NUMERICAL SIMULATION OF MESO- AND SUBMESOSCALE FEATURES OF THE NORTH-WESTERN BLACK SEA SHELF CIRCULATION USING HIGH SPATIAL RESOLUTION

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A numerical experiment on reconstruction of currents was conducted with real atmospheric forcing data in autumn period of 2007 on the basis of Marine hydrophysical institute (MHI) hydrodynamic model, which was adapted to the coastal area of the Black Sea with an open boundary (north-western shelf). A high resolution (horizontal grid 500×500 m and 44 vertical layers from 1 m to 49 m) and detailed bathymetry with resolution ~1.6 km were used in the calculation. A higher spatial resolution allowed to get a detailed mesoscale and submesoscale structure of currents in the upper and deep layers of the north-western shelf and to obtain quantitative and qualitative characteristics of the eddies and jets more accurately in comparison with previous calculations.

Key words: numeral modeling, high spatial resolution, north-western shelf, mesoscale and submesoscale features of circulation

I. INTRODUCTION

A study of hydrodynamics of coastal regions has a practical importance in connection with intensive development of its resources. North-western shelf (NWS) of the Black Sea is a vast shallow water lying to the north of the northern latitude 45°. The main features of NWS are estuarine areas of the Black Sea rivers, shallow bays and estuaries, formation of seasonal pycnocline due to heating of the surface waters and freshening them under the influence of river discharge in spring and summer, domination of the wind component in the formation of water circulation, intense water exchange with the open sea. A large number of papers is devoted to the study of large-scale and synoptic variability of hydrophysical fields of the Black Sea north-western shelf by means of mathematical modeling. Influence of bottom topography, direction and magnitude of wind velocity, atmospheric disturbances, river discharge in the formation of circulation on NWS was studied in [1–5]. In [6] analysis of climatic current fields was conducted in the region of north-western shelf using z-coordinate model developed in MHI [7, 8] (horizontal grid 5×5 km, 45 vertical layers). It was obtained that the main features of shelf circulation were eddies of various generation and jet currents.

Along with numerical simulation of the dynamics of the coastal zones, investigations based on using instrumental measurements of currents [9, 10] and the satellite altimetry data [11] were carried out. A high degree of variability in the horizontal and vertical structure of currents has been demonstrated.

Nowadays a study of spatio-temporal variability of sea shelf hydrophysical structure on the scale of a few kilometers and days is one of the urgent problems of modern oceanography. Small-scale eddies, regularly observed on satellite radar images, make a significant contribution
to the circulation of the coastal zone and are an effective mechanism for the transport of various kinds of contaminants of natural and anthropogenic origin.

New results on meso- and submesoscale features of circulation in the various regions of the World Ocean were obtained in [12–21]. In [12] complex spatio-temporal variability of the monsoon system currents of the Indian Ocean was reconstructed using the $\sigma$-model of the Institute of Computational Mathematics, Russian Academy of Sciences, with a high spatial resolution $1/8^\circ \times 1/12^\circ$ in accordance with data observations and the main features of the ocean eddy structure were investigated. In [13] simulation results of meso- and submesoscale variability using the ROMS model with a horizontal grid size 3.5 km were compared with RAFOS observations and satellite altimetry for the region of the Pacific Ocean in Central California. In [14] within-year variability of the World Ocean circulation was reconstructed using eddy-resolving model of high horizontal resolution ($1/10^\circ$). It enabled to reproduce spatio-temporal characteristics of the narrow boundary currents of World Ocean more accurately. In [15] a seasonal cycle of submesoscale flows in the upper ocean layers was investigated in an idealized model domain analogous to mid-latitude open ocean regions. It was shown that submesoscale processes became much stronger as the resolution was increased. In [16] characteristics of submesoscale eddies in the White Sea were mapped with the help of remote and contact observations. Areas of eddy activity were found on the basis of statistical analysis. In [17] five mesoscale eddy structures of different signs were observed in the coastal part of the Russian sector of the Black Sea according to the geological survey data in August 2004. Such a dynamic situation contributed to the intensive horizontal water exchange between the near-shore and open sea waters as well as to the redistribution of water masses over the vertical in the active sea layer. In [18] the results of observations of small-scale eddies (with a diameter of 2–8 km) in the coastal zone of the Black Sea in the Gelendzhik region were presented using various methods of hydrophysical investigations. The mechanisms of generation of such eddies were specified. In [19] a structure of Rim Current was analyzed in the upper 100-m layer near the coast of the Crimea on the basis of processing of tool data obtained in September 2008 with high spatial resolution. It was shown that a mesoscale variability of current field had ageostrophic character and essentially influenced circulation structure in the vicinity of Rim Current (visualized in the form of local eddies, as well as inertial currents). In [20] analysis of small-scale eddies of the Baltic, Black and Caspian Sea basins was conducted, according to satellite radar data. It was found that they were associated with either hydrologic fronts or peripheral areas of mesoscale eddies. In [21] simulation results of submesoscale variability and eddy generation of the north-eastern shelf of the Black Sea were presented on the basis of the numerical model with high spatial resolution. A comparison of these results with the data of direct measurements for September 2008, January 2011 and March 2013 were provided.

The aim of this investigation was to reproduce and analyze coastal circulation of the north-western shelf of the Black Sea on the basis of the z-coordinate three-dimensional non-linear model [7, 8] with a horizontal resolution of 500 m and with real atmospheric forcing data in autumn period of 2007. Influence of high resolution on reconstruction of meso- and submesoscale features of coastal circulation was shown on the basis of a comparison with calculation with coarser grid size ($\sim 1.6$ km).
II. STATEMENT OF THE PROBLEM AND DESCRIPTION OF NUMERICAL EXPERIMENTS

We considered a region of the Black Sea (Fig. 1) limited by latitude 45.5ºN located between meridians 29.5º and 33.5º E. We used more detailed presentation of bottom topography (with a resolution of ~1.6 km) obtained by digitization of navigation maps by staff of Shelf Hydrophysics and Waves Theory departments.

Fig. 1. Bathymetry of the north-western shelf of the Black Sea (m). Roman numerals indicate:
I – the Dnieper-Bug estuary, II – Yagorlytsky, III – Tendrovsky,
IV – Karkinitsky and V – Dzharylgach bays

The system of model equations using the Boussinesq approximation, hydrostatic approximation and incompressibility of seawater in the Gromeko–Lamb form, the boundary conditions on the surface, at the bottom, on the solid lateral walls were written as follows [7, 8]. Note that a reduced sea level $\zeta$ was calculated from a discrete analog of the continuity equation taking into account the specification of the velocities at the open boundary of the domain [22].

In order to adapt the numerical model of the dynamics [7, 8] for the calculation of NWS circulation we made the following steps. Data array of the region bathymetry was processed, model parameters were chosen on the basis of preliminary experiments, river inflow locations and depths of estuaries were assigned, boundary conditions on the open boundaries of the region were selected and implemented, initial fields as well as fields of wind stress, heat flows, short-wave radiation, precipitation and evaporation were processed in order to be used in the model.

The numerical experiment 1 was carried out with resolution 500 m. The time step was equal to 10 s. The choice of values of horizontal and vertical turbulent viscosity coefficients was based on a series of specialized numerical experiments.

The numerical experiment 2 was carried out with resolution ~1.6 km. The time step was equal to 30 s. Horizontal coefficients of turbulent viscosity and diffusion were equal to $\nu_H = 5 \cdot 10^5$ cm$^2$/s, $\kappa_H = 5 \cdot 10^5$ cm$^2$/s.
The total period of integration of model equations for the two experiments was 30 days (from October 14 to November 12 of 2007). Along the vertical, horizontal components of the current velocity were computed at 44 depths: 0.5; 1; 1.5; 2; 2.5; 3;…; 32; 34; 49 m.

Fields of currents, temperature and salinity, obtained from model for the entire sea on a 5 × 5 km horizontal grid within the Operative Oceanography project [23], were used to specify initial and the boundary conditions at the open boundary of the domain.

The u, v, T и S values, calculated at depths of 2.5, 5, 10, 15, 20, 25, 30 and 40 m, corresponding to the latitude of the liquid boundary, were linearly interpolated on the selected grids (500×500 m и 1.6×1.6km) at each time instant.

In order to specify conditions on the open southern boundary we used the results of [22], where an efficiency of combined approach was shown on the basis of the simulation numerical experiments. The components of the current velocity, temperature, and salinity (the Dirichlet conditions) were specified in the boundary regions where water flowed into the domain (v > 0); conditions ∂u/∂n = 0, ∂v/∂n = 0 for u, v and radiation conditions for T and S were specified in the boundary regions where water flowed out of the domain (v < 0).

The vertical coefficients of turbulent exchange of momentum and diffusion were calculated according to the Philander–Pacanowski approximation [24] with \( R_0 = 1, \upsilon_0 = 5 \text{ cm}^2/\text{s}, \nu_1 = 1 \text{ cm}^2/\text{s}, \kappa_1 = 1 \text{ cm}^2/\text{s} \).

The fields of tangential wind stress, heat fluxes, short-wave irradiance fluxes, as well as precipitation and evaporation, obtained from data of the regional atmospheric model ALADIN and provided by the department of Marine Forecasts of MHI [23] and linearly interpolated to the selected grid, were specified for each day.

Used fields of wind stress were characterized by significant variability during the calculating period, wind velocity varied from values of 2.4 to 14.3 m/s. Northern, north-eastern, north-western and south-western winds with a maximum velocity 14.3 m/s (was recorded on October 16) dominated from 14 to 20 October, south-western winds with a maximum velocity 10.2 m/s (October 23) – from 21 to 25 October, northern winds with a maximum velocity 11.3 m/s (October 27) – from 26 to 28 October, western and south winds with a maximum velocity 7.1 m/s (October 29) – from October 29 to November 2, northern, north-eastern and western winds with a maximum velocity 11.3 m/s (November 5) – from 3 to 12 November.

We took into account the discharges of three rivers: Dnieper, Dniester, and South Bug.

III. ANALYSIS OF CURRENT FIELDS OF NORTH-WESTERN SHELF

The main direction of currents in the upper water layer changed from the south-west to the south, north, north-east, east, west and north-west. This was caused by changeable weather pattern that was observed during the calculating period.

Intense jets, directed to the south, were formed at depths of 10–26 m in case when currents in the upper water layer were directed to the south north, north-east and north-west. Intense jet currents, directed to the north, were observed at depths below 10 m in case of southern and south-eastern directions of currents dominated in the upper water layer. Fig. 2 shows current fields on October 29 (Fig. 2a) and November 3 (Fig. 2b), obtained in Experiment 1 at the depth of 10 m (every fifth arrow was drawn). We noted that trajectories of jets coincided with isobaths 19–28 m.

We compared the current fields obtained in Experiments 1 and 2 during the calculating period and found a qualitative correlation between the fields. The maximum values of currents,
calculated in Experiment 1, were on average 5–10% higher than the values, obtained in Experiment 2.

Current fields of NWS had a complex mesoscale structure, characterized by eddies and jets. For the classification of obtained eddies we estimated a value of the local baroclinic deformation radius \((R_d)\) for the selected coastal area of the Black Sea.

As we know from [25], estimations of characteristic values of \(R_d\) for open areas of the Black Sea have a value of 15–20 km, for shelf and coastal areas – 5–10 km [18, 25].

The baroclinic Rossby deformation radius was calculated using the formula:

\[
R_d = \frac{g(\Delta \rho/\rho)H}{0.5f},
\]

where \(g\) – acceleration of gravity, \(\Delta \rho\) – density gradient in the thermocline (\(\sim 1.7 \times 10^{-3}\) g/cm\(^3\)), \(\rho = 1\) g/cm\(^3\), \(H\) – the upper layer thickness for October 2007 (\(\sim 24\) m), \(f\) – Coriolis parameter corresponding to 46° N (\(\sim 10^{-4}\) s\(^{-1}\)). \(R_d\) was equal to \(\sim 6.4\) km for the selected coastal zone. We assumed that mesoscale eddies had a radius bigger than local baroclinic Rossby deformation radius and Rossby number was much less than unity \((R>R_d, R_o<1)\). We assumed that sub-mesoscale eddies had a radius smaller than \(R_d\) and Rossby number was of the order of unity \((R<R_d, R_o\approx1)\).

Mesoscale eddies with a spatial scale of 8–12 km and a temporal scale of a few days were reproduced in the upper water layer near Odessa, in areas of Tendrovsky and Karkinitsk bays, in the western, eastern and central parts of the region, as well as near the open boundary during the calculating period. Fig. 3 shows these features of circulation, recovered in Experiment 1 (every fourth arrow was drawn).

Cyclonic eddy \((R\approx12\) km \(>R_d, R_o\approx0.18)\) was generated in the western part near the open boundary (Fig. 3a), anticyclonic eddies (Fig. 3b) were formed near Odessa \((R\approx12\) km \(>R_d, R_o\approx0.38)\) and in Tendrovsky bay \((R\approx8\) km \(>R_d, R_o\approx0.33)\). Anticyclonic eddy \((R\approx8\) km \(>R_d, R_o\approx0.3)\) was obtained in Karkinitsky bay (Fig. 3c), two cyclonic eddies \((R\approx10–12\) km \(>R_d, R_o\approx0.2)\) and one anticyclonic eddy \((R\approx12\) km \(>R_d, R_o\approx0.12)\) – in the central part of the region.
(Fig. 3d). Cyclonic eddy ($R \approx 8 \text{ km} > R_d, R_o \approx 0.12$) was observed in the eastern part of the region (Fig. 3e), anticyclonic eddy ($R \approx 12 \text{ km} > R_d, R_o \approx 0.22$) – in Dzharylgach bay (Fig. 3f). According to the classification these eddies can be attributed to the mesoscale eddies and quasigeostrophic. We noted that these features were also observed in the results of the Experiment 2.

Mesoscale cyclonic eddy with a radius $\sim 15$ km, which was repeatedly registered in satellite observations, was generated in the period from 16 to 20 of October and from 1 to 5 of November, 2007 at depths of 1–24 m between the meridians $30.8^\circ$ and $31.2^\circ$ E. Fig. 4 shows the fields of surface currents on October 17 and 18 of 2007 calculated in Experiment 1 and 2 (every fifth and second arrow were drawn respectively).
Intensification of currents inside the cyclonic eddy was observed in Experiment 1 on October 17 (Fig. 4a), and field structure was reproduced more accurately to the north of 46.4 °N compared with the results of Experiment 2 (Fig. 4b). This eddy wasn’t reproduced in Experiment 2 on October, 18 (Fig. 4e) in contrast to the results of Experiment 1 (Fig. 4d). Two anticyclonic eddies with a radius ~8 km were formed to the west and east of the cyclonic eddy. Correspondence between the results of Experiment 1 (Fig. 4a and Fig. 4d) and satellite observations on October, 17 and 18 of 2007 NOAA with resolution 1 km (Fig. 4c and Fig. 4f) was obtained. Formation of this eddy was a result of the influence of inhomogeneity of the bottom topography on the jet current. As it was noted in [26], cyclonic eddies were predominantly formed over submarine depressions.

We compared the current fields obtained in Experiments 1 and 2 during the calculating period and found a qualitative correlation between the fields, however, a number of eddies was absent and a field structure was smoother in the experiment with a lower resolution. Fig. 5 presents current fields obtained in experiments with a resolution of 500 m and ~1.6 km at depths of 5, 10 and 24 m on October 19, 2007 (every fifth and third arrow were drawn respectively, we marked on Fig. 5a, b, c elements of circulation that were absent on Fig. 5d, e, f)
Cyclonic eddy was reconstructed in the entire water layer in the eastern part of the region (between meridians 32.3° and 32.6° E) in Experiment 1. Cyclonic eddy in the central part of the area between meridians 30.8° and 31.2° E (Fig. 5a, b, c) was described above. It was observed in the entire water layer and its radius was ~12 km (Fig. 5a, b, c). Anticyclonic and cyclonic eddies with radius from ~4 to ~12 km in the central region at the depth of 5m (Fig. 5a), anticyclonic eddy with a radius ~10 km at the depth of 10 m in Karkinit bays (Fig. 5b), anticyclonic eddy with a radius of ~8 km at the depth of 24 m between the meridians 30.4° and 30.8° E (Fig. 5c) were reconstructed. These features were reproduced only in Experiment 1.

Fig. 6 shows fragments of current fields obtained in Experiment 1 on November 1, 4 and 10 of 2007 (Fig. 6a, b, c, every sixth arrow was drawn) and in Experiment 2 (Fig. 6d, e, f, every second arrow was drawn). We marked on Fig. 6a, b, c elements of circulation that were absent on Fig. 6d, e, f.

From the analysis of the current fields, calculated in experiments 1 and 2, we noted that due to the smaller grid size eddies with a radius of ~5 km between meridians 30.4° and 30.8° E on November 1 (Fig. 6a), cyclonic eddy with a radius of ~7 km between the meridians 31.9° and 32.1° E on November 4 (Fig. 6b), cyclonic eddies with a radius of ~12 km and anticyclonic eddy with a radius of ~5 km in the eastern part of the area on November 10 (Fig. 6c) were obtained.
Determining the type of small-scale eddies depends on the orbital velocity of an eddy. Analysis of the results of calculation of Rossby number $R_o$ showed that values $R_o \approx 1$, as well as values $R_o < 1$, have been obtained for the eddies with $R < R_d$ during the calculating period.

Fig. 6. Fragments of current fields (cm/c) at the depth of 5 m on November 1, 4 and 10, calculated in Experiment 1 (a, b, c) and Experiment 2 (d, e, f)

IV. CONCLUSIONS

Current fields of the north-western shelf of the Black Sea were reconstructed on the basis of numerical model with high spatial resolution, taking into account river discharge and real atmospheric forcing data in autumn period of 2007. It was shown that a field of currents had a complex meso- and submesoscale structure, characterized by eddies and jets. Bottom relief played a crucial role in their formation. Mesoscale eddies of various rotating signs were reproduced in the upper layer of water near Odessa, in areas of Tendrovsky and Karkinit bays, in the western, eastern and central parts of the region, as well as near the open boundary during the calculating period. Cyclonic eddy with a radius ~15 km was generated at the depth of 1–24 m between the meridians 30°.8’ and 31°.2’ E, which corresponded to the satellite observations. Intense jets, which trajectories coincided with isobaths 19–28 m, were formed at the depth of 10–26 m.

Due to the smaller grid size (500 m) meso- and submesoscale eddies have been obtained for the first time in the upper and deeper water layers of north-western shelf (anticyclonic and cyclonic eddies with a radius from ~4 to ~12 km in the central region, anticyclonic eddy with a radius of ~10 km in Karkinit bay, cyclonic eddies with a radius of ~12 km and anticyclonic eddy with a radius of ~5 km in the eastern part of the region).

These results convincingly confirm that a qualitative improvement in calculation accuracy of currents in the coastal zone requires the use of a few hundred meters of spatial resolution of numerical model.
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V. REFERENCES


