Using Oceanography To Control And Forecast Nuclear Accidents And Other Passive Particles Problems

M. Toscano-Jimenez, J.M Abril & R.Garcia-Tenorio

Engineering School. Applied Physics Department, University of Sevilla, Spain.

e-mail: mtoscano@esi.us.es Fax: +34 95 4 48 60 03

Abstract.-

This article is the last improved version of a previously published model [18] for the transport of the nuclear contamination and other passive particles in the ocean. Two interesting advances have been developed during last two years for my *PhD thesis* to be finished in the next months:

***(a)* A Suspended Particulate Matter (S.P.M.) sub-model, including erosion, transport and sedimentation.**

***(b)* A new advection-diffusion approach with numerical and computational improvements: Finite Elements (FE), Finite Differences (FD) and Monte Carlo (MC) methods have been compared and calibrated.**

These studies will be submitted to two different scientific journals to become an added guarantee of my PhD work.

The *Baltic Sea* has been elected as the validation scenario of the model and the radioisotope Cs^{137} is 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.

However, an important aim of this model is its potential usefulness in other oceanic scenarios affected by a nuclear disaster in the future. It could be an interesting tool to predict and minimize the ecological and economical *impacts of future accidents*. This model can also be extended easily to non-nuclear contamination problems such as: *oil accidents, nutrients dynamics and other biological problems*.

I. INTRODUCTION

It must be noted that the model is three-dimensional and its horizontal resolution is *10 km*, while for the vertical resolution a total of six layers are considered. A computation time of approximately *12 hours* was necessary to simulated *1 meteorological year*, using a *Matlab* code in a personal computer (AMD-1.4 GHz).

Some approaches adopted allow to save a lot of computational time [17] and minimize numerical errors.

The Circulation sub-model is based on some studies developed in the *S.M.H.I.* (Swedish Meteorological and Hydrological Institute).

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 have been modelled: *small* (kilometres), *medium* (decades of *km*), and *large* (hundreds of *km*)

Experimental information on current spectra has been analysed to be included in the circulation, diffusion and erosion-sedimentation sub-models. 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} data, either in the water column or in the sediments, thereby guaranteeing the validity of the model.

II. A SUSPENDED PARTICULATE MATTER (S.P.M.) SUB-MODEL

An important fraction of passive particles can be fixed to the suspended matter phase present in the water column, and consequently can be deposited on the seabed.

The logarithmic grain size has been used to classify the sediments:

$$\phi = -\log_2 \frac{d}{d_o} \quad d \equiv diameter \quad d_o = 1mm \qquad (1)$$

The grain size distribution (figure ?) has been modelled with a five class scheme (Bobertz et. al, 2004), and a modified Fermi function:

$$\left\{ \begin{array}{l} F(x) = 1 \Big/ \left[1 + \exp\left(-A \dfrac{x - x_{med}}{\sigma - sk \cdot \tanh(x - x_{med})} \right) \right] \\ F(x): \; \textit{Relative weight of grains below a given size x; A=1.7} \\ \{ x_{med}, \sigma, sk \} : \{ \textit{mean, variance, assimetry} \} \; \textit{parameters} \end{array} \right\} (2)$$

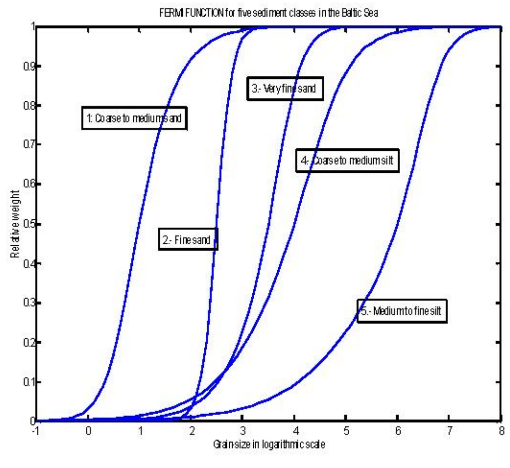

Fig. 1. Grain-size distribution (Femi Function) for five sediment classes (coarse-medium sand, fine sand, very fine sand, coarse-medium silt, medium-fine silt) in the system.

A good correlation between the depth and class has been found in the Baltic Sea, and the next map (figure 2) has been calculated for this work.

1-4244-0635-8/07/$20.00 ©2007 IEEE

The velocity v^* is defined in relation to the bottom stress τ, $\tau = \rho\,(v^*)^2$; and the fine particles (silt and clay) have modelled with three diameters $\phi = \{4, 7, 10\}$.

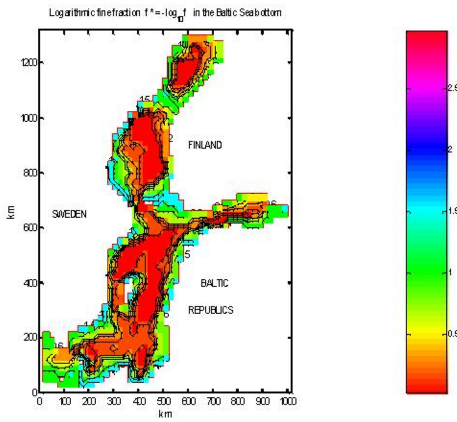

Fig. 2. Logarithmic fine fraction calculated for the Baltic Sea bottom.

On the one hand, the resuspension events take place [11] if the velocity $v^* \geq \{1,2,3\}\,cm/s$ for the diameters $\phi = \{4, 7, 10\}$. On the other hand, a mean sinking velocity $w_{sink} = 4.10^{-4}\,cm/s$ was chosen, with the next information about the erosion rate *ER* ([7],[14]):

$$\left\{ \begin{array}{c} ER = E \cdot f \cdot \left(\dfrac{\tau}{\tau_{ce}} - 1 \right) ;\ E : erosion\ constant \\ E = 0.04 gm^2/s\ ;\quad f : fraction\ of\ small\ particles \\ \tau_{ce}\ ,\ critical\ erosion\ stress\ : \\ \tau_{ce} \in [0.1, 1.5] N/m^2\ ;\ \overline{\tau}_{ce} = 0.4 N/m^2 \end{array} \right\} \quad (3)$$

A published work [9] about seasonal spectra of v^* have been used to calculate next tables (I and II).

TABLE I:
EVOLUTION OF $v^*_{max}(cm/s)$ DURING A METEOROLOGICAL YEAR.

Dec-Jan	*Feb - Mar*	*Apr - May*	*Jun - Jul*	*Aug - Sep*	*Oct - Nov*
6	4	3	2	3	4
5	3	2	1.5	2	3
4	2.5	1.75	1.25	1.75	2.5
3	2	1.5	1	1.5	2
2	1.5	1	0.5	1	1.5

TABLE II:
RESUSPENSION FREQUENCY IN THE SYSTEM

$v^*_{max}(cm/s)$	2	2.5	3	4	5	6
Events/year	1	3	7	31	44	69

An interesting map of $v^*_{max}(x,y)$ in the Baltic bottom [9] together with last two tables has completed the resupension dynamics of this work.

The initial conditions were $SPM(x,y,t=0) = 4 g/m^3$. The shore line, the rivers (mainly Neva, Vistula and Oder), and the organic primary production have played an important role as S.P.M. sources in accordance with the scientific literature.

The S.P.M. concentration $SPM(g/m^3)$, together with the sedimentation rate $SR(g/m^2/y)$ have been modelled and validated for this article(figures 3 and 4).

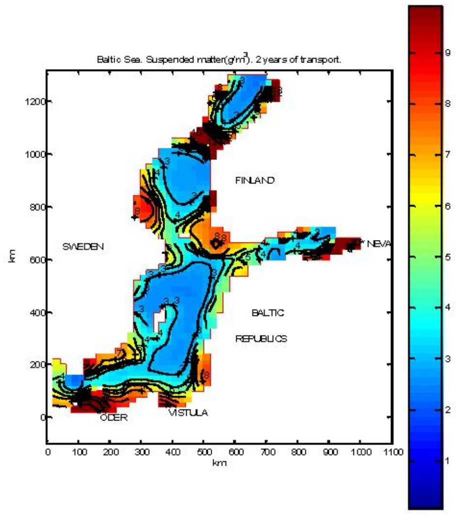

Fig. 3. Modelled $SPM(g/m^3)$ in the Baltic Sea for a typical January.

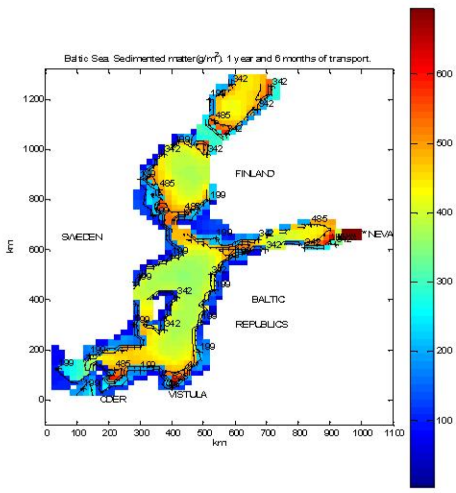

Fig. 3. Modelled *Sedimentation Rrate* (g/m^2) after 1.5 years of transport.

III. NUMERICAL METHODS

The Monte Carlo (MC) method has been calibrated (4) and compared with the Finite Differences (FD) method.

$$\left\{ \begin{array}{l} \textbf{2-D Calibration functions:} \\ A(x,y,t) = \dfrac{A_o}{4}\left[erf\left(\dfrac{x + h/2}{\sqrt{2}\sigma_x(t)} \right) - erf\left(\dfrac{x - h/2}{\sqrt{2}\sigma_x(t)} \right) \right] \cdot \\ \left[erf\left(\dfrac{y + h/2}{\sqrt{2}\sigma_y(t)} \right) - erf\left(\dfrac{y - h/2}{\sqrt{2}\sigma_y(t)} \right) \right];\quad with : \sigma_x(t) = \sqrt{2K_x^{dif}t}\ ; \\ \sigma_y(t) = \sqrt{2K_y^{dif}t}\ ;\ erf(z) = \dfrac{2}{\sqrt{\pi}} \displaystyle\int_0^z e^{-x^2} dx \end{array} \right\} \quad (4)$$

The MC method has been found to be better than FD method for dispersion problems with high gradients in concentrations functions, such as point-source accidents, spillages and biological blooms. It must be underlined that the MC method has been the best one to solve the numerical dispersion problem.

The 2D diffusion (K_{dif}=$250m^2$ /s) of a square (h=$20km$) spot is being simulated and calibrated (figures 5,6 and 7).

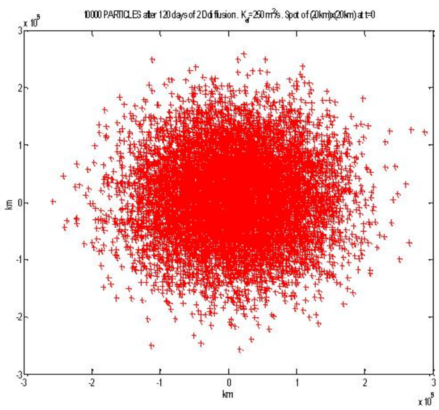

Fig. 5: Calibration of a 2D diffusion problem using 10000 particles, K_{dif}=$250m^2$ /s, 3 months of transport.

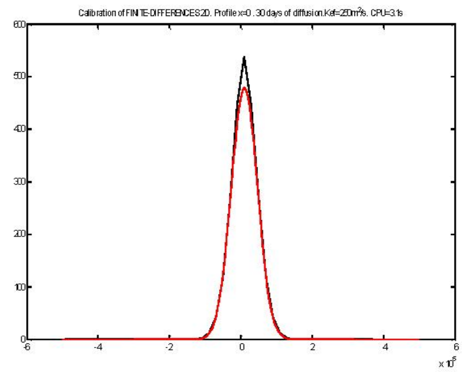

Fig. 5: Calibration of the FD method, 1 month of diffusion. CPU-time=3.1 s.

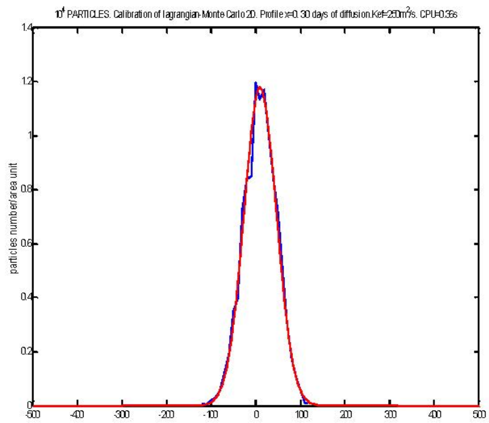

Fig. 5: Calibration of the MC method, 1 month of diffusion. CPU-time=0.36s.

The calibration of the advection has been successfully solved; the numerical dispersion has been controlled by the Prandle formula ([1],[13]) $K_{dif}^{num} = (\Delta x - v\Delta t)v/2$, for non-magical conditions.

Another original question of this work is the development of MC Eulerian method based on a "quasi-particles" and splines scheme (figure 8). Similar properties as the FE method have been found.

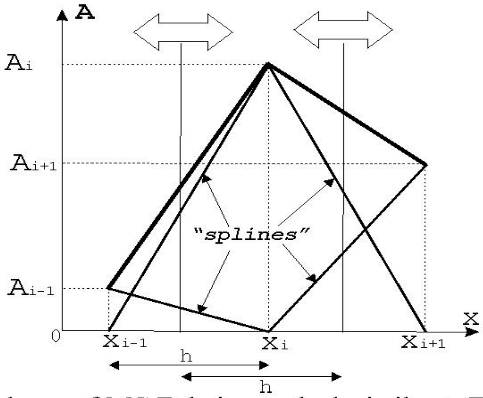

Fig. 8.- Scheme of MC Eulerian method, similar to FE method.

IV. CURRENTS MODELLING

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 ($\vec{v}'$).

$$\vec{v} = \vec{v}^m + \vec{v}' \qquad (5)$$

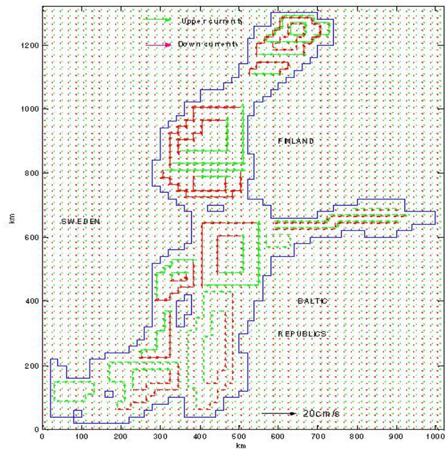

Fig. 9. Some circuits related to the annual mean currents in the Baltic Sea. Upper currents take place in the depths [0, 10]m, while down currents in [10, 20]m.

Special attention needs to be paid to [4], which modelled the average wind-driven currents in the Baltic Sea with horizontal resolution of 10 km. This model is based on a typical meteorological year with the most probable events and their results have been validated through comparison with some experiments [5].

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]. The figure 1 shows the annual mean velocities for the layer [0, 5]m: some circuits have been designed in this publication, keeping in mind the vertical currents influenced by up-welling and down-welling processes studied in [12].

Measurements in the Baltic Sea ([3] and [10]) show that current spectra have peaks for periods similar to those of wind spectra, i.e. in the order of days. 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:

$$\vec{v}' = \vec{u}' + \vec{w}' \qquad (6)$$

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.

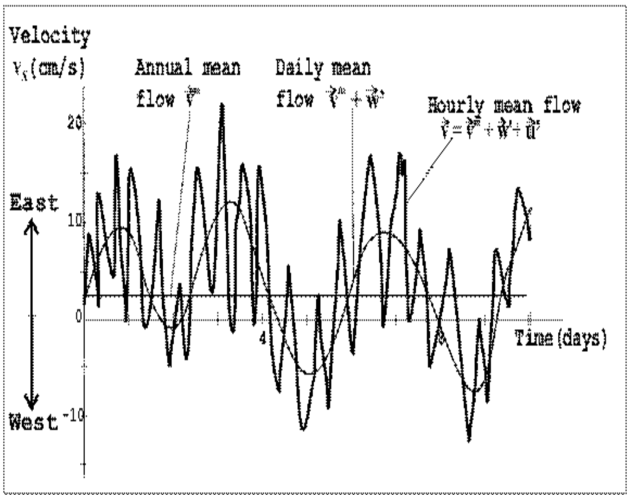

Fig. 10. A representative current spectrum (based on [3]) with the different mean flows proposed in this manuscript.

A. Small-scale horizontal diffusion.-

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:

$$\left\{ \begin{aligned} \sigma(u'_x) &\equiv \sqrt{\overline{(u_x')^2}} = \sqrt{\frac{K_x}{T_x}} \\ \sigma(u'_y) &\equiv \sqrt{\overline{(u_y')^2}} = \sqrt{\frac{K_y}{T_y}} \end{aligned} \right\} (7)$$

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 (7) we have used a set of average experimental values of K_x, K_y, T_x, and T_y compiled in [5]. The values of the average horizontal-diffusion coefficients which are compiled in Table I.

TABLE III
HORIZONTAL DIFFUSION COEFFICIENTS, $\{K_x, K_y\}$ (m^2/s), USED IN THE SMALL-SCALE DIFFUSION

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

B. Small-scale 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. The average vertical-diffusion (table IV)coefficients are applicable to every location of the system analysed.

TABLE IV
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

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 (7) 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.

C. Large-scale diffusion.-

Observations and analyses carried out at several stations distributed over the Baltic Sea indicate that it can be assumed (8) for the simulation of large-scale fluctuations:

$$\left\{ \begin{aligned} &\overline{w_x'} = \overline{w_y'} = 0\ ;\ \sigma(w_x') \equiv \sqrt{\overline{(w_x')^2}} = \sqrt{\frac{K_{w,x}}{T_{w,x}}} \\ &\sigma(w_y') \equiv \sqrt{\overline{(w_y')^2}} = \sqrt{\frac{K_{w,y}}{T_{w,y}}} \end{aligned} \right\} (8)$$

Therefore, based on (8), 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 $\left\{v'_x, v'_y\right\}$. The timescales and the variance of the velocities because of winds were in the intervals:

$$\left\{\sigma(w'_{x,y}) \in [3,10]\, cm/s \;;\; T_{w,xy} \in [1,3]\, days\right\} \quad (9)$$

V. OTHER VALIDATIONS AND 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.

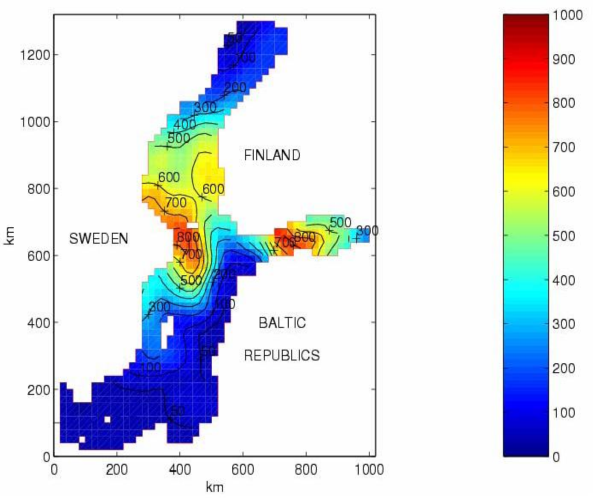

Fig.11.- Experimental ^{137}Cs specific activity distribution (Bq/m^3) at the surface of the Baltic Sea in summer 1986 (initial conditions), some weeks after the accident of CHERNOBYL.

The experimental spatial distribution maps of the ^{137}Cs concentrations on the initial and the final simulation dates, (see Figures 11 and 12) have been interpolated from experimental values found in several radiological journals ([6]and [15]).

All the simulation was carried out using the code Matlab 7 on a personal computer AMD-1.4 GHz. The computation time needed for the simulation of the complete year (summer´86-summer´87) was approximately 12 hours.

In the performed simulation, two different time steps have been chosen for the execution of the model: $\Delta t_w = 1\, days$ 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 12. Figure 13 corresponds to $K_{w,xy}$=*150m*^{2} */s* (Equations 8). The satisfactory agreement is evident.

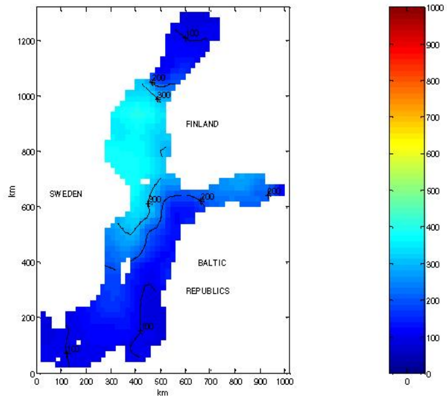

Fig. 12. Experimental ^{137}Cs specific activity distribution (Bq/m^3) at the surface of the Baltic Sea in summer 1987 (final conditions).

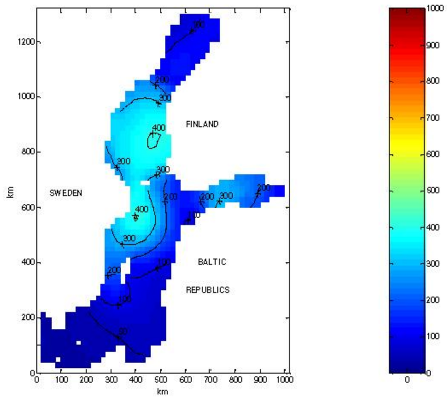

Fig. 13. Modelled ^{137}Cs specific activity distribution (Bq/m^3) at the superficial layer of the Baltic Sea in summer 1987, with and an average value $K_{w,xy}$=*150m*^{2} */s* (mild winds) .

VI. SOME CONCLUSIONS

The Monte Carlo method has been found to be better than Finite Differences method for dispersion problems with high gradients in the concentrations functions, such as point-source accidents (oil or nuclear accidents), spillages and biological blooms. It must be underlined that the MC method has been the best one to solve the numerical dispersion problem.

In the present work, the first S.P.M. model of the Baltic Sea as a whole has been presented, and also the first 3D radio-ecological model [18] of this important ecosystem.

The Cs^{137} model predictions are in an acceptable agreement with the experimental Cs^{137} data, either in the water column or in the sediments, thereby guaranteeing the validity of the model.

REFERENCES

[1] J.M. Abril and M.G. Leon. 1992. "A Marine Dispersión Model for Rasdionuclides and its Calibration from Non-radiological Information" *J. of Environmental Radioactivity,* vol.2, pp.127-46

[2] B.Bobertz and J.Harff. 2004. "Sediment facies and hydrodynamica setting: a study of the Baltic Sea"*Ocean Dynamics,* vol.54, pp.39-48
[3] E. Franke. "A contribution to the investigations of the current conditions in the surface layer in the area of Darss Sill". [Proceedings 12th Baltic Oceanographic Conference, Leningrad,1980]
[4] L. Funkquist and L. Gidhagen. "A model for pollution studies in the Baltic Sea". *SMHI-Report* RHO-39, 1984
[5] L. Gidhagen, L. Funkquist and R. Murthy, "Calculations of horizontal exchange coefficients series current meter data from the Baltic Sea". *SMHI-Report* RO-1, 1986.
[6] Z.G. Gritchenko et al., "Radiation situation in the Baltic Sea in 1986 in sea water and sediments". *Three years observations of the levels of some radionuclides in the Baltic Sea after the Chernobyl accident. Baltic Sea environment proceedings,* vol.31 pp.10-30, Helsinki, 1989(a).
[7] J.T. Holt and I.D.James. 1999. *Continental Shelf Research*, vol. 19, pp. 1617-1642.
[8] D.J. Jansen et al. 2003. "Deposition of organic matter and paticulate nitrogen and phosphorus at the North Sea -Baltic Sea transition- a GIS study", Oceanologia, vol.45, No.1, pp. 283-303.
[9] A. Jonsson, A. Danielsson and L. Rahm. 2005. "Bottom type distribution based on wave friction velocity in the Baltic Sea". *Continental Shelf Research,* vol. 25, pp. 419-435
[10] ,J. Kielmann, W.Krauss and K.H. Kennecke, "Currents and stratification in the Belt Sea and the southern Arkona Basin during 1962-68". *Kieler Meeresforsh.,*vol. 29, 1973.
[11] C. Kuhrts, W. Fennel & T. Seifert. 2004. "Model studies of transport of sedimentary material in the western Baltic". *Journal of Marine Systems,* vol. 52, pp.167-190
[12] A.Lehmann and H.H. Hinrichsen. 2000. "On the wind driven and thermohaline circulation of the Baltic Sea", *Physics and Chemistry of the Earth(B)*, vol.25, No.2, pp.183-189.
[13] D.Prandle. 1984. *Phil. Trans. R. Soc. Lond. A.*, vol. 310, pp. 407-36
[14] W.Puls and J.Sundmann. 1990 "Simulation of suspended sediment dispersion in the North Sea".In: *Residual currents and long term transport.* pp.356-372
[15] A. Stigebrandt, A. 1983. "A model for the exchange of water and salt between the Baltic Skagerrak", *Journal of Physical Oceanography*, vol.13, pp.411-27, 1983.
[16] A. Svansson, "The water exchange of the Baltic", *Ambio Special Report,* vol.1, pp.15-19, 1972.
[17] M. Toscano-Jimenez and R. García-Tenorio, "Modelling The Dispersion Of ^{137}Cs In Marine Ecosystems With Monte Carlo Methods", *Nuclear Instruments And Methods B*, vol.213, pp.789-793, 2003.
[18] M. Toscano-Jimenez and R. García-Tenorio, "A Three-Dimensional Model For The Dispersion Of Radioactive Substances In Marine Ecosystems. Application To The Baltic Sea After The Chernobyl Disaster", *Ocean Engineering*, vol.31, pp.999-1018, 2004.
[19] A. Viopio, "The Baltic Sea". Elsevier, Amsterdam, pp.162-167, 1981.
[20] D. Weiss, "The distribution of radionuclides in bottom sediments of the Open Baltic Sea and Greifswald Bodden", *Three years observations of levels of some radionuclides in the Baltic Sea after the Chernobyl accident. Baltic Sea environment proceedings,* vol.31 pp.94-122, Helsinki, 1989.