimean shelf. To gain the aforementioned goal and to assess the contribution of different factors forming the sea state in spring and summer at test water areas, a series of numerical calculations according to the model of Marine Hydrophysical Institute (MHI) with high spatial resolution [2, 3], were carried out.

The object of research was an area of the Black Sea, located near the coast and on the shelf slope near the Oceanographic platform (Katsiveli village).

The method of research is space-time and statistical analysis of temperature series, salinity and currents at selected Stations with the assistance of previous theoretical research results and expeditionary observations.

According to the adopted classification of variability of hydrophysical fields, the attention was focused on two intervals of spatial and temporal variability: mesoscale inhomogeneities (from hundreds of meters to kilometers, periods from hours to days), manifested in the form of internal waves, topographic, inertial and tidal fluctuations, and synoptic inhomogeneities (tens of kilometers, several days period), manifested in the form of Rossby waves and synoptic eddies. These variation forms make a decisive contribution to the dynamics of the marine pollution distribution on the background of a quasi-periodic circulation. In addition, internal waves can participate in the pollution capture and distribution over the long distances. The understanding of such effect mechanisms is impossible without specifying of their characteristics and the characteristics of the dynamics at different combinations of environmental conditions. In our research we basically tried to solve the problem of variability describing in the chosen scale by means of linear wave theory and the usage of the perturbation method, which was started in [4].

Along with the experimental and theoretical research of the current field and thermohaline structure of the Black Sea there is an extensive scientific literature concerning the offshore areas wave dynamics [5 – 8]. The southern coast of Crimea, Sevastopol stead, oceanographic platform in the village Katsiveli and the Kerch Strait traditionally were the area of the most intensive wave processes monitoring on inertial and subinertial frequencies. Particularly, in the 1980-s the most advanced autonomous buoy Stations (ABS) measurements of that period were summarized [7]. A comprehensive analysis of the arrays, which combines ABS data, ground installations, measurements, oceanographic platform measurements and hydrological survey on R/V *Professor Kolesnikov* is still unsurpassed by the density field experiment and breadth of the energy spectrum of researched dynamic processes. Also there were published several original works concerning the wave motion modeling [9 – 13], which form the understanding of shelf role as the waveguide that define these fluctuations; importance of shelf width variability and the coastline shape was highlighted; energy interchange mechanism of barotropic oscillations with quasi-steady stream current, conventionally representing the Black Sea Rim Current (BSRC) was described.

The works [14, 15] are dedicated to physics of barotropic and baroclinic oscillations in a stratified basin, to the wave motion interaction with the large-scale current field and their contribution to the water exchange between the shelf and the open seas. Thus, this spectrum of fluctuations (well-known due to experimental research [1]) at the inertial and subinertial frequencies was reproduced by means of three-dimensional numerical model of the Black Sea circulation *GHER* [14].

Description of the model. Model equations in the Boussinesq approximation, hydrostatic and incompressible sea water were recorded in a Cartesian coordinate system. x axis is directed to the east, the y axis – to the north, z axis – vertically downwards. Equation system is the following:

$$u_t - (\xi + f)v + wu_z = -g\zeta_x - \frac{1}{\rho_0}(P'+E)_x + (\nu_{\mathrm{V}} u_z)_z - \nu_{\mathrm{H}}\nabla^4 u\,, \qquad (1)$$

$$v_t + (\xi + f)u + wv_z = -g\zeta_y - \frac{1}{\rho_0}(P'+E)_y + (\nu_{\mathrm{V}} v_z)_z - \nu_{\mathrm{H}}\nabla^4 v\,, \qquad (2)$$

$$u_x + v_y + w_z = 0\,, \qquad (3)$$

$$\zeta_t + \int_0^H (u_x + v_y)dz = (Pr - Ev)/\rho_1\,, \qquad (4)$$

$$P = g\rho_0\zeta + g\int_0^z \rho d\mu = g\rho_0\zeta + P'\,, \qquad (5)$$

$$T_t + (uT)_x + (vT)_y + (wT)_z = -\kappa^{\mathrm{H}}\nabla^4 T + (\kappa^T T_z)_z - \frac{\partial I}{\partial z}\,, \qquad (6)$$

$$S_t + (uS)_x + (vS)_y + (wS)_z = -\kappa^{\mathrm{H}}\nabla^4 S + (\kappa^S S_z)_z\,, \qquad (7)$$

$$\rho = \varphi(T, S)\,, \qquad (8)$$

where u, v, w – are the components of velocity vectors; ζ – free surface elevation; f – Coriolis parameter; g – gravitational acceleration; P – pressure; Pr – precipitation flow; Ev – evaporation flow; T – temperature; S – salinity; ρ – the sea water density; ρ_0 = 1 g/cm^3; ρ_1 –the density deviation of ρ_0; ν_{V}, ν_{H} – coefficients of vertical and horizontal turbulent viscosity, respectively; κ^{H} – coefficient of the horizontal turbulent diffusion; κ^{T} – vertical turbulent diffusion coefficient of heat; κ^S – the vertical turbulent diffusion coefficient of salt;

$$\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\,,\quad E = \rho_0\frac{u^2 + v^2}{2}$$

The equation (4) was obtained under assumption of the linearized kinematic condition implementation $w = -\zeta_t + \frac{Pr - Ev}{\rho_1}$. The last term in (6) describes temperature change considering the effect of short-wave radiation.

Here

$$I(z) = Swr\left(a \cdot \exp\left(-z/b_1\right) + \left(1 - a\right)\exp\left(-z/b_2\right)\right), \qquad (9)$$

Swr – is a short-wave radiation on the sea surface; a, b_1, b_2 – are empirical constants which are chosen on the basis of numerical calculations. The parameterization of the equation (9) was obtained in [16].

To describe the vertical turbulent viscosity and diffusion the Pacanovski – Philander approximation [17] is used.

The boundary conditions for the system of equations (1) – (8) could be ritten in the following way:

– on the surface ($z = 0$)

$$\nu_{\mathrm{V}} u_z = -\tau^x, \quad \nu_{\mathrm{V}} v_z = -\tau^y,$$

$$\kappa^T T_z = Q^T, \qquad \kappa^S S_z = \frac{Ev - Pr}{\rho_1} S_0 + \beta(S^{\mathrm{cl}} - S_0), \tag{10}$$

where $(\tau^x, \ \tau^y)$ – the components of a tangential tension of wind friction; Q^T – heat flow minus short-wave radiation; S_0 – surface salinity; S^{cl} – climatic salinity; β – relaxation parameter;

– on the bottom ($z = H(x, y)$):

$$u = 0, v = 0, w = 0, T_z = 0, S_z = 0; \tag{11}$$

– on the solid sidewalls:

– for meridional areas of the border

$$\begin{gathered} u = 0, \quad \nabla^2 u = 0, \quad v_x = 0, \quad \nabla^2 v_x = 0, \\ T_x = 0, \quad (\nabla^2 T)_x = 0, \quad S_x = 0, \quad (\nabla^2 S)_x = 0, \end{gathered} \tag{12}$$

– for zonal areas of the border

$$\begin{gathered} v = 0, \quad \nabla^2 v = 0, \quad u_y = 0, \quad \nabla^2 u_y = 0, \\ T_y = 0, \quad (\nabla^2 T)_y = 0, \quad S_y = 0, \quad (\nabla^2 S)_y = 0; \end{gathered} \tag{13}$$

– in the border areas where water flows in the Dirichlet conditions are used:

– for meridional areas

$$\begin{gathered} u = u^{\mathrm{p}}, \nabla^2 u = 0, v_x = 0, \nabla^2 v_x = 0, \\ T = T^{\mathrm{p}}, S = S^{\mathrm{p}}, (\nabla^2 T)_x = 0, (\nabla^2 S)_x = 0, \end{gathered} \tag{14}$$

– for zonal areas

$$\begin{gathered} v = v^{\mathrm{p}}, \nabla^2 v = 0, u_y = 0, \nabla^2 u_y = 0, \\ T = T^{\mathrm{p}}, S = S^{\mathrm{p}}, (\nabla^2 T)_y = 0, (\nabla^2 S)_y = 0; \end{gathered} \tag{15}$$

– for the Bosphorus upper current and the reversal Black Sea flow

$$\begin{gathered} v = v^s, \quad \nabla^2 v = 0, u_y = 0, \nabla^2 u_y = 0, \\ T_y = 0, \quad S_y = 0, (\nabla^2 T)_y = 0, (\nabla^2 S)_y = 0. \end{gathered} \tag{16}$$

In the formulas (14) – (16) the following notations are used: $u^{\mathrm{p}}, v^{\mathrm{p}}, v^s$ – velocity in estuaries and straits, respectively; T^p, S^p – temperature and salinity in the rivers.

As the initial with $t = t^0$ the following conditions were taken:

$$u = u^0(x,y,z), \quad v = v^0(x,y,z), \quad \zeta = \zeta^0(x,y),$$
$$T = T^0(x,y,z), \quad S = S^0(x,y,z). \tag{17}$$

Thus, the system of equations (1) – (8) with appropriate boundary conditions (10) – (16) and initial conditions (17) was solved. The finite-difference discretization of the model equations, initial and boundary conditions was realized on the *C*-grid [18]. A discrete model, accurate up to the even step, has a second-order approximation according the space and the first-order approximation according the time. That is a result of Matsuno scheme occasional usage. The difference operators applied in this work and approximation features of the model equations are described in [19].

The numerical experiment. The calculation area is the entire Black Sea basin bounded by continuous coastline with external drain of the rivers Danube, Dnieper, Dniester, Bug, the rivers of the Caucasian and the Turkish coast, the Bosphorus and the Kerch Strait.

The calculations were performed on an even grid with a 1.6 km pitch in space (698×390 points) and also 27 vertical *z*-horizons with the 1.5 min time step were used.

Two numerical experiments with the different atmospheric forcing were performed. To calculate the hydrodynamic characteristics on the sea surface in 2006 the full flow of heat, precipitation flows, evaporations and tangential tensions of wind friction produced under a regional atmospheric model *ALADIN* [20] were set, and once a day the sea surface satellite temperature was assimilated. The last term in the right side of the equation (6) wasn't considered. For the May – September 2013 period the long-wave and short-wave heat flow components, the flows of the sensible and latent heat and evaporation according to the reanalysis data *Era-Interim* [21] were set. The tension tangents of a wind friction were calculated by the formula $\tau = \rho C_d |\mathbf{V}_{\text{wind}}|$ [22], where $\mathbf{V}_{\text{wind}}$ – is a wind velocity at 10 m height.

The temperature and velocity values in the estuaries and straits were set in accordance to the literature [23]. The salinity of rivers is 7 ‰. In the calculation was set that the temperature and salinity of the Bosphorus upper-level current and of the sea are equal. In the Bosphorous lower-level current salinity was assumed to be 25 ‰, the temperature – 12 °C. That conforms to an average annual characteristic of the Marmara Sea. It was also assumed that the Bosphorus upper-level current spreads to the depth of 27.5 m, lower-level current – up to 68.75 m.

The coefficients of horizontal turbulent exchange of the impulse and horizontal turbulent diffusion of heat and salt are the following: $\nu_{\text{H}} = 10^{16}$ cm^4/s, $\kappa^{\text{H}} = 10^{16}$ cm^4/s.

As the primary fields were used the fields of temperature, salinity, level and currents velocity obtained in the projects «Operational Oceanography» [24] for the first numerical experiment and *My Ocean* 2 [25] – for the second numerical experiment. The empirical constants values to consider the short-wave radiation are the following: $a = 0.85$, $b_1 = 1.5$, $b_2 = 2$. The relaxation parameter β of the formula (10) is 1.15×10^{-3} cm/s. The initial values of all the hydrothermodynamic variables are the result of the long numerical experiment by which the accorded values of the density fields and the vector field currents were calculated. Thus, it could be assumed that the observed oscillations will not be a response to the system perturbations caused by the non-equilibrium state, but will be considered as a manifest of the response to the external atmospheric exposure and at the fluid flow interaction with the bottom topography and the coastline features.

Due to the limited storage space and for easy processing, the calculation results were fixed with 30 minutes discreteness at four Stations in the nodes of the computational grid. The location of the Stations on the basis of numerical modeling results allows selecting the principle directions and the most common wave motions. Location of the Stations is shown in Fig. 1. For a detailed analysis the region of the Southern coast of Crimea (SCC) limited by the coordinates 33.5E – 35E and 44.15N – 44.8N was chosen. This area is characterized by narrow, few kilometers wide shelf and a steep continental slope. The midstream of the Black Sea Rim Current in this area comes particularly close to the coast (Fig. 2), forming a kind of dynamical energy source. In this case a narrow shelf and continental slope are the waveguide. Here is also situated the oceanographic platform (Katsively village), where the sea and atmosphere state monitoring is implemented. The Station 1 was placed maximally close to the oceanographic platform. During the numerical calculations the current velocity fields, temperature and salinity fields for the April 2006 and for May – September 2013 period were obtained.

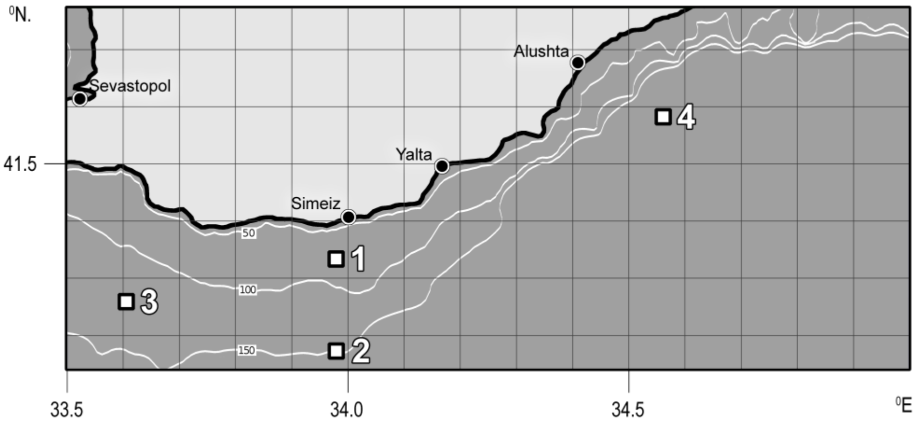

Fig. 1. Coastline location, bathymetry and Stations at which the results of numerical experiments were registered. Isobaths at the shelf are drawn every 50 m

The calculation data was processed by means of specialized software in the *Python* programming language with *numpy*, *scypy*, *mlab* and *matplotlib* libraries. The signal spectral density was calculated by means of the *psd* function, using a fast Fourier transform. The overlapping between the partition segments was 10 %. For the smoothing of the selection segments the Hann window was used and a linear trend was calculated.

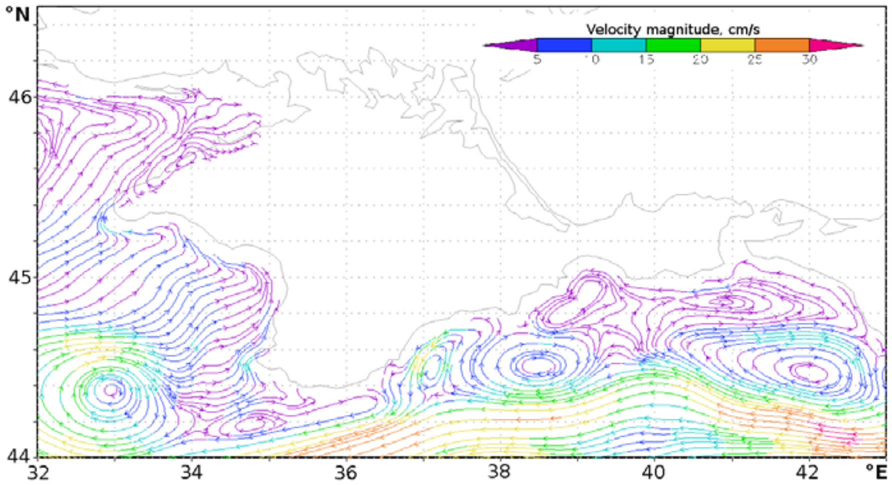

Fig. 2. Streamlines for vector velocity field of currents at 2.5 m depth for the region under study, according to the numerical modelling data for June 13, 2013

The results. We should notice a qualitative coincidence of modeling fields of the current velocity, temperature and salinity with the results of the field observations, which are typical for this region. This fact let us reasonably consider that the oscillations selected in this work coordinate with the density and current fields. That means that the obtained results could be correlated with the real physical processes. From the space and time averaged water masses scalar feature profiles we can see that the vertical structure corresponds to the data [5, 26], including the vertical gradients, seasonal thermocline and the permanent halocline, as well as the cold intermediate layer.

In the horizontal structure of the salinity field the typical drops of the values 1 – 1.5 ‰ between the deep-water and the coastal water masses could be observed. The horizontal salinity field space structure also coincides with the known circumcontinental configuration of isohalines.

The most intensive surface current corresponds to the concentration of the free surface elevation isolines. At the same time in the velocity field the synoptical eddies – the Crimean and Sevastopol anticyclones are distinctly reproduced. The intensity of currents decreases with the depth. In the average density profile of the kinetic energy a response to the changes of the wind friction tension is traced back. All along the Crimean coast the aticyclonic eddies are observed, which corresponds with the conclusions [5, 25].

Now the hydrophysical parameter oscillations of the calculation poshould be examined. During the analysis the changes of all the variables, which describe the thermohydrodynamics of the model at the 1 day time sections were analyzed. The dispersion diagram for the current velocity component vector (Fig. 3) shows two typical oscillation features – their damping with the depth and almost elliptic orbits of particles. The transposition resulting vector directs the southwest (along the Black Sea main current). Such the diagrams didn’t significantly change from Station to Station and from month to month.

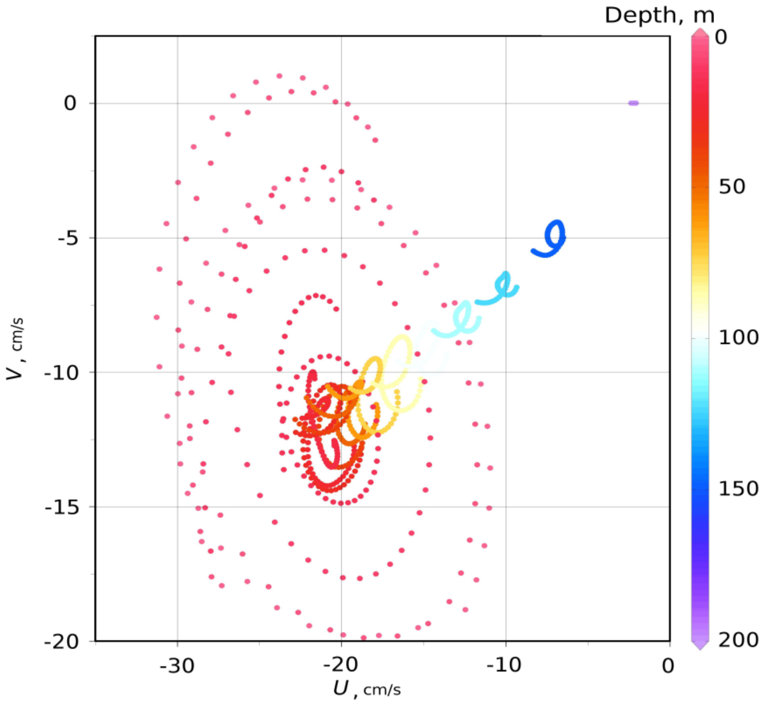

Fig. 3. Scatterplot for the velocity vector components at Station 2. Numerical calculation data for a time period of 24 hours, June 3, 2013

In Fig. 4 the example of the dispersion diagram for the velocity module values at the Station 2 in early summer 2013 is shown. Later just the differences of the oscillation characters for the other Stations are given. It is evident that the oscillation swing reaches maximum in 0 – 30 m upper layer. The maximum of Brunt –Väisälä (N_{BV}) frequency at this Station is located at ≈ 25 m depth (subsurface at 100 – 150 m). The diagram shows which way the velocity module oscillates surficial layers. During the summer months the oscillation prevailing period made up H=17 hrs, but the oscillation character changes by September, the intensity decreases and the 8 hours period become more obvious. That could be explained by the water vertical stability increase during the summer heating and by the local barotropic oscillations prevailing at inertial motions of the Black Sea Rim Current.

The Station 1 differs from the Station 2 by the fact that owing to the boundary condition features the meridional component of current velocity in the model makes 0, therefore the construction of diagrams similar to Fig. 5 is impossible here. It means that the oscillation and kinetic energy swing will be underestimated. On the other part, the Station is located farther from the coast than the oceanographic platform and the currents observed were more intensive. The velocity module oscillations showed that the 14 hrs period prevailed and the motion spread in the entire 0 – 40 m water mass. Here the motion intensity doesn’t change and the period increases up to 16 hrs by September.

At the Station 3, where the Black Sea Main Current stability is lower (typical location of $N_{\text{ВБ}}$ maximum is 10 m) and an active eddy formation takes place, such regularity is not observed, often all the water layers (to 120 m) are enveloped with oscillations and their period could change from 12 to 6 hrs.

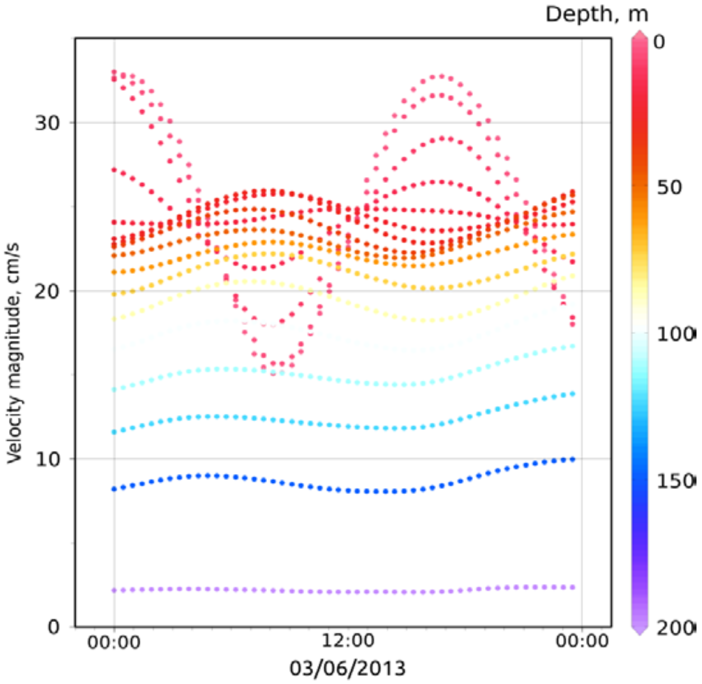

Fig. 4. Scatterplot for current velocity module at Station 2. Numerical calculation data for a time period of 24 hours, June 3, 2013. Color bar indicates the depth of measurement layer

At the Station 4 N_{BV} subsurface maximum is located at 100 m depth and the oscillation period there is more than 24 hrs.

The analysis of *wave processes*. It is known that one of the sufficient causes of the hydrophysical fields variability at meso- and synoptical spatio-temporal scales are gravity-inertial and eddy-gradient long waves. Besides, the formation of such kind of waves in the Black Sea occurs mainly in the shelf and the depth dump areas, which characterizes with substantial side buoyancy flows and maximal current velocity values. One of the basic long-wave motions, displayed by the oscillations of a free water surface, are seiches – barotropic mid-period gravitational standing waves, typical for closed basins [9]. Another type of the inherent oscillations of the closed basin (with the presence of rotation) is Kelvin waves [4]. The most intensive and varied set of hydrophysical field mesoscale variability is observed near the local inertial frequency. Such kinds of oscillations aren’t researched enough [4], so in this work we just mark out the signs of these oscillations and try to characterize them qualitatively.

At first, by means of *Python* programming language ~700 spectrograms were constructed: for each parameter, Station, month and for each of the first seven horizons of the numerical grid. During the analysis a small variability of spectrograms according the space and the time was revealed. Then five averaged spectrograms, which analysis showed that the spectral maximums pointed at them depicted the spectrum characteristics by the detached sections of the phase space well were constructed. The example of averaged spectrum for the temperature is shown in Fig. 5.

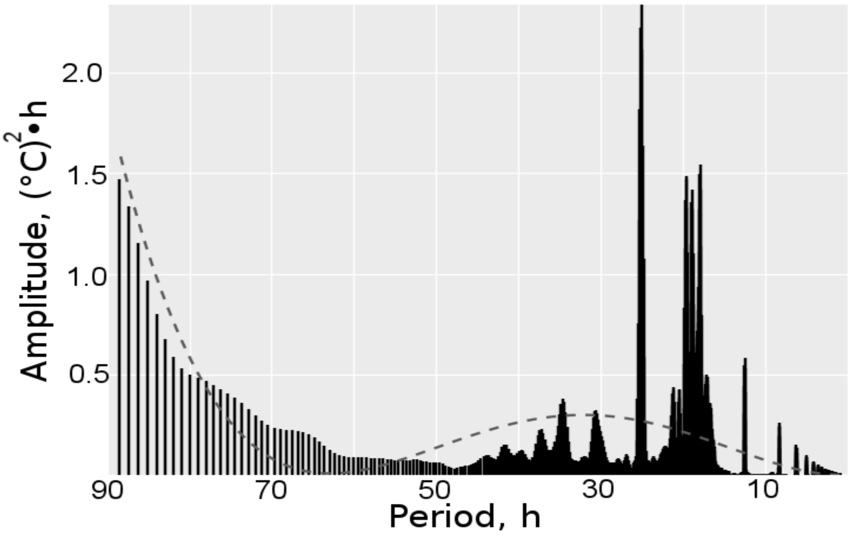

Fig. 5. A diagram of power spectral density for temperature fluctuations, space- and time-averaged for the studied region for May-September, 2013, according to numerical modeling data. Dashed line indicates the upper boundary of 99 % confidence interval

During the series of test runs, the durable numerical experiment and the analysis of its results there were selected two main energy-carrying intervals, their oscillations are reliably represented by the following model: relatively slow large-scale shifts with the periods from 4 days to one week and short-period subinertial oscillations with 10 hrs – 40 hrs period. At the long-period range certain statistically significant spectrum density maximums for 120, 260 and 360 hrs periods, which could be an occurrence of Kelvin waves or a response to the shelf water synoptical wind effect are pointed out. In general, low-frequency part of spectrum in the warm season is more smoothed, the energy increases uniformly when the frequency decreases and is greater than high-frequency part of spectrum.

For the Taman-Kerch shelf the value estimation of the seiche-shaped oscillation periods according to the observations near the Crimean shelf is given in [9]. According to the results of the performed calculation several maximums which correspond to such oscillations were sorted out in the spectral diagrams.

Maximums in the 4 – 10 hrs periods correspond to the oscillations, which prevail in the observations [9], but their nature now has no definite explanation because at the points of observation the oscillations with no analogues at other parts of the sea were fixed. Such oscillations were also obtained according to the results of numerical experiments [9] that allow us to interpret them as typical for the Southern cost of Crimea high-frequency level budge oscillations. So far as each divining force, which deflects the isopycnic surfaces from geostrophic balance generates a great number of oscillations at the frequency range, which is higher than inertial, these oscillations could be connected with first baroclinic mode the internal waves or with its overtones. Within the data of the given numerical experiment we also have such oscillations but they are fixed at the confidence limits and decline during the summer months. Temperature oscillations, which are referred to the seiche-type, are fixed at the high-frequency part of spectrum near the surface. Certain divergence of data may be explained by the spectrum noisiness and by the time delay of isotherm deformation.

Typical features of the obtained mid-frequency zone spectrums are the following:

- statistically significant period maximums are grouped in 10 – 40 hrs range with the major concentration at the inertial period zone. This fact indicates a complex oscillation combination close to the inertial period and complicates the interpretation;
- in the spectra for the temperature and salinity difference between the oscillations with a 70 hrs period is greater than for the current velocity components. It means that in the numerical model more slow oscillations of thermohaline sea parametes prevail;
- the spectrum maximum, which corresponds to 25 hrs period for the temperature, apparently shows a boundary conditions contribution – the sea surface temperature which was predetermined with 24 hrs discreteness.;
- also the oscillations with less than 14 hrs period for the temperature have an energy density which is multiple of 14 hrs period density. We consider these maximums to be the principle oscillation harmonics;
- generally, a small amount of statistically reliable maximums indicates a high oscillation noisiness at the high-frequency zone.

Here the principle energy-carrying periods obtained from the spectrum density diagrams in the mid-frequency range in May – September 2013 period under the numerical modeling data, are enumerated.

Period, hr	Parameter
14	T
17	u, v, w, T
19	u, v, w, T, S
26	T
35	T, S

Spectral analysis of level, kinetic energy density and temperature changes at the Stations 1 and 2 allows us to sort out the energy-carrying period maximums shown at the table. This data was processed by means of information from the previous works and was complemented with the oscillation characteristics. Diagram amplitudes for the level coincide with average experimental spectrums for the Crimean coast [1] with order-of-magnitude accuracy. Oscillation energy decreases in the direction from shelf to the high sea.

Maximums 1 and 2 in the table are reckoned among incident and reflected Poincaré waves, which spread by the normal to the Black Sea main current. Measures of such wave system were performed at the Crimean shelf during the 14th expedition of R/V *Professor Kolesnikov* [8]. Due to the fact that oscillation intensity decreases with depth, these maximums have not been found for the 120 m depth spectrums.

Spectral maximums for low-frequency oscillations of oceanographic sea parameters for Stations 1 and 2 with possible interpretation

N max	Period, hour	Frequency, 1/hour	Parameter	Interpretation
1	14.50	0.069	T	Baroclinic Poincare wave (falling)
2	16.30	0.061	T	Baroclinic Poincare wave (reflected)
3	17	0.059	ВУ, dE_k	Local inertial maximum
4	30	0.034	ВУ	Captures topographic/shelf wave
5	37.70	0.027	dE_k	
6	50	0.020	ВУ	Kelvin wave of the first barotropic mode
7	52.70	0.019	dE_k	
8	65.90	0.015	dE_k	Captures topographic/shelf wave of the second mode
9	68	0.015	ВУ	
10	120	0.005	T	Response to synoptical variability of atmospheric forcing
11	220	0.003	ВУ	Waves captured by the shore, with the source outside the SCC shelf, caused by adjustment to geostrophic balance
12	250	0.004	dE_k	

Note: dE_k – kinetic energy density, T – temperature, ВУ – level rise

Maximums 4 and 5 correspond to the captured topographical waves. Typical spatial scales for the first mode of barotropic shelf waves at the Black Sea are 20 – 100 km with 20 – 40 hrs periods [9].

Dispersive estimations for the Kelvin wave first mode with 50 – 300 km length give 40 – 50 hrs period values (maximums 6 and 7) [9].

Maximums 8 and 9 (68 hrs) are in the frequency range, which is related to topographical alongshore current spread according to [6, 9]. In [8] under the current-meter data, the wave with 64 hrs period, 360 km length and 5.6 km/h phase velocity was fixed. Minor period divergence could be explained by averaging performed in this work and by interpolation errors.

Maximums 11 and 12 correspond to the long captured wave spread and appear to be a feedback at distant wind effect, according to the conclusion about the feedback and wind effect incoherence [7]. Our analysis showed that these maximums are represented stronger near the Stations, which are located closer to the shore, and it could be an indirect evidence of the captured wave passage.

Conclusion. The statistical oscillation analysis of oceanographic features and numerical modeling results of the Black Sea marine dynamics at the Southern coast of the Crimea shelf (2013) was performed.

Historical expeditionary data and idealized model calculations in V.A. Ivanov, A.S. Blatov and A.E. Yanovsky's two-dimensional channel approximation model [4 – 8] were extended by contemporary expeditionary observations and formulation of coordinated numerical experiment, which supplements data about an understanding of internal wave physical nature and specifies information about three-dimensional high-resolution numerical model capability to reproduce a wide oscillation spectrum.

During the high-frequency variability of thermohydrodynamical sea characteristics analysis at the Southern coast of the Crimea shelf statistically significant energy-carrying maximums set of spectral density was obtained. Statistical stability of this frequencies set during the summer months was shown. An interpretation of oscillations is given and their spatial characteristics estimation is obtained.

During the numerical experiment two principle energy-carrying intervals whose oscillations are significantly reproduced by the model (relatively slow large-scaled shifts with periods from 4 days to one week and short-period subinertial oscillations with 10 – 40 hrs periods) were singled out.

Marine Hydrophysical Institute high spatial resolution model showed an ability to reproduce a wide range of barotropic and baroclinic oscillations.

Due to the smoothed relief, at the 1.64 km grid, and features of boundary conditions during the whole basin modeling sometimes it's hard to follow the high-frequency oscillations passage, which is noticed during the measuring from an oceanographic platform.

Current velocity vector components could be a good information source of model feedback for boundary condition modification.

The results of the work one more time highlight a necessity of short-period wave motion primary energy sources consideration. These sources are the following: atmospheric vorticity flows, mass and heat. During the problem definition it is necessary to select atmospheric boundary conditions carefully or to isolate one or another type of effect, which generates sea oscillations.

REFERENCES

1. Blatov, A.S., Ivanov, V.A., 1992, "*Gidrologiya i gidrodinamika shel'fovoy zony Chernogo morya (na primere Yuzhnogo berega Kryma)* [Hydrology and hydrodynamics of the Black Sea Shelf (Southern Coast of the Crimea)]", Kiev, Naukova dumka, 242 p. (in Russian).
2. Demyshev, S.G., Dymova, O.A., 2013, "*Chislennyy analiz mezomasshtabnykh osobennostey tsirkulyatsii v pribrezhnoy zone Chernogo morya* [Numerical analysis of the circulation mesoscale peculiarities in the Black Sea coastal area]", *Izv. RAN, Fizika atmosfery*, vol. 49, no. 6, pp. 655-663 (in Russian).
3. Demyshev, S.G., Korotaev, G.K., 1992, "*Chislennaya energosbalansirovannaya model' baroklinnykh techeniy okeana s nerovnym dnom na setke C* [Numerical energy-balanced baroclinic model with rough bottom on Arakawa's C grid]", *Chislennye modeli i rezul'taty kalibrovochnykh raschetov techeniy v Atlanticheskom okeane*, Moscow, INM RAS, pp. 163-231 (in Russian).
4. Blatov, A.S., Bulgakov, N.P., Ivanov, V.F. [et al.] 1984, "*Izmenchivost' gidrofizicheskikh poley Chernogo morya* [Variability of hydrophysical fields of the Black Sea]", Leningrad, Gidrometeoizdat, 239 p. (in Russian).
5. Ivanov, V.A., Yankovskii, A.E., 1991, "*Harakteristiki zakhvachennykh voln v shel'fovoy zone Yuzhnogo berega Kryma* [Features of trapped waves in the shelf of Southern Coast of the Crimea]", *Okeanologiya*, vol. 31, no. 2, pp. 200-206 (in Russian).
6. Blatov, A.S., Ivanov, V.A., 1983, "*Prostranstvenno-vremennaya struktura vnutrennikh inertsionno-gravitatsionnykh i topograficheskikh voln v more na chastotakh, blizkikh k inertsionnoy chastote* [Spatio-temporal structure of the inertial-gravitational and topographic waves in the sea on the frequencies close to inertial one]", *Izv. AN SSSR. FAO*, vol. 19, no. 8, pp. 868-877 (in Russian).

7. Ivanov, V.A., Yankovsky, A.E., 1994, “*Dinamika vod na shel'fe Kryma v letniy sezon* [Dynamics of the waters in the coastal area of the Crimea in summer]”, *Morskoy gidrofizicheskiy zhurnal*, no. 3, pp. 38-56 (in Russian).

8. Ivanov, V.A., Yankovsky, A.E., 1992, “*Dlinnovolnovye dvizheniya v Chernom more* [Long-wave motions in the Black Sea]”, Kiev, Naukova Dumka, 112 p. (in Russian).

9. Ivanov, V.A., 1996, “*Srednemasshtabnaya dinamika vod v yuzhnykh moryakh: sovremennoe predstavlenie* [Medium-scale water dynamics in the southern sea: contemporary idea]”, Sevastopol, MGI NAN Ukrainy, 312 p. (in Russian).

10. Demirov, E. 1994, “Numerical modelling of the Black Sea eigen-oscillations on a curvilinear boundary fitted coordinate system”, *Dyn. Atmos. Ocean*, vol. 21, no. 2-3, pp. 83-103.

11. Rachev, N.H., Stanev, E.V., 1997, “Eddy processes in semi-enclosed seas. A case study for the Black Sea”, *J. Phys. Oceanogr.*, vol. 27, no. 8, pp. 1581-1601.

12. Yankovsky, A.E., Chapman, D.C., 1997, “Anticyclonic eddies trapped on the continental shelf by topographic irregularities”, *J. Geophys. Res*. vol. 102, no. C3, pp. 5625-5639.

13. Stanev, E.V., Rachev, N.H., 1999, “Numerical study on the planetary Rossby modes in the Black Sea”, *J. Mar. Syst.*, vol. 21, no.1-4, pp. 283-306.

14. Stanev, E.V., Beckers, J.M., 1999, “Barotropic and baroclinic oscillations in strongly stratified ocean basins. Numerical study for the Black Sea”, *J. Mar. Syst.*, vol. 19. no. 1-3, pp. 65-112.

15. Stanev, E.V., Beckers, J.M., Lancelot, C. [et al.], 2002, “Coastal-open ocean exchange in the Black Sea: Observations and modeling”, *Estuar. Coast Shelf Sci.*, vol. 54, no. 3, pp. 601-620.

16. Paulson, C.A., Simpson, J., 1977, “Irradiance measurements in the upper ocean”, *J. Phys. Oceanogr*., vol.7, no. 6, pp. 952-956.

17. Pacanowski, R.C., Philander, S.G.H., 1981, “Parameterization of vertical mixing in numerical models of Tropical Oceans”, *J. Phys. Oceanogr.*, vol. 11, no. 11, pp. 1443-1451.

18. Arakawa, A., 1966, “Computational design for long-term numerical integration of the equations of fluid motion: Two-dimensional incompressible flow”, *J. Comput. Phys.*, vol. 1, no. 1, pp. 119-143.

19. Demyshev, S.G., 2012, “Chislennaya model' operativnogo prognoza techeniy v Chernom more [Numerical model of the operative forecast of currents in the Black Sea]”, *Izv. RAN*, *Fizika atmosfery i okeana*, vol. 48, no. 1, pp. 137-149 (in Russian).

20. Farda, A., Déué, M., Somot, S. [et al.], 2010, “Model ALADIN as regional climate model for Central and Eastern Europe”, *Studia Geophysica et Geodaetica*, vol. 54, no. 2, pp. 313-332.

21. Dee, D.P., Uppala, S.M., Simmons, A.J. [et al.], 2011, “The ERA-Interim reanalysis: Configuration and performance of the data assimilation system”, *Quart. J. Roy. Meteorol. Soc.*, vol. 137, no. 656, pp. 553-597.

22. Voltsinger, N.E., Pyaskovsky, R.V., 1968, “*Osnovnye okeanologicheskie zadachi melkoy vody* [Shallow water principal oceanographic problems]”, Leningrad, Gidrometeoizdat, 300 p.

23. 1991. “*Gidrometeorologiya i gidrokhimiya morey SSSR* [Hydrometerology and hydrochemistry of the seas of the USSR”. Vol, IV. Chernoe more, Iss. 1, “*Gidrometeorologicheskie usloviya* [Hydrometeorological conditions]”, Saint Petersburg, Gidrometeoizdat, 429 p.