Calculations of hydrophysical fields in the coastal regions of the Black Sea with high spatial resolution

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Calculations of hydrophysical fields in the coastal regions of the Black Sea with high spatial resolution

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Abstract. Numerical experiments have been carried out using a hydrodynamical model with nonlinear equations of motion and heat and salt advection to reconstruct the fields of hydrophysical parameters in the coastal regions of the Black Sea taking into account the real atmospheric forcing and river discharges for the winter and summer seasons of 2006. A higher spatial resolution allowed to get a detailed meso- and submesoscale structure of hydrophysical fields in the upper and deep layers of the Southern Coast of Crimea and the north-western shelf and to obtain quantitative and qualitative characteristics of the eddies and jets more accurately in comparison with previous calculations.

1. Introduction
The tasks of construction of coastal and port facilities, tourism, fishing and fish farming, mining and environmental monitoring are inseparably connected with a study of hydrodynamics of the waters of the shelf zones, their mixing and exchange with open parts of the sea. Nowadays a reconstruction and study of spatio-temporal variability of hydrophysical fields in the coastal areas on a scale of a few kilometers and days is one of the urgent problems of oceanography. New results on meso- and submesoscale features of circulation in the various regions of the World Ocean were obtained in the following investigations on modeling, forecasting and observation of hydrophysical fields with high spatial resolution [1–10].

Information about small-scale eddies in the coastal zone of the Black Sea according to satellite monitoring data was presented in [1, 2]. Mechanisms of their possible formation were suggested. In [3] areas of eddy activity in the White Sea were found with the help of remote and contact observations, characteristics of submesoscale eddies were mapped. In [4] according to satellite radar data it was found that small-scale eddies of the Baltic, Black and Caspian Sea were associated with either hydrologic fronts or peripheral areas of mesoscale eddies. In [5] water circulation of the Adler-Sochi region was reconstructed with an improved spatial resolution of the coastal zone due to the changing grid step (with uniform spatial resolution ~4 km and uniform, with a step reduction to 50 m). It was shown that an eddy circulation was reproduced more adequately by the model with a higher spatial resolution. In [6] mesoscale eddies, generated by the instability of alongshore wind currents, were described with the help of an idealized system of currents similar to the California Current. In [7] mesoscale variability of the World Ocean, based on altimetric data, was studied using an automated procedure of identification and tracking of mesoscale structures. 35 eddies with a lifetime of more than 16 weeks were described. In [8] 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 when a resolution was increased. In [9] mechanisms of generation and instability of submesoscale flows (density fronts, filaments, topographic traces and coherent vortices) in the ocean were considered. The paper [10] was devoted to numerical modeling of submesoscale structures in the Gulf of Finland of the Baltic Sea during coastal upwelling events in July–September 2006 using POM-model.

The aim of this investigation is a reconstruction of hydrophysical fields in the winter and summer seasons with high spatial resolution on the basis of the hydrodynamic model [11, 12] in the coastal regions of the Black Sea, a determination of possible mechanisms of the formation of meso- and submesoscale features of circulation and their dependence of the season. In addition, to show an importance of a use of high spatial resolution on reconstruction of meso- and submesoscale structure of fields on the basis of a comparison with the results of the calculation with a coarser grid size (~1.6 km). The work, presented in this paper, is a continuation of our previous investigation [13].

We consider these areas of the Black sea (a coastal zone of the Southern Coast of the Crimea and the north-western shelf) because they contribute significantly to the dynamics and energy of the circulation.

2. Statement of the problem and description of numerical experiments

The main tool, used in this investigation, is a z-coordinate three-dimensional nonlinear energy-balanced prognostic model of baroclinic currents of the Black Sea, which was developed at the Marine Hydrophysical Institute under the guidance of Dr. Sc. Demyshnev S.G. and has been successfully used for solving theoretical and applied problems. 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 [11]. System of equations, including equations of motion, heat and salt advection, continuity equation, equation of state and equation for the pressure with the boundary and initial conditions was solved numerically, using a C-grid finite-difference approximation. It should be noted that the sea level was calculated from the discretized analogue of the continuity equation. The following steps were made in [12] in order to adapt the model [11] to the conditions of the coastal zone of the Black Sea with open boundaries. New data arrays of the region bathymetry were processed, boundary conditions on the open boundaries were selected and implemented, model parameters were chosen on the basis of preliminary experiments, river inflow locations and depths of estuaries were assigned, 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.

Experiments 1 and 2 were conducted for the coastal zone of the Southern Coast of Crimea (SCC), located between parallels 44.25°N and 44.72°N and the meridians 33.95° and 34.55°E, from 1 to 31 of January, 2006 and from 1 to 31 of July, 2006 respectively. The region had three open boundaries: western, southern and eastern, a maximum depth was 2 km. We used high spatial resolution (horizontal grid 350×350 m and 38 vertical layers from 1 m to 2 km) and took into account a detailed representation of the bottom relief with a resolution of ~500 m. The time step was equal to 10 s. Horizontal coefficients of turbulent viscosity and diffusion were equal to \( \nu_H = 35 \cdot 10^4 \text{cm}^2 / \text{s}, \kappa_H = 35 \cdot 10^4 \text{cm}^2 / \text{s} \).

Experiments 3 and 4 were conducted for the north-western shelf (NWS) of the Black Sea from 1 to 31 of January, 2006 and from 1 to 31 of July, 2006 respectively. We considered a region of the Black Sea, limited by latitude 45.5°N and located between meridians 29.5° and 33.5° E, a maximum depth was 50 m. We used high spatial resolution (horizontal grid 500×500 m and 44 vertical layers from 1 to 49 m). The time step was equal to 10 s. We used more detailed presentation of bottom topography (with a resolution of ~1.6 km), interpolated to 500×500 m. It has been obtained by digitization of navigation maps by staff of Shelf hydrophysics and Waves Theory departments of Marine Hydrophysical Institute. Horizontal coefficients of turbulent viscosity and diffusion were equal to \( \nu_H = 3 \cdot 10^5 \text{cm}^2 / \text{s}, \kappa_H = 3 \cdot 10^5 \text{cm}^2 / \text{s} \). We took into account the discharges of three rivers: Dnieper, Dniester, and South Bug.

Fields of currents, temperature and salinity, obtained from the model for the entire sea on a 1,64 × 1,64 km horizontal grid [14], were used to specify initial and boundary conditions at the open boundaries.
of the domain for experiments 1–4. The vertical coefficients of turbulent exchange of momentum and diffusion were calculated according to the Philander–Pacanowski approximation [15]. The fields of tangential wind stress, heat fluxes, as well as precipitation and evaporation, obtained from data of the regional atmospheric model ALADIN, were linearly interpolated to the selected grids for each day.

The following boundary conditions were specified on the open boundaries. The components of the current velocity, temperature and salinity (the Dirichlet conditions) were assigned in the boundary regions where water flowed into the domain; conditions \( \partial u / \partial n = 0, \partial v / \partial n = 0 \) for \( u, v \) and radiation condition [16] for \( T, S \) were specified in the boundary regions where water flowed out of the domain.

For the classification of obtained eddies we estimated a value of the local baroclinic deformation radius \( (R_d) \) for the selected coastal areas of the Black Sea. It was equal to \( \sim 6–7 \) km. We assumed that submesoscale eddies had a radius bigger than local baroclinic Rossby deformation radius and Rossby number was less than unity \( (R > R_d, R_0 < 1) \). We assumed that submesoscale eddies had a radius smaller than \( R_d \) and Rossby number was of the order of unity \( (R < R_d, R_0 \approx 1) \).

3. The results of experiments

3.1. SCC, winter

The Rim Current (RC) is the main element that determines a circulation of the Black Sea in general and the selected region specifically. The winter period was characterized by a dominance of the alongshore jet of the RC, it was directed to the west and southwest during the calculating period from 1 to 31 January, the maximum velocity in the upper horizons was 140 cm/s. Submesoscale eddy formations of various signs of rotation were obtained in the upper 30-m water layer between the coastline and the RC. A possible mechanism of their formation was the flow of the RC over inhomogeneities of the bottom relief and coastal orography. Those small-scale structures had a short lifetime \((1–2 \) days\) and were generated near the cape Ayu-Dag, in the eastern part of the region and in the Gulf of Yalta. Figure 1 shows current fields at the depth of 5 m on January 12 and 20, in which the following eddies were reconstructed: cyclonic in the vicinity of the cape Ayu-Dag \((R \approx 5 \) km\(< R_d, R_0 \approx 1.1, \) figure 1a) and anticyclonic in the eastern part of the region \( R \approx 5 \) km\(< R_d, R_0 \approx 0.8, \) figure 1b).

![Figure 1](image)

We compared current fields with the results with a more coarse resolution [14] and found a correlation between them during the calculating period, however a number of eddies was absent and a field structure was smoother in the experiment with a lower resolution.

The following structure was typical for the temperature and salinity fields: warmer and less saline waters were located along the coast \((10–11^\circ C, \less 18\%)\), colder and more saline waters \(–\) in the deep-water part of the region \((8–9^\circ C, \more 18\%)\).
3.2. **SCC, summer**

A circulation was characterized by a certain weakening of the jet of RC (for example, figure 2a) and meso- and submesoscale eddy structures were generated during the calculation period from 1 to 31 of July. Anticyclonic eddy formations with a radius of about 20 km and a lifetime of 3–4 days were obtained in the upper 100-m layer between the coastline and the RC from 10 to 12, from 18 to 21, from 24 to 26 of July, moving along the direction of the RC (for example, figure 2b). Analysis of the equations of energetics showed that processes of baroclinic instability of the RC were observed in the coastal zone. It was a possible cause of the formation of mesoscale eddies. Eddies were generated in the regions, which were characterized by negative values of the buoyancy force and, as a consequence, a transition from kinetic energy to potential energy took place. A correspondence was found between obtained features of the circulation and a number of satellite images.

Submesoscale features of circulation with a radius less than 5 km were reconstructed in the upper water layer, for example, anticyclonic eddy formations in the eastern part of the region (R≈4 km<Rd, R0 ≈0.9, figure 2a). The analysis showed that they were formed as a result of the flow of the RC along the coastline of the SCC and inhomogeneities of the bottom relief.

We compared current fields with the results with a more coarse resolution [14] and found a correlation between them during the calculating period, however a use of higher spatial resolution allowed to reconstruct a field structure more accurately.

![Figure 2](image.png)

**Figure 2.** Current fields (cm/s), calculated in the upper water layer (every fourth arrow was drawn): a – July 8, b – July 19.

Analyzing thermohaline fields, we noted thickening of isotherms and isohalines along the coast, separating warmer and less saline waters (along the coastline) and colder and more saline waters (in the deep-water part).

Vertical structure of the velocity, temperature, salinity was also investigated in order to estimate the influence of horizontal resolution on vertical profiles. We found a correlation between the results of experiments with a fine and coarse resolution during the calculating period, however some features of the circulation, associated with eddy formation, were absent in the experiment with a coarse resolution. In particular, anticyclonic eddies were distinguished as areas of deepening of the isopycnic surfaces, as well as reduced salt reserve and maximum heat reserve.

3.3. **NWS, winter**

Surface shelf currents were intense (maximum velocity was 100 cm/s), cyclonic vorticity was observed in the fields (the prevailing direction of currents was west and south-west) during the calculating period from 1 to 31 of January.
A field of currents had a complex mesoscale structure, characterized by eddies and jets. Eddies of various sizes and rotating signs were reproduced in the upper layer of water near estuary of the river Dniester, near Odessa, in central part of the region, in areas of Tendrovsky and Karkinit bays, as well as near the open boundary during the calculating period.

Eddy structures, associated with to the topography of the bottom, were revealed in the field of currents. There was a correspondence between the zones of eddy generation and topographic inhomogeneities located between 30.8 and 31.2°E and 31.8 and 32° E from 14 to 19 of January. A possible mechanism of formation of those eddies – influence of inhomogeneity in the bottom topography on the fluid flow.

Figure 3 shows mesoscale cyclonic eddies, reconstructed on January 19 at the depth of 10 m. Bottom relief played a crucial role in the formation of jets in the western part of the region (for example, intense jet about 15 km wide, directed to the north, was limited by 20–28 m isobaths).

Intense jets, which trajectory coincided with the isobaths of 20–28 m, were directed to the south. They were observed below the depth of 10 m from 1 to 12 of January. Meandering of those currents could lead to the formation of eddies of different signs of rotation in the western part of the north-western shelf.

We compared current fields with the results with a more coarse resolution [14] and found a correlation between them during the calculating period, however a use of higher spatial resolution and more detailed bathymetry allowed to reconstruct the field structure more accurately. In particular, a number of eddies was absent and a field structure was smoother in the experiment with a lower resolution.

Thermohaline fields were also analyzed. Under the influence of the northern winds and heat fluxes with negative values, there was an intensive cooling of the shallow areas. The values of temperature varied from 0–1.0°C along the coastline to +7–8°C in the open part of the region. The salinity of the sea surface layer in the north-western part was 17–18‰, it decreased to 16‰ near the shores, salinity was about 0 – 1‰ in the region of river estuaries. A zone of relatively warm water, limited by an isotherm of 3°C and corresponding to an eddy formation in the field of currents, was formed in the center of the region.
3.4. NWS, summer

The main direction of surface shelf currents was western, southern and south-western (maximum velocity was 50 cm/s) during the calculating period from 1 to 31 of July. Eddy formations were reproduced in the upper 30-meter layer near Odessa, near estuary of the river Dniester, in areas of Tendrovsky and Karkinit bays, as well as in central part of the region and near the open boundary during the calculating period.

Mesoscale cyclonic eddy, which was repeatedly registered in satellite observations, was generated at a depth of 1–24 m between the meridians 30.8 and 31.2 E. A possible mechanism of formation of that eddy − influence of inhomogeneity in the bottom topography on the fluid flow. According to the calculation results, it was obtained from 5 to 8 and from 14 to 20 of July 2006. The lifetime of those eddies was 1–3 days.

Intense jets were generated and developed in the upper horizons, as well as deep horizons. Figure 4 shows current field at the depth of 10 m on January 16. We compared current fields with the results with a more coarse resolution [14], and found a correlation between them during the calculating period, however a use of higher spatial resolution and more detailed bathymetry allowed to reconstruct the field structure more accurately. In particular, a number of eddies was absent and a field structure was smoother in the experiment with a lower resolution (figure 4b).

Figure 4. Current fields (cm/s) for the western part of NWS, calculated on July 16 at the depth of 10 m: a – with a resolution of 500 m (every fifth arrow was drawn), b – with a resolution of ~1.6 km (every second arrow was drawn).

4. Conclusions

Prognostic calculations of hydrophysical fields during the winter and summer periods with a spatial resolution of 350 m in the region of the SCC and 500 m in the area of the NWS have been carried out on the basis of the hydrodynamic model, adapted to the conditions of the coastal zone of the Black Sea with open boundaries. Possible reasons of the formation of meso- and submesoscale features of the coastal circulation were described.

A dominance of RC was typical for the region of SCC in the winter season, submesoscale eddy formations of various signs of rotation were obtained in the upper layer between the coastline and the RC (near the cape Ayu-Dag, in the eastern part of the region, in the Gulf of Yalta) by flowing the RC along coastal orography and the bottom relief.

A certain weakening of the jet of RC was noted in the summer season for the region of SCC, anticyclonic mesoscale eddy formations were generated between the coastline and the RC, moving along the direction of the RC. A possible mechanism of their formation was a baroclinic instability of the RC.
A field of currents of NWS in the winter and summer seasons had a complex meso- and submesoscale structure, characterized by eddies and jets. Eddies of various sizes and rotating signs were reproduced in the upper layer of water near estuary of the river Dniester, near Odessa, in central part of the region, in areas of Tendrovsky and Karkinit bays, as well as near the open boundary during the calculating period. A possible mechanism of formation of eddies in the central part – influence of inhomogeneity in the bottom topography on the fluid flow.

Bottom relief played a crucial role in the formation of jets in the western part of the shelf. Meandering of those currents could lead to the formation of eddies of various signs of rotation.

In comparison with previous calculations, new meso- and submesoscale eddies and jets have been reconstructed due to higher spatial resolution and more detailed bathymetry and coastline, some of them were confirmed by observational data.

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