THREE DIMENSIONAL SIMULATION OF RADIONUCLIDES DISPERSION IN THE STRATIFIED ESTUARIES

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Abstract

THREE-dimensional model of TOXicants transport (THREETOX) was developed for assessment of potential and real emergency situations in the coastal area of seas and the inland water bodies. It includes the high resolution numerical hydrodynamic submodel, dynamic-thermodynamic ice submodel, submodels of suspended sediment and radionuclide transport. The results of two case studies are described. The first one concerns to two-year simulation of the Chernobyl origin radionuclide transport through Dnieper-Bug estuary into the Black sea. In the second case study the simulations were performed for the assessment of potential emergency situation caused by the radionuclide release from reactors and containers with the liquid radioactive wastes scuttled in the Novaya Zemlya fjords (Tsivolki, Stepovogo and Abrosimov). The presented results demonstrate the capability of THREETOX model to describe the wide spatial and temporal range of transport processes in the coastal area of seas.

1. INTRODUCTION

The use of computational fluid dynamics models is important for operative forecasts of pollutant dispersion in coastal waters and emergency preparedness and response in the case of accidental industrial releases. Complicated dynamics of the estuaries that is governed by freshwater inflow, wind, tides, sea level variations makes it necessary to use the models that take into account all these factors in the radionuclide transport processes. An advanced THREE - dimensional model of TOXicants transport (THREETOX) was recently developed [1] for the prediction and re-analysis of the pollution transport in the coastal areas of seas and inland water bodies. A brief description of the model is presented in the paper. Two case studies are considered: a two-year simulation of the 1986 accidental Chernobyl radionuclide contamination of the Dnieper-Bug estuary, and a multiyear simulation of a situation caused by a potential radionuclide release from scuttled reactors, and containers with the liquid radioactive wastes, in the Novaya Zemlya fjords.

2. MODEL

The THREETOX code includes a set of submodels.

Hydrodynamics submodel. The hydrodynamics is simulated on the basis of the three-dimensional, time-dependent, free surface, primitive equation model. The prognostic variables of the hydrodynamics code are the three components of the velocity, temperature, salinity and surface elevation.

Ice submodel. The submodel was used to simulate seasonal cycle of moving ice in the seas of temperate zone. The submodel describes the momentum balance, the ice rheology, the mass balance and the ice strength. The ice thickness distribution is a two-level representation that considers the compactness and the mean ice thickness, averaged over an entire grid cell.

Suspended sediment transport submodel. The suspended sediment transport is described by the advection-diffusion equation, taking into account the fall velocity of the sediment grains. The bottom boundary condition describing sediment resuspension or deposition depends on the ratio between equilibrium and actual near bottom suspended sediment concentrations. The thickness of upper (movable) layer of sediments is governed by the equation of the bottom deformation.

Radionuclide transport submodel. The equations of radionuclide transport govern the radionuclide concentration in solute, in the suspended sediments and in the top layer of the bottom deposits. The exchanges between these variables are described as adsorption-desorption and sedimentation-resuspension processes. Three - dimensional advection -diffusion equations are used to simulate the radionuclide transport in the water column and an ordinary differential equation is applied to simulate the concentration of a radionuclide averaged over the thickness of an upper, mobile layer of bottom deposits.

3. CASE STUDIES

3.1. Dnieper-Bug Estuary

The Dnieper-Bug Estuary (DBE) located on the north-west coast of the Black Sea, is the sea's largest estuary, with a surface area of 1006,3 km^2, and a volume of 4.24 km^3. The Estuary is connected with the Black Sea through the Kinbourn strait. The regime of this drowned-river estuary varies from stratified to partially mixed. The sources of fresh water discharge are the Dnieper and Southern Bug rivers. The DBE is the end of the radionuclide riverine transport from the Chernobyl accident area to the Black Sea. The radioactive contamination of the DBE offered the opportunity to study the behaviour of dissolved and particulate substances in the transition zone between fresh and salty aquatic systems. The dynamics of ^{137}Cs and ^{90}Sr in the Dnieper- Bug Estuary and in the adjacent shelf area of the Black Sea was simulated over two years after the Chernobyl accident. The monthly averaged concentrations of the sediment, radionuclide in solute and radionuclide adherent to the sediment in the Dnieper and Southern Bug mouth, were prescribed from May 1986, to April 1988 using the data of [2-4]. At the open sea boundary the concentrations of ^{137}Cs and ^{90}Sr were prescribed according to [5]. In Fig. 2 the measured concentrations of dissolved ^{137}Cs [2] at the surface and in the near bottom layer are compared with the simulated concentrations of the radionuclide along the A-A cross-section in Fig. 1. The data are represented in nondimensional units in order to make it possible to compare results from different years. The variations of dissolved radionuclide concentrations C from the averaged along the DBE concentration $\overline{C}$ were normalised to the maximum difference in radionuclide concentrations along the DBE ΔC. A reasonable agreement of the simulated data with the available measurements was obtained. Discrepancies between the observed [4] and simulated distribution of ^{90}Sr do not exceed the range of the exchange parameters, boundary and initial values uncertainty (see Fig. 3). There was a marked distinction between simulated radionuclide fluxes of ^{137}Cs and ^{90}Sr through the Kinbourn strait. The net flux of ^{137}Cs was much less than the influx and the outflux. In the period covered by the simulation the net flux of ^{137}Cs was directed predominantly towards the Black Sea.. Only at small river influx the net flux of ^{137}Cs was directed to DBE. . The outflux of ^{90}Sr from DBE also dominated throughout year. Calculations showed that more than 90 % of the total inventory 0.72 TBq of ^{137}Cs in DBE in the spring of 1988 was deposited in the bottom sediments while 76% of the total inventory 1.3 TBq of ^{90}Sr was in the solute. The outflux of ^{137}Cs from the DBE during May 1986 - April1988 was found to be equal to 0.67 TBq, that is 48 % from the total input 1.39 TBq. The outflux of ^{90}Sr was equal to 15.5 TBq, that is 92 % from the total input 16.8 TBq. More detailed description of the results of the simulation of radionuclides dispersion in the DBE are presented by [6].

3.2 Novaya Zemlya fjords

The consequences of the possible leakage from the nuclear reactors and containers with liquid wastes that have been scuttled in the Novaya Zemlya fjords and in the Kara Sea in the Novaya Zemlya

Depression (NZD) during the period 1960-1991 have been intensively studied last years by the international groups of the

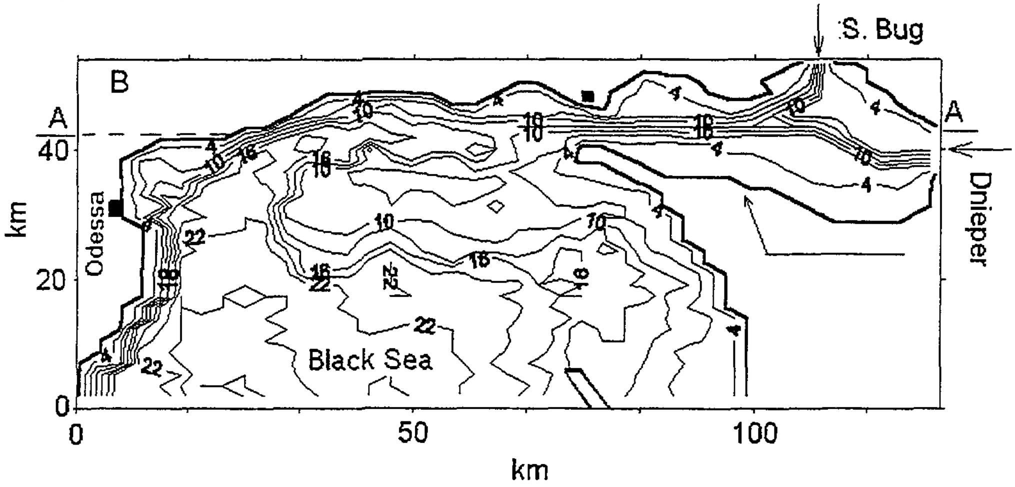


FIG.1 Bottom topography of the Dnieper-Bug Estuary area.

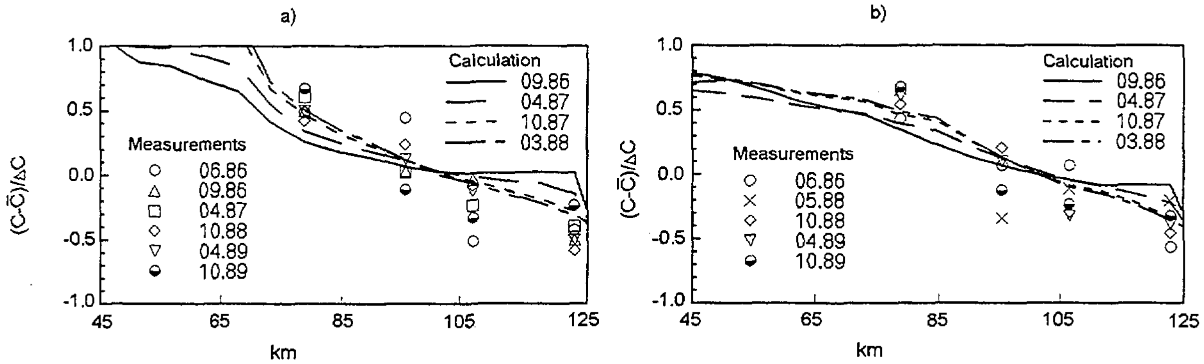


FIG. 2 Computed [6] vs. measured [2] distribution of dissolved ^{137}Cs along the A-A cross-section of DBE and sea shelf in 1986-1989. (a) surface layer; (b) near bottom layer.

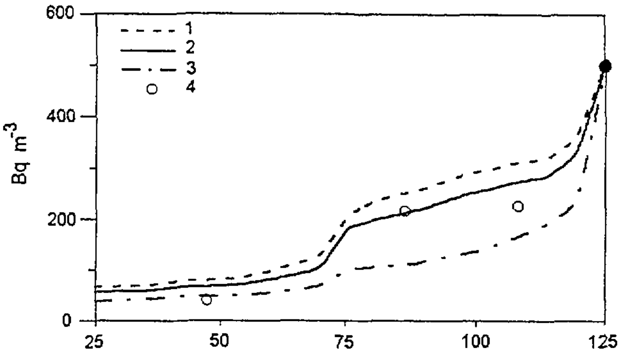


FIG. 3 Computed [6] vs. measured distribution of dissolved ^{90}Sr in the surface layer in March 1988. Circles are data [3] filled circle - [4]. Curve 1 - $K_{db}=0$; 2 - $K_{db}=3.0$ m^3/kg; 3 - $K_{db}=5.0$ m^3/kg, where K_{db} is the coefficient of radionuclides' equilibrium distribution in the "solute-bottom sediments"

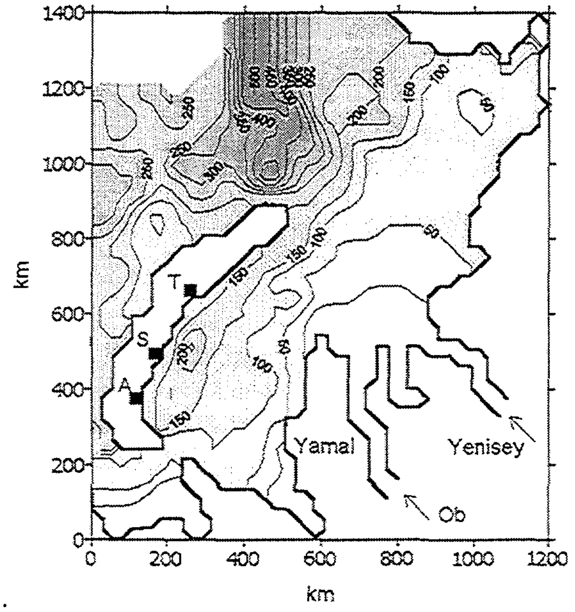


FIG. 4. *Bathymetry of the Kara Sea "A" Abrosimov fjord, "S" Stepovogo fjord, "T" Tsivolki fjord*

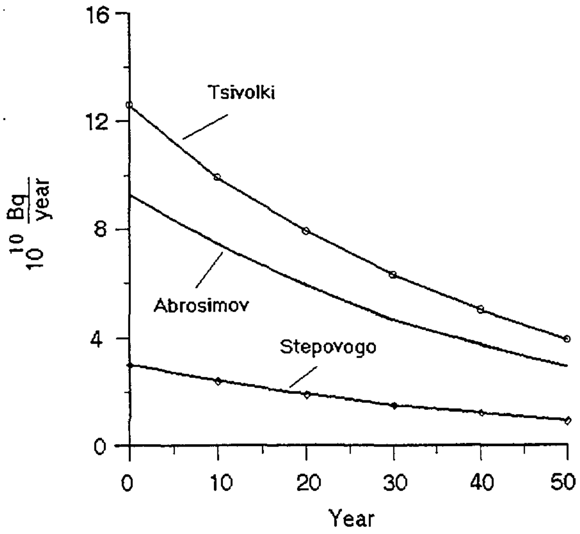


FIG. 5. *Scenario or ^{137}Sr release from dump sites in the Novaya Zemlya fjords [8].*

experts (e.g., [7]). The recent study [8] was focused on the radiological consequences of the release to man. The radiological collective dose calculations were carried out on the basis of the marine radionuclide concentration values predicted in the long-term projection by the box model [8]. The parameterisation of the water and radionuclide fluxes from the Novaya Zemlya bays required more insight in the hydrodynamic and radionuclide transport processes in the fjords. All these processes were considered in the presented in this paper modelling study, that was provided as a part of the European Commission project [8]. The local scale modelling was performed for dump sites in three fjords (Abrosimov, Stepovogo and Tsivolki). Two years of the radionuclide (^{137}Cs and ^{239}Pu) dispersion were simulated for the potential releases. Information on the fjords has been obtained from the cruise reports [7]. The scenarios of the release of ^{137}Cs in the fjords [8] are given in Fig. 5. According to these scenarios the continuous release will begin from 2050. Strong seasonal effects on the circulation in the fjords caused by summer run-off from a snow melting, and winter ice sheets, in addition to wind and semidiurnal tides were shown in calculations. Let us consider as an example the Stepovogo fjord with the east-west spacing about 9 km and north-south spacing of 3.6 km (Fig. 6). A summer fresh water discharge from the western part of the basin results in the strong water stratification. The halocline depth at summer is about 15-30 m with the salinity variation of 15 $^{\circ}/_{\circ}$ [7]. The nuclear submarine NS 601 was dumped in the relatively shallow channel near the bay mouth. The distribution of ^{137}Cs in the Stepovogo fjord in summer and winter is shown in Fig. 7. The release rate of ^{137}Cs from this fjord is presented in Fig. 8. As shown in Fig.7a, the vertical distribution of ^{137}Cs in the August is inhomogeneous. The concentration of ^{137}Cs in the mouth increases to the surface whereas in the inner part of the fjord it is maximal near the bottom. It can be explained by the seasonal specifics of the tracer transport in the stratified fjords. At winter the outflux of the radionuclides is relatively weak because the ice covers the fjord (Fig.8). It is governed by semidiurnal tides. An influx of fresh water in July-August "pushes" the contaminated water of the upper layer to the fjord mouth. It corresponds to first maximum *F* in Fig. 8. Then flux of more clear water in the upper layer drastically reduced the outflux of ^{137}Cs in Fig.8. In the bottom layer the water flows from the sea and transports radionuclide to the inner part of the fjord. Here the contaminated water rises in the upper layer. A secondary maximum of outflux *F* in Fig. 8 took place while this water found its way to the bay mouth.

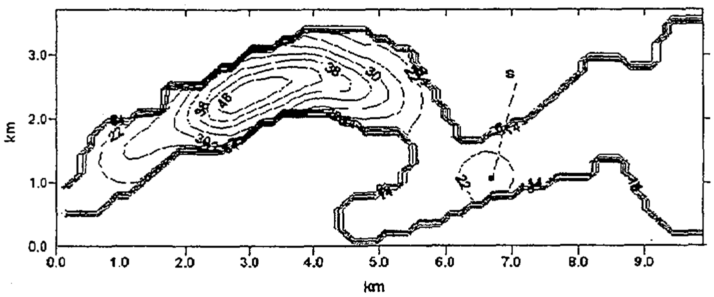
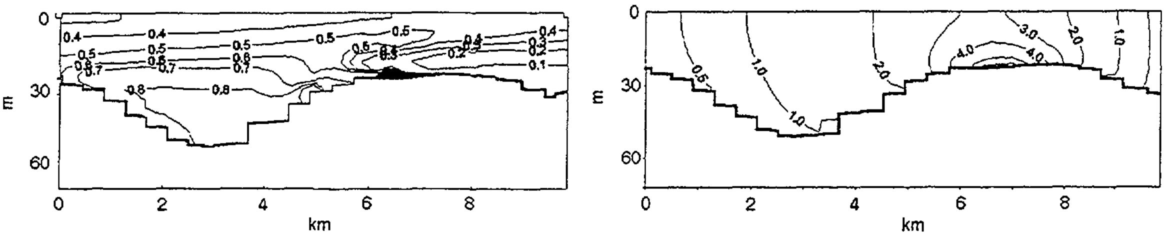


FIG. 6. Bathymetry of the Stepovogo fjord [7].



(a) (b)

FIG.7. Vertical cross-section of ^{137}Cs distribution in the Stepovogo fjord at summer(a) and winter (b) after half and one year since the beginning of a release, respectively.

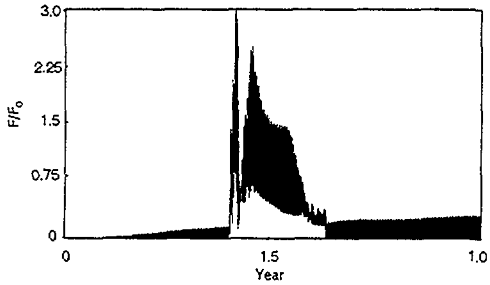


FIG. 8. The release rate of ^{137}Cs from the Stepovogo fjord F normalised to the source release rate F_0. Calculations were made by THREETOX.

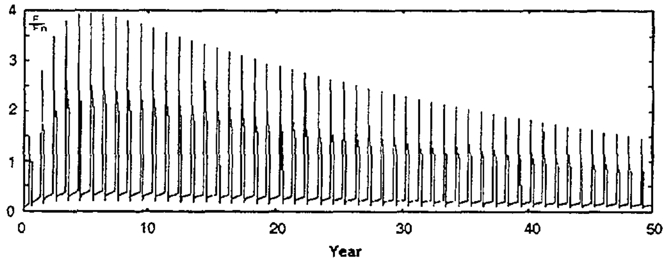


FIG. 9. The release rate of ^{137}Cs from the Stepovogo fjord F normalised to the source release rate F_0. Calculations were made by the box model.

TABLE. I THE OUTFLUX OF ^{137}CS FROM FJORDS AND NOVAYA ZEMLYA DEPRESSION CALCULATED BY THE BOX MODEL ($\times 10^{10}$ BQ/YEAR)

Year	Outflux from Abrosimov	Outflux from Stepovogo	Outflux from Tsivolki	Source release in NZD	Total source release	Total flux into the Kara Sea
2051	0.4	1.0	3.3	2.2	26.9	6.9
2055	2.1	2.5	9.7	2.0	24.2	16.3
2060	3.3	2.3	9.9	1.7	21.4	17.2
2065	3.9	2.1	9.0	1.6	19.2	16.6
2070	4.1	1.9	8.0	1.4	17.1	15.4
2080	3.8	1.5	6.3	1.1	13.5	12.7
2100	2.8	0.9	3.9	0.7	8.3	8.3

The calculated flushing times ranged from 0.3 months (summer) to 3.4 months (winter) in the relatively small Stepovogo fjord, to 0.6 and 6.0 months for summer and winter, respectively, in the large Tsivolky fjord. Based on the THREETOX estimates of the flushing times, a simple box model for the fjords was developed to extrapolate the results of the 3-D simulation from a few years to the fifty years. The calculated by the box model release rate is given in Fig. 9. This model predicts that the average concentration of ^{137}Cs in the water of fjords didn't exceed 80 Bq m^{-3} (Abrosimov). The box model predicted that, after 50 years since the beginning of a release, the residual amount of the ^{137}Cs in the fjords is about 3 % from the total input. The results of computation are summarised in Table 1. The maximum of the total influx in the Kara Sea is attained after 10 year of the release. The simulation of the radionuclide transport in the Kara Sea was done by THREETOX [8, 9] on the basis of these estimates. It was shown that the marine radionuclide concentration due to the releases are much less than the present day concentration.

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