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Modelling of marine radionuclide dispersion in IAEA☆ MODARIA program: Lessons learnt from the Baltic Sea and Fukushima scenarios

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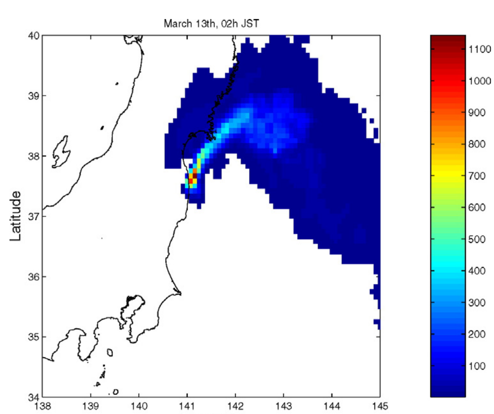
HIGHLIGHTS

- Models applied to simulate ^{137}Cs marine dispersion after nuclear accidents.
- Not good agreement initially found in highly dynamic environments.
- Difficulties in developing models for decision making after emergencies highlighted.

GRAPHICAL ABSTRACT



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ABSTRACT

State-of-the art dispersion models were applied to simulate ^{137}Cs dispersion from Chernobyl nuclear power plant disaster fallout in the Baltic Sea and from Fukushima Daiichi nuclear plant releases in the Pacific Ocean after the

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2011 tsunami. Models were of different nature, from box to full three-dimensional models, and included water/sediment interactions. Agreement between models was very good in the Baltic. In the case of Fukushima, results from models could be considered to be in acceptable agreement only after a model harmonization process consisting of using exactly the same forcing (water circulation and parameters) in all models. It was found that the dynamics of the considered system (magnitude and variability of currents) was essential in obtaining a good agreement between models. The difficulties in developing operative models for decision-making support in these dynamic environments were highlighted. Three stages which should be considered after an emergency, each of them requiring specific modelling approaches, have been defined. They are the emergency, the post-emergency and the long-term phases.

1. Introduction

The International Atomic Energy Agency (IAEA) has organized programmes on radioactivity dispersion model testing since the VAMP (Validation of Model Predictions) program in 1988 (see IAEA, 2000, for the aquatic group work). The most recent effort is the MODARIA[1] (Modelling and Data for Radiological Impact Assessments) project, launched in 2012. Ten working groups were organized in four main topics: Remediation of Contaminated Areas, Uncertainties and Variability, Exposures and Effects on Biota, and Marine Modelling.

Because of recent developments in marine science and marine modelling, as well as the radioactive pollution due to the Fukushima Daiichi nuclear power disaster in March 2011, it was considered worthwhile to carry out a new exercise on dispersion model comparisons for the marine environment. Marine modelling draws special attention after the catastrophic earthquake and tsunami which severely damaged the Fukushima Daiichi Nuclear Power Plant (FDNPP) and resulted in uncontrolled release of radioactivity into the air and ocean. Approximately 80% of the radioactivity released due to the accident in March–April 2011 was either directly discharged into the ocean or deposited onto the ocean surface from the atmosphere (Povinec et al., 2013). ^{137}Cs concentrations in the ocean reached a maximum in mid-April of 2011 and have thereafter quickly declined. However contamination of the bottom remains quite high, showing sign of a slow decrease with time.

Working Group 10 (Modelling of marine dispersion and transfer of radionuclides accidentally released from land-based facilities) was consequently defined within MODARIA. It included experts from the following institutes and countries: Instituto de Engenharia Nuclear (IEN/CNEN, Brasil), Institut de Radioprotection et de Sûreté Nucléaire (IRSN, France), National Technical University of Athens (NTUA, Greece), Japan Atomic Energy Agency (JAEA, Japan), Korea Institute of Ocean Science and Technology (KIOST, Republic of Korea), Korea Atomic Energy Research Institute (KAERI, Republic of Korea), Norwegian Radiation Protection Authority (NRPA, Norway), University of Seville (USEV, Spain), Institute of Mathematical Machines and System Problem (IMMSP, Ukraine) and Ukrainian Centre of Environmental and Water Projects (UCEWP, Ukraine).

State-of-the-art models were assessed in the frame of this project. Models showing different characteristics and levels of complexity, from those based on a box-type approach to those making use of the shallow-water and advection/diffusion equations were tested. The performed exercises provided the opportunity to learn more about the appropriate usage of models for the management of complex environmental problems in view of the uncertainty and, often, of the vagueness of the input data, the uncertainty of the model parameters and the compatibility of different kinds of models applied to a specific contamination scenario.

In particular, two contamination scenarios were investigated: deposition and subsequent dispersion of ^{137}Cs on the Baltic Sea from the Chernobyl nuclear power plant disaster in 1986 and the dispersion of ^{137}s released from Fukushima Daiichi nuclear power plant in the Pacific Ocean after the earthquake and tsunami in March 2011 (originating from both liquid releases into the ocean and from atmospheric deposition on the sea surface). Significants amounts of ^{137}Cs were introduced in the marine environment as a consequence of these accidents. In particular, 4.7 PBq were deposited on the Baltic Sea after Chernobyl (HELCOM, 2013). Regarding Fukushima accident, it was estimated (Kobayashi et al., 2013) that 3.5 PBq of ^{137}Cs were introduced in the Pacific Ocean from March 26th to June 30 due to direct releases and leakages from the plant. Additionally, about 6 PBq were deposited on the ocean surface between March 12th and April 6th (Min et al., 2013; Kawamura et al., 2011).

Although a detailed description of the modelling exercises was given in separate papers [Periáñez et al. (2015a,b) for the Baltic and Fukushima respectively], the objective of this paper consists of providing a discussion on the lessons learnt from both scenarios.

2. Methods

Models which participated in the exercises are listed in Table 1, where appropriate references for detailed descriptions are included. They range from box models to finite difference and finite element numerical models solving simultaneously the Navier-Stokes equations for water circulation together with a sediment transport model and the radionuclide dispersion model including adsorption/release of radionuclides between water and the solid phases (suspended matter in the water column and bed sediments). Also, both Eulerian and Lagrangian dispersion models were tested.

In the case of the Baltic Sea four models were applied. They were two box-models: NRPA and POSEIDON; a 2D depth-averaged model forced by annual mean wind: USEV-2D; and a full 3D model including thermodynamics: THREETOX. In the case of Fukushima box models were not applied. Instead, all models were Eulerian or Lagrangian three dimensional dispersion models. The origin of the water circulation fields

Table 1
Models participating in the exercises.

Institute and country	Model	Scenario[a]	Reference
NRPA, Norway	Box model	BS	Iosjpe et al. (2002, 2009)
IMMSP, Ukraine	POSEIDON	BS	Lepicard et al. (2004)
IMMSP, Ukraine	THREETOX	BS	Maderich et al. (2008)
USEV, Spain	USEV-2D	BS	Periáñez et al. (2013)
IMMSP/KIOST, Ukraine/Rep. of Korea	I/K-E (Eulerian) I/K-L (Lagrangian)	F	Roland et al. (2012)
KAERI, Rep. of Korea	LORAS	F	Min et al. (2013)
IEN, Brasil	SisBahia	F	Lamego (2013)
JAEA[b], Japan	SEA-GEARN	F	Kobayashi et al. (2007)
USEV, Spain	USEV-3D	F	Periáñez et al. (2012)

[a] BS, Baltic Sea; F, Fukushima.
[b] JAEA has applied the model in two configurations: finite differences (JAEA FDM) and particle-tracking (JAEA PT).

[1] http://www-ns.iaea.org/projects/modaria/default.asp?l=116