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EXPANSION OF THE REGIONAL FORECASTING SYSTEM OF THE STATE OF THE EASTERNMOST PART OF THE BLACK SEA WITH ECOLOGICAL PROBLEMS

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Contribution of the Black Sea to a social and economic status of the Black Sea riparian countries is very important. Besides that the Black Sea is a source of biological and mineral resources, it has the large recreational and transport value. Therefore ecological safety of coastal / shelf zones, which are exposed to the large anthropogenous loading, is very important for these countries. In such situation the large value gets functioning of the reliable forecasting system of the Black Sea state, which will allow to receive in an operative mode the information not only about the dynamic state of the sea, also to predict zones of pollution concentrations of oil and other substances in extreme situations, etc.

Nowadays at M. Nodia Institute of Geophysics of Iv. Javakhishvili Tbilisi State University the regional forecasting system of the dynamic state of the Black Sea is functioning in the near-real time mode for its easternmost part including the Georgian water area (liquid boundary coincides with a meridian taking place near Tuapse). The regional forecasting system is one of the components of the Black Sea Nowcasting/Forecasting System. The regional system was developed within the framework of the international scientific and technical projects EC ARENA and ECOOP in cooperation with Black Sea riparian countries at coordination MHI (Sevastopol/Ukraine).

The regional forecasting system provides 3-days forecasts of current, temperature and salinity fields with resolution 1km for the easternmost part of the Black Sea.

In our presentation we shall present the extended version of the regional forecasting system by inclusion in the system some numerical ecological models. Before to report on such models, we would like to describe briefly bases of functioning of the regional forecasting system developed earlier on which was already reported at the previous two conferences in Sevastopol.

Regional Forecasting System

The regional Forecasting system is based on the regional baroclinic model of Black Sea dynamics of the Institute of Geophysics (RM-IG, Tbilisi, Georgia) with spacing 1 km. The regional model is nested in the BSM of Black Sea dynamics of MHI. All needed input data are received from MHI in operative mode via Internet.

The input data are:

- 3-D initial fields of current velocity, temperature and salinity;
- 2-D fields of velocity components, temperature and salinity on liquid boundary;
- 2-D meteorological fields: heat fluxes, atmospheric precipitation, evaporation and wind stress on the sea surface.

-The conditions on the liquid boundary represent prognostic values of hydrophysical fields calculated from BSM model of MHI,

- the meteorological fields on the upper boundary are prognostic fields received from regional model of atmospheric dynamics ALADIN.

The following stage of development of the regional forecasting system was the construction of a shallow water numerical model and its inclusion in this forecasting system. Here as the input data are used data received from MHI via Internet as well as for the regional model of sea dynamics.

Scheme of functioning of the forecasting system with inclusion of the shallow water model is shown on the next slide.

PScheme of Functioning of the regional Forecasting system

Wind stress and atmospheric pressure gradients at the sea surface

Model of Atmospheric dynamics ALADIN(Bucharest, Romania)

Upper boundary conditions

BSM of Black Sea dynamics of MHI (Sevastopol)

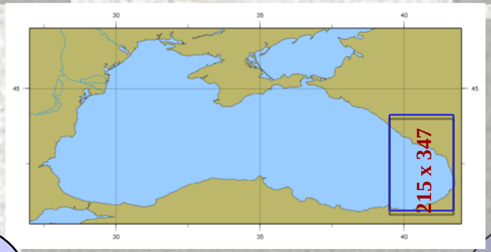
Upper boundary conditions

Initial and boundary conditions on the liquid boundary

Regional model of Black Sea dynamics (RM-IG)

Shallow water model of Institute of Geophysics for the Easternmost part of the Black Sea (Tbilisi/Georgia)

Model product

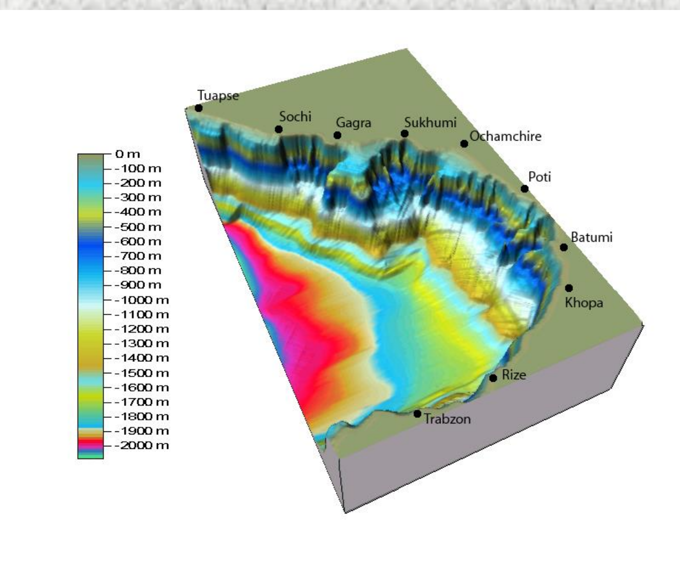


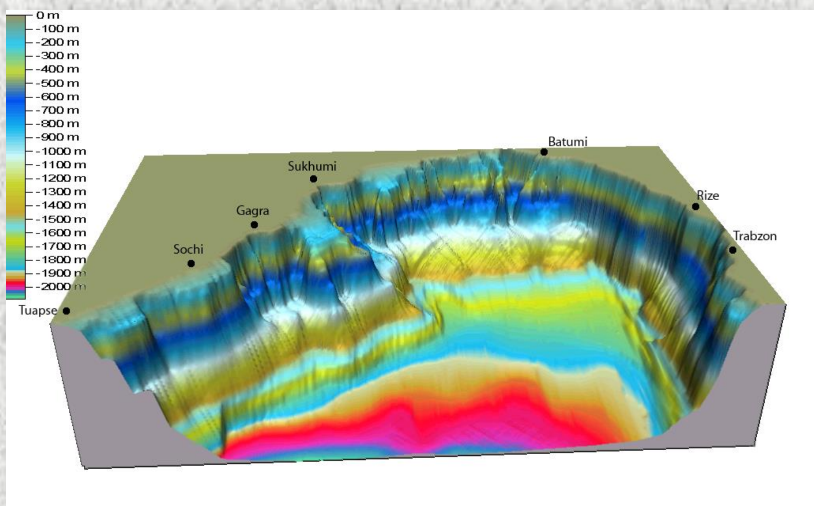
Model Product

Forecasted fields of sea current, temperature and salinity in the Easternmost part of the Black Sea

Forecast of change of the sea level and averaged on a vertical flow velocity

At realization of the regional model the grid 215 x 347 with a horizontal step of 1 km is used. On a vertical 30 calculated levels are located on the following depths: 2, 4, 6, 8, 12, 16, 26, 36, 56, 86, 136, 206, 306, …, 2006 m. The time step is equal to 0.5 h.





Configuration of the considered Easternmost part of the Black Sea

Circulation Processes in the Easternmost Part of the Black Sea in the first half 2013

In our presentation in last year in Sevastopol (September 2012) on the basis of calculated prognostic fields for 2010-2012 we have shown that the easternmost part of the Black Sea, including Georgian water area, represents dynamically very active zone. For this period circulating processes here developed, which were characterized by significant inner-annual variability. For the last period our database was added by new results, which well reflect circulating processes developing in present 2013 in the easternmost region of the Black Sea. Therefore before to describe ecological tasks planned for inclusion in the regional forecasting system it will be expedient to illustrate these processes with some circulating pictures constructed on the basis of our prognostic calculations in 2013.

On the following slides prognostic sea current fields corresponding to time interval January - July 2013 are shown. Thus for each month three circulation pictures are selected which are more characteristic for the appropriate month.

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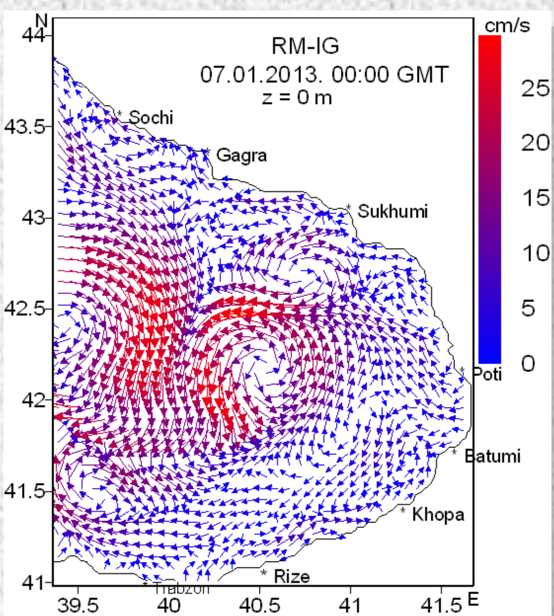
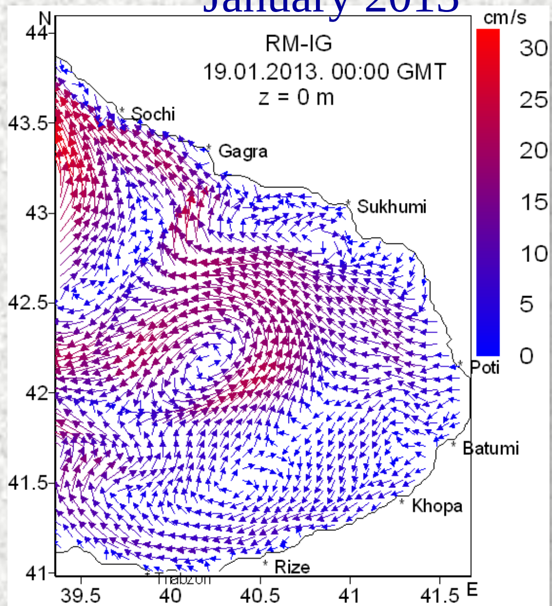
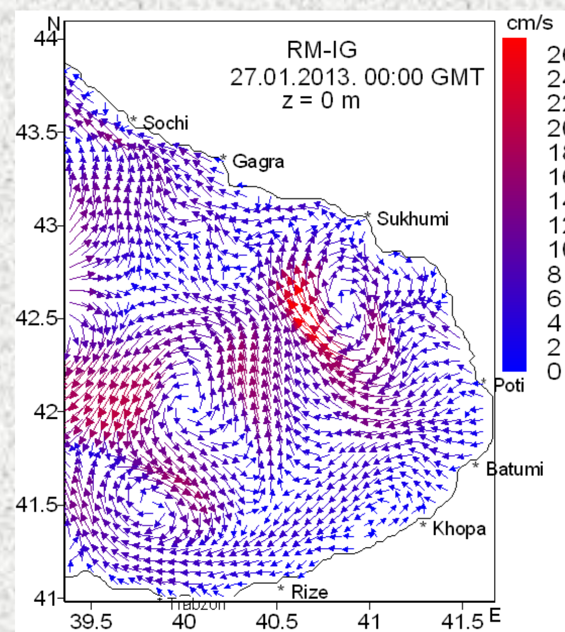
Winter Circulation

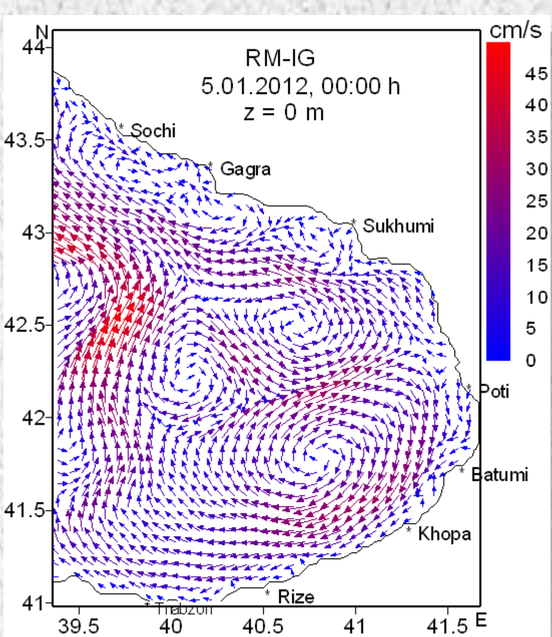
January 2013

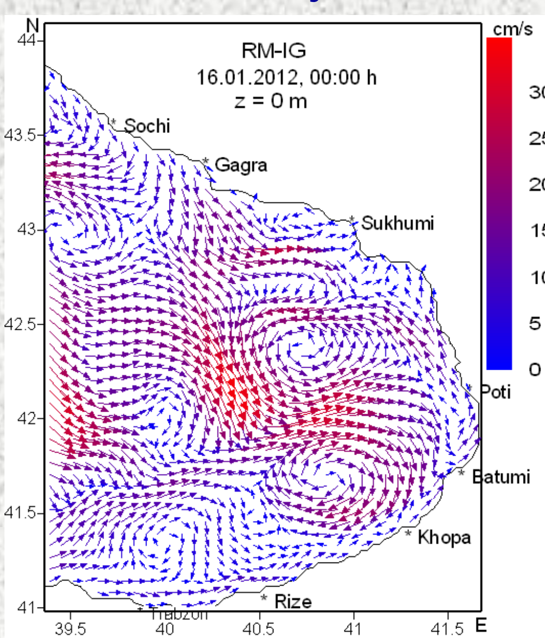


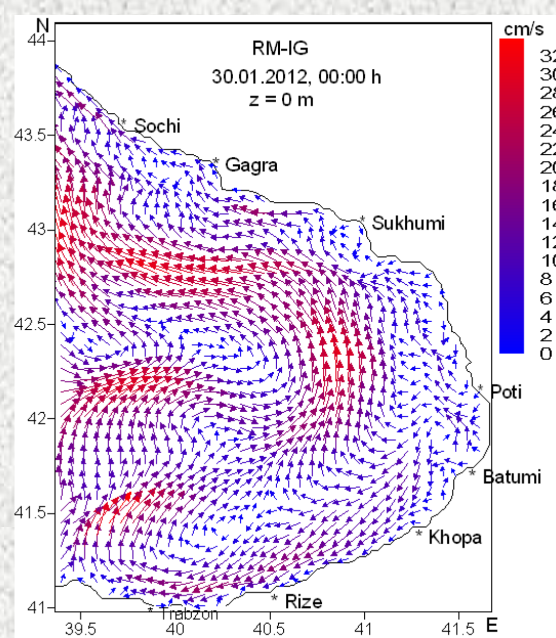




January 2012

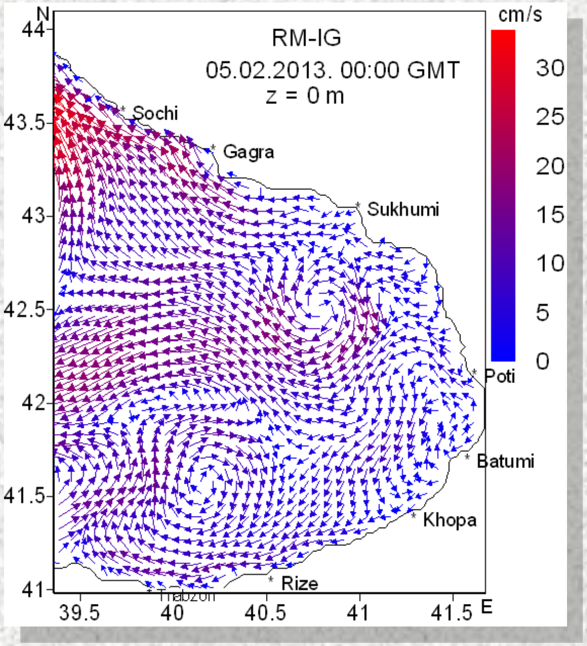


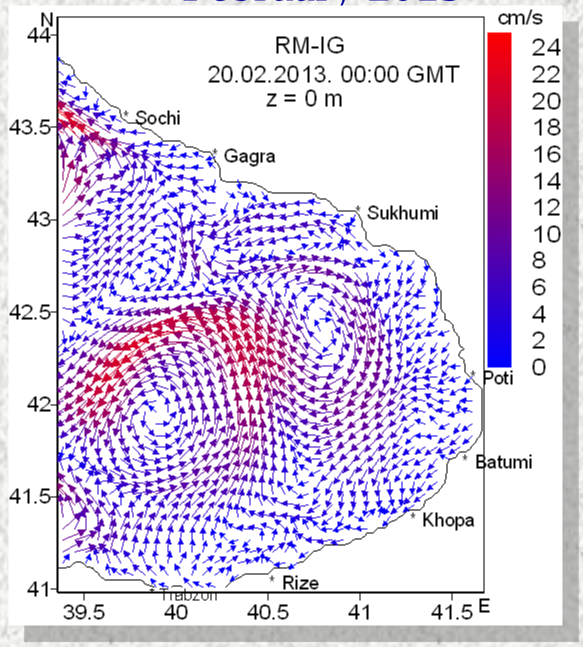


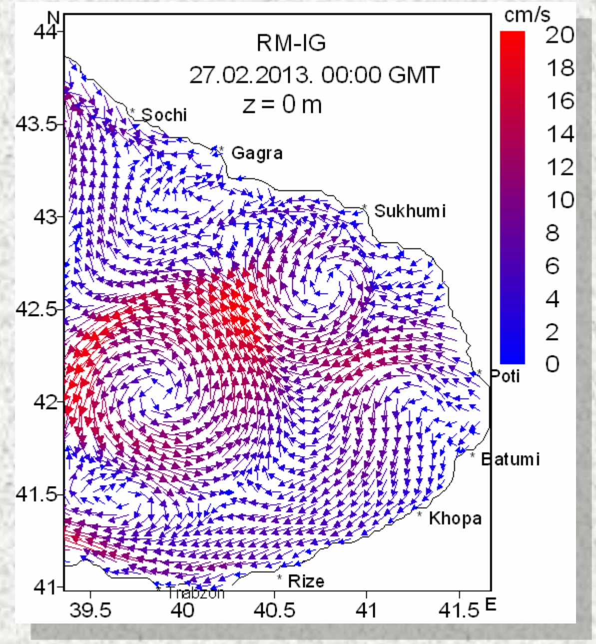


Winter Circulation

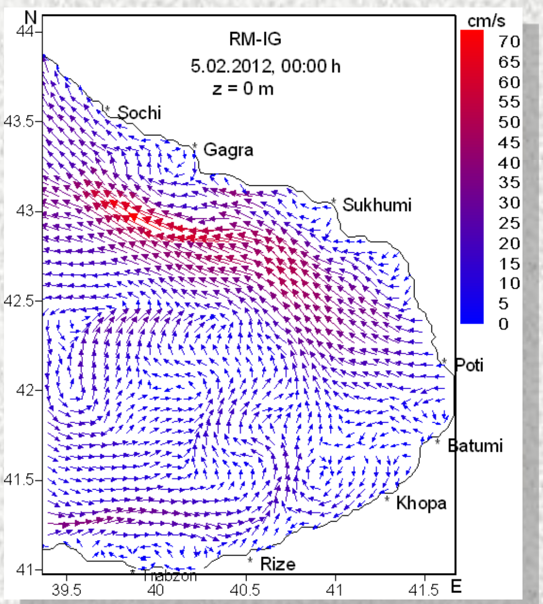
February 2013

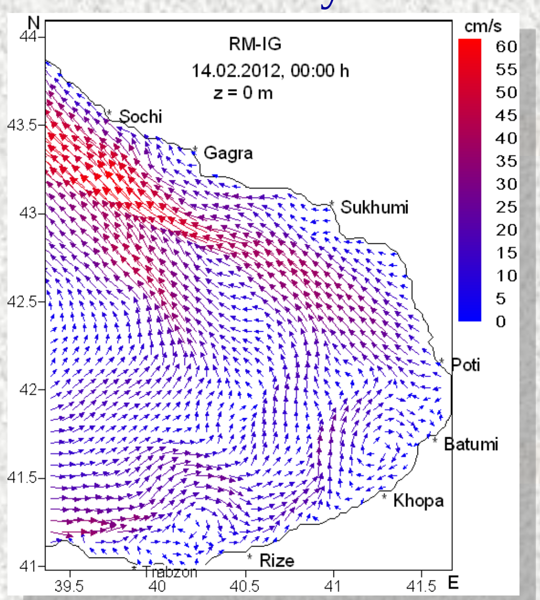


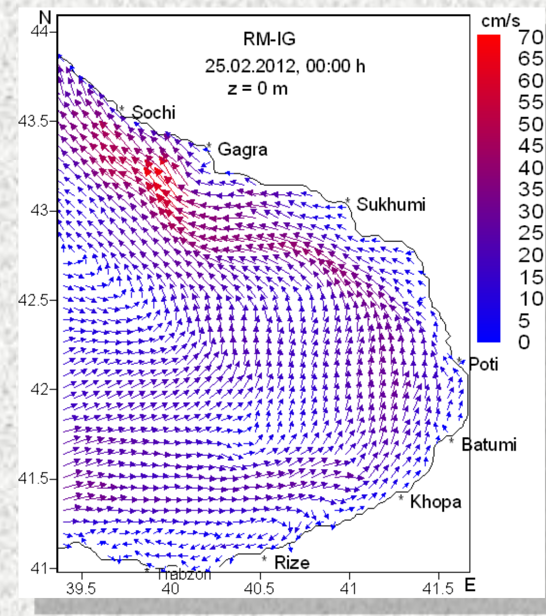




February 2012

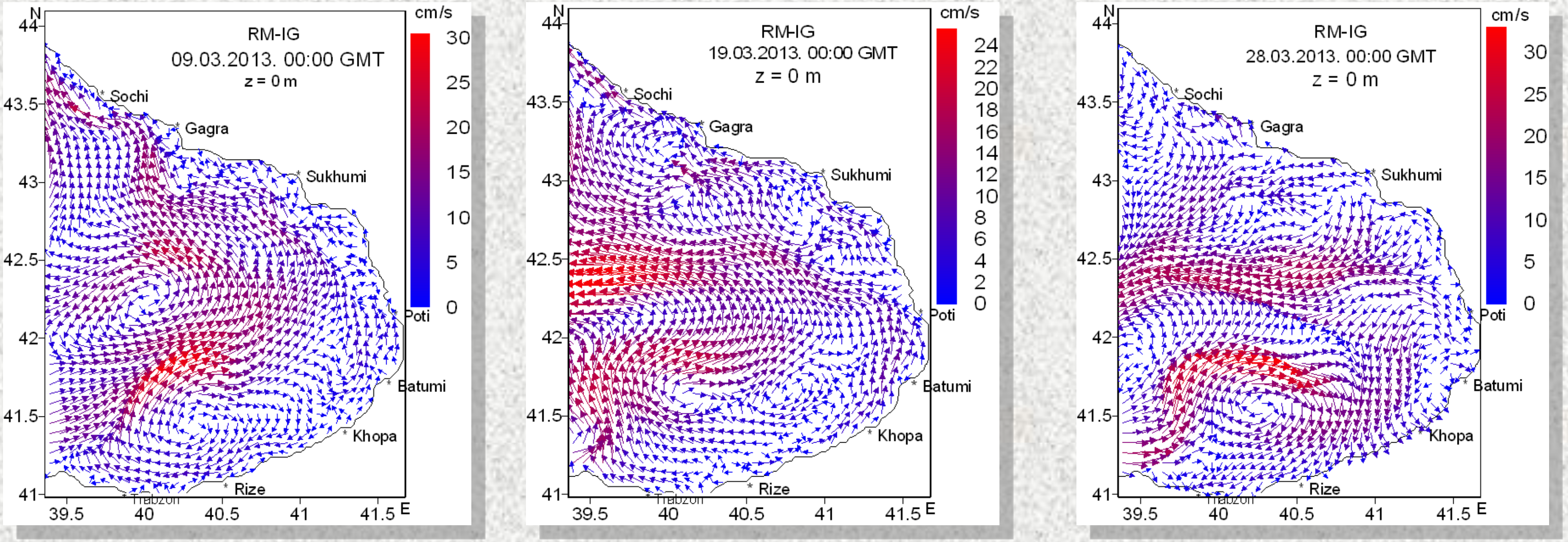




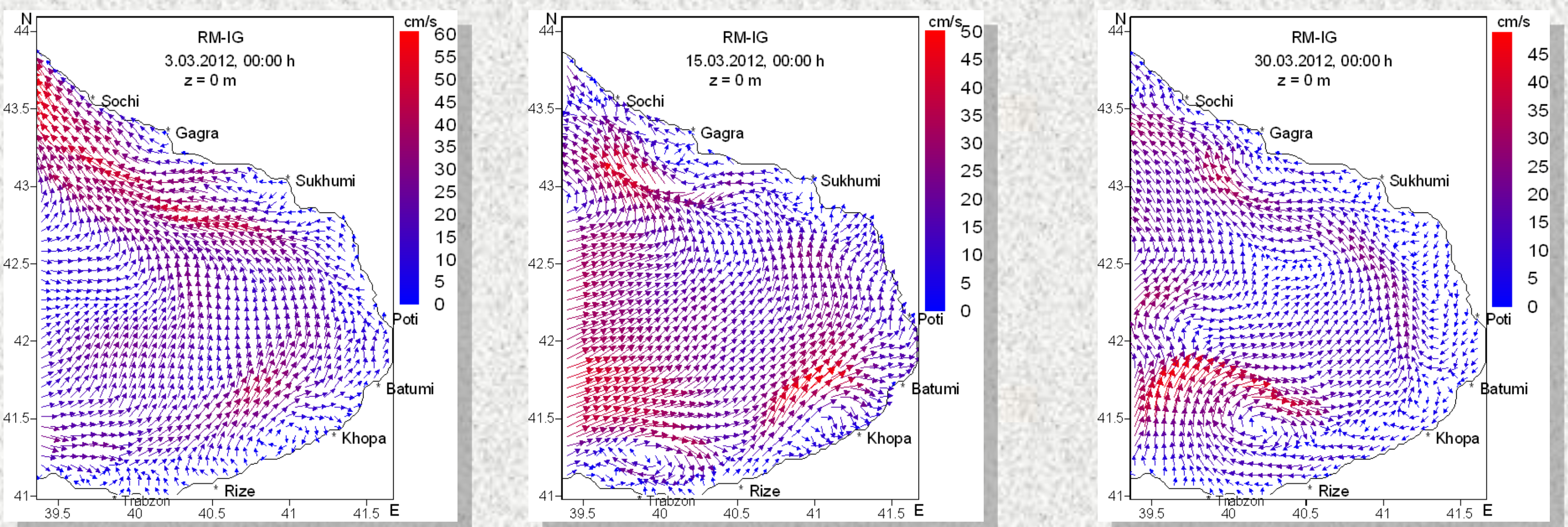


Spring circulation

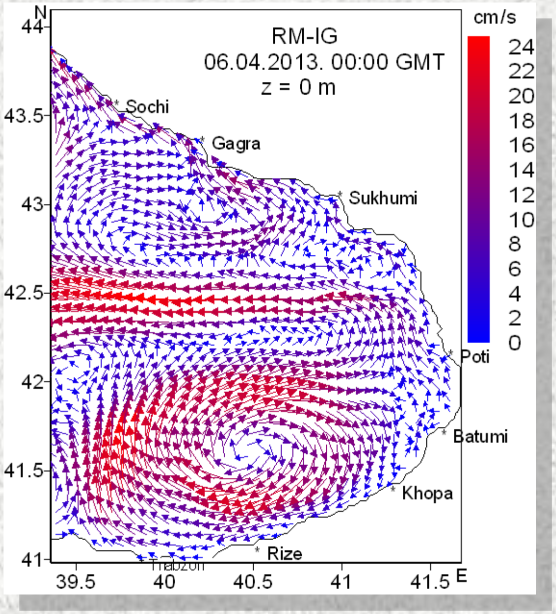
March 2013

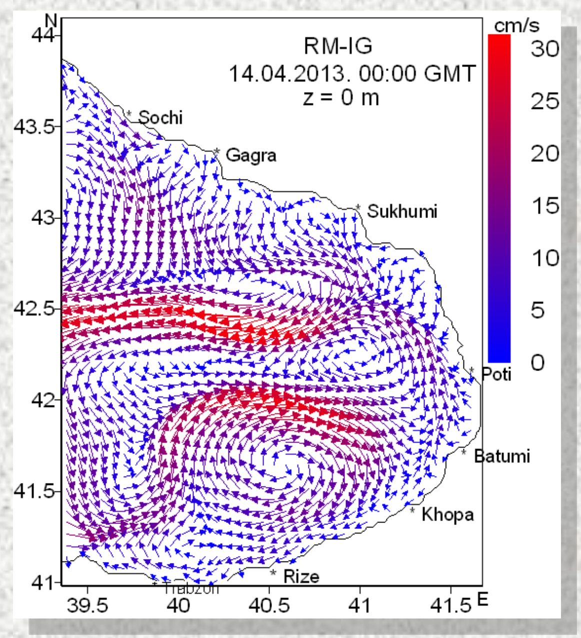


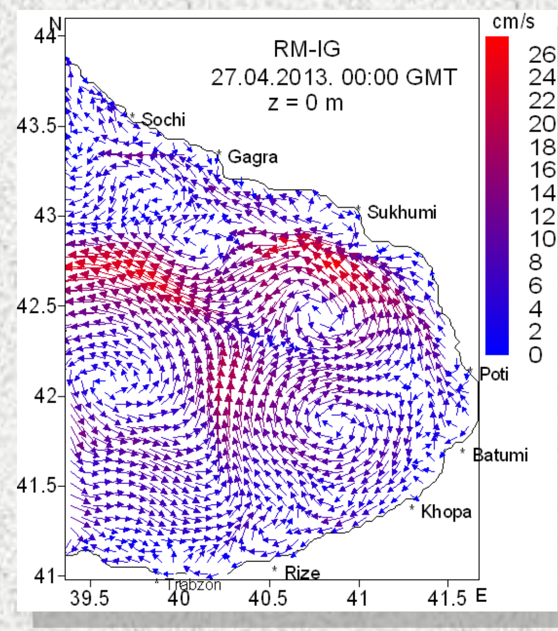
March 2012



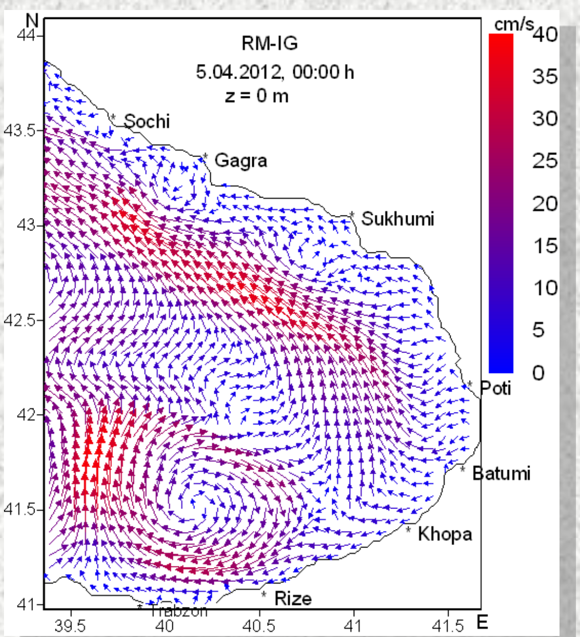
April 2013

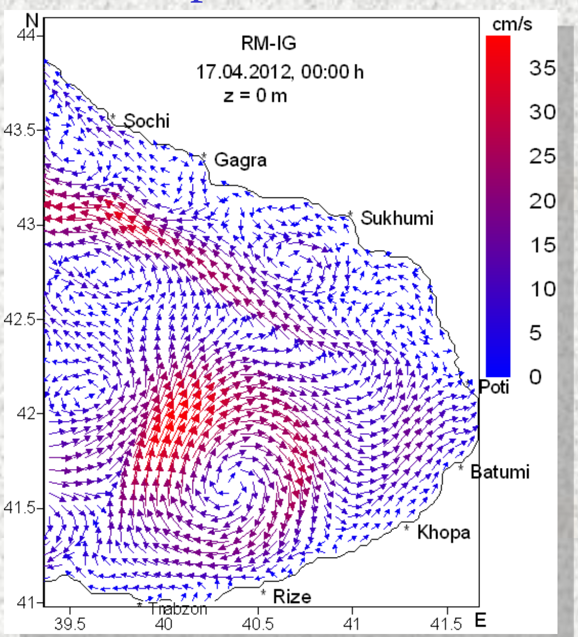


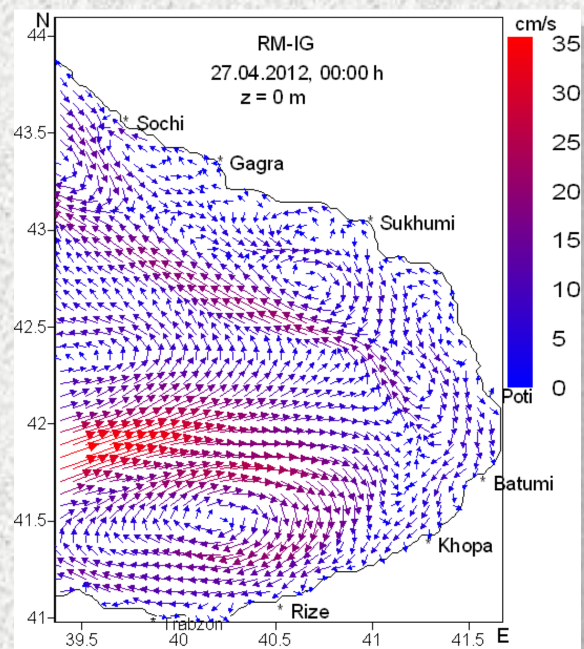




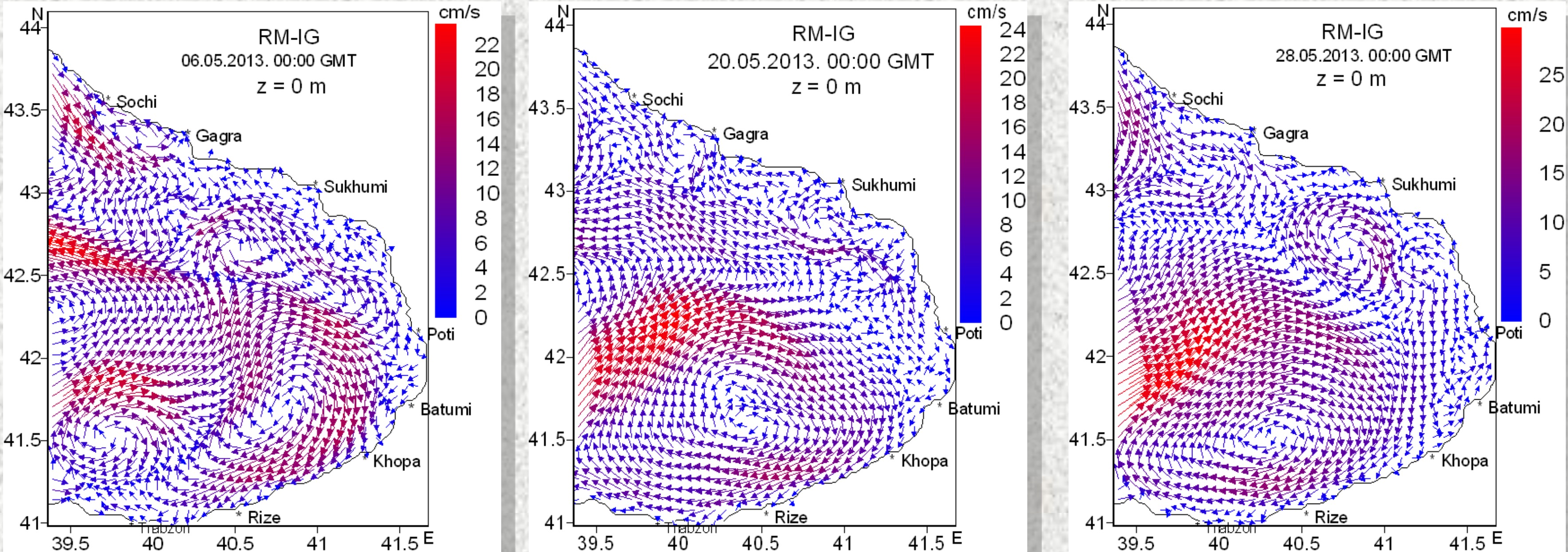
April 2012



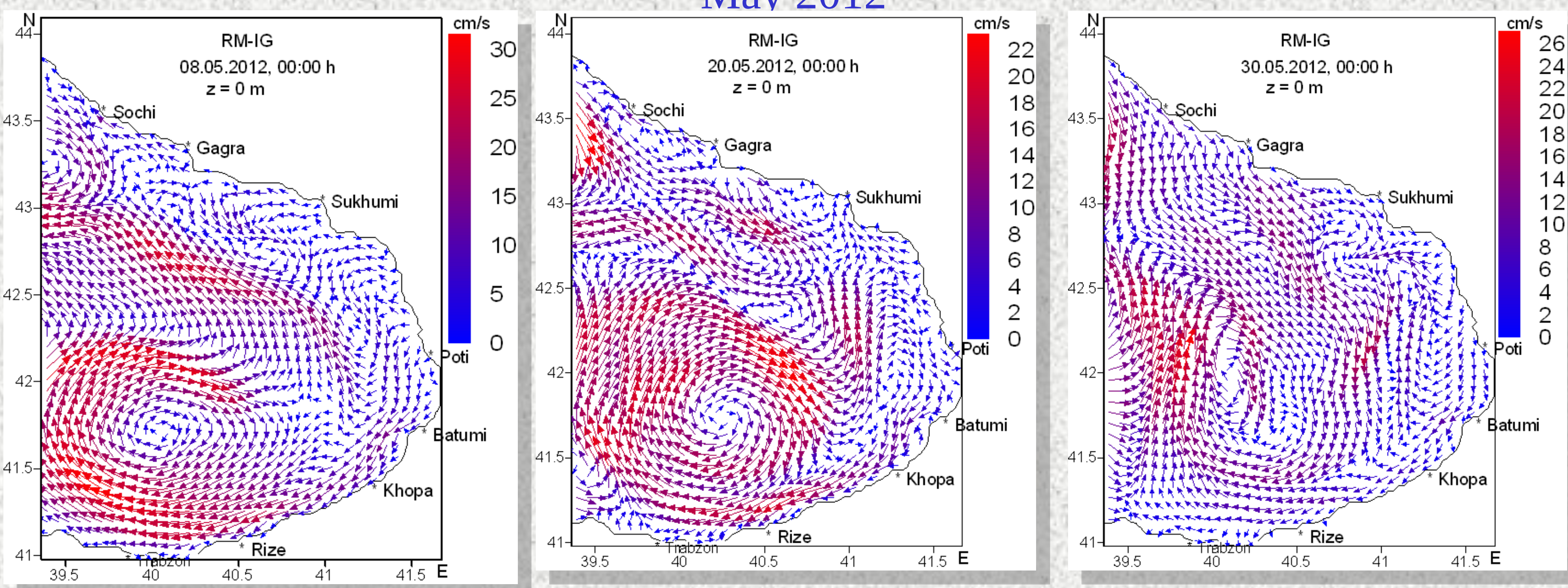




May 2013

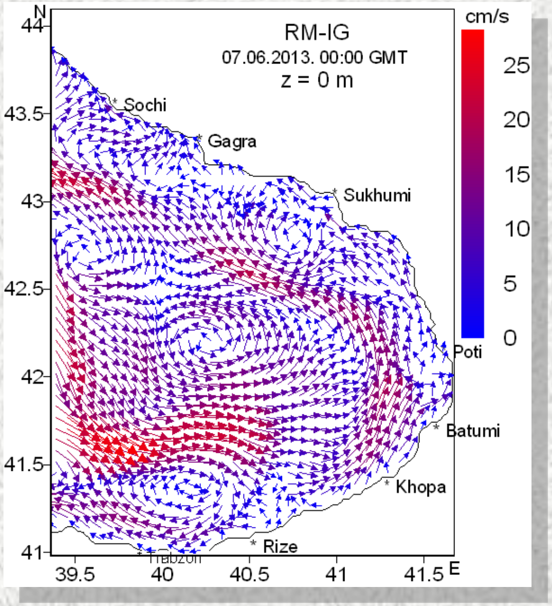


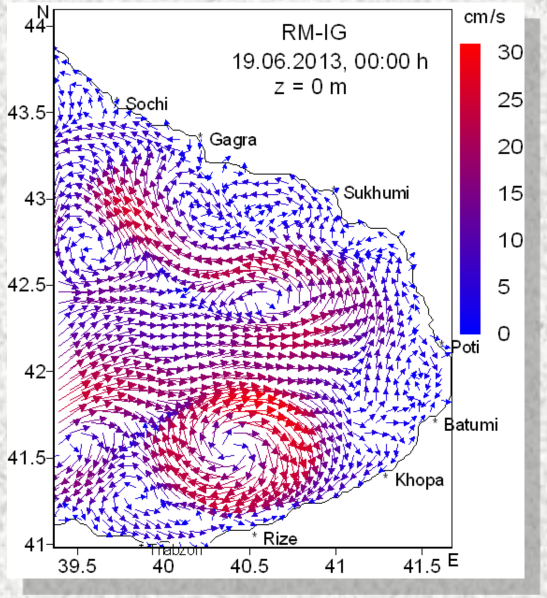
May 2012

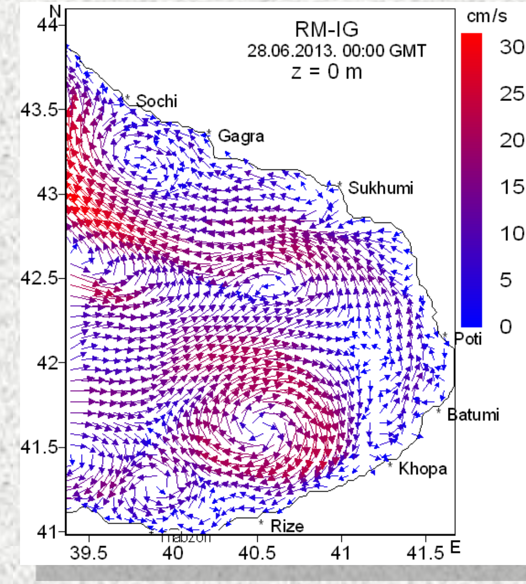


Summer Circulation

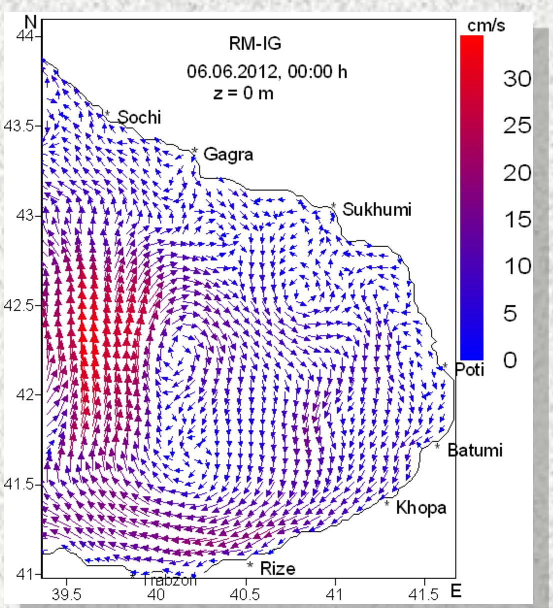
June 2013

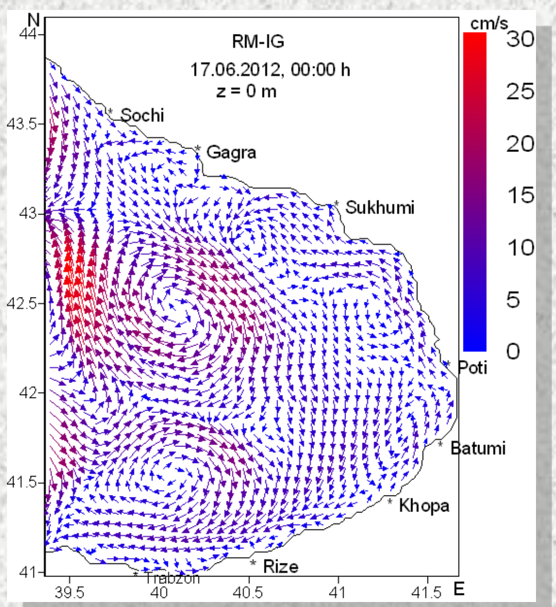


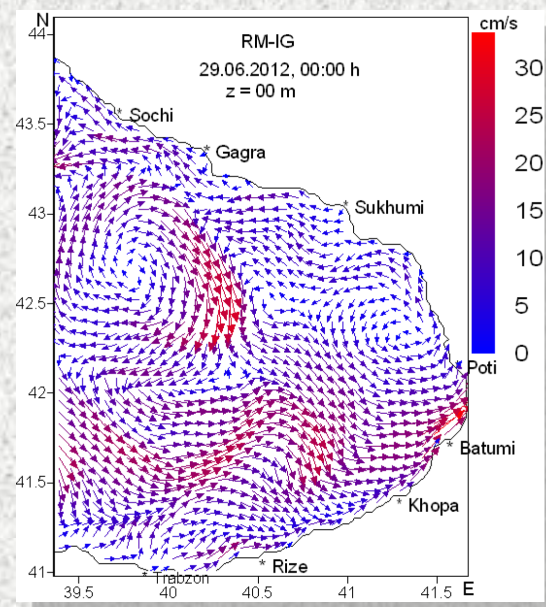




June 2012

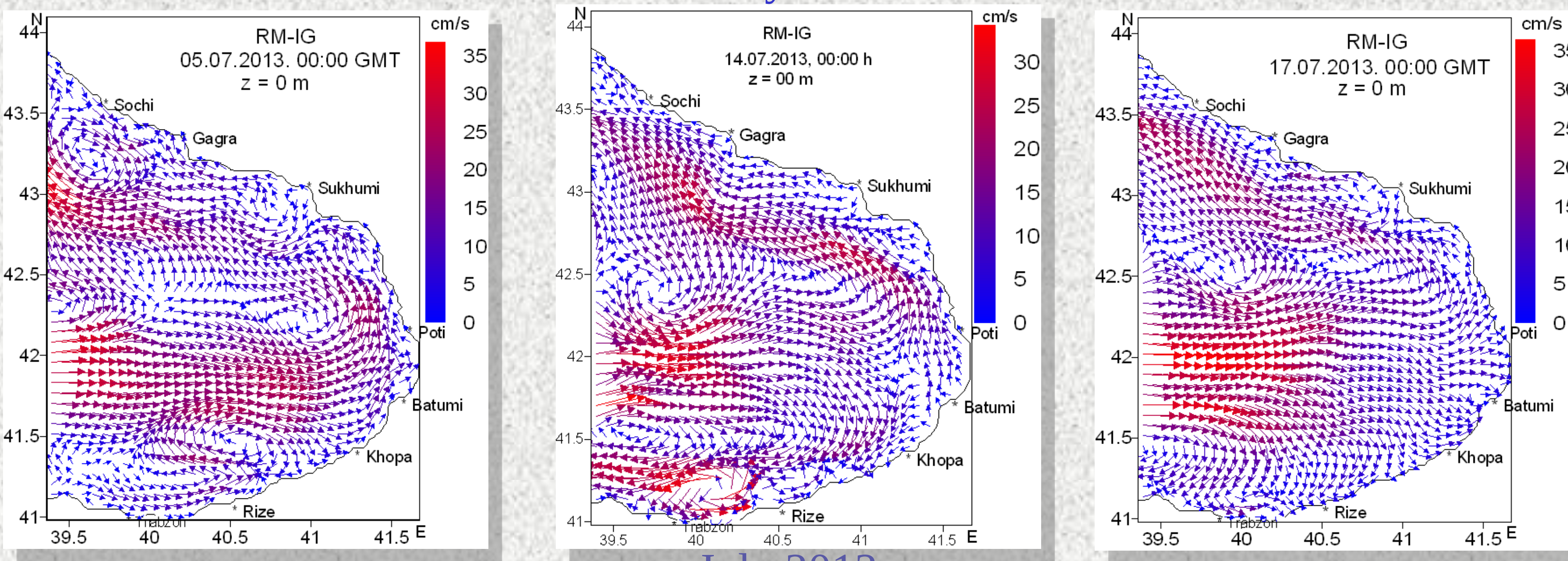




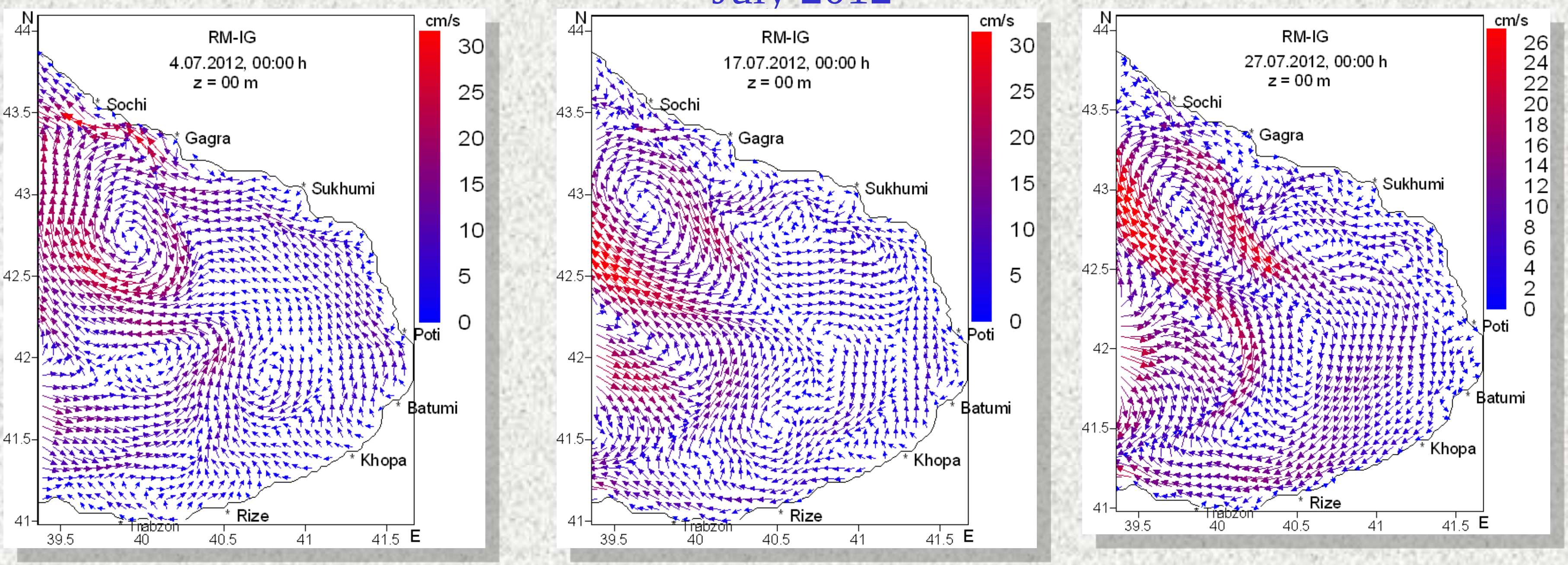


Summer Circulation

July 2013

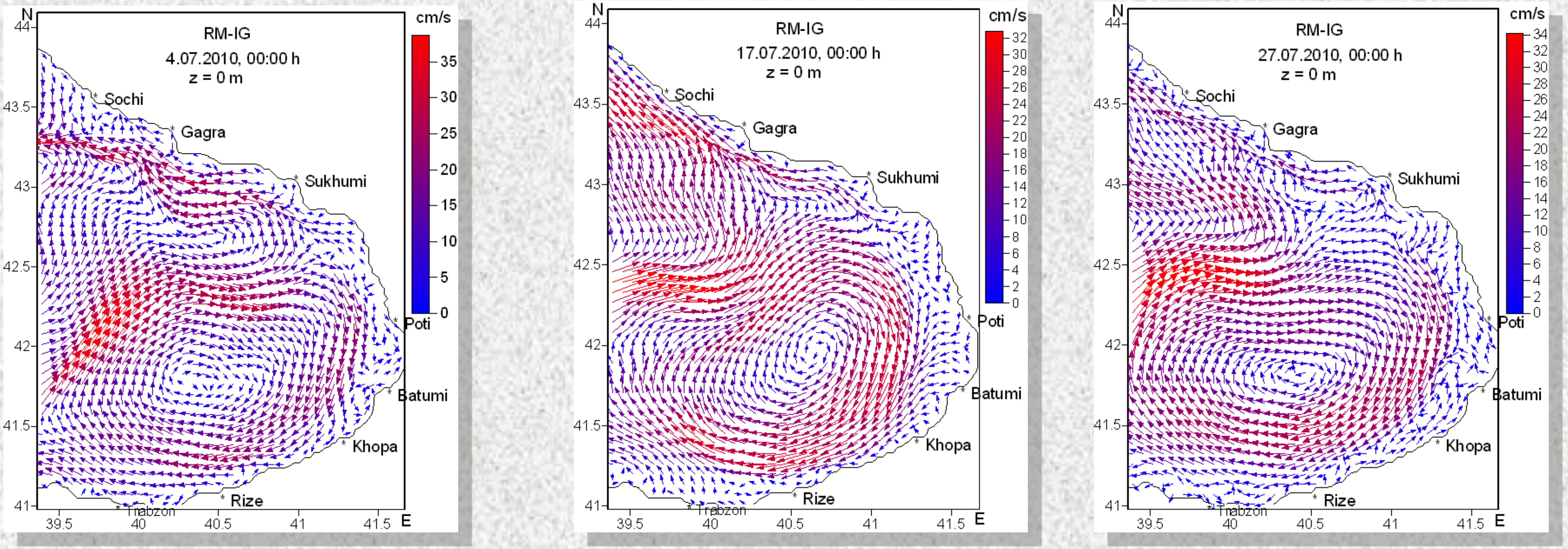


July 2012

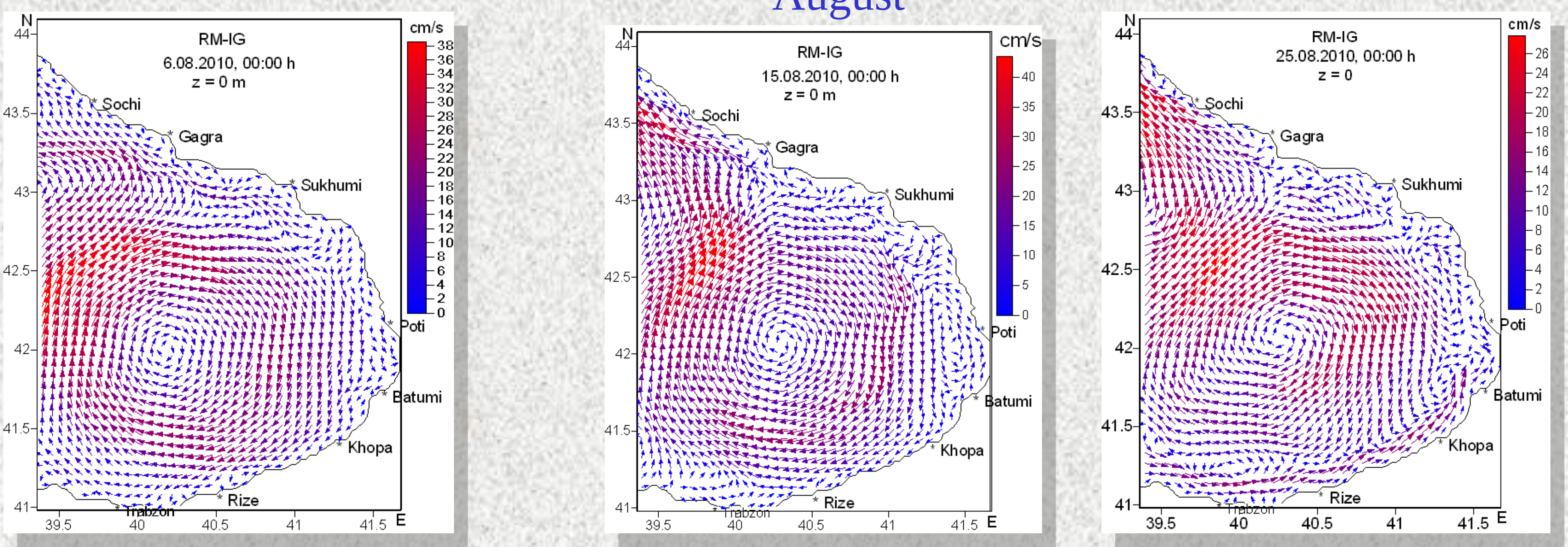


Summer Circulation 2010

July



August



The winter circulation of 2013 was characterized, in general, by continuous formation and evolution of local vortical formations. The east branch of the Main Black Sea current, evidently in 2013 winter season passed outside of the considered easternmost area unlike 2012 winter circulation. It the first half of January 2013 the cyclonic vortex was observed, which further exposed to the certain deformation and was increased in the sizes with a diameter approximately from 60 up to 100 kms. This vortex existed within all January, in the beginning of February disappeared and then again occurred. Except for this vortex in 2013 winter circulation other cyclonic and anticyclonic vortexes are also observed with rather smaller sizes. Among these vortexes it is possible to note small coastal anticyclonic vortex in the water area close to Sukhumi, which was observed within January and February with some updating and moving of the centre of the vortex . In the south-west part of the considered easternmost area during January - February the formation of anticyclonic vortex was observed also which continuously was exposed to significant changes.

The comparative analysis of 2012 and 2013 winter circulating modes shows that the January circulations of these years have both the similar and distinctive features. January circulating modes of 2012 and 2013 years were characterized by intensive formation of vortical formations. In both cases the formation of cyclonic vortex was observed, but location, configuration and the character of evolution of this vortex were different in these years.

Unlike 2013 February circulation, the circulating mode in February 2012 was characterized by weak vorticity of sea current. Besides there is clear observed the east branch of the Main Black Sea Current on circulation pictures of February 2012 with maximal speeds 60-70 cm/s on the core of the Main Black Sea Current.

The formation and development of the anticyclonic vortex is characteristic for spring circulation in the southern part of the considered regional area, which becomes more intensive in the second half of May 2013. In May the formation of the anticyclonic vortex in the water area close to Sukhumi was well observed also.

With the purpose of comparison of spring circulating modes 2012 and 2013 the circulating pictures 2012 here are also shown. From comparison of these pictures the significant difference of circulating modes in March is well visible. The circulating mode of the first half of March 2012, as against 2013, was characterized basically by movement without vortex formation. Within entire March 2013 the anticyclonic vortex was well advanced in the southern part of the considered area whereas in 2012 this vortex arose only from middle of March.

In circulation pictures of April 2012 and 2013 the anticyclonic vortex is obviously present in the southern part. In pictures of 2012 the narrow zone of intensive vortex formation along Caucasian seashore is more precisely expressed were the small coastal cyclonic and anticyclonic eddies are generated and transformed. The anticyclonic eddy is presented also in May 2012 and 2013, but by the end of May 2012 this eddy was strongly deformed and became less expressed, whereas in 2013 by the end of May becomes more intensive.

The structure of 2013 summer circulation significantly differed from structure of 2012 summer circulation. The anticyclonic eddy with diameter about 60-70 kms in a southern part of the considered water area existed since June till July. The middle of July 2013 was characterized practically by movement without vortex formation. In circulating pictures of 2013 the formation of small coastal vortical formations along the Caucasian coast (between - Sochi and Gagra, Gagra and Sukhumi, Poti and Batumi; nearly Trabzon) is well visible.

It is necessary to note, that the Batumi anticyclonic eddy, existence of which is well known in the considered easternmost region of the Black Sea in a warm season, in the summer seasons of 2012 and 2013 was less expressed. The summer 2010 in this respect was allocated, where the main element of regional circulation in the easternmost part of the Black sea was the Batumi anticyclonic eddy, which territory with a diameter approximately 150 kms.

The following stage to develop the regional forecasting system is the inclusion in the forecasting system the numerical models of ecological character. These models use results of already considered forecast of dynamic state of sea environment. Thus, received forecasting system consists of hydrodynamic and ecological modules.

The ecological module represents set of tasks describing distribution of various non-conservative impurity in the sea environment, mathematical model of definition of the location of a pollution source and also, in the long term, the Black sea ecosystem model.

The hydrodynamic module provides the ecological module with information concerning 3-D fields of sea current and turbulence. The problems including in the ecological module are based on direct and conjugate 2-D and 3-D advection-diffusion equations for non-conservative impurity.

On the next slide the extended scheme of the regional forecasting system is shown.

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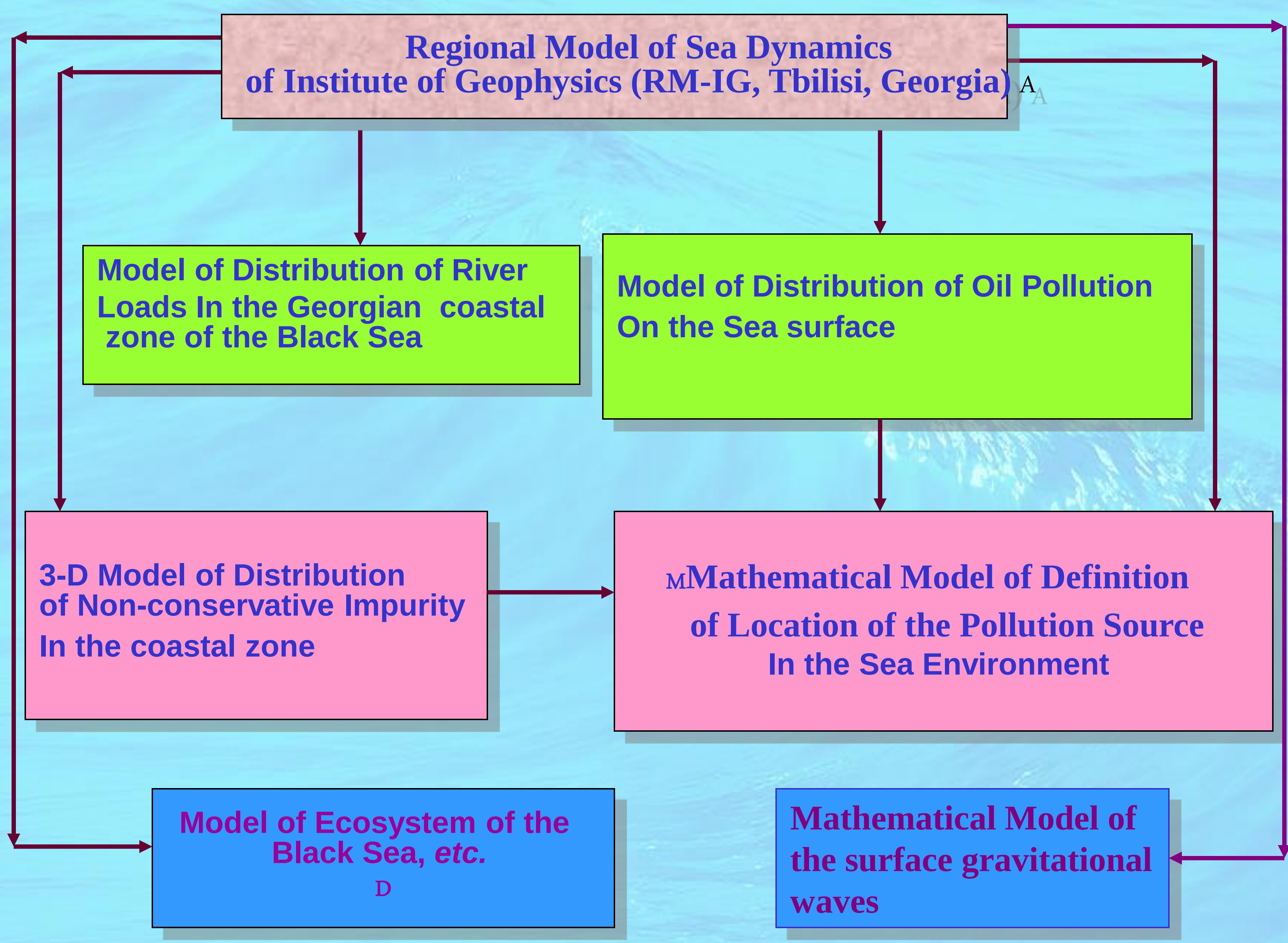
Scheme of Extended Regional Forecast for the Easternmost Black Sea



Mathematical Model of distribution of imputity (*Kordzadze, Demetrashvili, 2000a, 2000b, 2010*; *Kordzadze, 2007*)

As an example, let us consider statement of a 3-D problem of distribution of non-conservative impurity in a sea environment which is based on the advection-diffusion equation of substance

$$\frac{\partial \varphi}{\partial t}+\frac{\partial u\varphi}{\partial x}+\frac{\partial \mathrm{v}\varphi}{\partial y}+\frac{\partial (w+w_G)\varphi}{\partial \mathrm{z}}+\sigma\varphi=\nabla\mu_\varphi\nabla\varphi+\frac{\partial}{\partial \mathrm{z}}\nu_\varphi\frac{\partial \varphi}{\partial \mathrm{z}}+\mathrm{f},$$

$$\nabla\mu_\varphi\nabla\varphi=\frac{\partial}{\partial \mathrm{x}}\mu_\varphi\frac{\partial \varphi}{\partial \mathrm{x}}+\frac{\partial}{\partial \mathrm{y}}\mu_\varphi\frac{\partial \varphi}{\partial \mathrm{y}}$$

Here *u*, *v* and *w* are the components of flow velocity in the sea along axes *x*, *y* and *z* (x is directed eastward, y is directed northward, z is directed from the sea surface downward); μ, ν are factors of horizontal and vertical turbulent diffusion; σ = ln2/T is the parameter of non-conservatively, which in a case of radioactive impurity describes reduction of concentrations Because of radioactive disintegration (T – decay period), w_G is speed of gravitational sedimentation , f is the function describing distribution of power of pollution source.

One of the versions of boundary and initial conditions:

$$\varphi = a(x,y,t) \text{ или } \partial\varphi/\partial z = b(x,y,t) \quad \text{при} \quad z = 0,$$

$$\partial\varphi/\partial z = \alpha\varphi \quad \text{при} \quad z = H,$$

$$\partial\varphi/\partial n = g \quad \text{на} \quad \Gamma,$$

$$\varphi = \varphi^0 \quad \text{при} \quad t = 0,$$

n is the outer normal to lateral surface Γ; α is some parameter describing interaction of polluting substance to the sea bottom; a, b and g are given functions; H(x, y) is the depth of the sea; φ^0 is initial distribution of pollution concentrations.

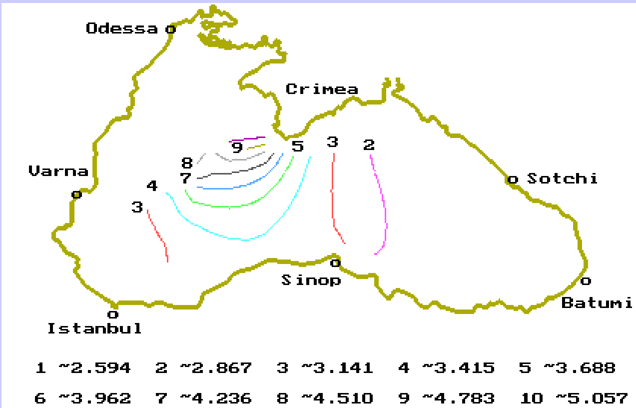
The problem is solved numerically on the basis of a two-cycle splitting method on space coordinates. For approximation of transfer-diffusion equation on time variable Crank-Nicholson scheme is used. As a result, a set of more simple one-dimensional finite-difference equations is received, which are solved effectively by method of factorization. The received numerical scheme is absolutely steady and has the second order accuracy of approximation on all variables.

Here we present results of numerical experiment, when the radioactive impurity strontium-90 was continuously allocated in the Black Sea with amount 2000 Ci per one year. The transfer-diffusion equation was integrated up to achievement of dynamic balance, which was established after 39 modelling years from the beginning of action of the source and distributions of concentrations were analyzed to this time moment.

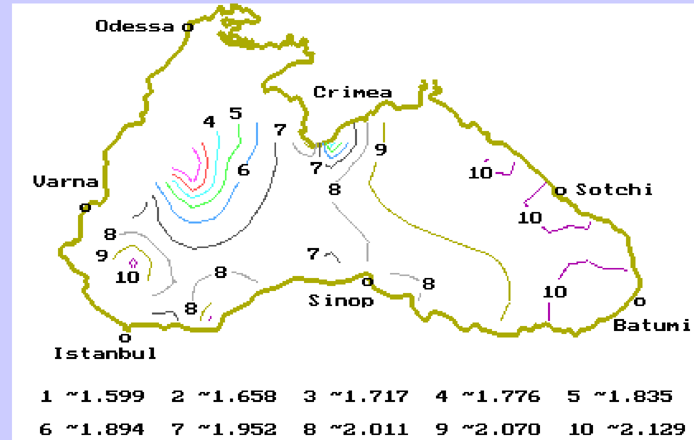
In Figures results of modeling are presented, when the pollution source was allocated on a horizon 1205 m in the water area near Sevastopol. In upper Figures isolines of pollution concentrations are shown on horizons 1105 и 85 m, and in lower Figures – in vertical sections, close to the section where is allocated the source.

On the slide results of modeling of spreading of nonconservative admixture (on an example of Strontium -90) from the point source, allocated in the deep layers of the Black Sea, are shown.

(a)

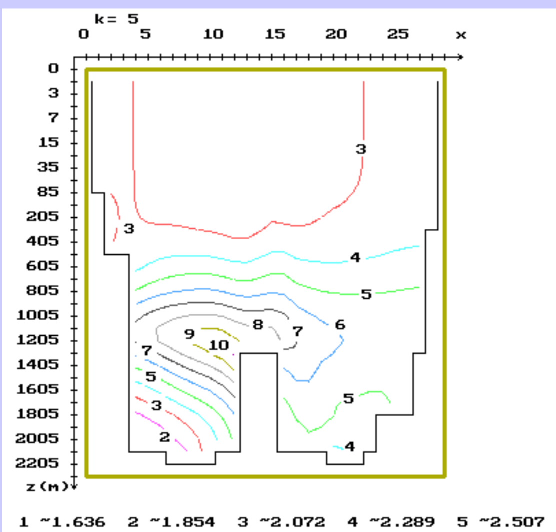


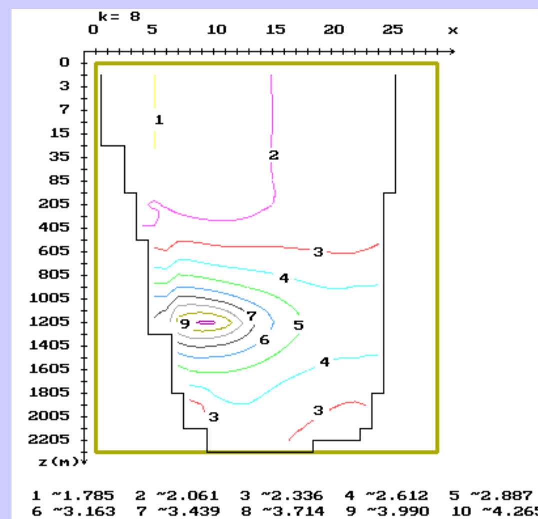
(б)



Concentrations Sr^{90} (Bq/м3) on horizons (a) - 1105 m; (b) - 85 m .

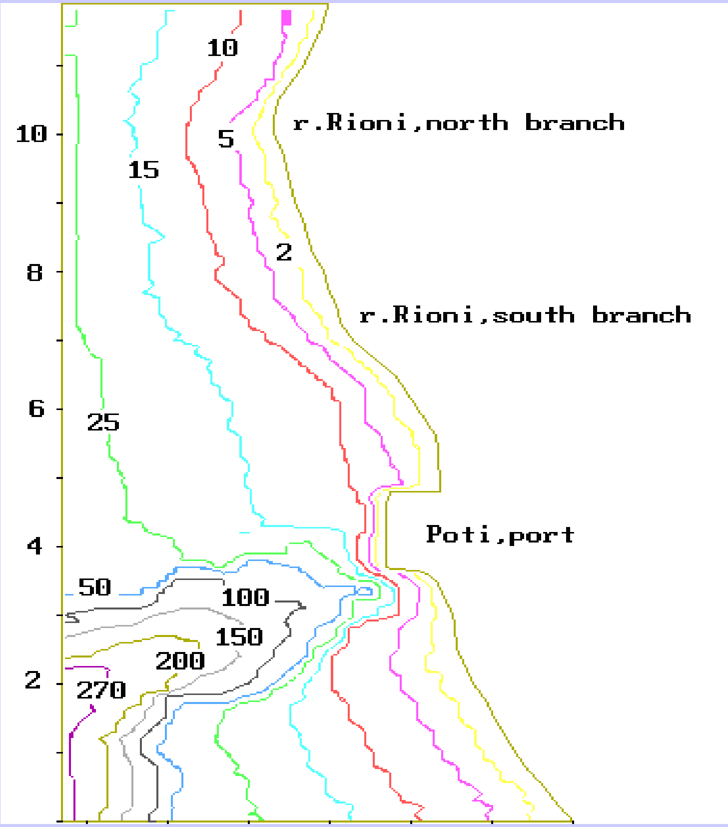
The source was on the deep 1205 m.





Concentrations Sr^{90}(Bq/м3) in the vertical sections. The source was on the deep 1205 m.

Modeling of spreading of Rioni River load in the Georgian coastal zone



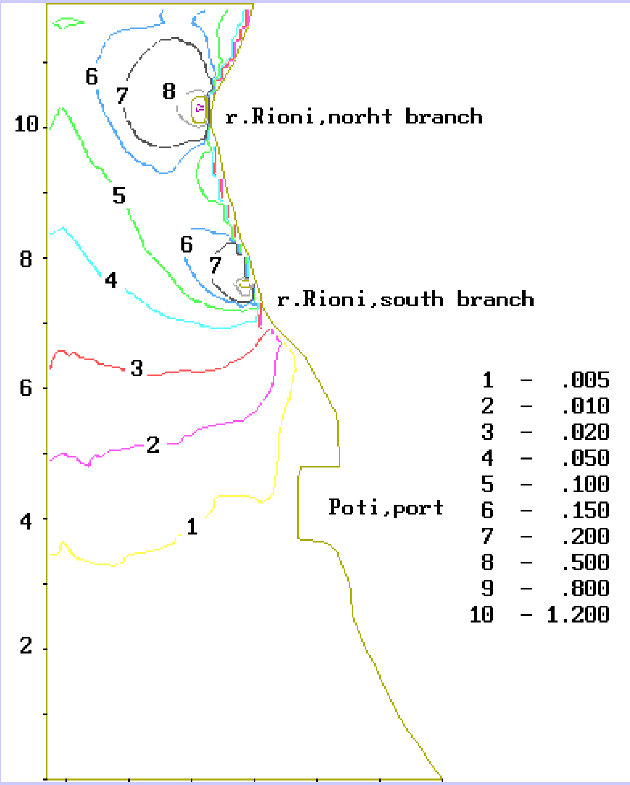
The area of modeling and sea bottom relief

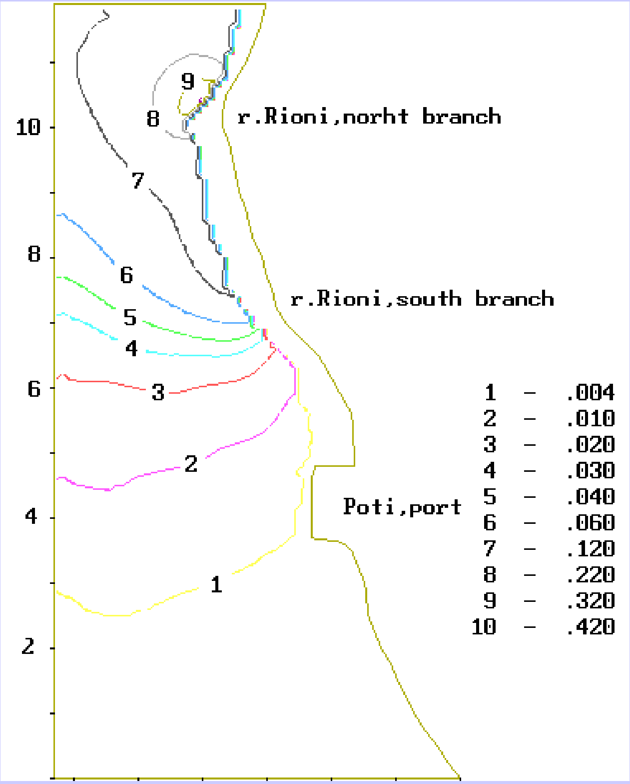
The rectangular area with sizes (5.9 x11.9) km (water area near Poti port), was covered with a grid having space step100 m, on a vertical 30 calculated levels were taken with minimal vertical step 0.5 m near the sea surface and maximal step – 35 m at the deep sea bottom (the maximal depth – 274 m). The time step was equal to 1 h. The gravitational vertical speed of particles was 0,003 cm/s, which corresponded to particles with radius about 0.0031mm according to Stock's formula .

It was supposed that the particles with such radius make 60 % of the sediment loads, which between south and north branches of Rioni River are distributed as follows: 2/3 parts pass through northern branch, and other part - through the southern branch.

On the basis of the offered model the numerical experiment on seasonal variability within one modelling year was carried out. At the initial moment $t = 0$ concentration of solid particles in the sea environment was considered zero, and the calculation was carried out for one modelling year. The beginning of calculations corresponded to January 15. In the numerical experiment climatic monthly data (1971-1984, 1988-1991) about the discharges of Rioni River loads into the Black Sea were used.

With the purpose of illustrating in the next Figure the concentration field of light fraction of the sediment load is shown ($w_G = 0,003$ cm/s) in the coastal zone on depths 1 and 5 m corresponding to February.





Concentrations *of Rioni River loads on the depths 1 u 5 m in February (kg/m3)*

From Figures is well visible that high concentration zones are localized in the mouth regions of the south and north branches of the Rioni River.

Mathematical model of definition of the location of the pollution source

(*Kordzadze, Demetrashvili*, *2001a, 2001b, 2010; Kordzadze 2007*)

In the monograph by G. I. Marchuk «*Mathematical modeling of the Environmental Problems*» on the basis of conjugate equations and the theory of functionals solution of important ecological problems are offered. Among them we note the problem of definition of the pollution source in the atmosphere. This theory can be also used for other important ecological problem – for determination of the location of the pollution source in water basin on known concentrations of a polluting substance in some points of the upper layer of the sea basin.

The method is based on solution of non-stationary conjugate transfer-diffusion equation and the principle of duality of corresponding functionals . According to this principle, functionals can be calculated as by solving of a basic transfer-diffusion problem, also by solving of its conjugate problem.

In brief the essence of the method consists in the following. We will assume that the concentration field in a water area Ω with lateral boundary Γ and depth H is generated as a result of action of the point source by power Q, location of which is unknown and as a result of observations pollution concentrations are known in some points $\vec{\xi}_i \in \Omega (i=1,2,..,N)$ of the upper layer of the sea during time interval (0, T). The point source may be presented by the delta function $\delta(\vec{r}) = Q\delta(\vec{r}-\vec{r}_0)$, where $\vec{r}$ is any point with coordinates x, y and z, $\vec{r}_0$ - is the point of location of the source with coordinates and x_0 and y_0 .

Our problem consists in determination of the domain $\omega \subset \Omega$, where the source is located. For salving of the problem of determination of the pollution source location we consider N quantity of the advection-diffusion conjugated equations with the appropriate right part p_i

$$-\frac{\partial \varphi_i^*}{\partial t} - u\frac{\partial \varphi_i^*}{\partial x} - v\frac{\partial \varphi_i^*}{\partial y} - w\frac{\partial \varphi_i^*}{\partial z} + \sigma \varphi_i^* = D\varphi_i^* + P_i \,, \quad i = 1,2 \ldots N \tag{1}$$

were

$$\mathrm{D}\varphi_i^* = \frac{\partial}{\partial x}\mu\frac{\partial \varphi_i^*}{\partial x} + \frac{\partial}{\partial y}\mu\frac{\partial \varphi_i^*}{\partial y} + \frac{\partial}{\partial z}\nu\frac{\partial \varphi_i^*}{\partial z}$$

These equations are salving with use of following initial and boundary conditions:

$$\varphi_i^* = 0 \quad \text{или} \quad \frac{\partial \varphi_i^*}{\partial z} = 0 \;\; \text{при} \;\; z = 0 \tag{2}$$

$$\frac{\partial \varphi_i^*}{\partial z} = \alpha \varphi_i^* \qquad \text{при} \qquad z = H, \tag{3}$$

$$\frac{\partial \varphi_i^*}{\partial n} = 0 \qquad \text{на} \qquad \Gamma, \tag{4}$$

$$\varphi_i^* = 0 \qquad \text{при} \qquad t = T. \tag{5}$$

There is possible to choose the function p_i differently, proceeding from physical essence of a considered problem. In our problem this function we shall define with the help delta function

$$P_i(\vec{r}, t) = \delta\left(\vec{r} - \vec{\xi}_i\right)$$

Thus, the conjugate task (1) - (5) is solved so much time how many points are picked up in the upper layer of the sea. As against the basic task, solution of the conjugate problem occurs on decrease t in an interval $T \geq t \geq 0$

It is not difficult to show, that the following equality takes place

$$J_{P_i} = \int_0^T dt \iiint_\Omega P_i \varphi \, d\Omega = \int_0^T dt \iiint_\Omega \varphi_i^* f \, d\Omega$$

$$J_{P_i} = \int_0^T dt \iiint_\Omega P_i \varphi \, d\Omega = \int_0^T dt \iiint_\Omega \varphi_i^* \, f \, d\Omega \qquad (6)$$

The equality (6) expresses a duality of the functional J_{P_i}. It means, that the functional J_{P_i} can be calculated both by the solution of the direct task and the conjugate task. If p_i and f we will express with the help delta function, the equality (6) can be write as follows

$$J_{p_1} = \int_0^T \varphi\left(\vec{\xi}_i, t\right) dt = Q\int_0^T \varphi_i^*(\vec{r}_0, t)\,\mathrm{dt}.$$

The location of the source will be determined as follows. For each selected point $\vec{\xi}_i \in \Omega$ (*i=1,2,..,N*) the conjugate problem (1)-(5) will be solved and we shell calculate the appropriate functional

$$Q\int_0^T \varphi_i^*\left(\vec{r}_k, t\right)\mathrm{dt}.$$

The subsets of points of a possible location of the pollution source ω_i (i = 1, 2,…, *N*) for each selected point will be determined from the duality property of the functionals (6). The area of an arrangement of a source ω is determined as a crossing of the subsets ω_i.

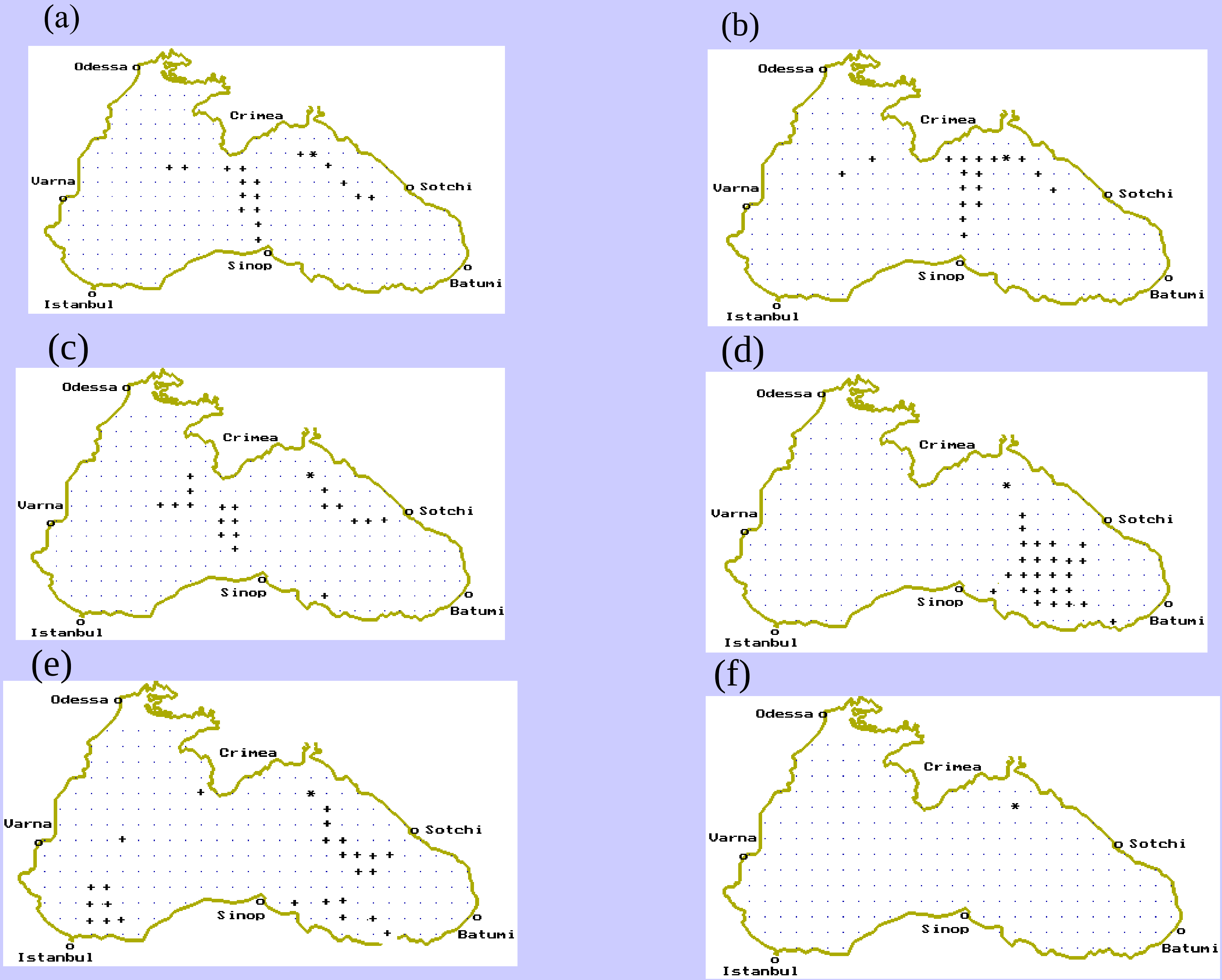
Test numerical experiments were following: as a result of solution of a direct transfer-diffusion problem in time interval (0, T) on known power and coordinates of pollution source, we received calculated field of pollution concentrations for the Black Sea basin. After that we "forget" coordinates of the source and aimed to determine the source location on the basis of the introduced theoretical method.

The method was tested for the Black Sea basin in two cases:

(a) The pollution source was allocated in deep layers of the sea (3D problem).

(b) The pollution source was allocated on the sea surface (case of oil dispersion on the sea surface, 2D problem).

The next slide illustrates the determination of coordinates of the pollution source location in that case, when the source was on a depth of 805 m. As a result of solution of the direct advection-diffusion problem the concentration field was received after 10 modeling year and 5 points were selected in the surface layer. In the Figure the subsets ω_i (i =1,2,…5) corresponding to selected points determine the possible areas of the source location. Crossing of these subsets ω contains one point, which shows a true location of the source.



Subsets of possible points of location of the pollution source: (a) - ; ω_1 (b) - ω_1;
(c) - ω_3; (d) - ω_4 ; (e) - ω_5 ; (f) - ω ;

In summary is necessary to note, that the extended version of the regional forecasting system allows to calculate 3 - days forecasts not only for currents, temperature and salinity in the easternmost part of the Black Sea, but also to predict zones of high concentration of oil and others polluting substances at extreme situations, and also to define location of the pollution source in a case of necessity.


Thank You