A Three-Scales Model for the Dispersion of Radioactive Spots from Nuclear Emergencies. Application to the Baltic Sea after the Accident of Chernobyl

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Abstract.-

This model is a improved version of a previously published Two-Scales model [11] and includes the transport of particles in three spatial scales: small (kilometres), medium (decades of *km*), and large (hundreds of *km*). A 3-D dispersion model has been developed to analyse and simulate the dispersion of nuclear contaminants in marine ecosystems. This model is characterized by presenting high spatial resolution, by taking into account the possible binding of a fraction of the contaminants to the suspended matter as well as its consequent sedimentation, and especially by formulating the diffusion processes using an original approach. The horizontal resolution of the model is 20 km, while for the vertical resolution a total of six layers are considered. The Baltic Sea has been elected as the validation scenario of the model and the radionuclide Cs-137 as the radiotracer to be analysed. This scenario was the most contaminated ecosystem out of the Soviet Union due to the Chernobyl accident occurred at the end of April 1986, and the elected radiotracer Cs-137 was the main long-lived radioisotope emitted to the environment. A computation time of approximately 9 hours by using a Matlab code in a personal computer (AMD-1.4 GHz) was necessary. Different classical tools in Oceanography as well as different numerical methods (Monte Carlo, Finite differences) have been properly implemented in the model. The approaches adopted allow to save a lot of computational time [10].

I. INTRODUCTION

The internal structure of the model can be described as follows: It is formed by three sub-models (Circulation, Diffusion and Sedimentation), together with the numerical and mixing algorithms implemented for the individual cells into which the scenario was divided. The influence of the winds, tides, and inertial forces is obviously very important in the numerical simulations. Eddy-like motions with variable intensities and scales are superimposed on the average circulation field.

Experimental information on current spectra has been analysed. The model as a whole has been validated by comparing the evolution of the Cs-137 concentrations with experimental data taken from the literature. The Cs-137 model predictions are in an acceptable agreement with the experimental Cs-137 maps, thereby guaranteeing the validity of the model.

II. MATERIALS AND METHODS

A. Circulation Sub-Model

The velocity ($\vec{v}$) of a general point of our system can be described in a straightforward way as the sum of its annual mean velocity ($\vec{v}^m$) plus its associated fluctuation ($\vec{v}'$).

$$\vec{v} = \vec{v}^m + \vec{v}' \qquad (1.1.)$$

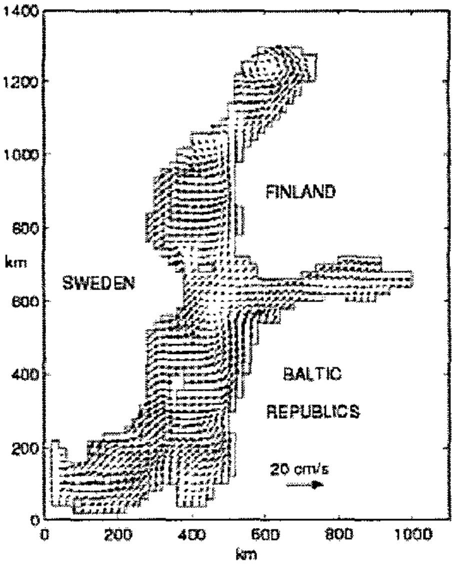

Fig. 1. Annual mean currents in layer 1, [0, 5]m

Special attention needs to be paid to [2], which modelled the average currents in the Baltic Sea (considering the winds as the essential producing agent) with horizontal resolution of 10 km. Their results have

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been validated through comparison with experimental measurements [3].

The thickness of the six layers considered are the following: [0,5]m, [5,10]m, [10,20]m, [20,40]m, [40,60]m and [60m,bottom], which are coincident with those considered in the Funkquist model. An interesting simplification was performed in [2], constructing a typical year which included the most probable meteorological events. The figure 1 shows the annual mean velocities for the layer [0, 5]m.

B. Horizontal diffusion

This is one of the most important processes governing the dispersion in a complex system. Measurements in the Baltic Sea ([1] and [6]) show that current spectra have peaks for periods similar to those of wind spectra, i.e. in the order of days. In order to calculate turbulent exchange parameters, an essential step is to separate the mean flow and the associated fluctuations from the time series data.

In Figure 2, and as an example, a representative current spectrum together with the different mean flows used in this work are shown. In this way, the fluctuations with regard to the annual mean velocity, $\vec{v}'$, can be expressed as the sum of two terms:

$$\vec{v}' = \vec{u}' + \vec{w}' \qquad (2.1.)$$

where the field $\vec{v}'$ represents the small-scale fluctuations shorter than two days, and where $\vec{w}'$ represents the large-scale fluctuations affecting the system longer than two days.

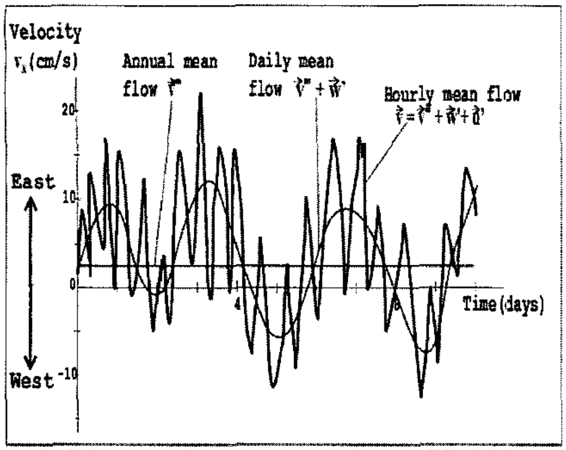

Fig. 2. A representative current spectrum (based on [3]) with the different mean flows proposed in this manuscript.

B.1. Horizontal small-scale velocity fluctuations.-

The first objective therefore is to simulate the value of the small-scale velocity fluctuation terms u'_x and u'_y for all the points of the ecosystem analysed.

For the performance of these calculations, the variances of the two terms can be expressed in the following way:

$$\sigma(u'_x) \equiv \sqrt{\overline{(u'_x)^2}} = \sqrt{\frac{K_x}{T_x}}$$

$$\sigma(u'_y) \equiv \sqrt{\overline{(u'_y)^2}} = \sqrt{\frac{K_y}{T_y}} \qquad (2.2.)$$

where K_x and K_y denote the horizontal diffusion coefficients, and T_x and T_y are the Eulerian integral timescales in the horizontal directions.

Based on equations (2.2.) we have used a set of average experimental values of K_x, K_y, T_x, and T_y compiled in[3]. The values of the average horizontal-diffusion coefficients which are compiled in Table I.

TABLE I
HORIZONTAL DIFFUSION COEFFICIENTS, $\{K_x, K_y\}$ (m^2/s), USED IN THE DIFFUSION SUB-MODEL.

$\{K_x, K_y\} m^2/s$	30	10	8	6	4
$depth(m)$	[0,10]	[10,20]	[20,40]	[40,60]	[60,bott.]

As regards to the set of experimental values of T_x and T_y, we can indicate that they were in the interval [1.5,2.5] hours, with a clear maximum at 2.0 hours. In fact, through equations (2.2.) we can determine u'_x and u'_y at any point of the system, by the assignment of values from the Monte Carlo method, according to Gaussian distributions of probability.

B.2.Horizontal large-scale velocity fluctuations.-

Observations and analyses carried out at several stations distributed over the Baltic Sea indicate a correlation between the large-scale fluctuation velocities $\{w'_x, w'_y\}$ and the annual mean velocities $\{v^m_x, v^m_y\}$.

Hence, and as a first approximation, our model assumes the following functions $\{F(v^m_x), F(v^m_y)\}$ for the simulation of large-scale fluctuations:

$$\left\{\begin{array}{l} \overline{w'_x} = \overline{w'_y} = 0 \\ \sigma(w'_x) \equiv \sqrt{\overline{(w'_x)^2}} = F(v^m_x) = \lambda \mid v^m_x \mid \\ \sigma(w'_y) \equiv \sqrt{\overline{(w'_y)^2}} = F(v^m_y) = \lambda \mid v^m_y \mid \end{array}\right\} (2.3.)$$

where $\lambda \in [1,3]$, according to the study of the different spectra obtained in most of the stations distributed over the Baltic sea. Therefore, based on (2.3.), the calculations of the velocities $\left\{w_x', w_y'\right\}$ for each point of the system were also based on the Monte Carlo method in the same way as $\left\{v_x', v_y'\right\}$.

C. Vertical diffusion

The modelling of the vertical component of the small-scale fluctuation velocity, u_z', is based on the same theoretical fundamentals as those used for the horizontal simulation. Additionally, and at a depth of approximately 40 metres, the exchange of particles between upper and lower levels is clearly mitigated due to the presence of a halocline layer. For all these reasons, and based on the experimental values compiled in [12], for the simulation of the small-scale vertical turbulent velocities we have used the average annual values of K_z for different depths which are shown in the Table II. These average vertical-diffusion coefficients are applicable to every location of the system analysed.

TABLE II
VERTICAL DIFFUSION COEFFICIENTS, K_z (cm^2/s), USED IN THE DIFFUSION SUB-MODEL.

$K_z\ (cm^2/s)$	1.00	0.50	0.20	0.20	0.05
$depth(m)$	5	10	20	40	60

D. Sedimentation Sub-Model

It is necessary to bear in mind that a fraction of the radionuclide ^{137}Cs can be fixed to the suspended matter present in the water column, and consequently can be deposited on the seabed.

This sub-model is based on the hypothesis of the existence of equilibrium in the distribution of the analysed radionuclide between the dissolved and particulate phases.

The magnitude of the equilibrium of a radionuclide between the dissolved and the particulate phases in an aquatic system is described by the partition coefficient K_d (m^3/kg). Determining the fractions F_{sus} and F_{sol} and considering an average sedimentation rate of matter S_{sed} $(kg.m^{-2}.y^{-1})$ for each water column characterized by height $h(m)$, the proportion of the activity deposited per year in the sediment, K_{ws}, is given by the expression:

$$K_{ws} = \frac{K_d \cdot S_{sed}}{h \cdot (1 + K_d \cdot S_{sus})}(year^{-1}) \qquad (3.1.)$$

which constitutes the core of this 2-D sedimentation sub-model. By its application at different points of our ecosystem, it is possible to evaluate the losses, through sedimentation, of the analysed radionuclide (^{137}Cs).

For the description of the salinity dependence of the partition coefficients, we have taken the empirical formulation proposed by Weiss into consideration to correlate the commented magnitudes in the Baltic Sea in [13]

$$K_d(m^3/kg) = 30.0 \cdot \exp\left[-0.117 \cdot S\right] \qquad (3.2.)$$

while the average values of salinity (S=S(‰)) at different locations of the Baltic Sea have been extracted from [9].

III. RESULTS

The model as a whole permits the simulation of the evolution of the ^{137}Cs concentrations in the Baltic Sea for the time interval June 1986- June 1987.

The experimental spatial distribution maps of the ^{137}Cs concentrations on the initial and the final simulation dates, (see Figure 3) have been interpolated from experimental values found in several radiological journals [4], [5], [7] and [13].

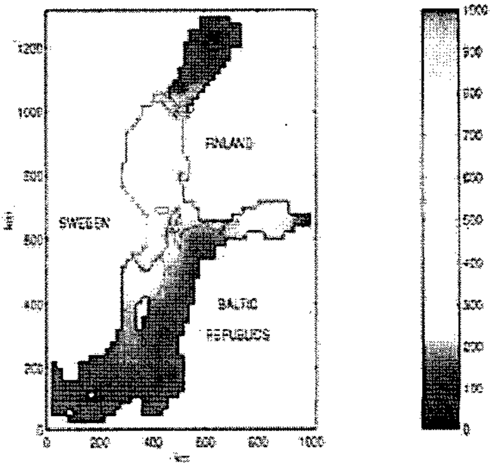

Fig. 3. Experimental ^{137}Cs specific activity distribution (Bq/m^3) at the surface of the Baltic Sea in summer 1987 (final conditions).

All the simulation was carried out using the code Matlab 5.3 on a personal computer AMD-1600 MHz. The computation time needed for the simulation of the complete year (summer'86-summer'87) was approximately ten hours.

In the performed simulation, two different time steps have been chosen for the execution of the model: $\Delta t_w = 3\ days$ and , $\Delta t_u = 6\ hours$ were adopted in agreement with the decay times of the large- and small-scale velocity fluctuations, respectively, observed in the spectra. The sedimentation sub-model was run by using $\Delta t_s = 6\ hours$ as time step.

As an example, only the modelled ^{137}Cs distribution map for the superficial layer, in June 87, is going to be shown, which needs to be compared with the experimental distribution map shown in Figure 3. Figure

4 corresponds to $\lambda = 3/2$ (Equations 2.3.). The satisfactory agreement is evident.

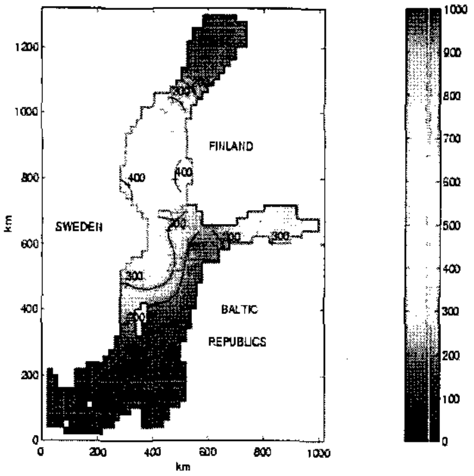

Fig. 4. Modelled ^{137}Cs specific activity distribution (Bq/m^3) at the superficial layer of the Baltic Sea in summer 1987 ($\lambda = 3/2$).

IV. CONCLUSIONS

This implemented model is formed by three sub-models (circulation, diffusion and sedimentation), together with appropriate numerical and mixing algorithms. The model is presently restricted to simulations of short/medium timescales, and is therefore valid in the prediction of the dispersion of contaminants after hypothetical accidents.

The dispersion model as a whole was first validated by analysing the evolution of the ^{137}Cs concentrations in the Baltic Sea waters for the time interval June 1986-June 1987. The model predictions are in an acceptable agreement with the experimental distributions on the same date, thereby guaranteeing the validity of the model.

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