Numerical Modelling of the Circulation and Pollution Transport from Rivers and Wastewater Treatment Plants in the Sochi Coastal Area

Nikolay Diansky[1,2,3][a], Vladimir Fomin[1][b], Irina Panasenkova[1][c] and Evgeniya Korshenko[1][d]
[1]*Department of Numerical Modelling of Hydrophysical processes, Zubov State Oceanographic Institute, Moscow, Russia*
[2]*Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
[3]*Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow, Russia*

Keywords: Black Sea, Coastal Circulation, Downwelling, Sea Ventilation.

Abstract: This paper provides a brief description of the technique for simulation Black Sea circulation and pollution spreading in the Sochi coastal area. Two versions of the ocean circulation INMOM model are used: M1 model with coarse spatial resolution of 4 km and M2 model with non-uniform spatial resolution. Large-scale structure and mesoscale large eddies of Black Sea are simulated using M1 model. M2 model is applied for simulating mesoscale and sub-mesoscale dynamics, in addition to simulating large-scale structure of the Black Sea circulation in the coastal zone near Sochi. In this study we analyse the structure of horizontal and vertical coastal currents and estimate concentration and spread of pollution. The results of numerical modelling in the coastal zone were successfully validated using laboratory and observation data from Elkin et al., 2017.

SCITEPRESS SCIENCE AND TECHNOLOGY PUBLICATIONS

1 INTRODUCTION

Numerical modelling of the dynamics of coastal currents is a challenging, yet timely problem. Coastal currents, in turn, define the dynamics of pollution spreading.

This paper presents a technique for reproducing circulation of the Black Sea and modelling the spreading of pollutants in the Black Sea coastal zone near Sochi. Three-dimensional sigma-coordinate model of ocean circulation INMOM (Institute of Numerical Mathematics Ocean Model) is used for simulating the Black and Azov Seas' dynamics. The INMOM model is based on primitive equations of ocean dynamics with incompressibility, hydrostatic and Boussinesq approximations (Diansky, 2013).

The main objectives of this work are to study the mechanism of vertical circulation and pollution transport characteristics in the Sochi coastal area and to validate the model by comparing the results of numerical modelling to available laboratory experiments and observations.

Small-scale coastal processes and their impact on pollution spreading in the Big Sochi region in the Black Sea has already been reviewed in the work by Diansky et al., 2013. However, the results of numerical modelling of pollutants' vertical transport were considered controversial, till laboratory experiments studying downwelling coastal current dynamics were carried out at the Shirshov Institute of Oceanology, Russian Academy of Sciences (IO RAS) (Elkin et al., 2017).

2 METHODOLOGY

Two versions of the INMOM model (model M1 and model M2) were developed for simulation of hydrophysical fields of the Black Sea.

[a] https://orcid.org/0000-0002-6785-1956
[b] https://orcid.org/0000-0001-8857-1518
[c] https://orcid.org/0000-0002-8338-4825
[d] https://orcid.org/0000-0003-2310-9730

Diansky, N., Fomin, V., Panasenkova, I. and Korshenko, E.
Numerical Modelling of the Circulation and Pollution Transport from Rivers and Wastewater Treatment Plants in the Sochi Coastal Area.
DOI: 10.5220/0007836203780383
In *Proceedings of the 5th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2019)*, pages 378-383
ISBN: 978-989-758-371-1
Copyright © 2019 by SCITEPRESS – Science and Technology Publications, Lda. All rights reserved

2.1 The M1 Model for Simulation of the Black and Azov Seas' Circulation

The detailed description of the M1 model is provided in the work by Diansky et al., 2013.

Computational grid covers the entire areas of the Black and Azov Seas in the M1 model. It has uniform horizontal resolution of 4 km and contains 287 × 160 nodes in the horizontal plane. The M1 time step equals 5 minutes. It has forty nonuniformly distributed vertical sigma levels.

Bathymetry data of the Black Sea were obtained from the global GEBCO atlas with spatial resolution of 30'' available to download from www.gebco.net.

Three dimensional monthly mean climatic fields of temperature and salinity for the Black Sea basin made by the Marine Hydrophysical Institute of the National Academy of Sciences of Ukraine (MHI NASU) (Ivanov and Belokopytov, 2011) were used as the M1 model initial conditions, after they were interpolated on the M1 model grid.

Temperature and salinity horizontal turbulent diffusion were parameterized using a second order operator with coefficient of 50 m^2 s^{-1}. Parametrization of the horizontal viscosity was performed by an operator of the fourth order with coefficient of 10^9 m^4/s. Vertical turbulent processes were parameterized according to Philander–Pacanovsky suggestions (Pacanovsky and Philander, 1981): the coefficient of vertical viscosity ranged from 10^{-4} to 10^{-3} m^2/s, the coefficient of vertical temperature diffusion varied in the range from 0.5×10^{-5} to 0.5×10^{-4} m^2/s and the coefficient of vertical salinity diffusion ranged from 0.1×10^{-5} to 0.1×10^{-4} m^2/s.

Condition of temperature and salinity zero fluxes were set at the bottom and lateral boundaries. The zero-velocity condition was set at the boundaries. The free-slip condition was specified at the lateral boundaries. Finally, squared friction was used at the bottom.

The nudging condition was used for salinity with the relaxation parameter of 1/120 day^{-1}. This was made to fit the model salinity to the climatic values at the depths below 300 m. For surface salinity special correction of its climatological values was added to the salinity flux with the relaxation parameter equaling 10 m/120 days. This coefficient means the relaxation of the average over 10 m depth model salinity to the climatic values with a 120 days time step.

The atmospheric data consist of temperature and humidity, wind speed at a height of 10 m, sea level pressure, precipitation, and downwelling long- and short-wave radiation. These atmospheric characteristics were downloaded from the Era Interim global atmospheric reanalysis of the European Center for Medium Range Weather Forecast (ECMWF) (https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/). Bulk-formulas were used to calculate sensible and latent heat fluxes, short- and long-wave radiation, momentum flux and net salt flux, consisting of evaporation, precipitation and climatological runoff.

To set rivers' discharge in the M1 model data from the climatic year CORE (Coordinated Ocean-ice Reference Experiments) (Large and Yeager, 2004) was taken in the form of pseudoprecipitation concentrated in the basins near the river mouths.

2.2 The M2 Model for Simulation of the Black Sea Circulation and Pollution Spreading

The M2 model was described in detail in Diansky et al., 2013. Only the basic features will be mentioned here.

M2 version of the INMOM model was applied to simulate the Black Sea circulation with increased resolution in the area of waters near the Sochi coast. Spherical coordinates are used for writing primitive model equations with one of the poles situated in the land point with geographic coordinates (40.0052° E, 43.5913° N) near Krasnaya Skala village. Such grid with variable step and refinement in the area of interest makes it possible to vary horizontal resolution from 50 m near Sochi to 5-9 km in the western part of the Black Sea (Figure 1). The M2 model has twenty nonuniformly distributed vertical sigma levels.

The M2 model computational grid has 759x600 nodes in the horizontal plane. In other words, the M2 grid is much larger than the M1 grid. The M2 model time step is 30 s. Considering large domain dimension and small time step the M2 model requires significant computational resources and it is very time consuming, in contrast to the M1 model, which has a reasonable experiment time.

Vertical diffusion coefficients used in the Philander–Pacanovsky parametrization were set to the same values as in the M1 model. Horizontal diffusion coefficients for temperature and salinity were considered proportional to the spatial step of the M2 model grid. Horizontal viscosity coefficient of the forth order was set proportional to the square of the spatial grid step.

Bottom bathymetry was defined similarly to the M1 model, by interpolating global GEBCO data on the M2 grid domain (Figure 2). Main rivers of the

Sochi region (Sochi, Khosta, Mzymta) and 18 sewage discharge pipe heads included into the model experiment are marked on the Figure 2.

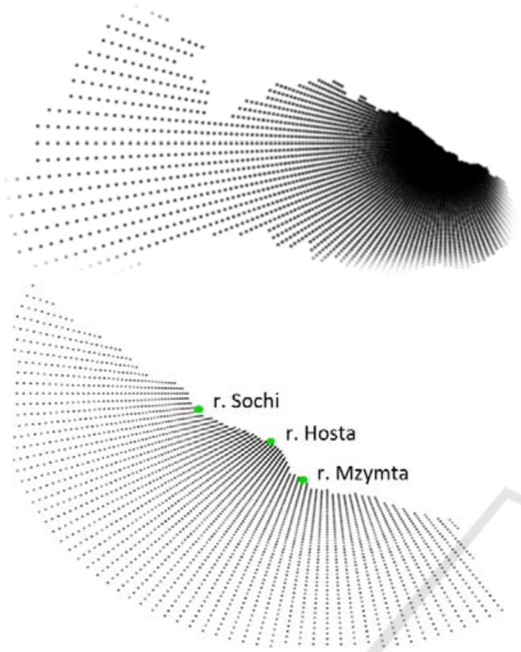

Figure 1: The M2 model computational grid with zooming of the Big Sochi domain area with high resolution. Every fifth point along each coordinate is showed.

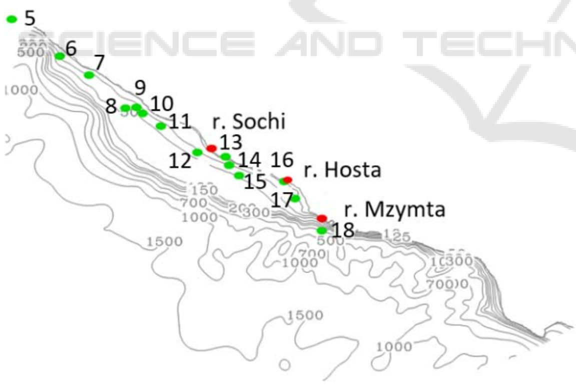

Figure 2: Bottom bathymetry of the M2 model. Colored points correspond to the rivers (red) and sewage discharge pipe heads (green).

Both models are eddy-permitting ocean circulation models which reproduce circulation of the Black Sea. The Black Sea Rim Current, eddies which accompany it, anticyclonic eddy vortices with diameters up to 50–100 km are reproduced by M1 model with coarse resolution of 4 km. However, M2 model with high spatial resolution allows us to simulate eddy circulation more qualitatively and small-scale coastal processes in the area of interest (in the eastern part of the Black Sea near Sochi). Moreover, mesoscale and sub-mesoscale eddies have a significant impact on the coastal water dynamics, which, for their part, determine pollution spreading.

2.3 A Technique for Modelling the Spread of Pollutants

A technique of numerical modelling of pollution spreading was proposed using the M1 and M2 models. At first, the M1 model is used to calculate Black and Azov Seas' circulation for the specified time period. Then, the M2 model is used to simulate the Black Sea dynamics and calculate pollution concentration and transport during the simulation time of the pollution spreading. Initial conditions for the M2 simulation start time is calculated by the M1 version of the model.

Equation of passive tracer transport–diffusion is solved to estimate pollution characteristics in the M2 model. This equation is similar to the diffusion equations used for temperature and salinity calculation, except the fact that the monotonous scheme of transport–diffusion is used and the diffusion coefficient for a passive tracer provides nonnegativity of the solution.

3 RESULTS AND DISCUSSION

Available laboratory and observation data along with the results of the model simulation will be used to study coastal circulation structure and pollution spreading in the shelf slope zone of the Black Sea.

If coastal sea current reaches the bottom, bottom Ekman layer is formed. In this layer in the Northern Hemisphere the net water transport is 90 degrees to the left of the surface current direction. In case if cyclonic current flows along the sea eastern coast, water in the bottom Ekman layer will be transported from the coast, resulting in the downwelling current accompanied by surface water sinking along an inclined bottom.

In the eastern part of the Black Sea alongshore current, as a part of large-scale cyclonic Rim Current, leads to the formation of the downwelling coastal current. Downwelling plays an important role in the ventilation of stratified water masses. As a result of enhanced ventilation, oxygen-rich surface waters enter deeper layers of the Black Sea. In the work by Elkin et al. (2017) it was suggested that this process leads to oxygen ventilation of the Black Sea aerobic layer. Furthermore, oxygen reduction in the coastal zone has unfavorable influence on the ocean biogeochemical cycles and marine ecosystems.

Sinking waters on the continental slope are one of the poorly studied ventilation mechanisms for the stably-stratified sea waters. Numerical modelling and laboratory experiments are the basic methods of studying this topic.

3.1 Numerical Experiment

We simulated pollution spreading during the flood period from April 1, 2007 to April 30, 2007 using the M2 model. The results of the Black Sea circulation modelling from the M1 model on April 1, 2007 was used as the initial conditions for the M2 model running. The atmospheric forcing for the M2 model was the same as for the M1 model.

In the numerical experiment the Sochi, Khosta, and Mzymta rivers and 18 deepwater sewage pipes were considered to be the main sources of pollutants in the coastal waters of the Sochi region. The Data about pipes' locations and their discharges were provided by the Sochi Special Center on Hydrometeorology and Monitoring of the Black and Azov Seas (SSCHM BAS).

As for the M1 model, the CORE database (Large and Yeager, 2004) was used to get the river runoff data, but for the discharges of the Mzymta, Sochi, and Khosta rivers. These rivers' discharges were estimated using the real climatic discharges from the work by Dzhaoshvili (1999). For the Sochi River discharge equaled to 42 m^3/s, for the Khosta River – 17 m^3/s, and for the Mzymta River – 144 m^3/s.

The coefficient of volume concentration of conventional pollutant in the river waters was 0.03 m^3/m^3 according to the estimates of the Zubov State Oceanographic Institute. The sewage waters from the pipes were assumed to be completely polluted with coefficient equaling 1.0 m^3/m^3.

The technique for calculating concentration of the pollutants in the cells of the grid domain was discussed in Diansky et al. (2013). It was considered that at each model time step the inflow of pollutants in the grid cell was calculated in accordance with the volume concentration coefficients of rivers and pipes multiplied by the corresponding concentration and the instantaneous dilution of pollutants over the grid cell volume. Pollution total transport from rivers was approximately 6 m^3/s, and the total transport of pollutants from all pipes was approximately 2 m^3/s.

The pollution concentration was dimensionless with the minimum considered level equaled to 10^{-7} volume parts of pollutants in the water. This value was comparable to the threshold limit value (TLV) for the main pollutants in seawater (Diansky et al., 2013).

Coastal currents play crucial role in the spread of pollutants from the rivers and pipes. Since mesoscale and sub-mesoscale eddies take the main part in transportation of pollutants, if the model is eddy-permitting, the accuracy of the model performance is higher. The pattern of pollution distribution can show involved eddy structures of the coastal currents in the Black Sea. It was shown by Diansky et al. that the M2 model qualitatively reproduces horizontal dynamics: the large-scale circulation (the Black Sea Rim current) and the large quasi-geostrophic eddies of ≈20–100 km (mesoscale processes).

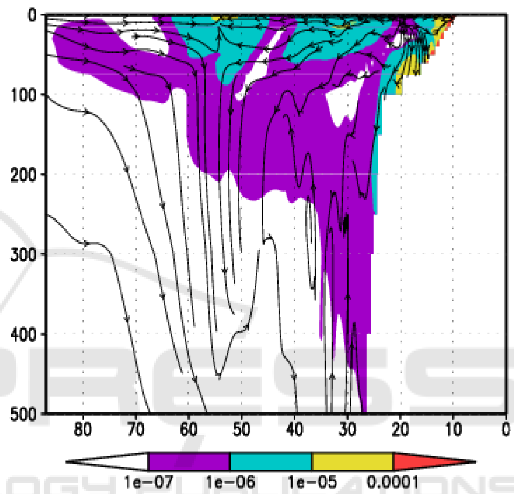

Figure 3: Pollution spreading vertical section normal to the coast on the end of the model calculations on April 30, 2007, in the point near Sochi where pipe number 13 (Figure 2) is located. X-axis corresponds to the sea depth in m, y-axes – distance in km.

Vertical section of total pollution spreading normal to the coast on April 30, 2007, was made in the point where pipe number 13 was located to study vertical structure of pollution spreading from all the rivers and pipes (Figure 3). Streamlines of currents are plotted on the Figure 3, in order to estimate the structure of pollution transport. According to the presented figure, vertical pollution movement has an advective character near the shore. In the coastal zone along sea slope, pollution penetrates from the surface to the deeper sea layers up to 500 m due to the downwelling current. In the range of depths from 250 to 500 m the concentration of pollution has minimal values. Due to the complicated eddy structure of coastal currents complex 3-dimensional pollution distribution is formed and pollutants travel significant distances around 80 km. At a distance of 30-60 km from the shore the pollution does not spread below

250-100 m depths, as salinity halocline of the Black Sea plays its locking role, preventing the ventilation of the deep layers.

3.2 Laboratory Experiments

Several laboratory experiments studying downwelling coastal current along a sloping bottom were carried out at the Shirshov Institute of Oceanology, Russian Academy of Sciences (IO RAS) using special equipment: rotating tank with a cone in the center of it. The results of experiments and experimental setup are reviewed in detail in Elkin et al., 2017.

This work showed that, in case of a sloping bottom and in case of different densities of the water in the tank and inflowing water, a bottom Ekman layer was formed with a downward transport of less dense water, which in turn experienced convective instability.

The results of the performed laboratory experiments were used to preliminary estimate characteristics of the bottom Ekman layer on the shelf of the Black Sea.

Field studies data (measurements of salinity, temperature, pressure, and current velocity), collected by the scientists from the IO RAS using the autonomous Aqualog profiler at the Gelendzhik study site from February 24, 2015 to March 2, 2015 were used to analyze current structure in the coastal zone at the study site of the Black Sea. Fluorescence concentrations of chlorophyll a collected during the monitoring of the Black Sea coastal zone on R/V Ashamba on February 27, 2015, were also used to study horizontal and vertical structure of pollution spreading. Fluorescence concentrations of chlorophyll a in upper 100 m layer in monitoring transect is shown on Figure 4. X-sign on the Figure 4 corresponds to the current direction from us (in the plane of the figure), so we can see alongshore current in the coastal zone at the Gelendzhik study site, which leads to the formation of the downwelling coastal current in the Ekman bottom layer.

Following the estimates of the possible depth of water sinking made in Elkin et al., 2017 and the results on Figure 4, depth of less dense water penetration is about 50 m. Moreover, waters with small concentration of chlorophyll a can penetrate lower than 100 m depth. Alternatively, according to the work of Stanev (Stanev et al., 2013), ventilation in the coastal zone spreads down to about 150–200 m. These results were obtained from the analysis of observations collected in the Black Sea from Argo floats with oxygen sensors.

Corresponding numerical simulation results were confirmed by laboratory experiments and observation data.

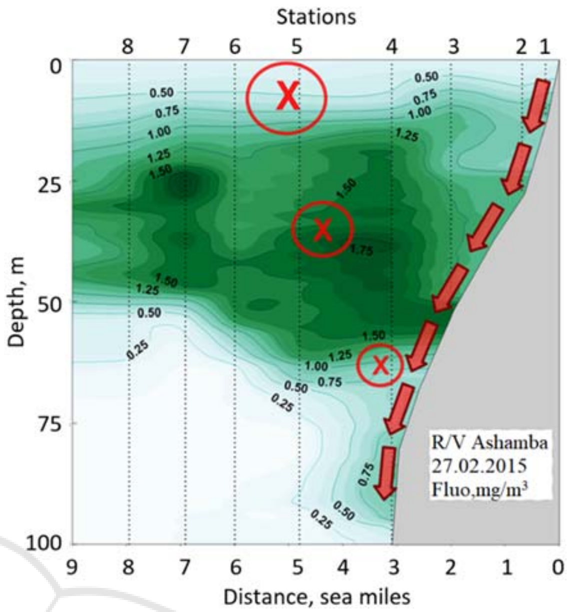

Figure 4: Vertical section of chlorophyll a fluorescence concentrations in the upper 100 m layer according to the monitoring transect of R/V Ashamba in Black Sea coastal zone on February 27, 2015, (Elkin et al., 2017). X-axis corresponds to the sea depth in m, y-axes – distance in sea miles.

4 CONCLUSIONS

We studied currents and the pollution transport in the eastern coastal zone of the Black Sea using numerical modelling technique. Proposed method makes it possible to simulate not only large-scale structure of the Black Sea circulation, but also the mesoscale and sub-mesoscale dynamics of the coastal zone.

Results of the numerical modelling of coastal dynamics and pollution spreading showed the effect of vertical advection and water sinking in the Sochi coastal area. Available experimental and observational data from the works by Elkin et al., (2017) and Stanev et al., (2013) was used to validate the results.

Reasonable, and in many cases good, agreement between the numerical and experimental data confirms the adequacy of the INMOM model in reproducing horizontal and vertical structure of the pollution spreading.

Future studies of the coastal dynamics and related mechanisms of water sinking, vertical and horizontal mixing of water will be conducted using numerical modelling.

ACKNOWLEDGEMENTS

The presented work was supported by the Russian Foundation for Basic Research according to the research projects №18-35-00512, №17-05-41101.

REFERENCES

Diansky, N.A., 2013. *Modelling of the ocean circulation and study of its response to short-term and long-term atmospheric forcing*. *1st **ed.*** Physmatlit, Moscow. (in Russian)

Diansky, N.A., Fomin, V.V, Zhokhova, N.V., Korshenko, A.N., 2013. Simulations of Currents and Pollution Transport in the Coastal Waters of Big Sochi. *Izvestiya, Atmospheric and Oceanic Physics*, 49(6): 611–621.

Dzhaoshvili, Sh.V., 1999. River runoff and sediment transport to the Black Sea. *Water Resources*, 26 (3): 243–250.

Elkin, D.N., Zatsepin, A.G., Podymov, O.I., Ostrovskii, A.G., 2017. Sinking of Less Dense Water in the Bottom Ekman Layer Formed by a Coastal Downwelling Current Over a Sloping Bottom. *Oceanology,* 57(4): 478–484.

Ivanov, V.A., Belokopytov, V.N, 2011. *Oceanography of the Black Sea*. NAS of Ukraine, Marine Hydrophysical Institute, Sevastopol. (In Russian)

Large, W., Yeager, S., 2004. Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. NCAR Technical Note, National Centre for Atmospheric Research.

Pacanovsky R.C., Philander G., 1981. Parametrization of vertical mixing in numerical models of the tropical ocean. *Journal of Physical Oceanography*, 11: 1442-1451.

Stanev, E.V., He, Y., Grayek, S., Boetius, A., 2013. Oxygen dynamics in the Black Sea as seen by Argo profiling floats. *Geophysical Research letters*, 40(12): 3085-3090.

SCITEPRESS SCIENCE AND TECHNOLOGY PUBLICATIONS