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A three-dimensional model for the dispersion of radioactive substances in marine ecosystems. Application to the Baltic Sea after the Chernobyl disaster

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Abstract

A 3-D dispersion model has been developed to simulate the dispersion of nuclear contaminants in marine ecosystems. This model is characterized by presenting high spatial resolution, by taking into account the possible sedimentation of a fraction of the contaminants, and by formulating the diffusion processes using an original approach.

The model has been applied and validated taking the Baltic Sea as its scenario, and using the ^{137}Cs originating from the Chernobyl accident as the substance which experienced the dispersion. The simulation of a year's dispersion of the ^{137}Cs in the Baltic sea (just after the Chernobyl accident) has been performed.

Keywords: 3-D model; Diffusion scales; ^{137}Cs; Chernobyl; Baltic Sea

1. Introduction

Since the discovery, about 60 years ago, of nuclear fission processes and their derived consequences, we have been aware of the consequent incorporation and accumulation in the environment of several artificial radionuclides, and that

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the marine environment is the part of the globe most affected by this type of contamination.

These radioactive substances, once they are incorporated to the marine compartment, experience a series of dispersion and transport processes. The comprehension of these processes is obviously an essential requirement for a greater understanding of the behaviour in the environment of the radionuclides analysed, and for an accurate prediction of the evolution of radioactive contamination which may be incorporated into marine environments in the future.

Mathematical models simulating dispersion processes experienced by radionuclides in marine environments can be of enormous help towards attaining greater understanding of their behaviour in this environmental compartment as well as for predictive analyses. In this paper, we show our contribution in this field, by describing the main characteristics and composition of a mathematical model developed, with the objective of studying the dispersion of radioactive substances in the oceans.

This model, based on the use of the numerical schemes of Monte Carlo and Finite Differences as well as on different classic tools in Oceanography, has been applied to the Baltic Sea as a first approach. There are two main reasons for the choice of this scenario: a) it is a semi-enclosed sea, which allows better control of the physical processes which influence the system, and b) outside the Soviet Union, it was the marine ecosystem most affected by the deposition of radioactive nuclides originating from the accident of the Chernobyl reactor, for which very detailed spatial and temporal information was available on the evolution of the ^{137}Cs concentrations after the date of the nuclear disaster. Furthermore, the peculiarity of the original distribution of the Chernobyl radionuclide contamination which presents high increments in ^{137}Cs levels in specific zones of this sea, and the knowledge that these levels experienced clearly identifiable spatial and temporal evolutions in the months following the accident, would allow us to check the power of the constructed model by simulation of the ^{137}Cs dispersion for only 1 year following the Chernobyl accident.

Several models can be found in the literature where, in a direct or indirect way, the dispersion in the Baltic Sea has been simulated by using different approaches in order to reach their specific objectives (Ribbe et al., 1991; Funkquist and Gidhagen, 1984; Evans, 1985). Our model, which takes some tools from the existing models (as will be detailed later on), contributes to an improved and more accurate description of the dispersion of radioactive contaminants in this sea by: a) using a high-resolution spatial scale which considers the effects of wind in the dispersion and the three-dimensional character of the system analysed, b) considering small- and large-scale diffusion processes, and c) taking into account the possible binding of a fraction of the radioactive substances to the suspended matter as well as the associated sedimentation processes.

In addition, the use of the model developed is not restricted to the simulation of the dispersion of punctual sources (in fact, the ^{137}Cs Chernobyl contamination needs to be treated as an extended source).

The internal structure of the model can be described as follows: It is formed by three sub-models (Circulation, Diffusion and Sedimentation), together with numerical and mixing algorithms implemented for the individual cells into which the scenario was divided. The main characteristics of each sub-model and the associated numerical algorithms will be described in Section 2 of this paper, although it is necessary to indicate that our main original contributions were focused on the development of: a) the diffusion sub-model and b) the numerical and mixing algorithms implemented for the performance of the dispersion model.

The model as a whole has been applied to the Baltic Sea for the simulation of the ^{137}Cs dispersion during the interval summer 1986–summer 1987, and is validated by comparing modelled with available experimental results in the time interval simulated. The main output of this application and validation exercise is shown in Section 3. A set of conclusions will be explained in Section 4.

2. Description of the model

2.1. Circulation sub-model

The water circulation pattern is specifically characterized in the Baltic Sea by complex turbulent movements. Eddy-like motions with variable intensities and scales are superimposed on the average circulation field. In this way, 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 ($\vec{v}'$).

$$\vec{v} = \vec{v}^m + \vec{v}' \tag{1}$$

Various well-recognised studies have been carried out on the Baltic Sea area devoted to the description of its physical oceanography as well as to the analysis, evaluation and simulation of its average-velocity current maps (Omstedt and Axell, 1998; Lehmann, 1995; Stigebrandt, 1983; Omstedt, 1990; Funkquist and Gidhagen, 1984; Kielmann, 1981; Simons, 1978). Special attention needs to be paid to the work of Funkquist and Gidhagen (1984), 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 been validated through comparison with experimental measurements (Gidhagen et al., 1986).

For this reason, we have used these results to build our annual mean current charts, after applying interpolations to fit them to our horizontal resolution of 20 km. A total of six layers were considered in our model for vertical resolution, following the proposal of Simons (1978), which accurately reproduces the dispersion effects provoked by the vertical current profiles (Shear effect). 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 60 m–bottom, which are coincident with those considered in the Funkquist model.

Since our circulation sub-model is based on that developed by Funkquist and Gidhagen (1984), in this paper only its main hypotheses and highlights are described. A complete description can be found in the aforementioned reference.

An interesting simplification was performed by these last authors constructing a typical year which included the most probable meteorological events. In this way, if the majority of the relevant information is included in the typical year, the variations between different years in the ecosystem analysed will be insignificant in comparison with the variations within the same year, and consequently the simplification performed can be considered appropriate and with sufficient accuracy. Additionally, the use of the information associated to this typical year will allow predictive studies to be carried out with enough confidence in the results obtained.

The typical year was constructed by Funkquist and Gidhagen (1984) after a statistical analysis of all the meteorological events which had affected the zone during the last 50 years.

The modelled annual current-velocity fields for the two upper layers, 0–5 and 5–10 m, are quite similar, being essentially dominated by the Ekman drift with predominant velocities of 3–4 cm/s to the east, due to westerly winds. In Fig. 1, as an example the annual current velocity field map is shown for the layer 0–5 m.

On the other hand, the average current velocity fields obtained for the four deeper layers show a circulation governed by the influence of the topography, a fact which can be deduced easily from the simultaneous observation of Fig. 2 (corresponding to the annual current velocity field map for layer 5) and the bathymetric map of the Baltic Sea, shown in Fig. 3.

2.2. *Diffussion sub-model*

As previously indicated, it is essential to superimpose the random movements ($\vec{v}'$) with variable intensities and scales over the annual average circulation pattern ($\vec{v}^m$), in order to suitably reproduce the complete field ($\vec{v}$) in the Baltic Sea. These additional superimposed movements affect the system in all directions and its modelling is the objective of the diffusion sub-model.

2.2.1. *Horizontal diffusion*

This is one of the most important processes governing the dispersion in a complex system. Measurements in the Baltic Sea (Kielmann et al., 1973; Franke, 1980) 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.

The selection of an appropriate numerical filter is a crucial step for this separation analysis. A digital low-pass filter, based on energetic arguments, was designed (Gidhagen et al., 1986) to analyse different stations in the Baltic Sea. The hourly mean flow was filtered to get the daily mean flow. The application of this filter removes almost all fluctuations shorter than 2 days, such as inertial (Coriolis force) and tidal motions. Oscillations with periods longer than 2 days (related to winds)

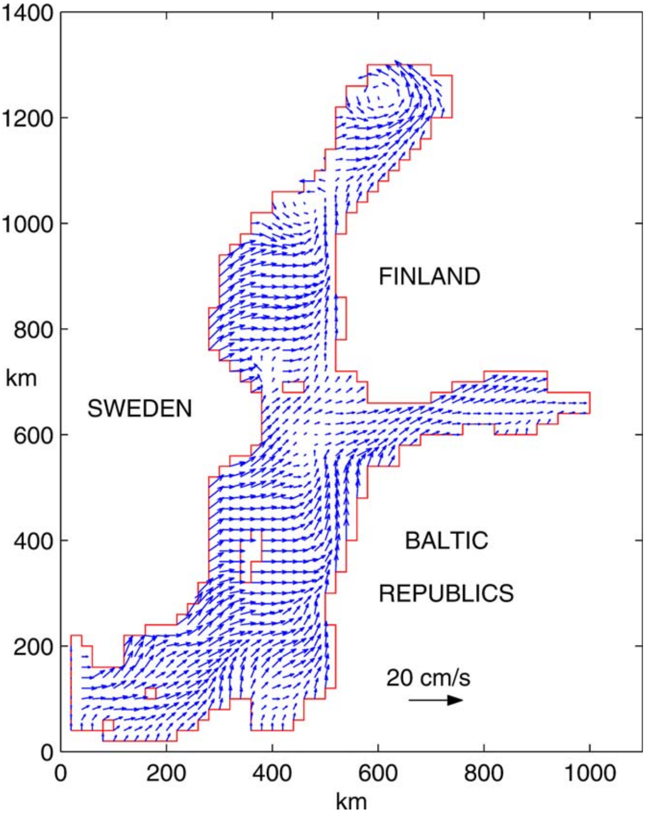

Fig. 1. Annual mean currents in layer 1 (0–5 m).

remain as part of the daily mean flow. In our model, the oscillations with periods longer than 2 days are considered as fluctuations with regard to the annual mean flow displayed by our Circulation Sub-model.

In Fig. 4, 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:

$$\vec{v}' = \vec{u}' + \vec{w}' \tag{2}$$

where the field $\vec{u}'$ 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.

2.2.1.1. 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.

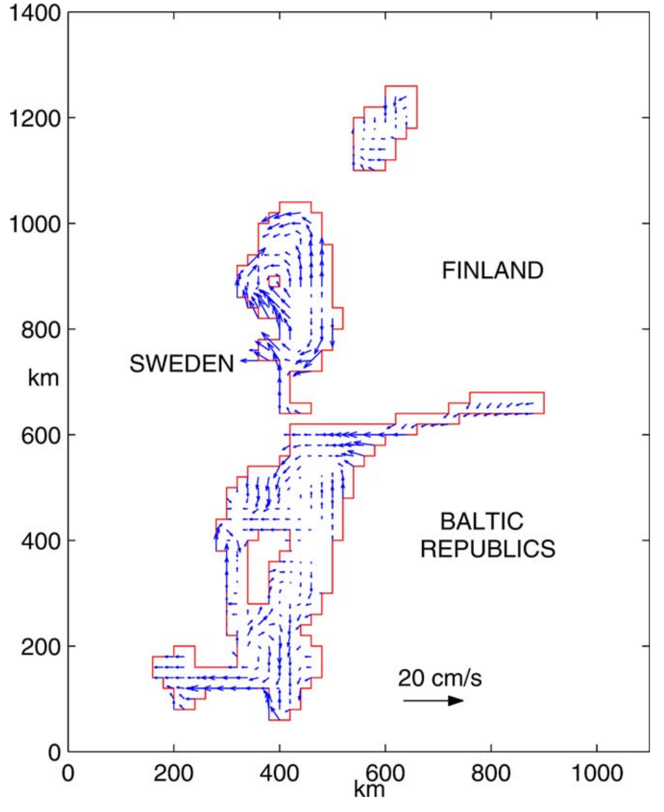

Fig. 2. Annual mean currents fields in layer 5 (40–60 m).

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

$$\sigma(u'_x) \equiv \sqrt{\overline{(u'_x)^2}} = \sqrt{\frac{K_x}{T_x}} \quad \sigma(u'_y) \equiv \sqrt{\overline{(u'_y)^2}} = \sqrt{\frac{K_y}{T_y}} \tag{3}$$

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 Eq. (3) we have used a set of average experimental values of K_x, K_y, T_x, and T_y compiled by Gidhagen et al. (1986) from the measurements carried out at several stations placed in the Baltic Sea. After the critical analysis of the experimental horizontal diffusion coefficients it was possible to observe: a) the existence of a close correlation between the experimental values of K_x and K_y and the depth, b) its constancy, in a first approximation, over the Baltic Sea at a given depth, and c) the existence of a clear and generalized isotropy on the horizontal scale, i.e. $K_x = K_y$. All these facts allow us to consider, within the different layers in which

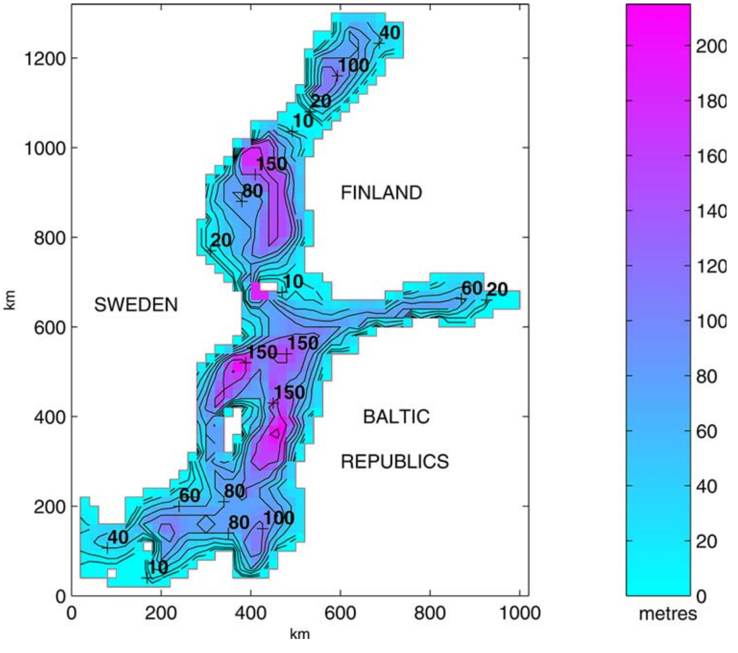

Fig. 3. Bathymetric map of the Baltic Sea.

we have sliced the Baltic Sea, the values of the average horizontal-diffusion coefficients which are compiled in Table 1.

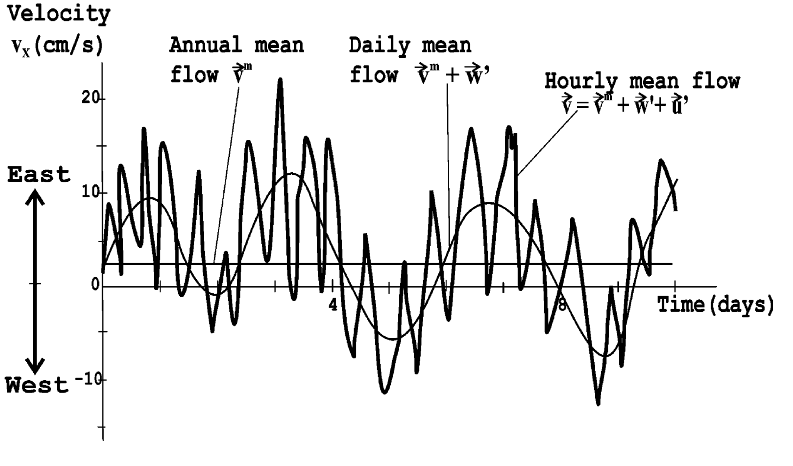

Fig. 4. A representative current spectrum (based on Gidhagen et al., 1986) with the different mean flows proposed in this manuscript.

Table 1
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–bottom

As regards to the set of experimental values of T_x and T_y, we can indicate that they are fairly uniform, with an average value of approximately 2 h for all stations and at all depths. This uniformity induced us to carry out its qualitative extrapolation for all the ecosystem analysed, where the values were in the interval 1.5–2.5 h, with a clear maximum at 2.0 h.

Once the average horizontal-diffusion coefficients and the integral Eulerian time-scales are known at any point of the system, the short scale fluctuation term of the velocities can be calculated. In fact, through Eq. (3) 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.

Monte Carlo simulation is made by assigning random numbers through the application of a lineal congruent method included in the code Matlab 5.3. Additionally, it has been checked that the Monte Carlo simulation performed is not sensitive to the variation of the seeds used to generate the turbulent velocities.

2.2.1.2. 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:

$$\left\{ \begin{array}{l} \overline{w'_x} = \overline{w'_y} = 0 \\ \sigma(w'_x) \equiv \sqrt{\overline{(w'_x)^2}} = F(v^m_x) = \lambda |v^m_x| \\ \sigma(w'_y) \equiv \sqrt{\overline{(w'_y)^2}} = F(v^m_y) = \lambda |v^m_y| \end{array} \right\} \quad (4)$$

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 Eq. (4), the calculations of the velocities $\{w'_x, w'_y\}$ for each point of the system were also based on the Monte Carlo method in the same way as $\{v'_x, v'_y\}$.

2.2.2. 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. Indeed, it is based on the construction of the average vertical diffusion coefficient (K_z) and the Eulerian integral time scale T_z maps, and on the application of the Monte Carlo method to determine the vertical fluctuation velocities.

In the construction of the aforementioned average vertical-diffusion coefficient map of the Baltic Sea, we have taken into account that the average vertical diffusion coefficients are also very much dependent on the depth, with higher turbulent levels in uppermost layers mostly due to the influence of the wind. Additionally, and at a depth of approximately 40 m, the exchange of particles between upper and lower levels is clearly mitigated due to the presence of a halocline layer. The existence of this interface has also been considered in the construction of the aforementioned average vertical-diffusion coefficient map, since it plays an important role in the increase in the K_z values in upper layers.

We have verified the non-existence of a clear dependence of the vertical diffusion coefficients on the geographical situation considered in the Baltic Sea. The values of this coefficient oscillates around an average annual value for a fixed depth. For all these reasons, and based on the experimental values compiled in Viopio (1981), 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 2. These average vertical-diffusion coefficients are applicable to every location of the system analysed.

On the other hand, the timescales associated to vertical diffusion, were exactly the same as those used in the small-scale horizontal diffusion study. The vertical dimensions of the Baltic Sea are much lower than the horizontal dimensions, thereby implying that w'_z must be negligible in the system and therefore is not being considered in our approaches.

2.3. 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, a fact which can be assumed with confidence if we take in consideration that the time needed to reach this equilibrium (approximately 2 h) (Ribbe et al., 1991) is quite small in comparison with the time step used in the sedimentation study.

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), which is defined as the ratio between the specific activity of the

Table 2
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

analysed radionuclide in suspended matter (A_{sus} Bq/kg) and its specific activity in dissolution (A_{sol} Bq/m^3). Defining this coefficient, and assuming a given amount of suspended matter, (S_{sus} kg/m^3), it is possible, by carrying out a simple balance (Clark and Webb, 1980), to determine the proportion of the activity existing in solution (F_{sol}) and in suspension (F_{sus}) in the studied water column, through the following expressions:

$$F_{sus} = \frac{K_d \cdot S_{sus}}{1 + K_d \cdot S_{sus}} \qquad F_{sol} = \frac{1}{1 + K_d \cdot S_{sus}} \tag{5}$$

where

$$K_d \text{ m}^3/\text{kg} = \frac{A_{sus} \text{ Bq/kg}}{A_{sol} \text{ Bq/m}^3} \tag{6}$$

Determining the fractions F_{sus} and F_{sol} and considering an average sedimentation rate of matter S_{sed} kg $\cdot$ 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:

$$K_{ws} = \frac{K_d \cdot S_{sed}}{h \cdot (1 + K_d \cdot S_{sus})} \quad \text{year}^{-1} \tag{7}$$

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).

Eq. (7) has been implemented in our model by assuming that the values of the sedimentation rate S_{sed} and the amount of suspended matter per unit volume S_{sus} are constant throughout the ecosystem, and by adopting the values defined by Evans (1985) for these parameters as representative for the Baltic Sea ($S_{sed} = 0.5$ kg $\cdot$ m^{-2}y^{-1} and $S_{sus} = 1.10^{-3}$ kg/m^3). Nevertheless, a similar assumption (constancy over the Baltic sea) cannot be made for K_d values since it has been experimentally demonstrated that partition coefficients K_d are very much dependent on salinity (Weiss, 1989) and in the Baltic Sea the value of the salinity has important spatial gradients, which decreases from the strait of Kattegat in the south to the core of the Baltic Sea in the north.

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 (Weiss, 1989)

$$K_d \text{ m}^3/\text{kg} = 30.0 \cdot \exp[-0.117 \cdot S] \tag{8}$$

where the average values of salinity ($S = S$(‰)) at different locations of the Baltic Sea have been extracted from Svansson (1972).

In this way, we have constructed a map of partition coefficients, K_d, for the Baltic Sea, where it can be observed that its range of values is extensive. In fact, it is possible to observe values as low as 3000 l/kg in the Danish Straits and as high as

18000 l/kg in the Bothnian Bay. With this map, it has therefore been possible to determine the radioactive sedimentation rate in throughout the scenario.

Finally, this sub-model also considers that another way in which ^{137}Cs is lost in the water column is simply due to radioactive decay ($T_{1/2} = 11\,000$ days). This sub-model also includes algorithms to take this decay into account.

2.4. Numerical and mixing algorithms

The mixing algorithm is applied between the boxes or cells in which we have divided ours scenario (the Baltic sea), each one characterized by the dimensions $h_x \times h_y \times h_z$, and by a velocity field, $\vec{v}'$. For greater understanding, we consider two neighbouring cells in the X direction which will be called cells 1 and 2, respectively, and only the dispersion in the west-east direction due to component v'_x is studied (see Fig. 5).

Nevertheless, although the following explanation will be performed considering only the dispersion in the direction of the OX axis, due to the three-dimensional character of our model, the real simulation is carried out by first computing the dispersion in the X direction (east–west), followed by the Y direction (north–south), and finally by the Z direction (vertical).

The formulated algorithm produces the exchange between the four sub-cells defined in association to cells 1 and 2 (see Fig. 5): $1 = 1U + 1D$; $2 = 2U + 2D$, where U and D stand for "up" and "down", respectively. The dimensions of each sub-cell is $L \times h_y \times (h_z/2)$, and the particles follow a circuit in its natural sense as illustrated in Fig. 5: $1U \Rightarrow 2U \Rightarrow 2D \Rightarrow 2U \Rightarrow 1U$.

Length L, is called the mixing length, and its value depends (for an OX problem) on the diffusion velocities $\{u'_x, w'_x\}$ and on the time steps $\{\Delta t_u, \Delta t_w\}$ considered for small- and large-scale mixing. In fact, the mixing length, in the OX direction, can be defined as:

$$L = \begin{cases} u'_x \Delta t_u \; ; & \text{small scale mixing} \\ w'_x \Delta t_w \; ; & \text{big scale mixing} \end{cases} \tag{9}$$

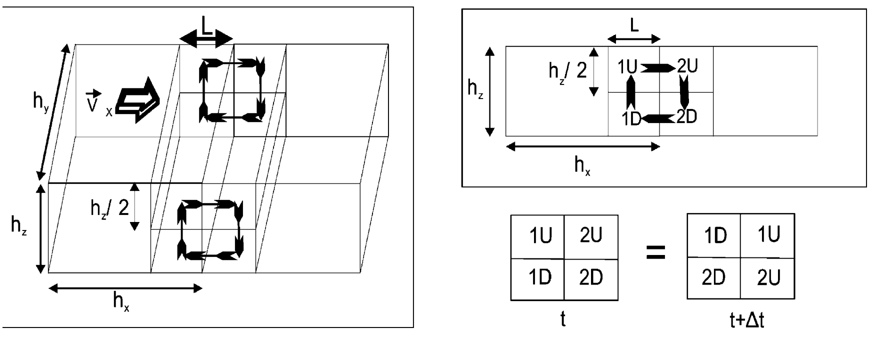

Fig. 5. Scheme of the mixing algorithm.

where the computational time steps $\{\Delta t_u, \Delta t_w\}$ have obviously been selected whilst bearing in mind the physical mechanisms involved, in order to assure a good mix in the area of length L.

The definition of L in this way, together with the exchange circuit, are the keys of the exchange algorithm since its application implicitly implies fulfilment of the fluid continuity equation and simultaneously avoids possible accumulation of particles in the coastal zones.

After the definition of the exchange mechanisms we have all the tools necessary to calculate the changes in the number of particles and in the activity in cell 1 $\{\Delta N_1, \Delta a_1\}$, after a mixing process shared with cell 2 (for time Δt). These details are included in Appendix A to make the line of this manuscript easier to follow, and can be better understood looking at Figs. 5 and 6. In these calculations we have interpolated activity $a(x)$ with function $A(x)$, being for that reason the numerical dispersion negligible compared to other approximations of our model.

Finally, in this formulation, and as an essential step, a simplification is performed: the transport produced by the annual mean flow $\vec{v}^m$ has been deliberately omitted. This simplification is based in the fact that in the majority of stations where the different components of the total velocity are known, the components of $\vec{v}^m$ are much lower than the components of $\vec{v}' = \vec{u}' + \vec{w}'$. In fact, for the simulation that we would like to perform (of the radionuclide dispersion for one year after the Chernobyl accident) the typical displacement of a particle in the system can be evaluated as tenths of kilometres, which can be ignored in relation with the eddies of hundreds of kilometres associated to $\vec{v}^m$. However, in the future, if we want to

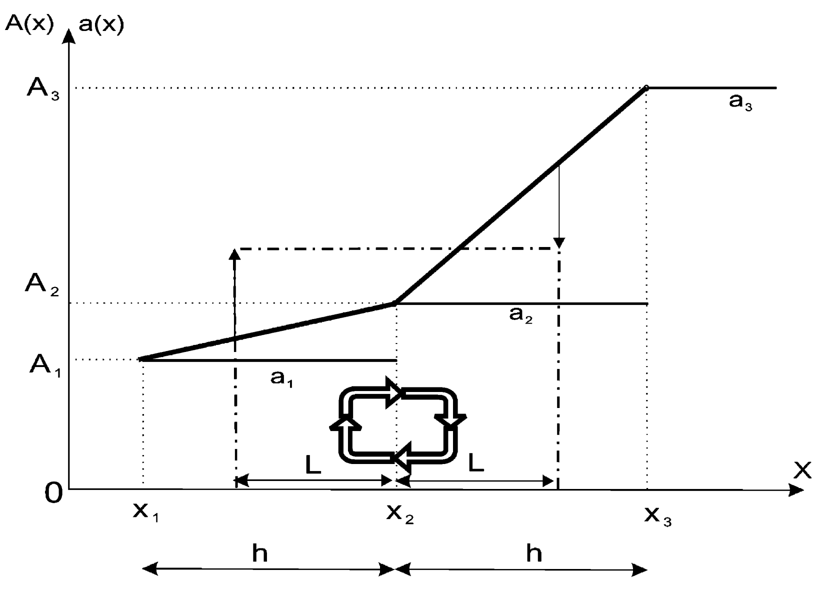

Fig. 6. One-dimensional scheme of the mixing algorithm.

simulate the dispersion of any contaminant for several years in the Baltic Sea, the implementation of advective eddies ($\vec{v}^m$) in the model will be obligatory.

The aforementioned simplification, on the other hand, does not invalidate the utility of the formulated circulation sub-model, since the simulations carried out for the determination in each cell of the large-scale velocity fluctuations, $\vec{w}'$, are based on the output of this sub-model.

3. 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. This particular time interval was selected for those reasons detailed in the introduction of this work, and fits with the restrictions imposed by the simplifications carried out in the formulation of the model.

The experimental spatial distribution maps of the ^{137}Cs concentrations on the initial and the final simulation dates, (see Figs. 7 and 8) have been reconstructed from experimental values found in several radiological journals (Gritchenko et al., 1989a; Gritchenko et al., 1989b; Nies, 1989), by applying the needed lineal

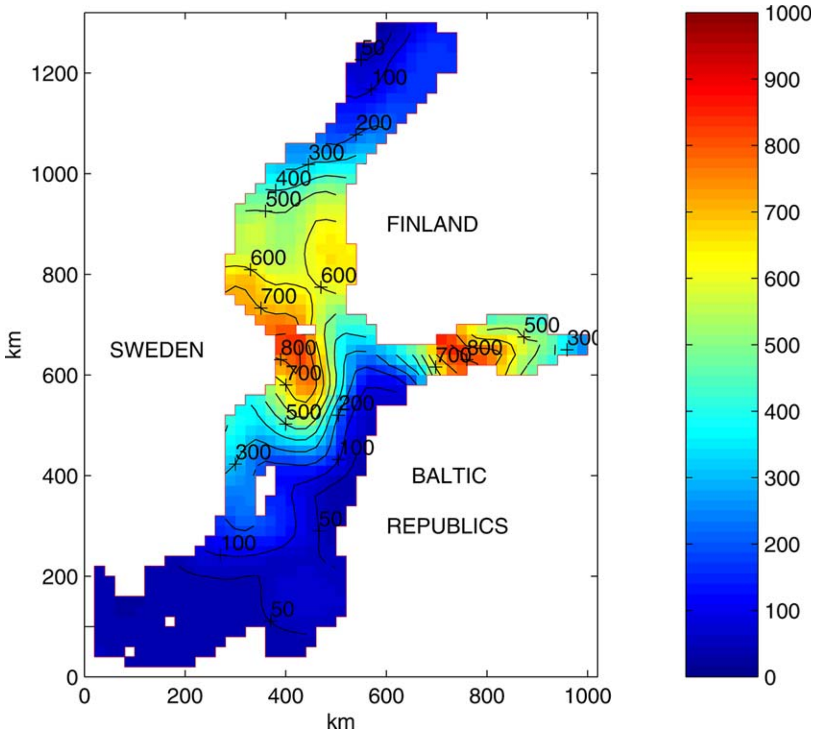

Fig. 7. Experimental ^{137}Cs specific activity distribution (Bq/m^3) at the surface of the Baltic Sea in summer 1986 (initial conditions).

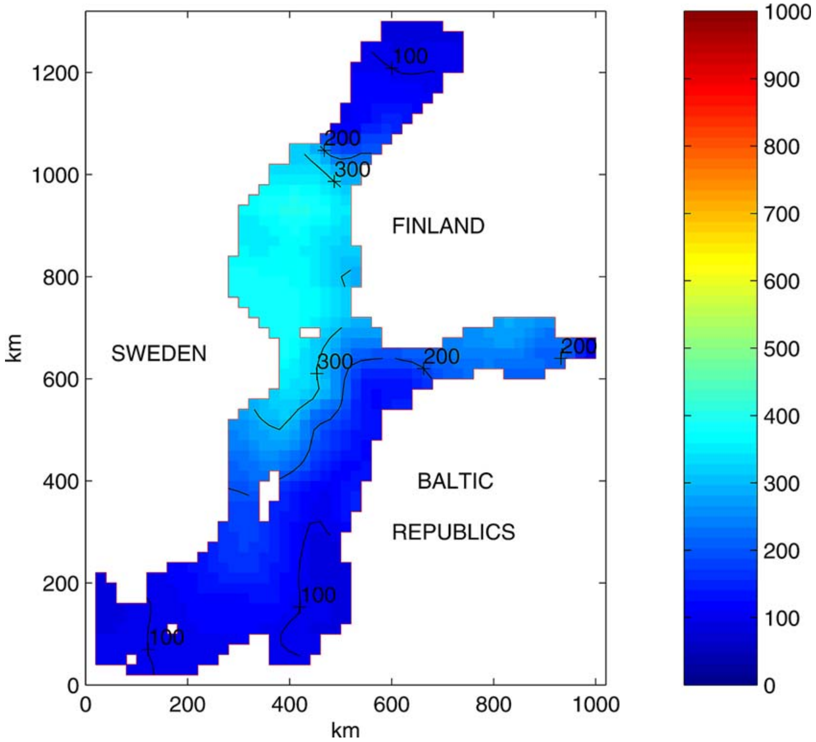

Fig. 8. Experimental ^{137}Cs specific activity distribution (Bq/m^3) at the surface of the Baltic Sea in summer 1987 (final conditions).

interpolations in accordance with the dimensions of our mesh. The initial ^{137}Cs distribution (June, 1986) has been implemented to the model as initial conditions to carry out the simulation, while the final experimental ^{137}Cs distribution (June, 1987) has been used for validation purposes by comparing it with the modelled spatial distribution obtained after the simulation.

All the simulation was carried out using the code Matlab 5.3 on a personal computer AMD-1.4 GHz. The computation time needed for the simulation of the complete year (summer 1986–summer 1987) was approximately 7 h.

In the performed simulation, two different time steps have been chosen for the execution of the model: $\Delta t_w = 3$ days and $\Delta t_u = 6$ h 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 $\Delta t_s = 6$ h as time step.

The selected simulated period (one year), is also clearly lower than the typical residence time of the waters in the Baltic Sea. Taking into account that the Atlantic Ocean, through the Kattegat strait, contributes with fairly high water residence periods (half-lives of 20–25 years) due to the relatively narrow and superficial transition interface (Svansson, 1980) together with the fact that in June 1986 the higher ^{137}Cs concentrations were moderately far from the strait which connects the Baltic Sea with the North Sea, it can be assumed that the influence of the North Sea in the spatial distribution of ^{137}Cs would be small in the time interval simulated. Hence, the influence of the waters which enter the Baltic Sea through the Kattegat strait has been deliberately omitted in our model.

The dispersion model gives the ^{137}Cs spatial distributions for the six layers in which the Baltic Sea has been divided. In order to be brief, not all the results are shown in this paper although good agreements are obtained with the experimental spatial distributions, independent of the layer considered.

As an example, only the modelled ^{137}Cs distribution map for the superficial layer, in June 1987, is going to be shown, which needs to be compared with the experimental distribution map shown in Fig. 8. Fig. 9 corresponds to $\lambda = 1$ (Eq. (4)), while Fig. 10 corresponds to $\lambda = 2$. The satisfactory agreement is evident.

Additionally, the model gives additional detailed information about the magnitude and spatial distribution of the ^{137}Cs deposited activities on the Baltic Sea bed.

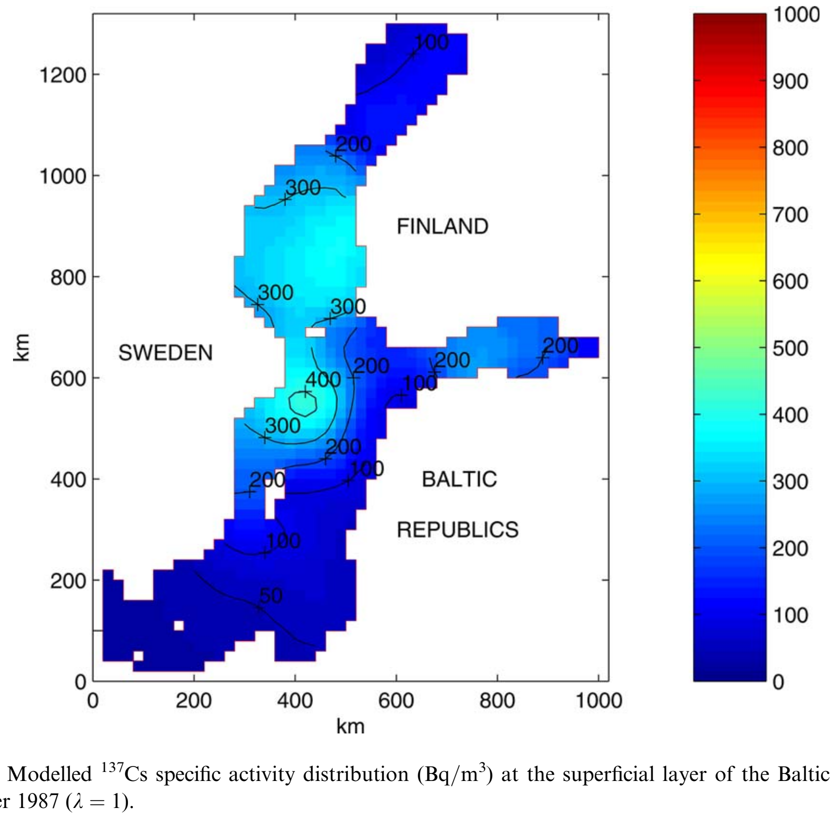

Fig. 9. Modelled ^{137}Cs specific activity distribution (Bq/m^3) at the superficial layer of the Baltic Sea in summer 1987 ($\lambda = 1$).

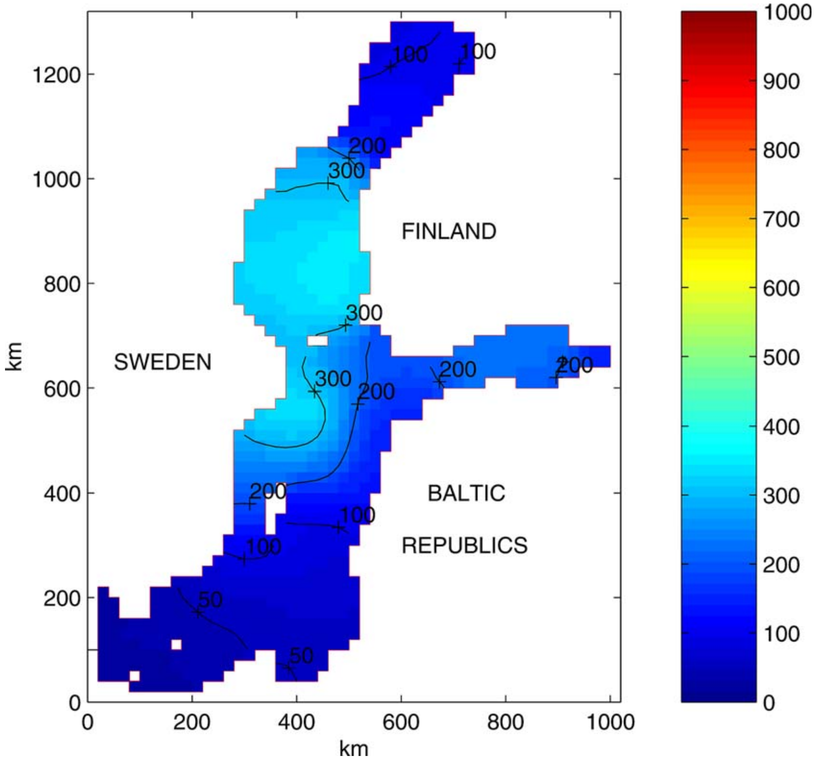

Fig. 10. Modelled ^{137}Cs specific activity distribution (Bq/m^3) at the surface of the Baltic Sea in summer 1987 ($\lambda = 2$).

The modelled spatial distribution map corresponding to the ^{137}Cs deposited activities in June 1987, is shown in Fig. 11.

From this spatial distribution, information has been extracted about the modelled ^{137}Cs deposited activities at a set of specific points which correspond with several stations located in different basins of the south, centre and north of the Baltic Sea and where the radionuclide ^{137}Cs have been measured in sediment cores. The comparison between the deposited activities determined experimentally at the aforementioned stations and the modelled deposited activities at the same points are reflected in Fig. 12.

From this figure, it is possible to deduce the existence of an acceptable correlation between the experimental and modelled values. This is an additional proof of the validity and power of our model. However, for a proper evaluation of this comparison it is necessary to take into account that the modelled ^{137}Cs deposited activities only reflects the deposition of this element until June 1987 with its origin in the Chernobyl accident, while the experimental ^{137}Cs deposited activities on the same date include, in addition to the Chernobyl contribution, the deposition of this radionuclide before the Chernobyl accident originating from the world-wide ^{137}Cs

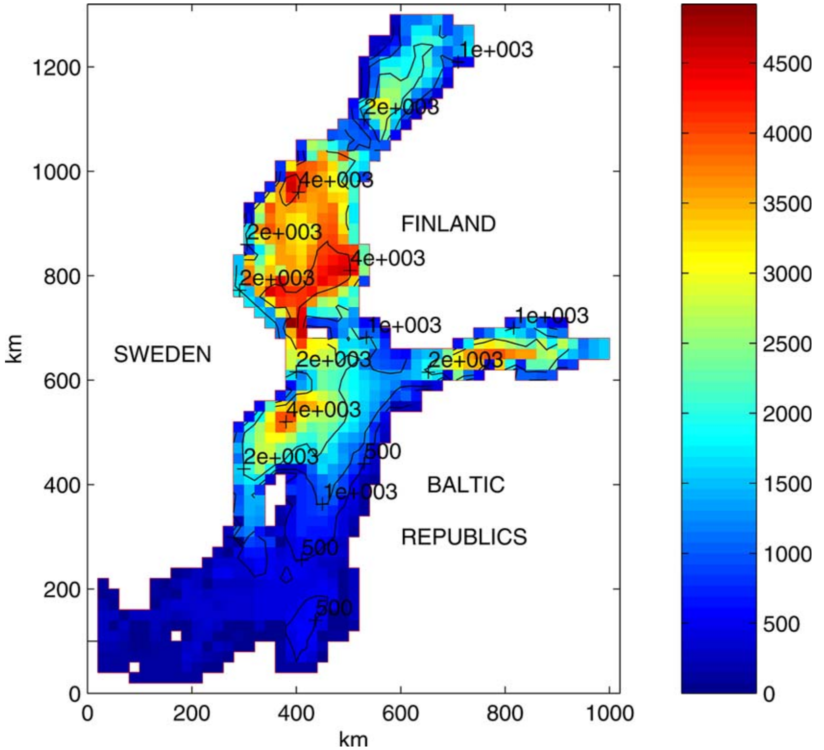

Fig. 11. Modelled ^{137}Cs deposition (Bq/m^2) at the seabed of the Baltic Sea one year after the Chernobyl accident.

contamination caused by weapon test fallout. Nevertheless, in June 1987, the ^{137}Cs weapon-test contribution to the experimental deposited activities values in the sediment cores measured in the Baltic Sea has minor influence on the total ^{137}Cs deposited amount due to the extremely high ^{137}Cs contamination caused by the Chernobyl accident in the Baltic Sea.

4. Conclusions

This implemented model is formed by three sub-models (circulation, diffusion and sedimentation), together with appropriate numerical and mixing algorithms. This model is characterized by the following features: a) it has a high spatial resolution, b) the diffusive transport is simulated by using an original approach based on the application of the Monte Carlo method and using small- and large-scales for mixing, and c) the sedimentation of a fraction of the contaminants bounded to the existing suspended matter is considered, evaluated and simulated. 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.

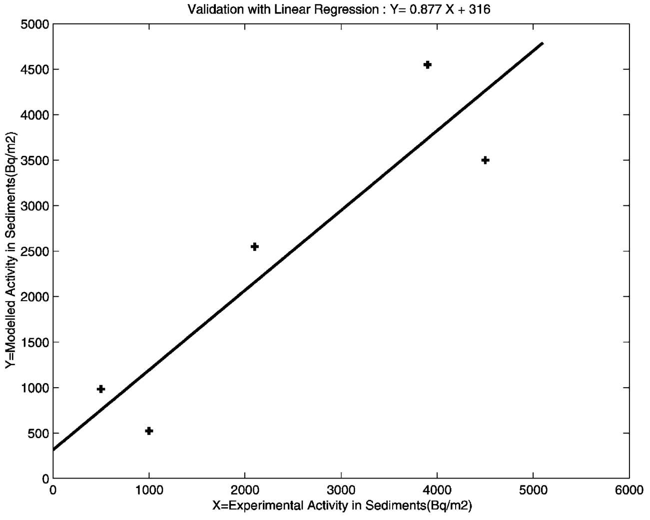

Fig. 12. Comparison between the experimental and modelled ^{137}Cs deposition activities (Bq/m^2) at several stations of the Baltic Sea (summer 1987).

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. However, an additional validation has also been obtained by comparing the modelled ^{137}Cs deposited activities on the Baltic sea bed for June 1987 with the experimental ^{137}Cs deposited activities determined at this date at specific points of this ecosystem.

Appendix A

This appendix is to calculate $\{\Delta N_1, \Delta a_1, \Delta N_2, \Delta a_2\}$. It must be follow in conjunction with Figs. 5 and 6.

$$\left\{ \begin{array}{l} \Delta N_1 = N_1(t+\Delta t) - N_1(t) = (N_{1D} + N_{2D}) - (N_{1U} + N_{1D}) = N_{2D} - N_{1U} \\ By \quad conservation: \quad \Delta N_2 = -\Delta N_1 \end{array} \right\}$$

Now we must calculate $\{N_{1U}, N_{1D}, N_{2U}, N_{2D}\}$:

$$\left\{ \begin{array}{l} N_{1U} = N_{1D} \\ N_{1U} + N_{1D} = \dfrac{A(x_2 - L) + A_2}{2} L \end{array} \right\} \quad and \quad \left\{ \begin{array}{l} N_{2U} = N_{2D} \\ N_{2U} + N_{2D} = \dfrac{A_2 + A(x_2 + L)}{2} L \end{array} \right\}$$

where

$$A(x_2 - L) = A_2 - A_1' L; \quad A(x_2 + L) = A_2 + A_2' L$$

and the derivatives are:

$$\frac{\mathrm{d}A(x)}{\mathrm{d}x} = \begin{cases} A_1' & x \in (x_1, x_2) \\ A_2' & x \in (x_1, x_2) \end{cases}; \quad \frac{\mathrm{d}^2 A(x)}{\mathrm{d}x^2} = \frac{A_2' - A_1'}{h} = A''$$

After solving this system of equations we have:

$$N_{1U} = N_{1D} = \frac{L}{4}\left(2A_2 - A_1' L\right); \quad N_{1U} = N_{1D} = \frac{L}{4}\left(2A_2 + A_2' L\right)$$

and therefore:

$$\boxed{\Delta N_1 = \frac{L^2}{4h}(A_3 - A_1)}; \quad \boxed{\Delta a_1 = \frac{L^2}{4h^2}(a_3 - a_1)}$$

Obviously:

$$\Delta N_2 = \frac{L^2}{4h}(A_1 - A_3); \quad \Delta a_2 = \frac{L^2}{4h^2}(a_1 - a_3)$$

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