MODELING OF DYNAMIC PROCESSES IN THE BLACK SEA AND ATMOSPHERE IN PERSPECTIVE OF THEIR COUPLING FOR THE BLACK SEA REGION

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ABSTRACT

At the modern stage of the development of Geosciences, the study of hydrothermodynamic and ecological processes occurring in the natural environment (sea, atmosphere, soil), their monitoring and forecasting become very relevant and are a necessary condition for sustainable development of society. The Caucasus region is one of the most difficult regions of the world from the point of view its physical and geographical features. These features include the Black and Caspian Seas and the complex terrain of the Caucasus. The Seas and the atmosphere are unified hydrodynamic systems, between subsystems of which processes of an exchange of energies, momentum and substances continuously take place. One of the most effective ways to study natural and environmental processes is methods of mathematical modeling, which allows reproducing these processes and phenomena and studying the quantitative contribution of various factors to the development of such processes.

The purpose of the paper is to discuss the models of the Black Sea and atmospheric dynamics developed at M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University, and some results of their implementation. The model of the Black Sea dynamics is based on a full system of ocean hydro-thermodynamics equations. Its high-resolution version, which is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol), is used to forecast main hydrophysical fields for the easternmost part of the Black Sea. The model of the atmospheric dynamics is based on a full system of atmospheric hydro-thermodynamics equations in hydrostatic approximation written in the terrain-following coordinate system and is realized for the extended territory including the eastern part of the Mediterranean Sea and Black and Caspian seas and for the Caucasus region.

These models, after some modification will form the basis of the coupled Black Sea-atmosphere limited-area modeling system.

Keywords: *circulation, hydro-thermodynamic processes, coupled modeling system, system of equations, boundary conditions*

INTRODUCTION

Scientific and technological progress, simultaneously with many benefits, has created serious problems related to increased anthropogenic impact and deteriorating ecological conditions of the natural environment (ocean, atmosphere, soil). Among the types of anthropogenic impact, it is especially important pollution of the sea and the atmosphere with impurities dangerous to humans, plants and animals, the main sources of which are transport, industrial, energy and agricultural facilities. The diffusion of different impurities into the Earth's liquid environment is a complex process and depends primarily on hydro and thermodynamic factors (circulation, turbulence, thermal stratification, *etc*.). Therefore, at the modern stage of development of Geosciences, the study of hydro-thermodynamic and ecological processes in the natural environment, their monitoring and forecasting becomes more relevant and is a necessary condition for sustainable development of society.

One of the most effective ways to study and forecast hydro-thermodynamic and ecological processes taking place in the natural environment is method of mathematical modeling, which allows reproducing natural processes and phenomena on a computer and quantifying the contribution of various physical factors to the development of environmental processes. Provided with real data, this method also allows predicting these processes.

The Caucasus region is one of the most difficult regions of the world from the point of view its physical and geographic features. These features include the Black and Caspian Seas and the complex terrain of the Caucasus. The Seas and the atmosphere are unified hydro and thermodynamic system, between subsystems of which processes of an exchange by energies, momentum and substances continuously take place.

The contribution of the Black Sea to formation of weather and regional climate is especially important for Georgia. In addition, the Main Caucasian Ridge plays a very important role in the formation of meteorological processes in the South Caucasus. The Main Caucasian Ridge protects Georgia from intrusion cold air from the north. Air masses flow around the ridge from the west and east, and under the influence of the Black Sea, more humid and less cold air masses enter the territory of Georgia.

The purpose of the paper is to discuss the numerical models of the Black Sea and atmospheric dynamics developed at M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University, and some results of their implementation. The model of the Black Sea dynamics is based on a full system of ocean hydro-thermodynamics equations. Its high-resolution version, which is nested in the basin-scale model of the Black Sea dynamics of Marine Hydrophysical Institute (MHI, Sevastopol), is used to simulate and forecast main hydrophysical fields for the easternmost part of the Black Sea. The model of the atmospheric dynamics is based on a full system of atmospheric hydro-thermodynamics equations in hydrostatic approximation written in the terrain following coordinate system and is realized for the extended territory including eastern part of the Mediterranean Sea and Black and Caspian seas and for the Caucasus region.

MODELING OF BLACK SEA DYNAMICS

Modeling of circulation and thermohaline fields of the Black Sea are carried out using basin-scale and regional versions of the Black Sea dynamics model.

Model description

The basin-scale model of the Black Sea dynamics is realized for the entire basin with 10 and 5 km spatial resolutions [1-3], but the regional model (RM-IG) - for the easternmost part of the Black Sea with 1 km resolution [4-6]. The regional water area is limited from the open part of the basin by the liquid boundary passing along the meridian 39.08^{o}E. Both models are based on a primitive system of ocean hydrothermodynamics equations in hydrostatic approximation, which is written in z-coordinates for deviations of thermodynamic values from their standard vertical distributions. The models take into account: sea bottom topography and configuration of shorelines, atmospheric forcing, absorption of solar radiation by the sea upper layer, spatial-temporal variability of the coefficients of horizontal and vertical turbulent viscosity and diffusion. In the basin-scale model water exchange between the Black and Marmara seas through the Bosphorus and the Danube river runoff are considered, while the RM-IG takes into account runoff of main rivers of Georgia.

To solve the system of equations, a two-cycle method of splitting with respect to physical processes, vertical coordinate planes and lines is used [7], [8]. The method allows the solution of a non-stationary spatial problem to be reduced to the solution of relatively simple two-dimensional and one-dimensional problems.

The RM-IG, which is a core of the regional forecasting system, is nested in the basin-scale model of MHI. All required input data with one-hour time step frequency corresponding to 3 days forecasting time period are available in a near operative mode from MHI via the Internet. These data providing initial and boundary conditions for the RM-IG are:

- 3D initial fields of velocity components, temperature and salinity;
- at the open boundary – values of velocity components, temperature and salinity predicted by the basin-scale model of MHI;
- on the sea surface – meteorological boundary fields predicted by the regional atmospheric models ALADIN or SCIRON.

Some results of modeling of the sea dynamics

Computational experiments on the basin-scale model to study average annual circulation and seasonal variability of hydrological fields were carried out with using average climatic data [1], [2]. In [3], [9], [10] detailed investigation of the vertical hydrological structure of the upper mixed layer of the Black Sea for different seasons were carried out.

The regional forecasting system makes it possible to calculate 3-days forecasts of the main hydrophysical fields - currents, temperature, salinity and density, but in emergency conditions, it is possible also to forecast the distribution of zones contaminated with oil products and other anthropogenic impurities in the Georgian coastal zone and the adjacent water area. The numerical experiments on modeling and forecasting hydrophysical fields were carried out using a computational grid covering the easternmost water area with a horizontal resolution of 1 km and with 30 vertical z-levels on depths 2, 4, 6, 8, 12, 16, 26, 36, 56, 86, 136, 206, 306,…,2006 m. The time step was equal to 0.5 h. The high-resolution of the regional model enables to reproduction of mesoscale and submesoscale eddies that are permanently generated throughout the year in the easternmost water area.

The model outputs (SST, currents) were compared with observational data – satellite SST and the Geostrophic currents reconstructed with use of satellite altimeter data [4], [5], [6].

As an example, Fig. 1 shows the prognostic fields of current, temperature and salinity by the time of July7 2020, 00:00GMT in the Georgian coastal zone and adjacent water area. Predicted fields correspond to t = 72 h after the initial time of forecast.

(a) (b) (c)

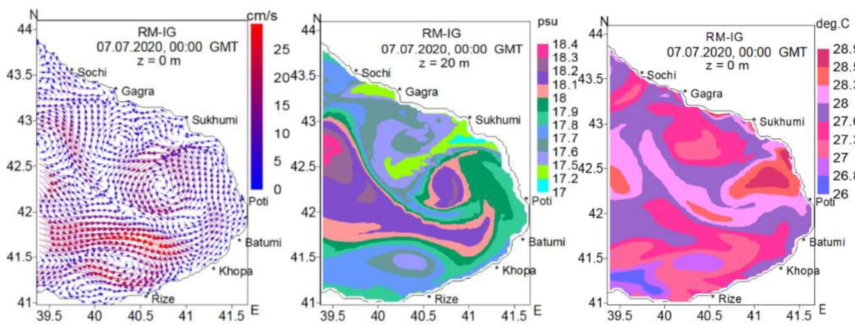

Fig.1. *Predicted surface flow (a), salinity (b) and SST(c) fields on 7 July 2020, 00:00 GMT. Salinity is on depth of 20 m.*

Figure 1 clearly shows several mesoscale eddy formations of cyclonic and anticyclonic nature. In most of the water area the temperature is $27.3^0 – 28.9^0$ C, relatively cold waters are observed in the southern part of the water area.

MODELING OF ATMOSPHERIC DYNAMICS

Model description

Hydrostatic model of atmospheric dynamics developed at M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University is based on a full system of atmospheric hydro-thermodinamics equations, written in the terrain-following coordinate system [11], [12], [13], [14]. A moving air mass in the troposphere is considered, which is limited from below by orographically inhomogeneous underlying earth surface and from above, at a height of the tropopause, by a free surface.

Numerical solution of the model equation system is based on Shuman-Hovermale and Crank-Nicholson schemes. The model is realized for the extended territory including the eastern part of the Mediterranean Sea and Black and Caspian seas and for the Caucasus region.

Some results of modeling of atmospheric dynamics

In the extended version of the model a non-uniform grid on a vertical covered the troposphere till 12 km with 32 calculated levels. the horizontal grid step was 40 km, the time step was 30 min. In Fig. 2 the relief is presented that was used in the model. The main features of the relief in the considered region is that the biggest and the lowest heights are in the Caucasian region. The maximal top (over 4500 m) is located on the Main Caucasian Ridge, and the lowest place is the level of the Caspian Sea, which is 28 m below the Black Sea level.

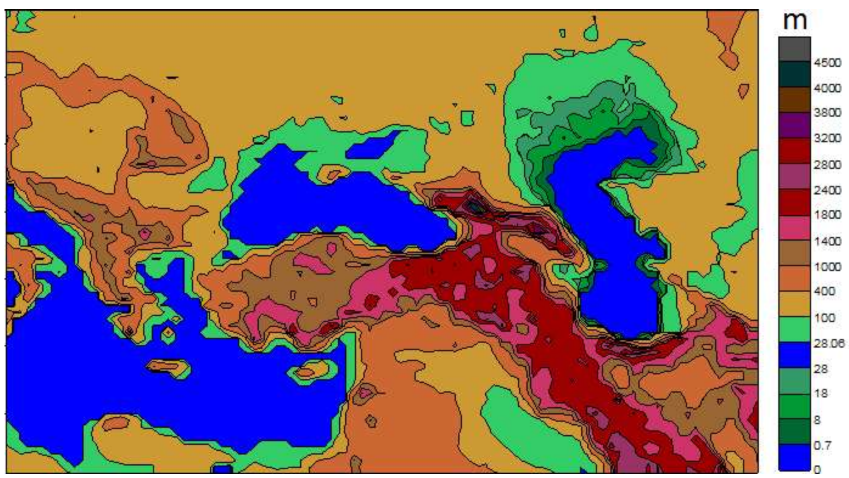

***Fig. 2.** The relief of the extended area used in the numerical model.*

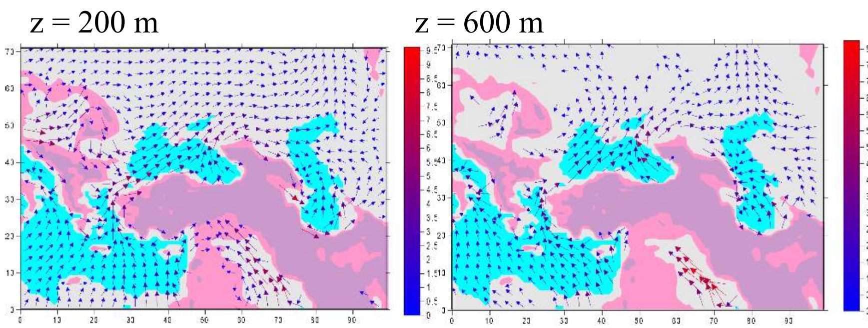

***Fig. 3.** Computed wind field on heights of 200 and 600 m at t = 24 h.*

In Fig. 3 simulated wind field on heights of 200 m and 600 m are presented, when at initial time moment t = 0 zonal western wind was accepted, which increased from 2 m/s on a ground surface up to 20 m/s on the top of the troposphere.

From the Figure it is clear that the terrain makes significant changes in the airflow and substantially changes the wind direction and speed. When approaching mountainous terrain, the direction of the airflow changes sharply, and in some cases the disturbed airflow takes the opposite direction to the background current.

To simulate meteorological processes over the Caucasus region, a relatively high-resolution version of the model of atmospheric dynamics with spatial resolution of 15 km was used. The important role of the relief geometry and mutual orientation of mountain ranges in the formation of the wind velocity field in lower troposphere is shown.

For the purpose of illustration, in Fig.4 the simulated airflow over the Caucasus at a height of 3 km is shown in case of the background south-eastern wind equal to 10 m/s. From the Figure is clear that the relief significantly affects the direction of the airflow and the distribution of wind speed. The maximum speeds equal to 20 m are observed approximately in the territory of Western Georgia at the foothills of the Caucasian ridge. The formation of a mesoscale anticyclonic eddy is observed over the Georgian sector of the Black Sea.

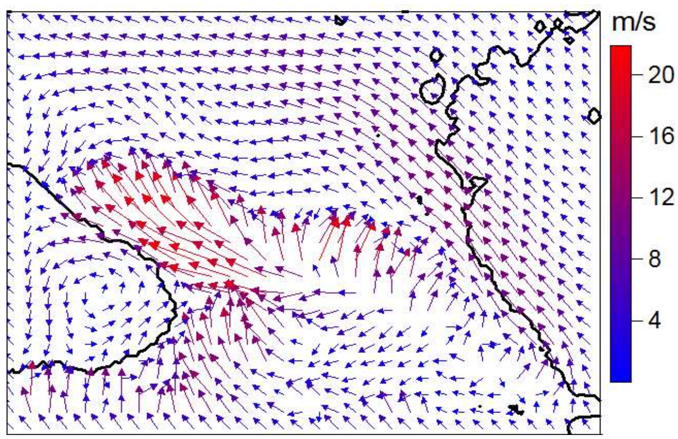

Fig. 4. *Simulated wind field over the Caucasus on height of 3 km in case of the background south-eastern wind.*

SOME ASPECTS OF A COUPLED BLACK SEA–ATMOSPHERE MODELING SYSTEM

The limited-area regional coupled the Black Sea – atmosphere model is considered for the area, which covers the Black and Caspian seas and some part of the Mediterranean Sea (Fig. 2).

The main components of the coupled modeling system will be above mentioned numerical models of the dynamics of the Black Sea and the atmosphere. Interaction with the underlying surface will be carried out with a quasi-one-dimensional model of the atmospheric boundary layer taking into account the active soil layer [15]. The goal of this task is to obtain vertical distribution of meteorological fields with very high resolution near the earth's surface, which is very relevant to adequately describe interaction processes with underlying surface.

The vertical structure of the model comprises the following layers:

1. Troposphere, which is considered above the surface layer up to the tropopause;

2. the atmospheric surface layer;

3. active layer of the soil;

4. Black Sea;

The equations describing processes in different layers are connected with one another with boundary conditions on a vertical, which basically express continuity of solutions and their first derivatives at transition from one layer to another. As one of boundary conditions on the underground surface (water, land) the equation of heat balance is considered.

Thus, the coupled model will be consist of separate modules, each of which describes hydro-thermodynamic processes in separate objects of the natural environment (sea, atmosphere, active layer of the soil).

CONCLUSION

The article provides a brief overview of the models of the dynamics of the Black Sea and the atmosphere, developed at M. Nodia Institute of Geophysics of I. Javakhishvili Tbilisi State University, which should become the basis for the development of a coupled modeling system for the Black Sea region. There are developed two versions of the model of Black Sea dynamics: basin-scale model, which provides to simulate main hydrophysical fields – the current, temperature and salinity for the entire sea basin with 5 km spatial resolution and regional model providing to simulate and forecast hydrophysical fields with 1 km spatial resolution for the easternmost part of the Black Sea covering Georgian coastal zone and surrounding water area. The hydrostatic limited-area model of atmospheric processes based on a full system of atmospheric hydrothermodynamics equations is realized for the areas of different scales.

The methodology to develop a limited-area coupled modeling system "The Black Sea - Land- Atmosphere" based on mentioned models of the Black Sea and the atmospheric dynamics is briefly described.

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