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

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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.

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..

The basin-scale model of the Black Sea dynamics is realized for the entire basin with 10 and 5 km spatial resolutions, but the regional model (RM-IG) - for the easternmost part of the Black Sea with 1 km resolution. The regional water area is limited from the open part of the basin by the liquid boundary passing along the meridian 39.08^0E. 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.

Model equation system

$$\frac{\partial u}{\partial t}+div\,\vec{u}u-lv+\frac{1}{\rho_0}\frac{\partial p'}{\partial x}=\nabla\mu\nabla u+\frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z},$$

$$\frac{\partial v}{\partial t}+div\,\vec{u}v+lu+\frac{1}{\rho_0}\frac{\partial p'}{\partial y}=\nabla\mu\nabla v+\frac{\partial}{\partial z}\nu\frac{\partial v}{\partial z},$$

$$\frac{\partial p'}{\partial z}=g\rho',\quad div\,\vec{u}=0,\quad \nabla\mu\nabla=\frac{\partial}{\partial x}\mu\frac{\partial}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial}{\partial y},$$

$$\frac{\partial T'}{\partial t}+div\,\vec{u}T'+\gamma_T.w=\nabla\mu_T\nabla T'+\frac{\partial}{\partial z}\nu_T\frac{\partial T'}{\partial z}+\frac{\partial\nu_T\gamma_T}{\partial z}-\frac{1}{c\rho_0}\frac{\partial I}{\partial z}-\frac{\partial\bar{T}}{\partial t},$$

$$\frac{\partial S'}{\partial t}+div\,\vec{u}S'+\gamma_S w=\nabla\mu_S\nabla S'+\frac{\partial}{\partial z}\nu_S\frac{\partial S'}{\partial z}+\frac{\partial\nu_S\gamma_S}{\partial z}-\frac{\partial\bar{S}}{\partial t},$$

$$\rho'=\alpha_T T'+\alpha_S S',\qquad \gamma_T=\frac{\partial\bar{T}}{\partial z},\quad \gamma_S=\frac{\partial\bar{S}}{\partial z}$$

$$T=\bar{T}(z,t)+T',\ S=\bar{S}(z,t)+S',\ \rho=\bar{\rho}(z,t)+\rho',\ p=\bar{p}(z,t)+p'$$

$$I=R_0'\,e^{-\alpha z},\quad R_0'=\eta(1-A)I_0,\quad I_0=a\sinh_0-b\sqrt{\sinh_0},$$

Boundary and initial conditions

At the sea surface z = 0

$$\frac{\partial u}{\partial z}=-\frac{\tau_{z\,x}}{\rho_0\nu},\quad \frac{\partial v}{\partial z}=-\frac{\tau_{zy}}{\rho_0\nu},\quad \nu\frac{\partial T}{\partial z}=Q^T-R_0\quad \nu\frac{\partial S}{\partial z}=(PR-EV)S_0$$

At the sea bottom $z=H(x,y)$

$u=0,\ v=0,\ w=0,\ \partial T'/\partial z=-\gamma_T,\ \partial S'/\partial z=-\gamma_S$

On the lateral surfaces

$u=0,\ v=0,\ \partial T'/\partial n=0,\ \partial S'/\partial n=0$ on Γ1 (rigid boundary).

$u=\tilde{u},\ v=\tilde{v},\ T'=\tilde{T}',\ S'=\tilde{S}'$ on Γ0 (liquid boundary),

At t = 0

$u=u^0,\ v=v^0,\ T'=T'^0,\ S'=S'^0$

For solving the problem a two-cycle splitting method is used with respect to physical processes and space coordinates (Marchuk 1974).

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 Internet. To solve the system of equations a two-cycle method of splitting is used. 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 Black Sea dynamics

Basin-scale model of Black sea dynamics was applied to study average annual circulation and seasonal variability of hydrological fields using average climatic data. The RM-IG is realized for the easternmost Black sea. The RM-IG, which is a core of the regional forecasting system, is nested in the basin-scale model of MHI. The numerical experiments were carried out using a computational grid covering the easternmost water area with a horizontal resolution of 1 km and with 30 vertical z-level on depths 2, 4, 6, 8, 12, 16, 26, 36, 56, 136, 306,..., 2006 m. Time step was equal to 0.5 h.
The model outputs (SST, currents) were compared with observational data – satellite SST and the Geostrophic currents reconstructed with use of satellite altimeter data.
Fig.1 shows the prognostic fields of current, temperature and salinity corresponding to July 7 2020, 00:00 GMT in the easternmost part of the Black Sea. Predicted fields correspond to t = 72 h after the initial time of forecast. Fig.1 clearly shows several mesoscale eddy formations of cyclonic and anticyclonic nature. In most of the water area the temperature is 27.3 – 28.9 deg.C, relatively cold waters are observed in the southern part of the water area.

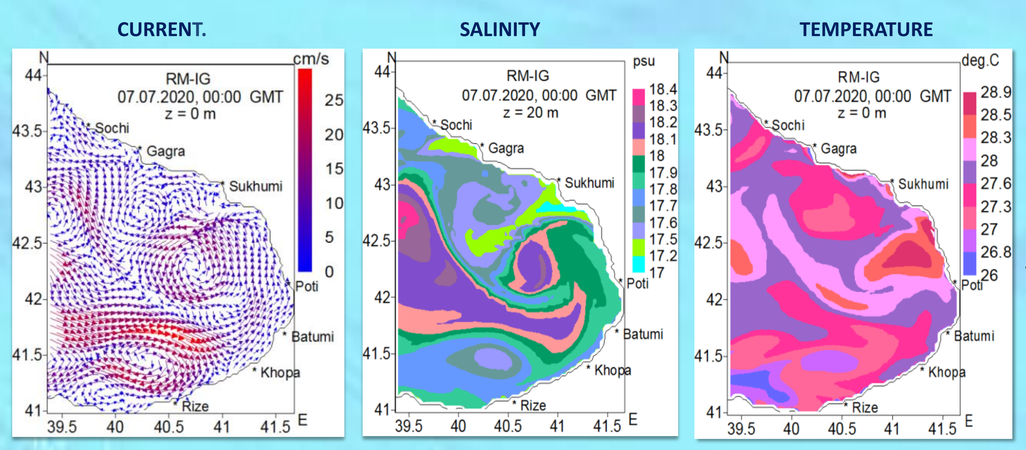

Fig.1. Predicted surface flow, salinity and SST fields on 7 July 2020, 00:00 GMT. Salinity is on depth of 20 m.

MODELING OF ATMOSPHERIC DYNAMICS

Hydrostatic model of atmospheric dynamics is based on a full system of atmospheric hydro-thermodynamics equations written in the terrain following coordinate system. Numerical solution Is based on Shuman-Hovermale and Crank-Nicholson schemes. The model is realized for the Extended territory including eastern part of the Mediterranean Sea and Black and Caspian seas and for the Caucasus region.

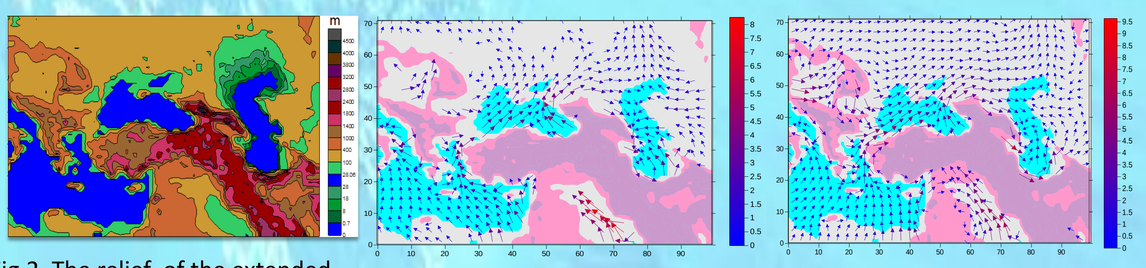

Fig.2. The relief of the extended area used in the numerical model.

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

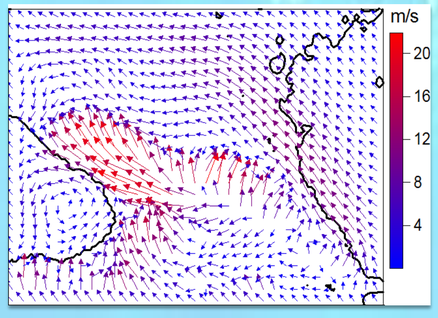

Fig.4.

To simulate meteorological processes over the Caucasus region, 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. in Fig.4 the simulated air flow over the Caucasus on height of 3 km is shown in case of the background south-eastern wind equal to 10 m/s. From the Figure it is clear that the relief significantly affects the direction of the air flow and the distribution of wind speed.

SOME ASPECTS OF A COUPLED BLACK SEA-ATMOSPHEREA MODELING SYSTEM

The limited-area regional coupled 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 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 (Demetrashvili, 1989). 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 presentation provides a brief overview of the models of the dynamics of the Black Sea and 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 with 5 km reresolution and regional model providing to simulate and forecast hydrophysical fields with 1 km spatial resolution for the easternmost part of the Black Sea. 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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